

Portland State University

PDXScholar

Environmental Science and Management
Faculty Publications and Presentations

Environmental Science and Management

12-31-2010

Urban and Rural-residential Land Uses: Their Role in Watershed Health and the Rehabilitation of Oregon's Wild Salmonids

Michael Harte
Oregon State University

Victor W. Kaczynski

Clinton C. Shock
Oregon State University

J. Alan Yeakley
Portland State University, yeakley@pdx.edu

Robert M. Hughes
Oregon State University

Follow this and additional works at: https://pdxscholar.library.pdx.edu/esm_fac
See next page for additional authors



Part of the [Environmental Health and Protection Commons](#), [Sustainability Commons](#), and the [Water Resource Management Commons](#)

Let us know how access to this document benefits you.

Citation Details

Independent Multidisciplinary Science Team (2010) Urban and Rural-residential Land Uses: Their Roles in Watershed Health and the Recovery of Oregon's Wild Salmonids. Technical Report 2010-1. Oregon Plan for Salmon and Watersheds, Oregon Watershed Enhancement Board. Salem, Oregon.

This Technical Report is brought to you for free and open access. It has been accepted for inclusion in Environmental Science and Management Faculty Publications and Presentations by an authorized administrator of PDXScholar. Please contact us if we can make this document more accessible: pdxscholar@pdx.edu.

Authors

Michael Harte, Victor W. Kaczynski, Clinton C. Shock, J. Alan Yeakley, Robert M. Hughes, Nancy Molina, and Carl B. Schreck

Urban and Rural-residential Land Uses: Their Role in Watershed Health and the Rehabilitation of Oregon's Wild Salmonids

IMST Technical Report 2010-1

Released December 31, 2010



Independent Multidisciplinary Science Team

Oregon Plan for Salmon and Watersheds
<http://www.fsl.orst.edu/imst>

Members:

Michael Harte
Vic Kaczynski
Clinton Shock
Alan Yeakley

Robert M. Hughes
Nancy Molina
Carl Schreck

Citation

Independent Multidisciplinary Science Team (2010) *Urban and Rural-residential Land Uses: Their Roles in Watershed Health and the Recovery of Oregon's Wild Salmonids*. Technical Report 2010-1. Oregon Plan for Salmon and Watersheds, Oregon Watershed Enhancement Board. Salem, Oregon.

Acknowledgements

This IMST report is based on initial draft documents prepared by current and previous IMST subcommittees* that included Robert M. Hughes, Alan Yeakley, Carl Schreck, Michael Harte, Stan Gregory, Logan Norris, and Jim Lichatowich. The subcommittee that managed the final draft of the report was composed of Alan Yeakley, Robert M. Hughes, and Carl Schreck with significant support by Kathy Maas-Hebner. Subcommittees received significant support from OSU Faculty Research Assistants*, Susie Dunham, Kathy Maas-Hebner, Ellen Deehan, Leah Gorman, and Cathleen Rose during development of this report. Additional directions and comments were made by the following Team members including John Buckhouse, Neil Christensen, Wayne Elmore, Victor Kaczynski, Katy Kavanagh, Nancy Molina, William Percy, Clinton Shock, and Carlton Yee. Additional technical and scientific support was provided by Ben Clemens, Jennifer Gervais, and Dan McGarvey.

IMST solicited materials and information from a wide array of agencies within Oregon's urban areas, and from a few urban areas in Washington and northern California. In addition, the Team received briefings from technical staff from the City of Portland, Metro, Portland Audubon, King County (Washington), the Willamette Urban Watershed Network, NOAA Fisheries, NOAA National Ocean Services, Oregon DLCD, and Oregon DEQ. A draft of the report was peer reviewed by the following scientific and technical specialists: Derek Booth, Jay Charland, Tracy Collier, Derek Godwin, Teresa Huntsinger, Jeff Kline, Kevin Masterson, Mike Meador, Judy Meyer, Logan Norris, Amanda Punton, Adam Stebbins, Josh Seeds, Don Yon, and Doug Drake. Portions of the final draft were unanimously adopted at the September 20 and October 28, 2010 IMST public meetings.

* Areas of major contributions by subcommittee members and staff were:

Introduction – S. Dunham, K. Maas-Hebner, L. Gorman, C. Rose;

Science Question 1 – R. M. Hughes, S. Gregory, J. Lichatowich, L. Norris, C. Schreck, A. Yeakley, S. Dunham, K. Maas-Hebner, E. Deehan, L. Gorman, C. Rose;

Science Question 2 – M. Harte, S. Dunham, L. Gorman;

Science Question 3 – R. M. Hughes, K. Maas-Hebner, E. Deehan;

Science Question 4 – R. M. Hughes, M. Harte, A. Yeakley.

Executive Summary

This technical report by the Independent Multidisciplinary Science Team (IMST) is a comprehensive review of how human activities in urban and rural-residential areas can alter aquatic ecosystems and resulting implications for salmonid recovery, with a geographic focus on the state of Oregon. The following topics are considered in the form of science questions, and comprise the major components of this report:

- 1) The effects of urban and rural-residential development on Oregon's watersheds and native wild salmonids.
- 2) Actions that can be used to avoid or mitigate undesirable changes to aquatic ecosystems near developing urban and rural-residential areas.
- 3) The benefits and pitfalls of salmonid habitat rehabilitation within established urban or rural-residential areas.
- 4) Suggested research and monitoring focus areas that will facilitate the recovery of salmonid populations affected by development.

The fundamental concepts presented in this report should be applicable to most native salmonid populations across the state. IMST encourages managers and policy-makers with interest in a specific species or geographic region to carefully research local ecological conditions, as well as specific life history characteristics of salmonids in the region.

Conserving watershed condition and salmonids in the face of increasing development requires consideration of two distinct sets of processes. First are the human social and economic processes that drive patterns in land use change. Second are the ecological processes, altered by land use, that underlie salmonid habitat changes. This report focuses on the latter and summarizes the effects of rural-residential and urban development on native, wild salmonid populations and the watersheds upon which they depend.

GENERAL EFFECTS OF URBANIZATION

The pressures of urban and rural residential land use affect aquatic ecosystems and salmonids through alterations of, and interactions among, hydrology, physical habitat structure, water quality, and fish passage. These alterations occur at local and, especially, watershed scales, and thus require study and management at multiple scales. Urban and rural-residential development causes profound changes to the pathways, volume, timing, and chemical composition of stormwater runoff. These changes alter stream physical, chemical, and biological structure and potential, as well as the connectivity of streams with their watersheds. Although some authors have reported effect or no-effect thresholds between percent urbanized or impervious watershed and biological or hydrological responses, IMST uncovered no evidence of consistent thresholds in its examination of results presented in the scientific literature. Urbanization generally results in the urban stream syndrome, marked both by increases in peak flows in streams, in channel erosion, and in non-native and tolerant species abundances, and by decreases in base flows in streams, in channel and physical habitat complexity, in physical and chemical water quality, in fish passage, and in intolerant species. The result of all these changes associated with the urban stream syndrome is a decline in overall biological condition. The magnitudes and rates of those

changes vary with prior land use and natural geographic or ecoregional factors (i.e., climate, geology, landform, soils, and natural vegetation).

RESEARCH AND MONITORING NEEDS

There are many research and monitoring needs directly related to urban and rural residential areas, some of which overlap with the research and monitoring needs for other land use types. Given the marked effects of developed areas on surface waters, the continued expansion of development in Oregon, the proportion of the human population residing in these areas and the limited amount of research and monitoring conducted on them, IMST believes that the following research and monitoring needs warrant greater attention from Oregon Plan agencies.

Better knowledge is needed on the *general effects of urban development*, including the major factors that impair aquatic ecosystems and limit salmonid populations in urban and rural residential areas. Specifically, there are needs to:

- 1) Assess how effective impervious area (including its proximity and connectivity to streams), landscape development indices, and measures of traffic or road density affect aquatic ecosystem responses to varying degrees.
- 2) Insure that research on water quality (e.g., toxic chemicals) is integrated into other inter-related factors that affect entire aquatic ecosystems (i.e., from headwaters to estuaries and near-shore marine environments) for salmonid recovery.
- 3) Consider large-scale, long-term changes and anticipate at least 50-100 years of human population and economic growth on salmonid-supporting watersheds, through the use of futuring and systematic analyses.

Better knowledge is needed on the *variation of effects of development* across Oregon, including how the effects of development on aquatic ecosystems vary across Oregon regions (e.g., Coast, Valley, Central, East). Specifically, there are needs to:

- 1) Assess the proportion of urban and rural residential stream length that is 303(d) listed, the proportions of streams with TMDLs, and the proportions of streams with reduced biological condition that are not listed.
- 2) Assess the current capacity of Oregon streams and rivers within their urban growth boundaries to support salmonids (in terms of parameters such as physical habitat, seasonal flows, storm flows, water temperature, dissolved oxygen, fine sediments, and biota).

Better knowledge is needed on *stormwater runoff*, including the adequacy of methods currently implemented in Oregon for alleviating or mitigating the adverse effect of stormwater runoff (increasing on-site retention) in both urban and rural residential areas. Specifically, there are needs to:

- 1) Assess the degree to which current technical methods that have been shown to be effective in increasing on-site water retention have been implemented by local development codes.
- 2) If methods increasing on-site water retention are ineffective and inconsistently implemented by local governments and residents, determine why.

Better knowledge is needed on **groundwater**, including future groundwater hydrologic responses to population pressures and the extent of groundwater contamination in Oregon's urban & rural residential areas. Knowledge is needed whether the current rates of groundwater extraction are sustainable and whether additional water resources are available to support urban and rural-residential growth.

Better knowledge is needed on **fish passage barriers**, including the extent and number of physical fish passage barriers in urban and rural residential areas, especially concerning prioritization of removal.

Better knowledge is needed on **toxic chemicals**, including the effects of, and possible treatment/remediation/elimination methods for, urban toxic substances and mixtures of toxic substances. Specifically, there are needs to:

- 1) Determine how, when, where, and how often to screen for and identify levels of contaminants and mixtures in aquatic ecosystems affected by urban and rural residential developments.
- 2) Evaluate the ecologically relevant and chronic toxicities of a wide range of chemicals on salmonids, and compare those toxicities with those that may occur at the concentration found in the aquatic environment.
- 3) Assess the degree that cumulative and synergistic effects of commonly-occurring chemicals prevalent in urban areas alter salmonid behavior, reproduction, and mortality.
- 4) Assess the degree to which the cumulative and synergistic effects of commonly-occurring urban chemicals alter salmonid-supporting food webs.
- 5) Conduct research on the relative technical and economic feasibility of pretreating and/or removing endocrine disrupting chemicals and other toxic chemicals from the waste stream through sewage and stormwater treatment, prohibitions on chemical sales, or both.
- 6) Determine the best available strategies for keeping pesticides, herbicides, personal care products, pharmaceuticals and other health care products, metals, and other anthropogenic-derived products out of surface and ground waters.

Better knowledge is needed on the **effectiveness of policies and regulations**, including the strengths and areas for improvement of measures currently implemented in Oregon to avoid, remedy or mitigate the impact of urban and rural residential development in headwaters, wetlands, riparian zones, floodplains, and key watersheds. Specifically, there are needs to:

- 1) Assess whether or not planning measures for protecting streams, wetlands, riparian zones, floodplains, and other sensitive areas are effective.
- 2) If planning measures are failing to mitigate or remedy the adverse effects of development or are inconsistently implemented, determine why.
- 3) Assess the most cost-effective low impact development practices.
- 4) Determine how much low impact development is required in a developed watershed to protect aquatic ecosystems or to improve the condition of already affected streams, rivers and estuaries.

Better knowledge is needed on the *effectiveness of rehabilitation efforts* for streams in urban and rural-residential areas. Specifically, there are needs to:

- 1) Assess the effects of urban rehabilitation projects in Oregon on salmonids, aquatic assemblages, and aquatic physical and chemical habitat.
- 2) Evaluate the current technical and implementation processes and estimated costs of removing fish barriers.
- 3) Assess the ecological and economic benefits and costs that would likely result from rehabilitation efforts directed toward recovering salmonids in developed areas. Evaluate project costs and benefits for households as well as municipalities.

Better knowledge is needed regarding *communication and citizen science*, including how to communicate science information more widely and effectively to the broadest possible audience via formats that go well beyond technical journal articles. Additionally, the effectiveness of “citizen science” could be evaluated. Citizen groups offer potential both to extend the scope of research and to produce a public that is more cognizant of environmental issues.

All identified research gaps need more effective *intra- and inter-disciplinary communication*. It is critical that government bodies at all levels, including university and agency researchers, work together to ask, evaluate, and answer the preceding questions in a coherent, consistent manner through use of consistent and spatially extensive study designs, sampling methods, indicators, and a shared database. In other words, just as spatial and temporal fragmentation limit species richness, fragmented information and management practices limit knowledge and effectiveness.

CONCLUSIONS

This report has identified several research needs that would allow the State of Oregon to better implement the Oregon Plan for Salmon and Watersheds with respect to salmonid and watershed conditions in urban and rural-residential areas in Oregon. Those identified research needs include better knowledge on hydrologic and water quality aspects, and their associations with the biota, such as stormwater runoff, groundwater, fish passage barriers, and the effects of toxics. Further knowledge is also needed on the general effects of urbanization and how they vary across ecoregions in Oregon. Additionally, further research is needed on the implementation of improvements to salmonid and watershed conditions in urban and rural-residential areas in Oregon, including the effectiveness of policies and regulations, the effectiveness of rehabilitation efforts, and the facilitation of better communication and citizen science.

Table of Contents

Executive Summary	i
Preface: IMST Perspective and Approach	vii
List of Acronyms and Abbreviations	x
Introduction and Background Information	1
Section 1.0: Scope of this Report.....	1
Section 1.1: A Landscape Approach to Science Questions.....	3
Section 1.2: Terminology Used in this Report	4
Section 1.3: Policy Context.....	6
Section 1.4: Oregon’s Human Population Growth Trends.....	19
Section 1.5: A Landscape Perspective on Rivers in Oregon’s Urban and Rural-residential Areas.....	26
Science Question 1: How does urbanization alter aquatic ecosystems and what are the implications for salmonid rehabilitation?.....	38
Section 2.0: Stormwater.....	39
Section 2.1: Stormwater Management	40
Section 3.0: Wastewater.....	42
Section 3.1: Wastewater Management	42
Section 3.2: Wastewater-related Issues Important to Aquatic Ecosystems.....	45
Sections 4 to 8: Aquatic Ecosystem Processes Altered by Urban and Rural-residential Development.....	48
Section 4.0: Hydrology.....	48
Section 4.1: Factors and Mechanisms that Alter Hydrology in Urban and Rural-residential Areas.....	50
Section 4.2: Nature, Magnitude, and Timing of Hydrologic Changes.....	57
Section 5.0: Riparian and Aquatic Physical Habitat.....	61
Section 5.1: Factors and Mechanisms that Alter Physical Habitat in Developed Areas...	61
Section 5.2: Nature, Timing, and Magnitude of Physical Habitat Changes.....	67
Section 6.0: Fish Passage through Urban and Rural-residential Areas	76
Section 6.1: Factors and Mechanisms that Alter Fish Passage in Developed Areas.....	77
Section 6.2: Nature and Magnitude of Fish Passage Changes in Oregon	79
Section 7.0: Water Quality.....	81
Section 7.1: Sources of Variation in Water Quality Response to Development.....	83
Section 7.2: Suspended Sediment and Turbidity in Urban and Rural-residential Areas ..	86
Section 7.3: Nutrients in Urban and Rural-residential Areas	90
Section 7.4: Water Temperature in Urban and Rural-residential Areas.....	94
Section 7.5: Dissolved Oxygen in Urban and Rural-residential Areas	101

Section 7.6:	Toxic Pollution in Urban and Rural-residential Areas.....	104
Section 8.0:	Biological Responses of Aquatic Ecosystems to Urban and Rural-residential Development.....	123
Section 8.1:	Linking Assemblage and Population-level Changes to Development.....	125
Section 8.2:	Assemblage-level Responses to Development.....	127
Section 8.3:	Salmonid Population-level Responses to Development.....	134
Science Question 2 – How might Oregon accomplish the mission of the Oregon Plan in the face of an increasingly urbanized landscape?		140
Section 9.0:	Potential Contributions to the Oregon Plan.....	140
Section 9.1:	Futures Analysis as a Planning Tool.....	141
Section 9.2:	What actions can be taken to protect salmonids in the face of a developing landscape?	148
Section 9.3:	Offsetting Impacts of New Development.....	159
Section 9.4:	Determining the Effectiveness of Actions Taken to Minimize or Offset the Effects of Development on Aquatic Ecosystems	165
Section 9.5:	Spatial Scale and Regional Planning.....	169
Section 9.6:	A Role for Education.....	170
Science Question 3 – What is the current state of knowledge for rehabilitating adverse ecological effects associated with rural-residential and urban development?		171
Section 10.0:	Rehabilitating Aquatic Ecosystems in Developed Areas.....	171
Section 10.1:	Determining Rehabilitation and Enhancement Success.....	173
Section 10.2:	Current State of Knowledge of Various Rehabilitation Approaches.....	175
Section 10.3:	Common Assumptions about Successful Aquatic Rehabilitation.....	181
Section 10.4:	Information Needs for Rehabilitation in Developed Areas.....	183
Science Question 4: What are the major research and monitoring needs for urban and rural-residential landscapes?		185
Section 11.0:	Research and Monitoring Needs.....	185
Section 11.1:	Needs Related to General Effects of Urban Development.....	186
Section 11.2:	Needs Related to Variation in Effects of Development across Oregon	186
Section 11.3:	Needs Related to Stormwater Runoff.....	188
Section 11.4:	Needs Related to Groundwater	188
Section 11.5:	Needs Related to Fish Passage Barriers	189
Section 11.6:	Needs Related to Toxic Chemicals	189
Section 11.7:	Needs Related to the Evaluation of Effectiveness of Policies and Regulations.....	191
Section 11.8:	Needs Related to Rehabilitation.....	192
Section 11.9:	Needs Related to Communication and Citizen Science.....	193
References.....		194
Appendix A. Indices of Biological Integrity		246

Preface: IMST Perspective and Approach

General Information

The Independent Multidisciplinary Science Team (IMST) is a statutory committee, established in 1997 in legislation (Oregon Revised Statute (ORS) 541.409) that created the Oregon Plan for Salmon and Watersheds (Oregon Plan). The seven-member Team, appointed jointly by Oregon's Governor, Senate President, and House Speaker, provides independent and impartial advice to the State on matters of science related to the Oregon Plan.

The IMST performs this mission primarily by 1) conducting scientific peer reviews of agency reports and assessments, and 2) developing reports that synthesize best available science on key questions relating to salmonid and watershed recovery and the management of natural resources. In its reviews and reports, the IMST frequently makes formal recommendations to Oregon state agencies with the existing *or potential* ability to affect needed changes in management or regulation. IMST looks beyond an agency's *current* ability to implement recommendations in cases where changes in laws, regulations, or funding may be needed in order to accomplish the goals of the Oregon Plan. The Team assumes that each agency has the knowledge and expertise to determine how best to identify and eliminate impediments to implementation and to determine appropriate timeframes and goals needed to meet the intent of recommendations. IMST recognizes that an agency may already have ongoing activities that address a recommendation; inclusion of such "overlapping" recommendations is intended to provide reinforcement for needed actions.

Requirement for Agency Response to IMST Recommendations

ORS 541.409 (3) states "If the Independent Multidisciplinary Science Team submits suggestions to an agency responsible for implementing a portion of the Oregon Plan, the agency shall respond to the Team explaining how the agency intends to implement the suggestion or why the agency does not implement the suggestion." State agencies are expected to respond to IMST recommendations within six months after a report is issued. Once agency responses are received, the IMST reviews the scientific adequacy of each response and determines whether further action or consideration by the agency is warranted. IMST reviews of responses are forwarded to the Governor and the State Legislature.

Guiding Principles for Development of Reports and Recommendations

The recovery of wild salmonids in Oregon depends on many factors, including the availability of quality freshwater and estuarine habitats, favorable ocean conditions, and enlightened management of fish harvest. Salmonid habitats extend across Oregon and encompass all land uses. Estuaries provide a critical transition between freshwater and the ocean. The ocean area on which salmonids depend extends well beyond Oregon and is subject to fluctuations in productivity that markedly affect survival and subsequent reproduction. Fish propagation and fish harvest are critical activities by which humans directly affect anadromous fish. Given this complexity, the IMST has developed the following basic concepts to guide the development of reports and recommendations. These concepts apply across fish species and land/water uses typically considered in IMST reports, and are based on IMST's interpretation of findings in current literature from a broad spectrum of scientific disciplines.

1. *Wild salmonids are a natural part of Pacific Northwest ecosystems, and have co-evolved with these ecosystems.* The contemporary geological landscape of the Pacific Northwest of North America was established with the formation of the major river/stream basins of the region, approximately two to five million years ago. The abundance of these species at the time of Euro-American migration to Oregon was a reflection of more than 10,000 years of adaptation to the post-glacial environment and 4,000 to 5,000 years of adaptation to contemporary climatic, vegetation, and disturbance patterns. The salmonid stocks of today co-evolved with the environment over thousands of years, a much longer time period than that since Euro-Americans entered the Pacific Northwest landscape.

2. *Watershed and habitat conditions were historically dynamic, not static.* The full recovery of wild salmonids is a long-term process operating within large-scale environmental fluctuations. At any given location, there were times when freshwater habitat quality was high and times when habitat quality was low. At any given time, there were locations where habitat quality was better and locations where it was worse. Over time, the location of high quality habitat shifted and fluctuated in total area. Ocean habitat also exhibits dynamic change over several time scales. There are inter-decadal variations in climate, as well as shorter-term variations, that affect the ocean productivity for salmonids.

Wild salmonid stocks historically accommodated changes in their environment through a combination of four evolutionary factors. *High genetic diversity* provided the raw material for the evolution of varied life history forms in response to environmental change. *Long-term genetic adaptation* produced the highly varied life history forms of these species, providing the behavioral diversity needed to persist in a wide range of changing conditions. *High fish abundance distributed in multiple locations (stocks)* increased the likelihood that metapopulations and their gene pools would survive. *Occupation of refuges* (higher quality habitats) provided the base for recolonization of poorer quality habitat as conditions improved over time. In addition, improved conditions in freshwater and estuarine habitats may have (and continue to) buffer salmonid populations from the effects of poor ocean conditions

3. *Euro-American settlement and present-day land and water uses have altered natural environments and processes in ways that are not well-understood, and that have unknown long-term consequences for wild salmonids.* One of the legacies of salmonid evolution in a highly variable environment is the ability to colonize and adapt to new and changing habitats. Anthropogenic activities accentuate and interact with these environmental fluctuations altering salmonid populations in ways that are difficult to predict. The extent of anthropogenic disturbance in the Pacific Northwest is much larger today than prior to Euro-American colonization, and continued population and economic growth are expected to limit recovery of wild salmonid populations.

Since the mid 1850s, the rate and extent to which habitats and management have changed have exceeded the ability of salmonids to adapt. Although refuges exist, wild salmonid stocks are seriously depressed, as are the rate and extent to which recolonization occurs. Hatchery practices likely diminished the genetic diversity of salmonids, potentially limiting their physiological and behavioral diversity, and thus their ability to cope with environmental fluctuations.

4. *“Range of historical conditions” is a valid hypothesis upon which to build habitat management plans, but its application should be informed by understanding of the likely effects of climate change.* The best available science suggests that restoring or enhancing ecosystem processes and structures to reflect the range of conditions within which wild salmonids evolved provides hope for ensuring their survival. High quality habitat for wild salmonids was the result of naturally occurring structures and processes that operated across the landscape and over time. These same processes and structures occur today, but humans have altered their extent, intensity, frequency, and nature. Humans will continue to exert a substantial force on the terrestrial, freshwater, coastal, and marine ecosystems of the Pacific Northwest.

The persistence and abundance of salmonids under historical ecological conditions is evidence that those habitats were compatible with salmonid reproduction and survival. The historical range of ecological conditions and the diversity of salmonid stocks in the Pacific Northwest are important because they provide a framework for developing policy and management plans for the future. The use of these concepts in land and resource planning must also take into account that the future environment may be considerably different than any environments experienced in the past.

List of Acronyms and Abbreviations

CWA	Clean Water Act (federal)
DDT	dichloro-diphenyl-trichloroethane
DDE	1,1-dichloro-2,2-bis(p-chlorophenyl)ethylene
DLCD	Department of Land Conservation and Development
DO	dissolved oxygen
DPS	distinct population segment
EIA	effective impervious area
ESA	Endangered Species Act (federal)
ESU	evolutionarily significant unit
GAO	Government Accounting Office
GSRO	Governor's Salmon Recovery Office (Washington)
IBI	Index of Biological Integrity
IMST	Independent Multidisciplinary Science Team
ISP	Independent Science Panel
LCD Act	Land Conservation and Development Act (Oregon)
LCDC	Land Conservation and Development Commission
LCREP	Lower Columbia River Estuary Partnership
LID	low impact development
MS4	municipal separate storm sewer system
MTBE	methyl <i>tert</i> -butyl ether
N	nitrogen
NAQWA	National Water-Quality Assessment Program
NARS	National Aquatic Resource Survey
NOAA	National Oceanic and Atmospheric Administration
NMFS	National Marine Fisheries Service
NPDES	National Pollutant Discharge Elimination System
NRC	National Research Council
ODEQ	Oregon Department of Environmental Quality
ODFW	Oregon Department of Fish and Wildlife
ODOT	Oregon Department of Transportation
Oregon Plan	Oregon Plan for Salmon and Watersheds
ORS	Oregon Revised Statute
OWEB	Oregon Watershed Enhancement Board
OWRRI	Oregon Water Resources Research Institute
P	phosphorus
PAH	polycyclic aromatic hydrocarbons
PBDEs	polybrominated-diphenyl-ethers
PCB	Polychlorinated biphenyls
PPCPs	pharmaceuticals and personal care products
SER	Society for Ecological Restoration
TIA	total impervious area
TMDL	total maximum daily load
TSS	total suspended sediment
UGB	urban growth boundary
US	United States of America
USDA	US Department of Agriculture
USEPA	US Environmental Protection Agency
USFWS	US Fish and Wildlife Service
USGS	US Geological Survey

Introduction and Background Information

Urban areas currently cover a small fraction of Oregon's landscape but will expand to accommodate an increasingly large proportion of the state's growing population and economic activity (Hulse *et al.* 2002; Kline *et al.* 2003; US Census Bureau 2005). Residential developments on rural lands now cover more than twice the area occupied by Oregon's urban developments and are growing rapidly. Alig *et al.* (2004) projected an 82% increase in developed land in the Pacific Northwest by 2025. Lackey *et al.* (2006) estimated that the Pacific Northwest human population may increase from its present 15 million to 60–80 million by 2100. The location and intensity of this growth could profoundly influence salmonid habitat, water quality, and the long-term success of the Oregon Plan for Salmon and Watersheds (Oregon Plan 1997; Hulse *et al.* 2004; Van Sickle *et al.* 2004; Lackey *et al.* 2006).

In Oregon, both urban and rural-residential developments are frequently located along streams, rivers, estuaries, and coasts (Figure 1-1). Associated landscape alterations in these areas can impair aquatic ecosystems in a variety of ways. In the Pacific Northwest, there is a growing understanding that aquatic habitat affected by development is important for salmonid populations (e.g., Pess *et al.* 2002; Regetz 2003; MacCoy & Blew 2005; Sheer & Steel 2006; Bilby & Molloy 2008). Rehabilitation and protection of water quality and habitat complexity in these waters could contribute to the recovery of depressed stocks of salmonids (Tinus *et al.* 2003; Booth *et al.* 2004; Booth 2005; Konrad & Booth 2005).

Section 1.0: Scope of this Report

This technical report by the Independent Multidisciplinary Science Team (IMST) is a comprehensive review of how human activities in urban and rural-residential areas alter aquatic ecosystems and the potential implications for salmonid recovery in Oregon. The following topics comprise the primary focus of this report.

- The effects of urban and rural-residential development on Oregon's watersheds and native wild salmonids.
- Actions that can be used to avoid or mitigate undesirable changes to aquatic ecosystems near developing urban and rural-residential areas.
- Suggested actions that will facilitate the recovery of salmonid populations affected by development.
- The effectiveness of salmonid habitat rehabilitation actions within established urban or rural-residential areas.

The geographic scope of this report is the state of Oregon although some information is drawn from research and examples from other areas. A wide range of diversity exists among Oregon's

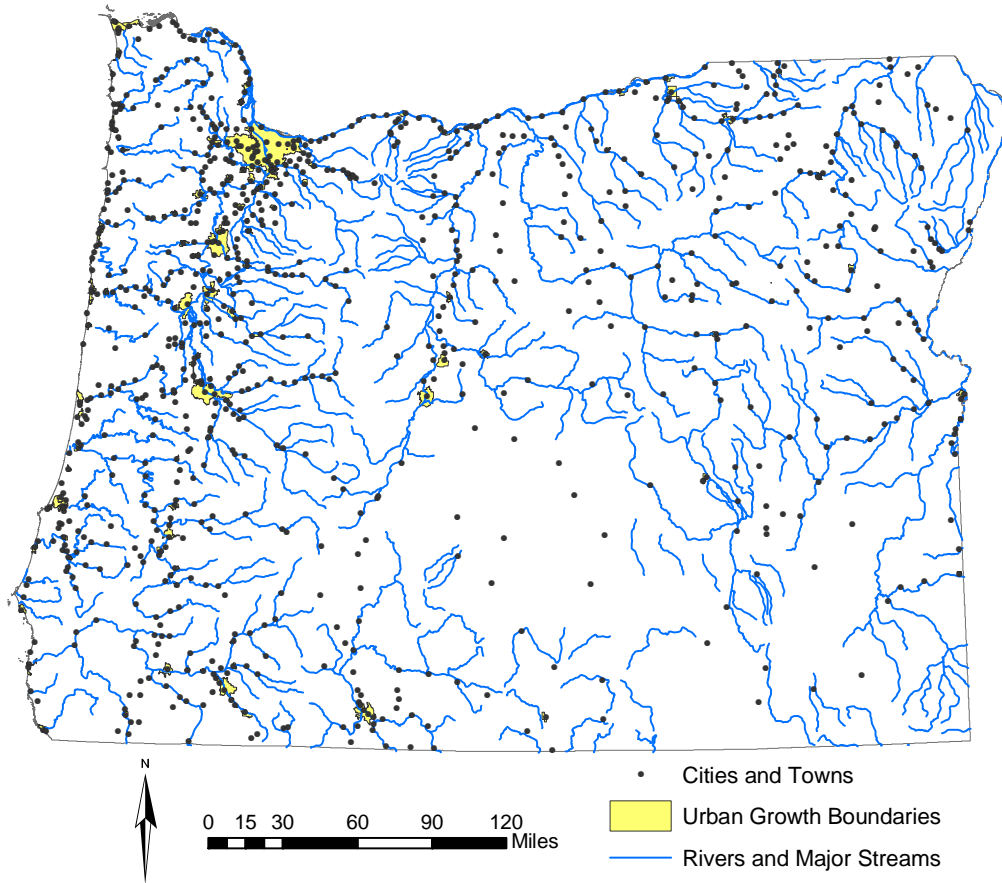


Figure 1-1. Locations of Oregon's rivers, incorporated cities, unincorporated towns and urban growth boundaries in relation to major rivers and estuaries. (City and town data from <http://www.oregon.gov/DAS/EISPD/GEO/alphalist.shtml>, October 28, 2004.) Several points, particularly in eastern Oregon represent sparsely populated towns that currently do not affect aquatic ecosystems. However, these areas contain infrastructure that can facilitate future rural-residential development.

aquatic habitats, climate, geology, hydrology, and aquatic biota. The fundamental concepts presented in this report are likely to be applicable to most native salmonid populations across the state. IMST strongly encourages managers and policy-makers with interest in a specific species or geographic region to carefully research local ecological conditions as well as specific life history characteristics of salmonids in the region. Conserving watershed conditions and salmonids in the face of increasing development requires consideration of two distinct sets of processes. First are the human social and economic processes that drive patterns in land use change. Second are the ecological processes, altered by land use, that underlie salmonid habitat changes. This report focuses on the latter and summarizes the effects of rural-residential and urban development on native wild salmonid populations and the watersheds upon which they depend.

Section 1.1: A Landscape Approach to Science Questions

The discussions in this report emphasize a landscape perspective on urban and rural-residential land uses and salmonid management. The application of landscape ecology concepts to land management decisions throughout watersheds shifts the focus from individual stream reaches or habitat components to more comprehensive biological and physical patterns and processes. Such an approach means considering how concepts such as scale (both resolution and extent), interrelationships of patterns and processes, connectivity/proximity or fragmentation, and upstream/downstream movement of nutrients, sediment, energy, and organisms can aid our understanding of how development affects salmonids and watersheds (Steel *et al.* 2010b). IMST approaches these discussions by considering four science questions.

Science Question 1: *How does urbanization alter aquatic ecosystems and what are the implications for salmonid rehabilitation?*

In Sections 2.0 through 8.0, IMST assesses how urban and rural-residential development alter ecological and physical patterns and processes at reach, watershed, and river basin scales and reduce the landscape's ability to support salmonid populations.

Science Question 2: *How might Oregon accomplish the mission of the Oregon Plan in the face of an increasingly urbanized landscape?*

In Section 9.0, IMST examines the implications of landscape ecology and salmonid biology for future urban and rural-residential land management. Oregon's population is expected to increase by over one million in the next two decades. What will the landscape of Oregon look like with sprawling cities and increasing rural residences? Is such a landscape compatible with the goals of the Oregon Plan for Salmon and Watersheds? What scientifically credible approaches exist for evaluating and minimizing the adverse effects of future landscape-scale change on salmonid recovery?

Science Question 3: *What is the scientific evidence that ecological structure and function in existing urban and rural-residential areas can be rehabilitated and/or mitigated?*

In Section 10.0, IMST discusses how stream ecosystems within urban and rural-residential areas might be rehabilitated and the challenges of doing so.

Science Question 4: *What are the major research and monitoring needs for urban and rural-residential landscapes?*

Finally in Section 11.0, IMST addresses what substantial information gaps exist concerning salmonids and urban and rural-residential areas. These may include gaps in what is known about how salmonids use urban streams, what factors appear to most limit salmonids, and how rehabilitation and mitigation projects affect salmonids.

Section 1.2: Terminology Used in this Report

Throughout out this report, IMST uses various terms that are used in relation to research on and management of aquatic ecosystems and urban and rural-residential areas. Several of these terms can have a range of meanings depending on the user's perspectives. To clarify the use of these nine key terms (*urban*, *urbanization*, *rural-residential*, *development*, *restoration*, *rehabilitation*, *river basin*, *watershed*, and *stream reach*) used in this report; other terms are defined within the body of the report.

Urban versus Rural-residential Development

Urbanization is the process whereby humans move into cities resulting in the expansion of residential, commercial, and industrial land uses (Brown *et al.* 2005a). Many definitions of 'urban' incorporate population density and land use zoning criteria. However, identifying the point at which land use becomes 'urban' varies by author and location (reviewed by McIntyre *et al.* 2000; Table 1-1). For example, the US Census Bureau (2003) changed its working definition of 'urban' three times during the past 60 years. Varying definitions create significant discrepancies over the proportion of a land base or population categorized as urban. In this report, IMST defines *urban areas* as incorporated cities and towns that include land designated for residential, commercial, and industrial uses. Throughout this report, use of the terms *urban* or *urbanization* refers specifically to these land uses.

Rural-residential (also known as exurban) development is usually defined by some minimum number of structures or persons per unit area but terminology and definitions used in published literature vary considerably (see review by Theobald 2005). In this report, IMST defines *rural-residential areas* as developed land outside of urban growth boundaries (UGB; i.e., set boundaries separating urban land from rural land), including unincorporated towns, upon which multiple housing units are situated. IMST excludes from this definition houses and buildings on lands zoned for agriculture or forest resources. Additional terms that imply rural-residential land use (e.g., low-density residential) will be used when necessary to convey the definitions or intent of original authors. Throughout this report, general use of the term *development* refers to both rural-residential and urban land uses.

Table 1-1. Definitions of Urbanization. Much of the research summarized in this report uses urbanization as a predictive variable. This table summarizes the variables most commonly used to quantify the intensity or extent of development.

Variable	Definition	Example References
Total Impervious Surface Area	The fraction of a watershed covered by materials that prevent water infiltration into soil	Arnold & Gibbons 1996
Connected (Effective) Impervious Surface Area	The subset of impervious surfaces in a watershed that drain directly to streams	Wang <i>et al.</i> 2003b; Walsh <i>et al.</i> 2005a
Population Density	Persons per sq. mi. or sq. km	Brandes <i>et al.</i> 2005
Percent Developed Land Percent Urban Land	The fraction of land cover with low or high intensity development within a defined area	King <i>et al.</i> 2005; Poff <i>et al.</i> 2006a
Structure Density	The number of human built structures per unit area	Azuma <i>et al.</i> 2004; Burnett <i>et al.</i> 2007
Urban Intensity Index	An index that integrates information from several factors that quantify human influence (e.g., land cover, population, and socio-economic population distributions)	McMahon & Cuffney 2000; Tate <i>et al.</i> 2005

Restoration vs. Rehabilitation

Restoration and rehabilitation are often used interchangeably by natural resource managers, policy makers, watershed stewards, and researchers but the differences between the terms are important. Ecological *restoration* is often defined as the process of “restoring systems to the point where they can provide the natural materials and ecological functions that create habitat” (p. 297, Gregory & Bisson 1997). The long-term goal of restoration is to achieve an ecosystem that maintains ecological functions and processes with little or no assistance. In urban and rural-residential areas, restoring ecological condition of watersheds and aquatic ecosystems may not be feasible because of societal constraints and/or irreversible landscape changes. In many cases, restoration of self-sustaining natural aquatic functions and structures that create salmonid habitat are unlikely in developed areas.

This report emphasizes the *rehabilitation*, or return to partial function, of ecological processes and physical, chemical, and biological characteristics of aquatic habitat within urban and rural-residential areas. The ability to return to fully functioning conditions is limited because of permanent or semi-permanent alterations like dams, channelization, channel incision, floodplain losses, estuary losses, and impervious land cover. However, even partial improvements on these highly altered lands might increase the long-term success of the Oregon Plan.

River Basins, Watersheds, and Stream Reaches

Throughout this report, developed landscapes and the water bodies running through them are characterized at river *basin*, *watershed*, or *reach scales*. Each of these spatial perspectives offers important context when evaluating the effects of past, present, and future human activity on salmonid populations, the quality of habitat available to them, and watershed condition. River

basins and watersheds come in many shapes and sizes. Conveying scale-associated information using such terms requires specification of the type or area of land drained by a stream or river. The terms 'river basin' and 'watershed' are often used interchangeably and apply to the entire area drained by a river or river system. The IMST's intention in this report is to impart specific scale-related meaning with the use of these terms. *River basins* cover either the entire drainage area for a major river (e.g., Willamette, Rogue, John Day) or the combined drainage area of several rivers within a region that has unique physical or biological characteristics (e.g., the Lakes Basin in south central Oregon; OWEB 2003a). A *watershed* is the area that drains into a creek, stream, or smaller river that is a tributary to a major river. Typically, several smaller watersheds exist within a single river basin. Within watersheds, individual *stream reaches* are localized segments of a river along with the immediately adjacent riparian zone.

Section 1.3: Policy Context

Several policies at the federal (*Endangered Species Act* and *Clean Water Act*) and state (*Oregon Land Use Planning Regulations* and the *Oregon Plan for Salmon and Watersheds*) levels support efforts to restore salmonid populations in urban and rural-residential areas. The primary policies are briefly summarized here but are not be the only ones affecting developed areas in Oregon.

SECTION 1.31: US ENDANGERED SPECIES ACT

In Oregon, seven evolutionarily significant units (ESU) of anadromous salmon, four distinct population segments (DPS) of Pacific steelhead, and three DPSs of freshwater resident salmonids are currently listed as threatened under the federal US Endangered Species Act (ESA; Table 1-2). Two federal agencies have primary responsibility for administering the ESA with regard to these listings. The National Marine Fisheries Service (NMFS) within the National Oceanic and Atmospheric Administration (NOAA), also known as NOAA Fisheries, is responsible for anadromous salmon ESU and steelhead DPS listings. The US Fish and Wildlife Service (USFWS) is responsible for DPSs that usually complete their life cycles entirely in freshwater. While not federally listed, the anadromous form of the lower Columbia River DPS of coastal cutthroat trout (*Oncorhynchus clarkii clarkii*) is designated as critical by the Oregon Department of Fish and Wildlife (ODFW), and other cutthroat populations are considered vulnerable (Williams *et al.* 1989; Jelks *et al.* 2009). With the exceptions of Lahontan cutthroat trout (*Oncorhynchus clarkii henshawi*), and chum salmon (*O. keta*)¹, each species or subspecies ranges widely across Oregon (Figures 1-2 through 1-8) and migrates, spawns, rears young, or over winters in urban or rural-residential areas.

¹ Within Oregon, Lahontan cutthroat trout is restricted to a few remote areas in the southeastern portion of the state and chum salmon has been extirpated from much of its range.

Table 1-2. Salmonids in Oregon listed as *threatened* under the federal Endangered Species Act. Habitat refers to spawning, rearing, or migratory habitat and is not restricted to federally designated 'critical' habitat.

Threatened Salmonid Species	Evolutionary Significant Unit (ESU)/ Distinct Population Segment (DPS)	Oregon Regions Containing ESU or DPS Habitat ¹
Chum Salmon ; ESU (<i>Oncorhynchus keta</i>)	Columbia River	Columbia Basins Columbia River Mainstem
Coho Salmon ; ESUs (<i>O. kisutch</i>)	S Oregon/N. California	Southern Oregon Coast Basins
	Coast	Mid-south, Middle, and North Coast Basins
	Lower Columbia River	Lower Columbia Basins Lower Columbia River Mainstem
Chinook Salmon ; ESUs (<i>O. tshawytscha</i>)	Snake River Fall Run	NE Oregon Basins Columbia River Mainstem
	Snake River Spring/Summer Run	NE (historically SE) Oregon Columbia River Mainstem
	Lower Columbia River	Lower Columbia Basins Lower Columbia River Mainstem
	Upper Willamette River	Clackamas River Willamette Basin Lower Columbia River Mainstem
Steelhead Trout ; DPSs (<i>O. mykiss</i>)	Snake River Basin	Lower Columbia Basins Middle Columbia Basins Columbia River Mainstem NE Oregon Basins
	Lower Columbia River	Lower Columbia Basins Lower Columbia River Mainstem
	Middle Columbia River	Lower Columbia Basins Columbia River Mainstem North Central/ NE Oregon Basins
	Upper Willamette River	Lower Columbia Basins Lower Columbia Mainstem Willamette Basin
Lahontan Cutthroat Trout ; DPS (<i>O. clarkii henshawi</i>)	Entire Distribution	NW Lahontan Basin
Bull Trout ; DPS (<i>Salvelinus confluentus</i>)	Klamath River	Klamath River Basin
	Columbia River	Columbia River Basin

¹Regions are general descriptions of habitat distribution. For specific information about distribution, see NOAA and USFWS Technical Memoranda (USFWS 1995; Weitkamp *et al.* 1995; Busby *et al.* 1996; Johnson *et al.* 1997; Myers *et al.* 1998; USFWS 1998; Good *et al.* 2005, NMFS 2005a, b).

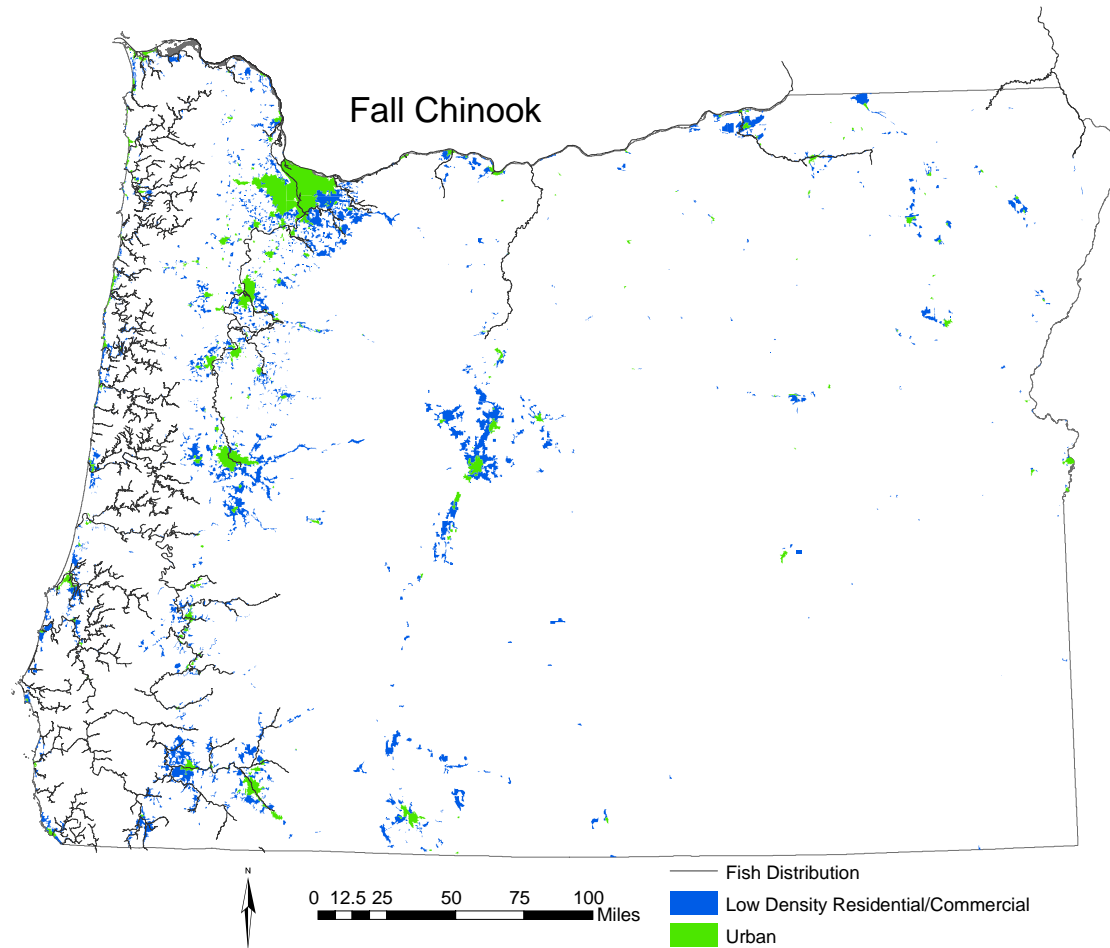


Figure 1-2. Currently known range of ESA listed fall Chinook in relation to Oregon's incorporated cities, unincorporated towns, and urban growth boundaries. (Fish distribution data from Oregon Department of Fish and Wildlife <http://nrimp.dfw.state.or.us/nrimp/default.aspx?pn=fishdistdata>, April 21, 2009).

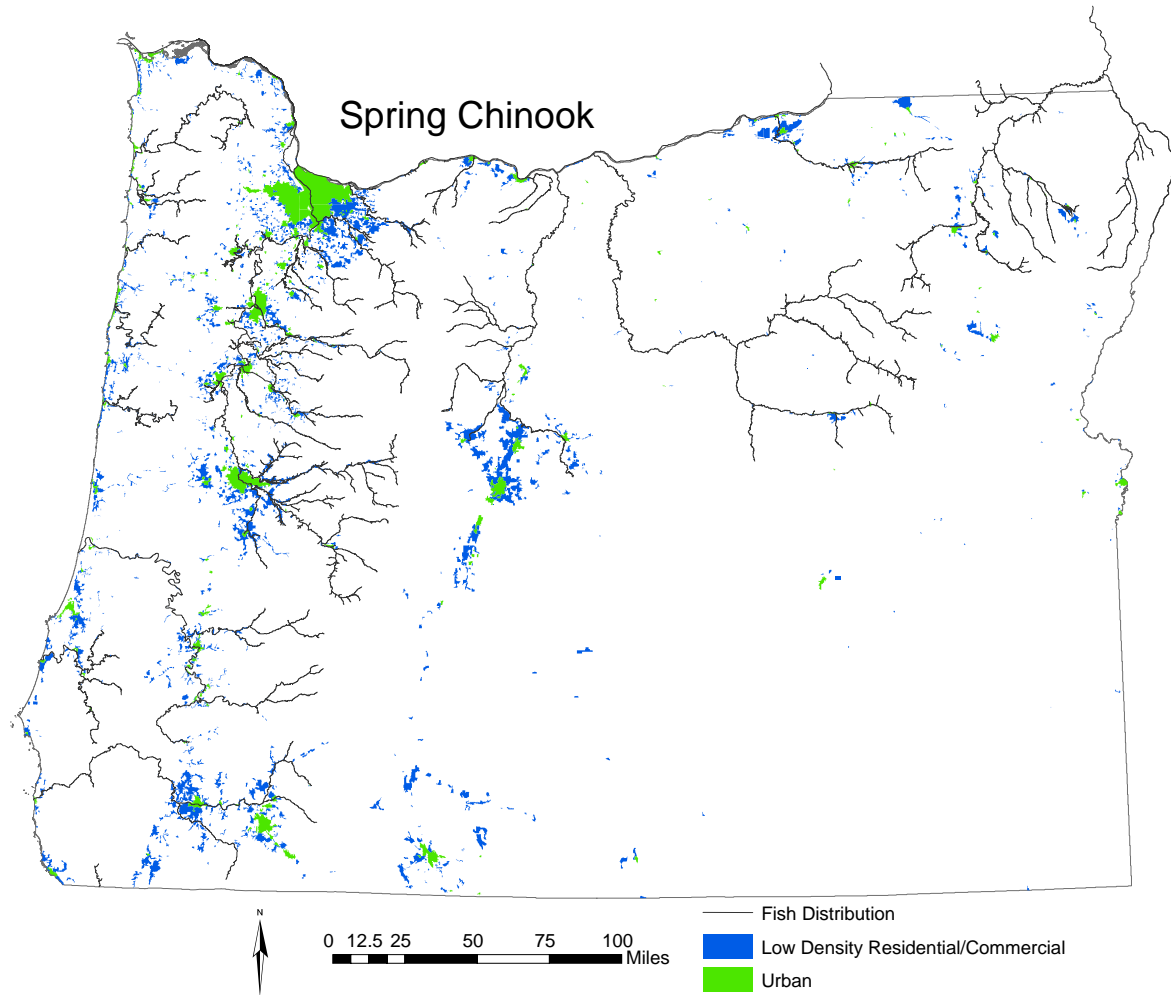


Figure 1-3. Currently known range of ESA listed spring Chinook in relation to Oregon's incorporated cities, unincorporated towns, and urban growth boundaries. (Fish distribution data from Oregon Department of Fish and Wildlife <http://nrimp.dfw.state.or.us/nrimp/default.aspx?pn=fishdistdata>, April 21, 2009).

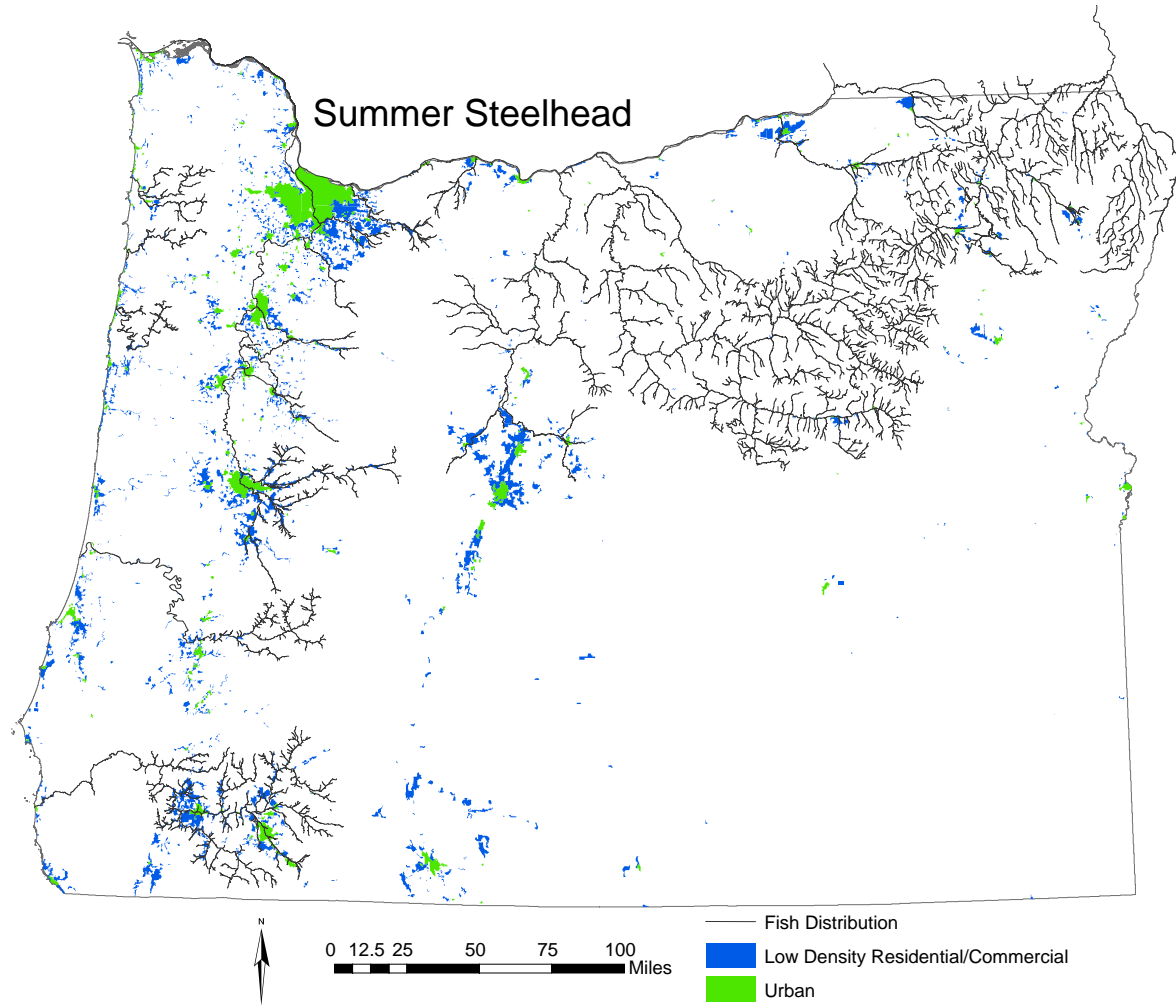


Figure 1-4. Currently known range of ESA listed summer steelhead in relation to Oregon's incorporated cities, unincorporated towns, and urban growth boundaries. (Fish distribution data from Oregon Department of Fish and Wildlife <http://nrimp.dfw.state.or.us/nrimp/default.aspx?pn=fishdistdata>, April 21, 2009).

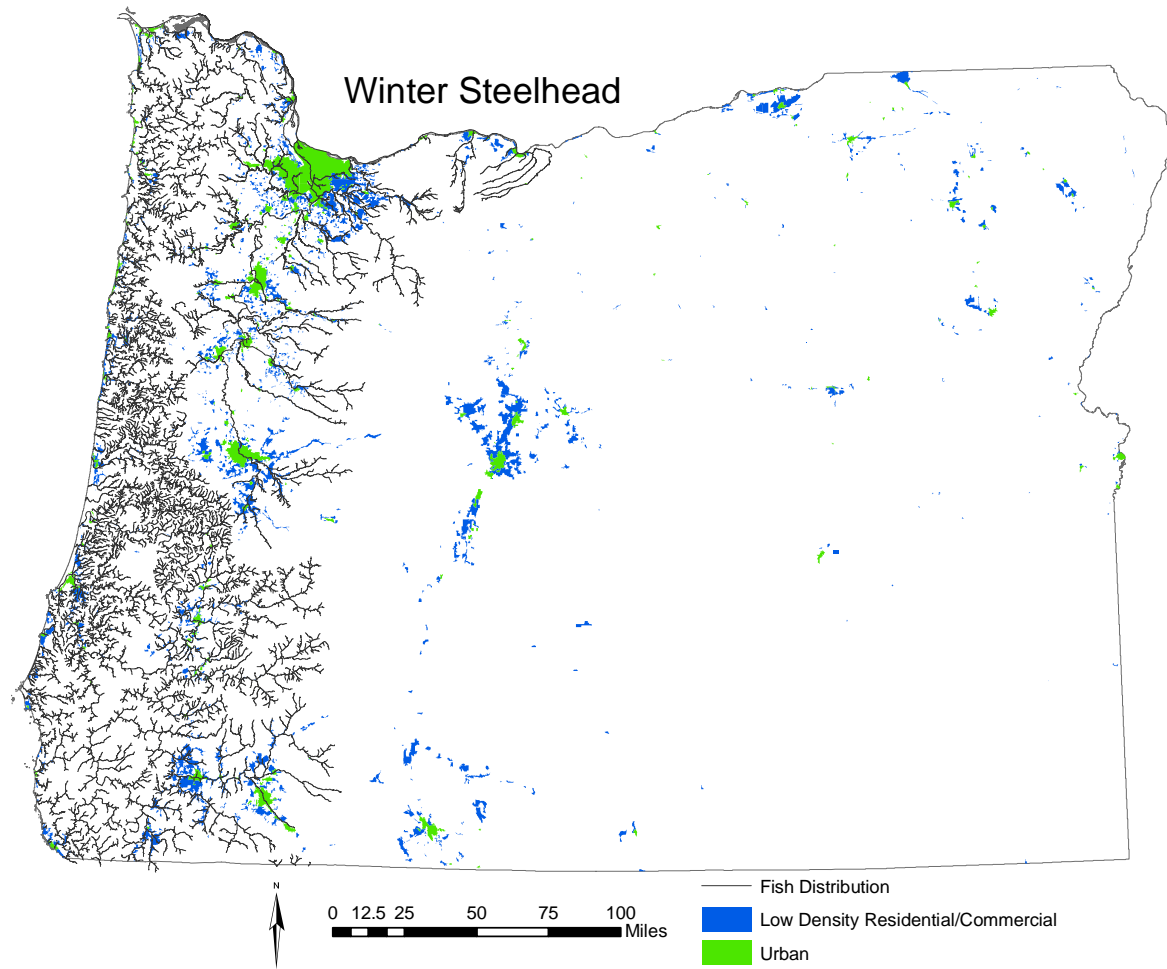


Figure1-5. Currently known range of ESA listed winter steelhead in relation to Oregon's incorporated cities, unincorporated towns, and urban growth boundaries. (Fish distribution data from Oregon Department of Fish and Wildlife <http://nrimp.dfw.state.or.us/nrimp/default.aspx?pn=fishdistdata>, April 21, 2009).

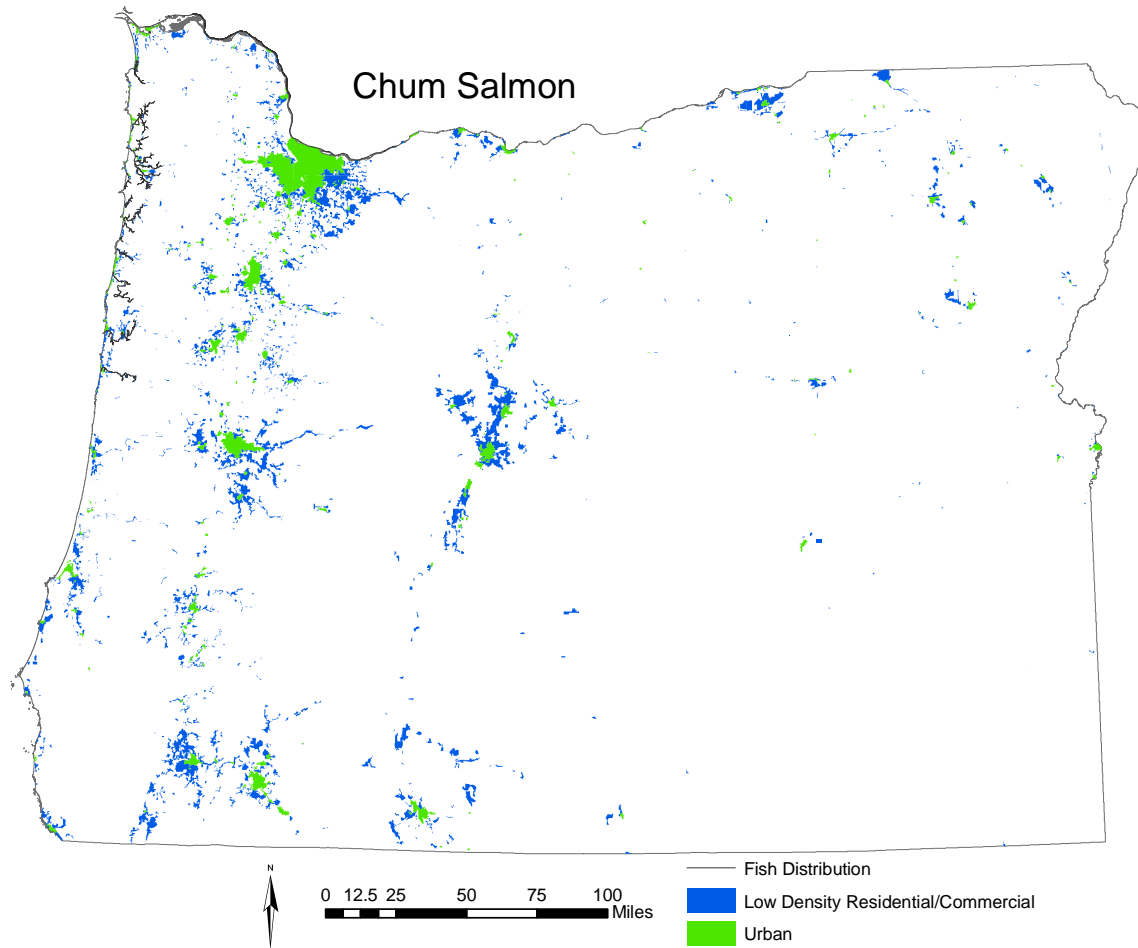


Figure1-6. Currently known range of ESA listed chum salmon in relation to Oregon's incorporated cities, unincorporated towns, and urban growth boundaries. (Fish distribution data from Oregon Department of Fish and Wildlife <http://nrimp.dfw.state.or.us/nrimp/default.aspx?pn=fishdistdata>, April 21, 2009).

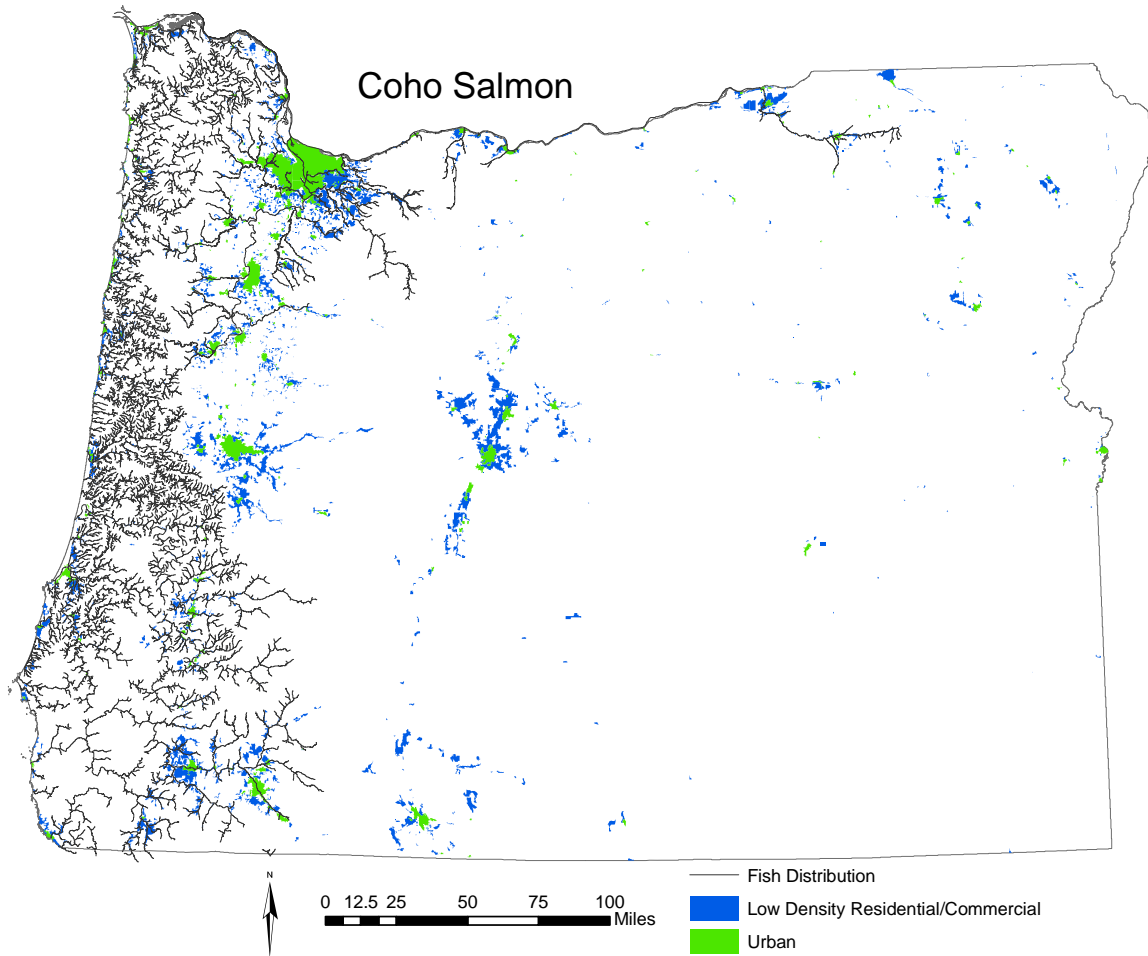


Figure1-7. Currently known range of ESA listed coho salmon in relation to Oregon's incorporated cities, unincorporated towns, and urban growth boundaries. (Fish distribution data from Oregon Department of Fish and Wildlife <http://nrimp.dfw.state.or.us/nrimp/default.aspx?pn=fishdistdata>, April 21, 2009).

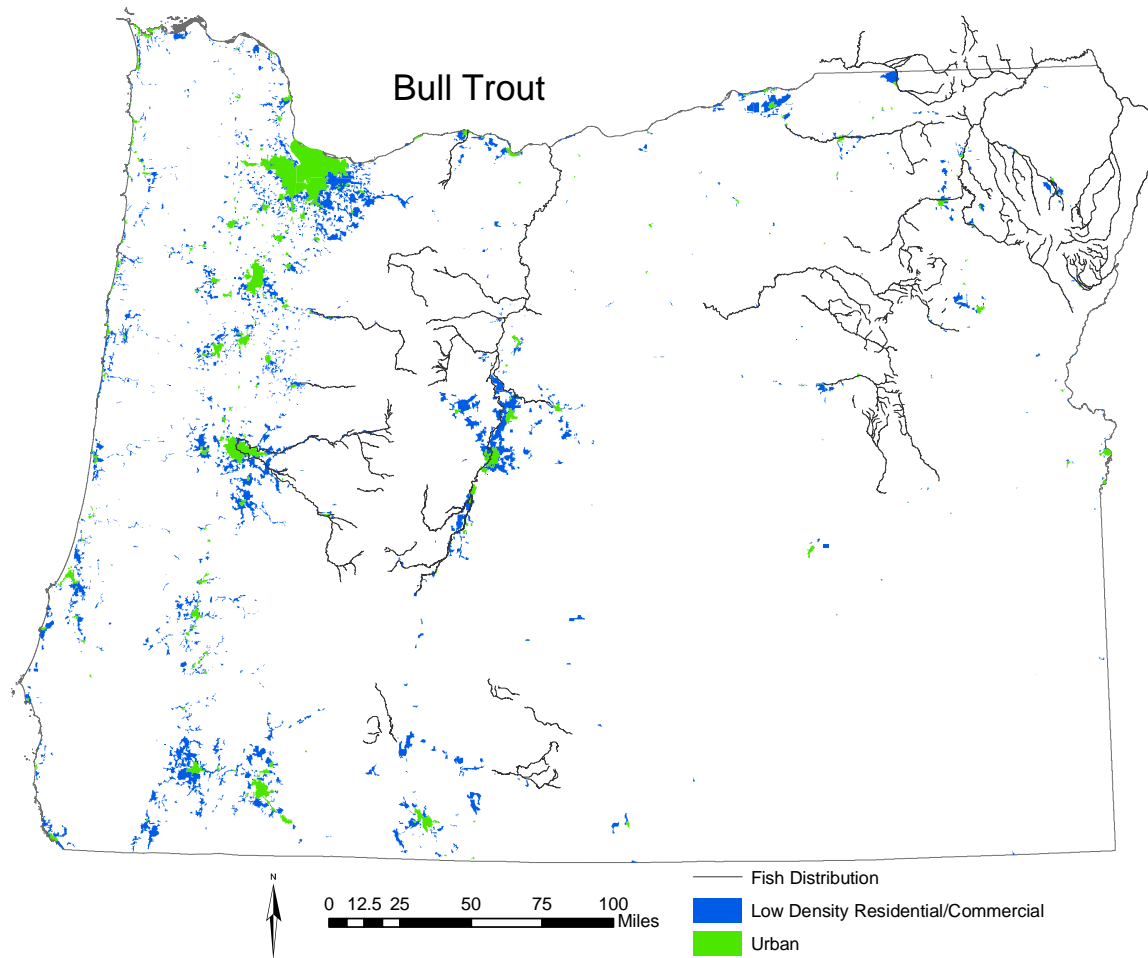


Figure 1-8. Currently known range of ESA listed bull trout in relation to Oregon's incorporated cities, unincorporated towns, and urban growth boundaries. (Fish distribution data from Oregon Department of Fish and Wildlife <http://nrimp.dfw.state.or.us/nrimp/default.aspx?pn=fishdistdata>, April 21, 2009).

Section 4(d) of the ESA mandates that NMFS create rules “necessary and advisable to provide for conservation of listed species.” NMFS (2000) determined that threatened salmon and steelhead ESUs require the full protection of ESA Section 9(a)(1) which prohibits any take (injury or harm) of listed species. To provide additional guidance regarding listed salmon and steelhead ESUs, NMFS (2000) published 16 categories of activities most likely to result in *take*. Many of these activity categories commonly result from new development and ongoing land uses in existing urban areas (Table 1-3).

Oregon jurisdictions that fall within the geographic range of listed salmonids and engage in activities likely to result in take can pursue ESA compliance through several routes. These include ESA Section 7 (required if federal funds are involved) or Section 10 (for nonfederal jurisdictions and private parties) *incidental take* consultations. In the case of threatened anadromous salmonid ESUs and DPSs, NMFS also developed a 4(d) rule and associated limits (exceptions) that relax take prohibitions for activities deemed to “contribute to the conservation of” threatened ESUs and their habitats. Two of the 13 limits cover road maintenance, and *Municipal, Residential, Commercial, and Industrial* development and redevelopment (NMFS 2000, 2006a; NOAA 2000).

The 4(d) rule allows exceptions to take prohibitions by letting governments and other entities either adopt plans specifically approved by NMFS or submit their own proposals for NMFS approval. For example, entities conducting road maintenance can meet ESA compliance requirements if they follow ODOT criteria determined by NMFS to be sufficiently protective of salmonids. Several Oregon jurisdictions responsible for routine road maintenance have obtained or are applying for these permits. For each 4(d) limit, NOAA (2000) has published criteria used to evaluate permit proposals. For municipal, residential, commercial, and industrial development, the criteria are extensive and include 12 parts that reflect many of the topics covered in this IMST report (Table 1-4).

SECTION 1.32: US CLEAN WATER ACT

The primary objective of the 1972 US Clean Water Act (CWA) is to “restore and maintain the chemical, physical, and biological integrity of the nation’s waters....” Interim goals aimed at meeting this objective included both “zero discharge of pollutants by 1985” and where possible “water quality that is both fishable and swimmable, by mid-1983.” Today the CWA authorizes use of federal funds for municipal sewage treatment plant construction and regulation of industrial and municipal dischargers. Ultimately, this requires that states develop plans to address violations of US Environmental Protection Agency (USEPA) water quality standards.

Sections of the CWA relevant to urban and rural-residential areas include the National Pollutant Discharge Elimination System (402), removal/fill permits (404), biennial 305(b) water body monitoring reports, and identification of “water quality limited” watercourses (303d). In the case of aquatic biota, there are many commonalities between the goals of the CWA and the ESA. There also are procedural links between these acts that the USEPA, USFWS, and NMFS have attempted to streamline (USEPA *et al.* 2001). In some situations, actions taken by jurisdictions in response to CWA requirements also reduce ESA liability. (Additional details on CWA implementation in developed areas can be found in Sections 2.0, 3.0, and 7.0 of this report.)

Table 1-3. Sixteen activity categories likely to result in injury or harm ("take") to listed salmonids. Text adapted from NMFS (2000).

1	Constructing or maintaining structures such as culverts, berms, dams, or reservoirs that eliminate or impede a listed species' ability to migrate or gain access to habitat
2	Discharging pollutants, such as oil, toxic chemicals, radioactivity, carcinogens, mutagens, teratogens, or organic nutrient-laden water (including sewage water) into a listed species' habitat
3	Removing, poisoning, or contaminating plants, fish, wildlife, or other biota that the listed species requires for feeding, sheltering, or other essential behavioral patterns
4	Removing or altering rocks, soil, gravel, vegetation or other physical structures that are essential to the integrity and function of a listed species' habitat
5	Removing water or otherwise altering streamflow in a manner that significantly impairs spawning, migration, feeding, or other essential behavior patterns
6	Releasing non-indigenous or artificially propagated species into a listed species' habitat or into areas where they may gain access to that habitat
7	Constructing or operating dams or water diversion structures with inadequate fish screens or passage facilities
8	Constructing, maintaining, or using inadequate bridges, roads, or trails on stream banks or unstable hill slopes adjacent to or above a listed species' habitat
9	Conducting timber harvest, farming, grazing, mining, earth-moving, or other operations that substantially increase the amount of sediment entering streams
10	Conducting land-use activities that may disturb soil and increase sediment delivery to streams – such as logging, mining, grazing, farming, and road construction – in riparian areas and areas susceptible to mass wasting and surface erosion
11	Harvesting in violation of fishing regulations
12	Causing various streambed disturbances that trample eggs or trap adult fish preparing to spawn
13	Engaging in illegal interstate and foreign commerce dealing in, imports, or exports of listed salmon or steelhead
14	Altering lands or waters in a manner that promotes unusual concentrations of predators
15	Causing shoreline and riparian disturbances (whether in the river, estuary, marine, or floodplain environment) that retard or prevent the development of certain habitat characteristics upon which the fish depend
16	Filling or isolating side channels, ponds, and intermittent waters (e.g., installation of tide gates and impassable barriers can destroy habitats that the fish depend upon for refuge during high flows)

Table 1-4. Suggested actions to protect ESA listed fish species. Mechanisms whereby cities, counties, and regional governments that undertake *Municipal, Residential, Commercial, and Industrial* development can ensure such activities are sufficiently protective of listed fish and consistent with ESA requirements. Text is abbreviated from NOAA (2000).

1	Avoid developing unstable slopes, wetlands, areas of high habitat value, or other similarly constrained areas
2	Prevent stormwater discharge impacts to water quality and quantity, and to streamflow patterns within the watershed, including peak and baseflows in perennial streams
3	Protect native riparian vegetation well enough to attain or maintain proper functioning condition and require riparian buffers widths equal to the height of the tallest tree that can grow at the site
4	Avoid constructed stream crossings wherever possible, and where unavoidable, minimize impacts through choice of type, sizing, or placement as well as monitoring and maintenance of the crossing
5	Protect historical stream meander patterns and channel migration zones; avoid hardening of stream banks
6	Protect wetlands, wetland buffers, and wetland functions by avoiding soil, vegetation, and hydrologic disturbance
7	Preserve the hydrologic capacity of any intermittent or permanent stream to pass peak flows without causing incision
8	Reduce need for watering and application of herbicides, pesticides, and fertilizer by landscaping with native vegetation
9	Prevent erosion and sediment discharge into streams during construction
10	Ensure that water supply demands can be met without affecting flows required by threatened salmon either directly or through groundwater withdrawals, and that any new water diversions are positioned and screened to prevent injury or death of fish
11	Provide all necessary implementation mechanisms including enforcement, funding, and reporting
12	Comply with all other State and Federal environmental or natural resource laws and permits

SECTION 1.33: OREGON'S LAND USE PLANNING REGULATIONS

In response to rapid human population growth and development during the 1960's and 70's, Oregon's legislature passed the Land Conservation and Development Act (LCD Act) in 1973 launching a statewide program for land use planning, establishing the Land Conservation and Development Commission (LCDC) and the Department of Land Conservation and Development (DLCD). The program is based on 19 statewide land use planning goals. The last three goals were added in 1977 to establish the land use components of the Oregon Coastal Management Program. Prior to 1973, cities and counties had the legal authority to manage growth through planning and zoning. While some jurisdictions chose to manage urban growth, development outside of incorporated cities was often unregulated (Gustafson *et al.* 1982). Soon after the LCD Act was passed, several statewide planning goals were implemented to limit the location and density of development on rural lands outside of UBGs, particularly in areas designated for farm or forest uses (Abbott *et al.* 1994).

Oregon's land use program is implemented by partnerships between the State and local governments. Comprehensive plans generally describe the means by which individual jurisdictions will meet program goals. These plans are implemented through local zoning and development codes. Currently, the LCDC has acknowledged comprehensive plans for all 36

counties and 240 of Oregon's 242 cities (Punton 2009, pers. comm.²). The overall objective of the land use program is to plan development in ways that manage the consequences of development on natural resources and livability. The program focuses development in urban areas to ensure that urban infrastructure is efficient and economically viable, and rural lands are preserved for agricultural and forest resources. Land Use Goals 5 and 6 include identifying wildlife habitats and aquatic resources and developing local measures to protect these resources from adverse impacts related to development, but not all jurisdictions have fully implemented these goals (see Wiley 2001 for a review of how Oregon's land use goals protect fish and wildlife habitat).

The urban growth boundary (UGB) is a key component in land use planning. UGBs are intended to provide for a 20-year supply of land to accommodate projected growth for each urban area. A buildable lands inventory and assessments of housing, commercial and industrial land needs can be used to expand UGBs. Land eligible for inclusion in a UGB is prioritized by factors that consider preservation of resource lands, efficiency of delivering public services, and access to the transportation network. Publicly managed wastewater treatment systems are not allowed outside of a UGB. Cities plan for urban development at urban densities within UGBs. As land is annexed into UGBs, cities will zone land and regulate development within the expanded UGB. Low density development is permitted in certain areas under Oregon's land use program. These are usually places with an existing settlement pattern not conducive to commercial farming or forestry activities (Einsweiler & Howe 1994). Rural-residential (e.g., 2, 5, or 10-acre home sites) is the most common low density development type; however small areas of commercial, industrial and even public uses also exist, as do some unincorporated communities that have the features of a small town. Very limited residential development may also be authorized on farm and forest land, as long as the development supports commercial farm or forest uses (LCDC 1996a, b).

Several authors (Durning *et al.* 2002; Azuma *et al.* 2002, 2004, 2009; Kline *et al.* 2005a;) have suggested that Oregon's land use law effectively limits development outside of UGBs. A recent study of land use change on non-federal lands in Oregon demonstrated that the rate of land conversion from forest, agriculture and rangeland uses to low-density residential and urban uses declined in the period from 1974 to 2005. The rate dropped most significantly during the period between 1984 and 1995, corresponding with implementation of Oregon's land use program (Azuma *et al.* 2009). In November 2004, Oregon voters passed Ballot Measure 37 that required state and local governments to either compensate landowners for a loss in property values resulting from land use regulations adopted after the property owner acquired the land or waive the relevant land use regulation³ (see also Gosnell *et al.* 2010 for impact of Measure 37 claims on land use). Measure 37 was subsequently modified by Ballot Measure 49 in 2007 which curbed the potential for a large amount of rural (mainly residential) development. The total amount of additional development to be authorized under Measures 37 and 49 has been estimated to be 7,000 dwellings, mainly on rural residential and farm lands in the northern Willamette Valley (Punton 2009, pers. comm.⁴).

² Amanda Punton, Oregon Department of Land Conservation and Development, Portland, Oregon, personal communication December 2, 2009.

³ http://www.sos.state.or.us/elections/nov22004/guide/meas/m37_text.html. Accessed August 17, 2010.

⁴ Amanda Punton, Oregon Department of Land Conservation and Development, Portland, Oregon, personal communication, December 2, 2009.

Section 1.4: Oregon's Human Population Growth Trends

Between 1950 and 2000, the population of Oregon increased 125% to 3,421,399 and the number of households correspondingly increased 177% (US Census Bureau 2005). The US Census Bureau (2005) has projected that Oregon's human population will reach 4,833,918 by 2030. The majority of Oregon's population growth has taken place in counties that lie west of the Cascade Mountains (US Census Bureau 2005). East of the Cascade Mountains, the majority of population growth has taken place in three regions defined by Kline *et al.* (2007) as the northeast region (Baker, Umatilla, Union, and Wallowa Counties), the central region (Crook, Deschutes, Jefferson Counties and the northern third of Klamath County) and the remainder of Klamath County. The 2000 census estimated that these three regions contained roughly 78% of Oregonians that reside east of the Cascade Mountains but only 10% of Oregon's total population (Kline *et al.* 2007).

SECTION 1.41: URBAN GROWTH AND DEVELOPMENT

There are 242 incorporated cities and towns in Oregon (Oregon Office of the Secretary of State 2005⁵; Figure 1-1). Historical data show that as the total population has grown, the proportion of the population living in urban areas also has steadily increased and reached 79% in 2000 (US Census Bureau 2003; Figure 1-9). This pattern mirrors national population growth trends (Alig *et al.* 2004; Brown *et al.* 2005a) and is likely to continue as Oregon's economy shifts from natural resource-based products and commodities to high-tech manufacturing and information management (Hulse *et al.* 2002; Huston 2005).

Oregon contains 28,706,000 acres (44, 853 sq. mi.) of land that are not owned by the federal government and are managed under the State's land use planning regulations (Azuma *et al.* 2009). Between 1974 and 2005 the proportion of these nonfederal lands occupied by urban developments increased from 377,000 to 546,000 acres (589 to 853 sq. mi.). Overall the majority of urban expansion, including rapid growth around Bend, Madras, Redmond, and Klamath Falls, has occurred in western and central Oregon (Figure 1-10; Azuma *et al.* 2009). The proportion of nonfederal land currently occupied by urban areas is relatively small and estimated at 4.07% for lands west of the Oregon Cascade Mountains and 0.54% on lands east of the Cascade Mountains⁶ (Azuma *et al.* 2002, 2004, 2009).

In the majority of river basins delineated by the Oregon Plan, less than 1% of total land area (both federal and non-federal) is currently committed to urban uses (OWEB 2003a, 2005). Across all 15 Oregon Plan basins, urban land areas range from roughly 0.04% (~7 sq. mi.) in the Lakes Basin (south central Oregon), to 5.1% (~584 sq. mi.) in the Willamette Basin (western Oregon). In 1990, the majority (68%) of Oregon's total population lived in the Willamette Basin with most living in the metropolitan areas of Portland, Salem, and Eugene/Springfield (Hulse *et al.* 2002).

⁵ <http://bluebook.state.or.us/local/cities/ad/index.htm>. Accessed February 16, 2010.

⁶ The reader should note that these percentages are calculated from different total land areas.

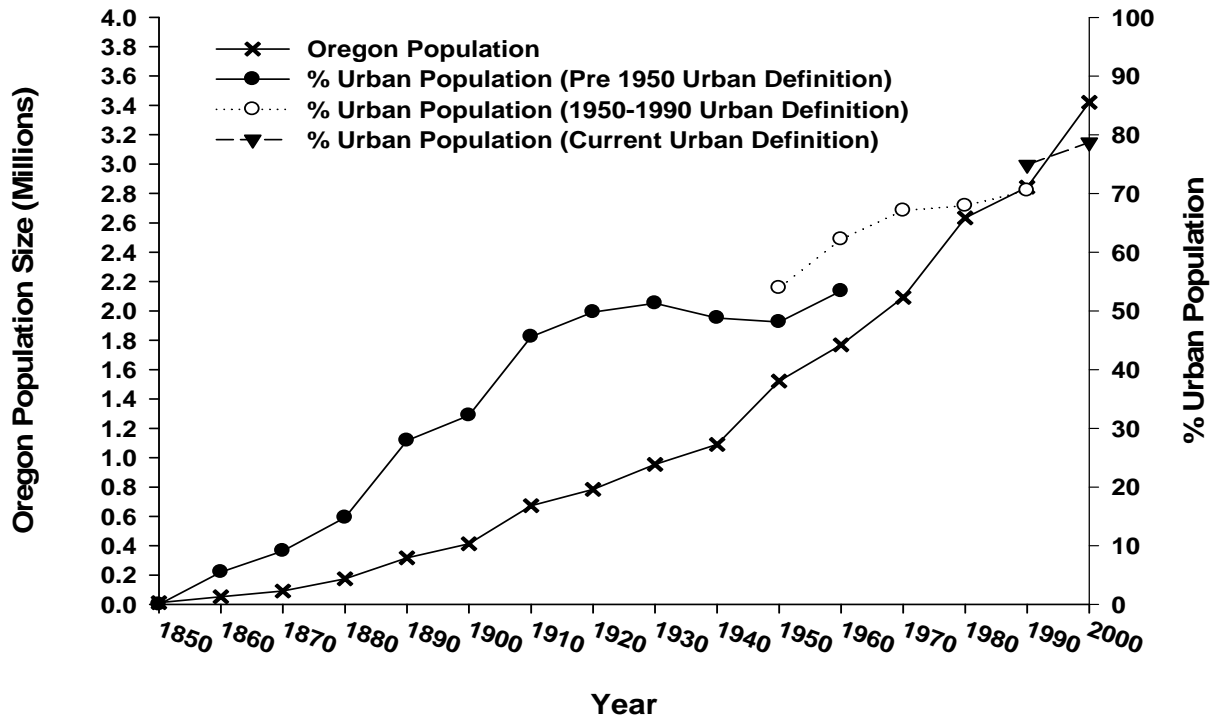


Figure 1-9. Oregon's Human Population Growth (1850–2000). Oregon's total population (left y-axis) from 1850 to 2000, and percent of total population occupying urban areas (right y-axis). The US Census Bureau revised its 'urban' definition three times during Oregon's census history, which also changed the population proportion considered urban. Horizontal overlap between the three urban population lines indicates census years where the urban population was estimated using two definitions. The current urban definition includes core census blocks with a minimum density of 1,000 people per sq. mi. surrounded by census blocks with a minimum of 500 people per sq. mi. The 1950–1990 urban definition included all territory, population, or housing units in urbanized areas and in places of 2,500 or more persons outside urbanized areas. The Pre-1950 definition included all territory, population, and housing units in incorporated places of 2,500 or more persons and areas specially classified as urban (data for this figure from US Census Bureau 2003, <http://www.census.gov/prod/cen2000/phc-3-39.pdf>).

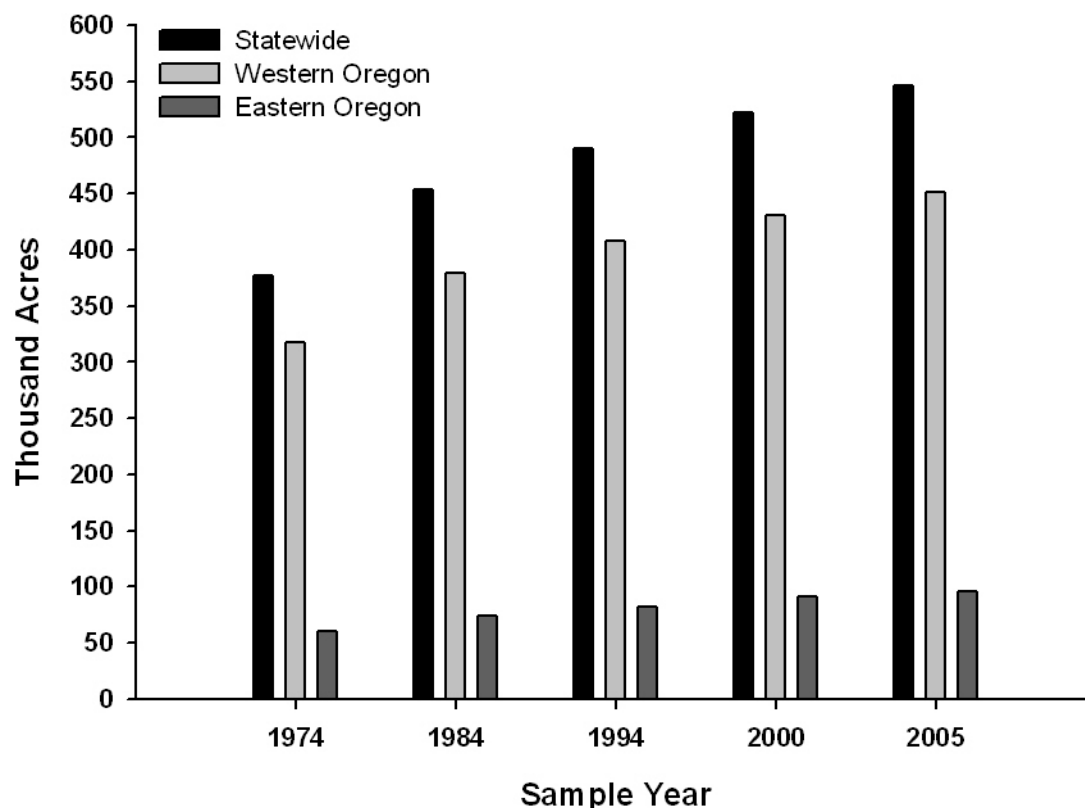


Figure 1-10. Estimated area of nonfederal land categorized as urban Oregon between 1974 and 2005. Data from Azuma *et al.* (2004, 2009). Urban land was defined as parcels greater than 40 acres zoned for commercial or residential use. Land area estimates were generated from 37,003 plots repeatedly sampled using aerial photography or digital imagery (2005 data). One thousand acres equals approximately 1.56 sq. mi.

SECTION 1.42: RURAL-RESIDENTIAL GROWTH AND DEVELOPMENT

Nationwide, residential development on rural land has outpaced urban development over the past two decades (Brown *et al.* 2005a; Theobald 2005). Between 1980 and 1997, rural-residential land use in the US grew from 56 to 73 million acres, approximately 1 million acres per year (Vesterby & Krupa 2002). The amount of developed area per person in the US also increased between 1982 and 1997 suggesting that the US is using land less efficiently (Alig *et al.* 2004).

Increases in rural-residential land use also have occurred in Oregon. Azuma *et al.* (2009) found that the area of nonfederal land used for low-density residential purposes increased from 790,000 to 1,186,000 acres (1,234 to 1,853 sq. mi.) between 1974 and 2005 (Figure 1-11). The highest rate of change to low-density residential land use occurred around the city of Bend (Azuma *et al.* 2004, 2009). The land area used for low-density residential development ranges from 1.7 to 4.4 times (west and east of the Oregon Cascade Mountains, respectively) the land area used for urban development. Azuma *et al.* (2002, 2004, 2009) found that proximity to developed land was a key factor explaining rates of conversion from other land uses (e.g., agriculture, timber

production) throughout Oregon. For example, private land in the Willamette Valley, particularly near Portland, had the highest rates of conversion. However, the social and economic factors that drive development differ significantly in western and eastern Oregon (Cho *et al.* 2005) and rural-residential development patterns in the two regions have the potential to diverge depending on local economies. Cho *et al.* (2005) found that land development west of the Cascade Range is more likely to change in response to economic variables, compared with development on the east side.

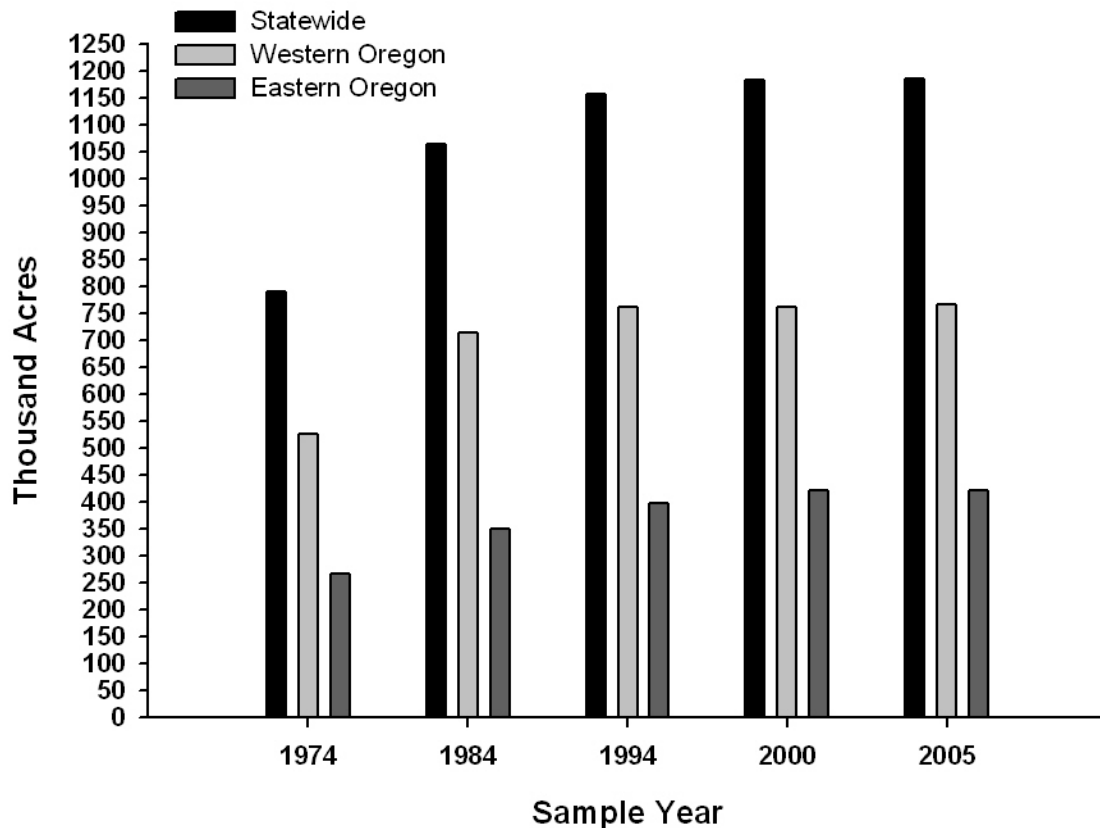


Figure 1-11. Estimated area of nonfederal land categorized as low-density residential in Oregon between 1974 and 2005. Low-density residential land use is defined as non-urban land with nine or more structures per square mile (data from Azuma *et al.* 2002, 2009). Land area estimates were generated from 37,003 plots repeatedly sampled using aerial photography or digital imagery (2005 data). One thousand acres equals approximately 1.56 sq. mi.

SECTION 1.43: FUTURE PROJECTIONS FOR URBAN AND RURAL-RESIDENTIAL AREAS

Alig *et al.* (2004) have projected a 54% population increase and an 82% developed land increase for the Pacific Northwest between 2000 and 2025. The US Census Bureau (2005) projects a 41% population increase in Oregon between 2000 and 2030. As Oregon's growing population continues to strain UGBs, the area zoned for development will continually increase and encroach on rural areas (Azuma *et al.* 2002, 2004, 2009; Baker *et al.* 2004). Kline *et al.* (2003) developed

an empirical model to project the location and density of future population growth using data on past changes in building densities (Figure 1-12). Results from this modeling effort indicate substantial expansion of both low-density and urban development in western Oregon by 2055. The proportion of land area covered by low-density development was estimated at 4.8% in 1995 and projected to expand to 5.6% by 2025 and 6.2% by 2055 (Kline *et al.* 2003). Similarly, the land area occupied by urban building densities was estimated at 2.0% in 1995 and projected to increase to 3.7% in 2025 and 6.6% in 2055 (Kline *et al.* 2003). Results from a similar, but unpublished, modeling study conducted by US Forest Service scientists on building densities in central Oregon also predict substantial expansion of low density development in this region by 2040 (Figure 1-13; Kline 2009, pers. comm.⁷).

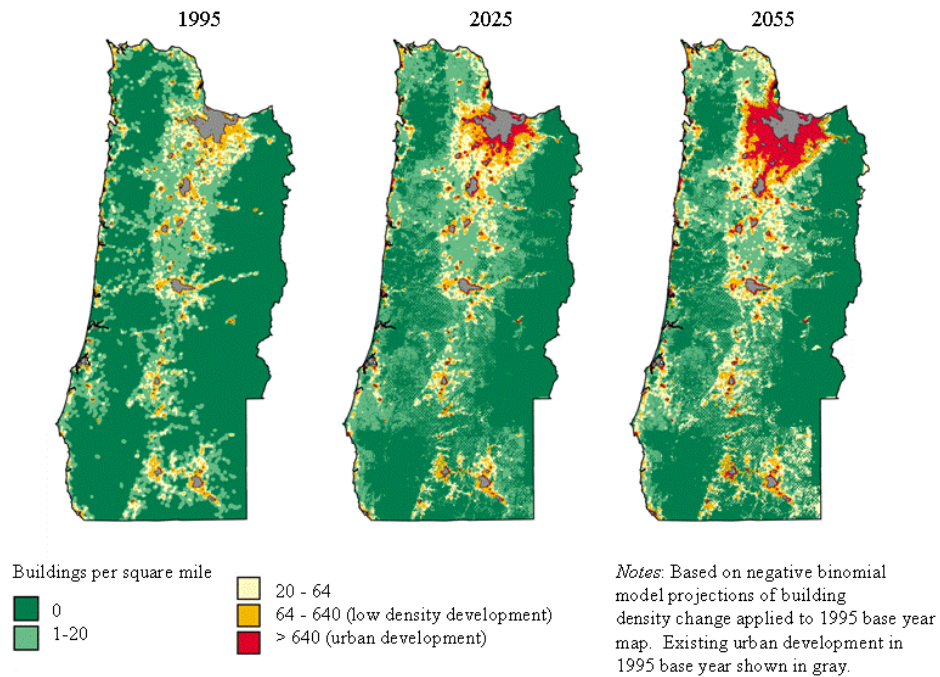


Figure 1-12. Spatial distribution and rate of change of future building densities projected for the western Oregon Region. This figure presents results from an empirical model that integrates information from an index of development pressure, topographic features, and current land use zoning policies. Modeled building densities are added to the actual building densities quantified in 1995. For comparison to the subsequent figure, one sq. mi. equals 640 acres or 2.59 sq. km. Figure provided by Jeffrey Kline, USDA Forest Service, Pacific Northwest Research Station, Corvallis, Oregon.

⁷ Jeffrey Kline, USDA Forest Service, Pacific Northwest Research Station, Corvallis, Oregon, personal communication June 2009.

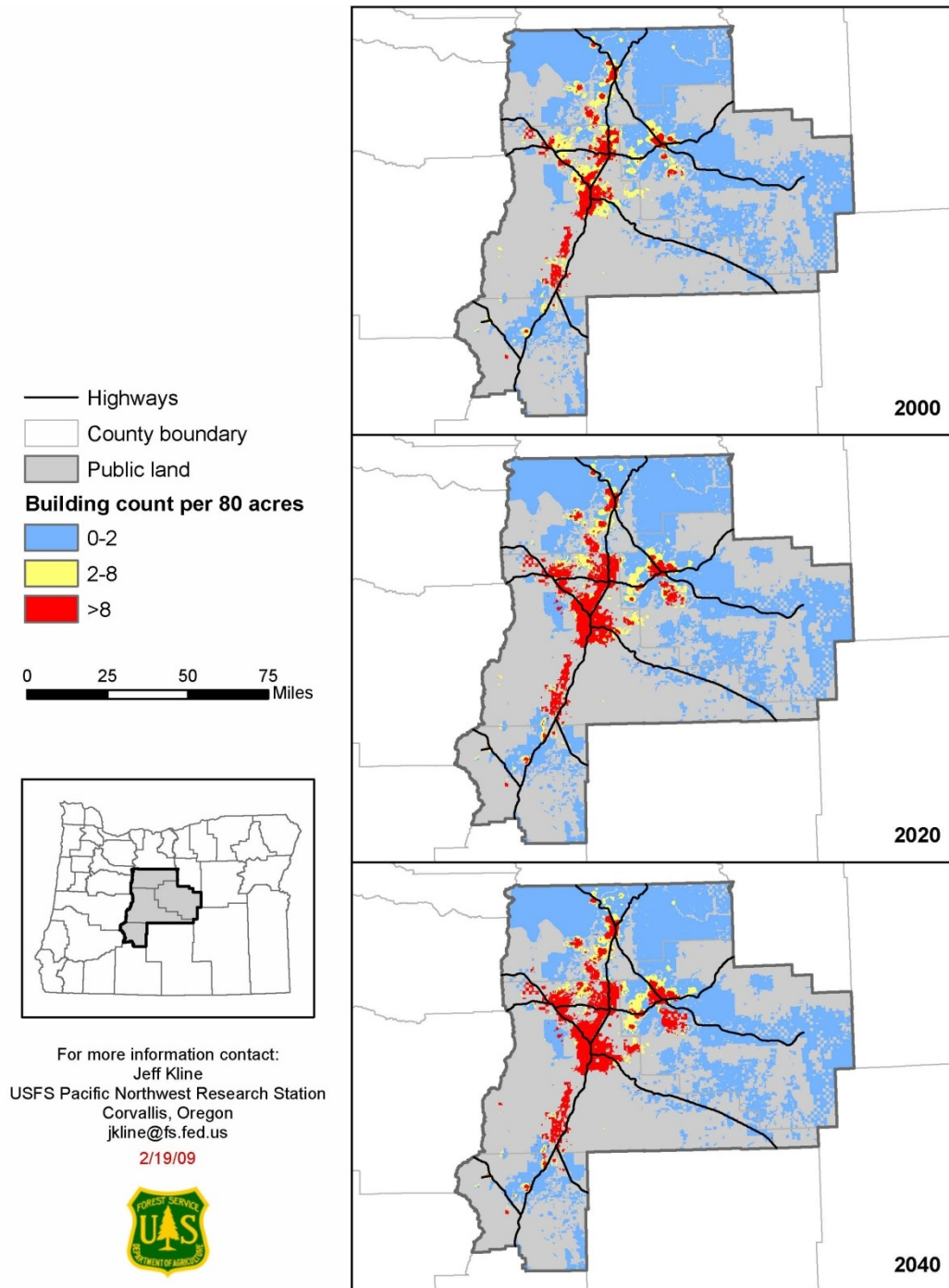


Figure 1-13. Spatial distribution and rate of change of future building densities projected for the Madras, Redmond, Bend, La Pine corridor in central Oregon. This figure presents results from an empirical model that integrates information from an index of development pressure, topographic features, and current land use zoning policies. Modeled building densities are added to the actual building densities quantified in 2000. For comparison to previous Figure 1-12, 80 acres is equal to 0.13 sq. mi. or 0.34 sq. km. For example, a density of eight buildings per 80 acres would equal approximately 60 buildings sq. mi. Figure provided by Jeffrey Kline, USDA Forest Service, Pacific Northwest Research Station, Corvallis, Oregon.

Coupled with Oregon's increasing human population is a decreasing trend in the number of persons per household. Since 1950, the statewide average household size decreased from 2.9 individuals to 2.3 in 2000 (US Census Bureau 2003). This trend may vary in different regions of the state, but overall it holds significant implications for land use and the goals of the Oregon Plan. Reduced household occupancy increases the total number of housing units used by a population, even if population growth is modest, stable, or declining (Liu *et al.* 2003). The size (i.e., square footage) of new homes is also increasing nationwide, and has more than doubled since 1950 (Wilson & Boehland 2005). The land area developed⁸ during the construction of new homes is also increasing nationwide (White *et al.* 2009). In Oregon, the average land area developed in association with the construction of a new home was estimated at 0.21 ha (0.5 acres) between 1982 and 1987 and 0.46 ha (1.14 acres) between 1992 and 1997 (White *et al.* 2009). Such trends can increase the per capita consumption of a population because fewer individuals living in larger houses have fewer opportunities to share goods and services (Liu *et al.* 2003; Wilson & Boehland 2005). Reduction in the number of persons per household, increasing home size, and increasing developed area per home have potential implications for development in Oregon. Predicting future land use, development, and resource use patterns in Oregon requires further study of these demographic parameters. Others have demonstrated the value of including similar demographic information in future landscape models of the Oregon Coast Range (Kline *et al.* 2001, 2003), the Willamette River basin (Baker *et al.* 2004; Hulse *et al.* 2002; 2004), and in central and eastern Oregon (Kline *et al.* 2007). For example, Baker *et al.* (2004; Figure 1-14) demonstrated that population growth in the Willamette Valley could drive development scenarios depending on how land use is regulated.

⁸ Calculated as the increase in developed area divided by the housing unit increase for any given time period (White *et al.* 2009).

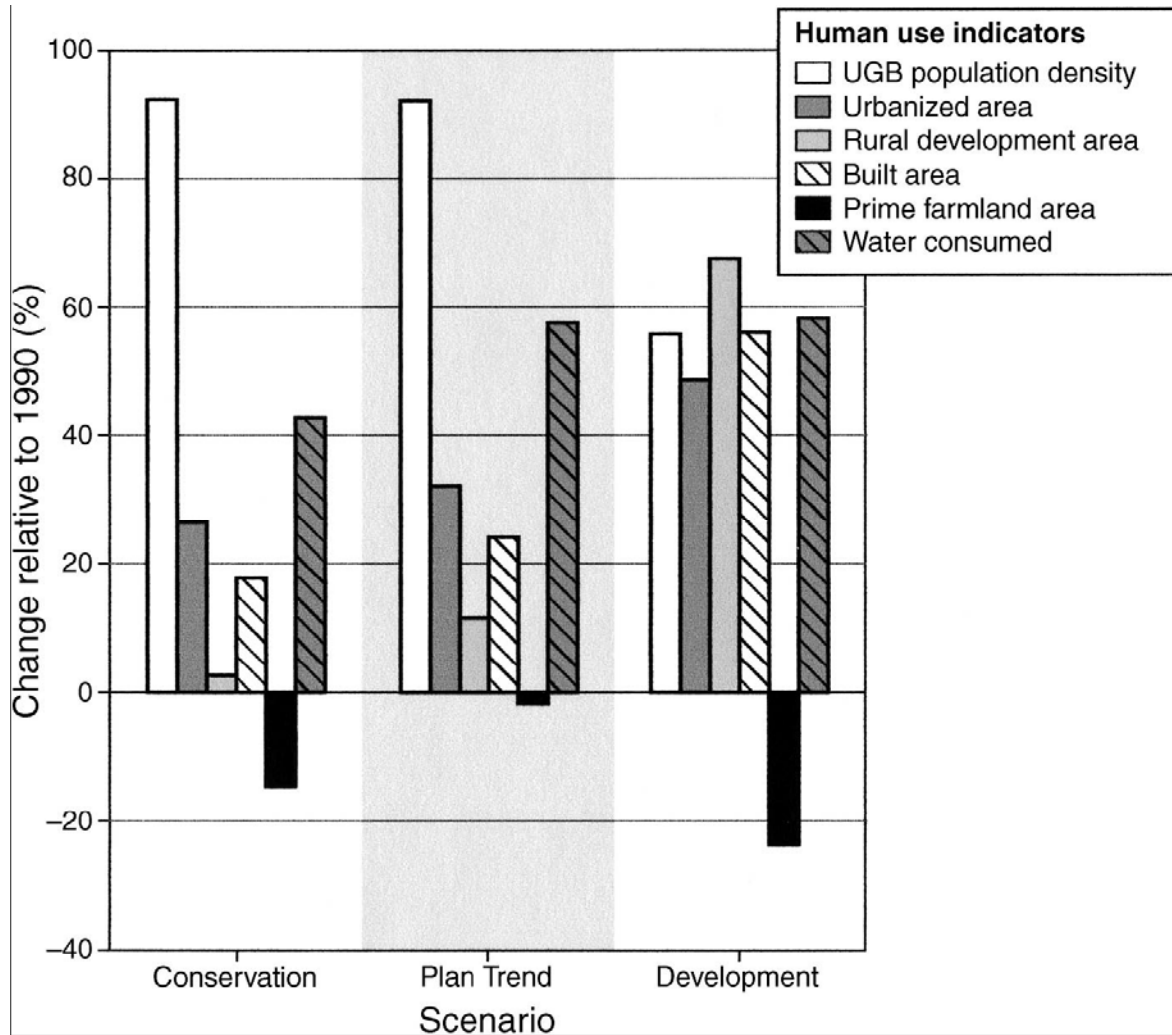


Figure 1-14. Percentage change, relative to 1990, in land use indicators in the Willamette River Basin in three future scenarios. Models projected land use change to 2050 using stakeholder input. The *Conservation* scenario placed emphasis on ecosystem protection and restoration while still reflecting a plausible balance between ecological, social, and economic requirements; the *Plan Trend* modeled the outcome of retaining current policies; the *Development* scenario modeled a relaxation of current policies in favor of free market forces. Indicators are mean human population density within urban growth boundaries (UGBs), total area affected by urban development, by rural development, by urban and rural development combined, area of prime farmland, and quantity of water consumed for out-of-stream uses. Figure 3 and associated figure title text, reproduced from Baker *et al.* (2004) with permission from the Ecological Society of America.

Section 1.5: A Landscape Perspective on Rivers in Oregon's Urban and Rural-residential Areas

The spatial and temporal scales at which salmonid habitat requirements are considered have important implications for interpretation of results from research or habitat rehabilitation. Patterns observed at one spatial scale are influenced by factors that operate at that scale as well as by factors that operate at both broader and finer scale. Processes that control individual stream habitat features (e.g., streamflow) also operate at multiple spatial scales and the relative strengths

of important processes vary across scales (Fausch *et al.* 2002; Scott *et al.* 2002; Strayer *et al.* 2003; Wang *et al.* 2003c; Moerke & Lamberti 2006b). Because rivers are hierarchically organized and respond to disturbance over variable timeframes, management actions aimed at achieving diverse habitat improvements must operate across multiple spatial scales and be applied over ecologically meaningful timeframes. Ultimately, rehabilitation of salmonid habitat must involve entire watersheds, ecological processes, and the diversity of habitats required for salmonids to complete their life histories (e.g., Fausch *et al.* 2002).

SECTION 1.51: TEMPORAL PERSPECTIVES ON SALMONIDS IN OREGON'S URBAN AND RURAL-RESIDENTIAL AREAS

Major changes to salmonid habitat began with the arrival of Euro-American settlers to the Pacific Northwest and with growth of Oregon's urban centers along large, navigable rivers and estuaries (Figures 1-1 and 1-2). To fuel local economic growth many river channels were converted from complex tangles of logs, side channels, and surrounding wetlands to unobstructed thoroughfares for boats or logs (Sedell & Luchessa 1981; Sedell *et al.* 1988; Benner 1992). A similar process occurred when wetlands were drained and braided streams were converted to single channels (e.g., Gammon 2005; Kondolf 2006). When biologists initiated habitat surveys of the radically altered rivers during the 1920s and 1930s, their observations led them to believe that channel and riparian complexity was not a natural part of salmonid habitat (Schoettler 1953). The cleared mainstem and lower tributary reaches (which in many cases were undergoing urban development) were viewed merely as salmon migration corridors.

Anecdotal evidence, current observations of habitat preferences, historical land surveys, and canning records (Gresh *et al.* 2000) indicate that large numbers of salmonids were found in the same river reaches that now support Oregon's urban centers (Groot & Margolis 1991; Stanford *et al.* 1996; Quinn 2005). Cities such as Eugene, Salem, and Portland are at major tributary confluences of the Willamette River that once supported expansive riparian forests and wetlands that experienced frequent flooding (Hulse *et al.* 2002). Likewise, small jurisdictions and rural-residential developments also concentrated along rivers and estuaries (Figures 1-1 and 1-2). Both types of development altered hydrology, water quality, physical habitat, and connectivity in ways that not only are detrimental to salmonids and aquatic life in general, but are also disproportionate to their land areas (Paul & Meyer 2001; Allan 2004; Booth 2005; Brown *et al.* 2005b, Walsh *et al.* 2005b).

As the land area used by Oregon's growing human population increased, the number of river miles directly affected by streamside developments also increased. Payne (2002) estimates that 45% of all river edge miles within Willamette River basin UGBs are now developed. These productive aquatic habitats likely were, and may still be, important spawning habitat, rearing habitat and/or migration corridors for threatened anadromous spring Chinook, coho, chum and steelhead ESUs (Friesen 2005; Table 1-5). More broadly distributed salmonid species (e.g., resident rainbow and cutthroat trout) also occupied lost side channel and wetland habitats associated with large rivers in addition to smaller streams that traverse large cities and growing towns (Reeves *et al.* 2002; Tinus *et al.* 2003; Table 1-5). These species exhibit diverse life history variation including migratory forms that now must repeatedly navigate urbanized river reaches during their migrations to large rivers or marine environments.

Table 1-5. Typical life cycles of native Oregon salmonids*.

Oregon Salmonid Species	Adults Present in Freshwater	Spawning Habitat	Eggs Present	Young Present in Freshwater & Estuaries	Marine Residence Time
Chum Salmon (<i>Oncorhynchus keta</i>)	September-March	Tidal/Intertidal streams	September-May	Migrate upon hatching January-May	2-5 years
Coho Salmon (<i>O. kisutch</i>)	October-February	Small streams	November-March	> 1 year	1-3 years
Chinook Salmon (<i>O. tshawytscha</i>) (Spring)	March-October	Large/Deep streams	October-February	1-18 months (freshwater) 6 months (estuaries)	2-5 years
Chinook Salmon (Fall)	August-January	Large/Deep streams	October-March	1-18 months (freshwater) 6 months (estuaries)	2-5 years
Pink Salmon (<i>O. gorbuscha</i>)	June-October	Tidal/Intertidal streams	July-March	Migrate upon hatching December-April	2 years
Steelhead Trout (<i>O. mykiss</i>) (Winter)	October-June	Small streams	December-May	1-4 years	1-3 years
Steelhead Trout (Summer)	Spring then spawn following year	Small streams	December-May	1-4 years	1-3 years
Resident Rainbow Trout (<i>O. mykiss</i>)	Year round	Stream, river, and lake life histories	March-June	2-3 years until maturity	None
Cutthroat Trout, sea-run (<i>O. clarkii</i>)	September-February	Small streams	January-April	2-4 years	2-5 months
Cutthroat Trout, resident	Year round	Stream, river and lake life histories	March-June	3-4 years until maturity	None
Bull Trout (<i>Salvelinus confluentus</i>)	Year round (majority)	Large streams with groundwater inputs	November-March	4-9 years until maturity	Limited anadromy
Mountain Whitefish (<i>Prosopium williamsoni</i>)	Year round	Stream, river, and lake life histories	November-March	3-4 years until maturity	None

* For more detailed reviews on salmonid life histories, see Groot & Margolis (1991), Kostow (1995), Spence *et al.* (1996), and Quinn (2005).

Habitat degradation is frequently cited as one of the factors contributing to the decline of most ESA listed salmonids (Nehlsen *et al.* 1991; Bisson *et al.* 1992). The degree to which Oregon streams and rivers have departed from natural conditions is a function of historical (i.e., changes since early Euro-American settlement) and contemporary land use (e.g., conversion of rural lands to urban uses). Past events that shape current ecosystem structure and function can constrain future outcomes of land use planning and rehabilitation efforts (Wissmar *et al.* 1994; McIntosh *et al.* 2000; Foster *et al.* 2003; Wohl 2005; McAllister 2008). If land use history and possible legacy effects are not taken into account, rehabilitation or recovery goals may be unrealistic because goals may be based on incorrect or incomplete assumptions about land use effects (Wohl 2005; McAllister 2008). This highlights the need to consider a long

temporal perspective when determining land management objectives. Recognizing and understanding land use legacy effects facilitates land managers in setting realistic objectives, and thus improves their attempts to achieve desired future conditions on developed lands (Swetnam *et al.* 1999; Casperson *et al.* 2000; Goodale & Aber 2001; Foster *et al.* 2003; Pijanowski *et al.* 2007).

Section 1.511: Legacy Impacts

Rural-residential and urban developments are commonly constructed on lands that have already undergone significant anthropogenic change from their natural state (Harding *et al.* 1998; Van Sickle *et al.* 2004). For example, much contemporary development occurs on lands previously used for agriculture (Meyer & Turner 1992; Ramankutty *et al.* 2002; Burcher & Benfield 2006). Early Euro-Americans settled in areas where productive soils and water availability were favorable for agriculture and livestock (Hansen *et al.* 2002; IMST 2002b). Consequently, settling along rivers and streams was common and served the dual purpose of facilitating transport of goods along river corridors. As the population of Euro-Americans increased in Oregon, demands for additional resources accelerated logging riparian forests, draining wetlands, removing wood from stream channels, mining, constructing dams, and diverting water for domestic, agricultural, and industrial uses (Wissmar *et al.* 1994; Taylor 1998; McIntosh *et al.* 2000; Hessburg & Agee 2003). As a result, lands adjacent to streams and rivers have often undergone a series of land use-related changes with unfavorable consequences for aquatic and riparian species (Huston 2005).

The possible impacts from historical land uses in older urban developments are poorly documented. Current land use rules and regulations were not in effect when such developments were built. Waterways were contaminated with a multitude of pollutants prior to important environmental legislation such as the Clean Water Act. Many long-lived pollutants (e.g., mercury, DDT⁹ and its breakdown products, PCBs¹⁰) persist in urban rivers and the extent of their biological effects may not be fully apparent (Hansen *et al.* 2005; Dale *et al.* 2005). Fully appreciating the altered state of aquatic ecosystems in developed areas requires knowledge of the cumulative land use history, environmental regulation, and natural disturbance (Harding *et al.* 1998; Konrad & Booth 2005; Walton *et al.* 2007).

The effects of previous land uses can influence aquatic ecosystem structure and function long after the disturbance has ended (e.g., Wissmar *et al.* 1994; Harding *et al.* 1998; McIntosh *et al.* 2000; Hessburg & Agee 2003; Allan 2004; McAllister 2008). In some situations, past land use is a better predictor of aquatic ecosystem condition than contemporary land use (Meyer & Turner 1992; Harding *et al.* 1998; McIntosh *et al.* 2000). Researchers working at fourteen Long Term Ecological Research¹¹ sites throughout the US have documented persistent effects extending from land use that occurred decades or even centuries ago (Foster *et al.* 2003). For example, Harding *et al.* (1998) identified persistent effects of past agriculture on aquatic assemblages long after sites had been reforested and aquatic structural habitat restored in western North Carolina watersheds. While many associations between contemporary land uses and degraded aquatic ecosystem conditions are indisputable, effects from historical land uses present significant

⁹ dichloro-diphenyl-trichloroethane

¹⁰ polychlorinated biphenyls

¹¹ Information on the National Science Foundation's Long Term Ecological Research program can be found at <http://www.lternet.edu/>. Accessed November 22, 2010.

covariates that complicate linking causal mechanisms to aquatic ecosystem impairment (Allan 2004; McAllister 2008) and to current stream morphology (Gammon 2005; Kondolf 2006).

In the Pacific Northwest, historical natural resource extraction has altered stream hydrology, channel structure, and water quality in Oregon's streams and rivers and reduced the capacity of some waters to support viable populations of salmonids (Taylor 1998; Sedell & Froggatt 1984; Benner & Sedell 1997; McIntosh *et al.* 2000). Historical land uses that have left persistent legacy effects include timber harvest operations, agricultural practices, mining, and various direct stream channel modifications (Wissmar *et al.* 1994; Hessburg & Agee 2003). The following sections contain brief examples of legacy effects that may persist on Oregon's developed lands or within undeveloped areas of UGBs. For more detailed information on land use history and its effects on streams and rivers, see the IMST review of land use on western Oregon lowlands (IMST 2002b).

AGRICULTURE: By the mid 1800s Oregon's centers of agricultural production were beginning to take shape. By the late 1800s agricultural land use was a common feature in western (and presumably eastern) Oregon valley bottoms (Taylor 1998). On lands adjacent to Portland, early commercial farmers cultivated a variety of food crops sold in the rapidly growing city. In the Willamette Valley, significant wetland loss was caused by draining floodplains for agriculture (Johannessen *et al.* 1971; IMST 2002b). Today, agricultural lands are frequently converted to developed land uses (Alig *et al.* 2004; Burcher & Benfield 2006) and the effects of past agricultural use have been shown to persist long after agricultural lands have been developed (Van Sickle *et al.* 2004; Burcher & Benfield 2006; ODEQ 2006; Pijanowski *et al.* 2007).

CHANNEL ALTERATIONS: Changes in stream, river and estuary channel structure can persist for especially long periods of time (Allan 2004; Gammon 2005). Consequently, channels disrupted by historical land uses may require extended periods to stabilize and may never do so if they are chronically disturbed by ongoing development (Chin 2006), channelization, and incision. Historical land uses that destabilized stream and river channels often occurred in reaches upstream of lands that are developed or are undergoing development (Wissmar *et al.* 1994; McIntosh *et al.* 2000; Hessburg & Agee 2003). Selected examples of historical activities that have caused persistent changes to the channel structure of Pacific Northwest streams and rivers follow.

- *Forestry* – Early loggers often used rivers to transport logs to saw mills and construction operations in downstream river valleys (Sedell *et al.* 1991; Taylor 1998). To facilitate downstream log transport, rivers and channels were straightened and diked. Large logs, boulders, and rock outcrops were removed to clear obstructions from channels. During transport, log drives from splash dams scoured channels so severely that the effects persist today (Wohl 2005). Historical logging activities in riparian forests continue to restrict recruitment of large wood into streams and rivers. The lack of large wood and low instream wood recruitment rates have ongoing consequences for structural habitat, as well as nutrient and carbon cycling, in streams and estuaries (Foster *et al.* 2003).
- *Log Removal* – Prior to Euro-American settlement, Pacific Northwest rivers naturally accumulated and transported large volumes of wood (see Section 5.13 of this report). In lowland areas, persistent log jams created braided channels connected to wide floodplains, numerous side channels, and sloughs. Beginning in the 19th century, large logs capable of supporting log jams were removed. This reduced the volume of wood in

ivers and the recruitment of new wood from riparian forests, fundamentally changed the geomorphic processes that shape channel dynamics of Pacific Northwest rivers (e.g., Sedell & Froggatt 1984; Benner & Sedell 1997; Collins *et al.* 2002; Hulse *et al.* 2002; IMST 2002b). Wood removal, coupled with other efforts to straighten channels (e.g., levees, dredging), has created stream and river channels that fundamentally differ from their pre-Euro-American settlement condition.

- *Beaver Trapping* – Abundant beaver (*Castor canadensis*) populations throughout the western US supported an active fur trading industry in the early to mid 1800s. Trappers working in the Willamette and Columbia River basins extirpated many beaver populations within a few decades (Hessburg & Agee 2003; Wohl 2005). Beaver dams exert significant control over the movement of water and sediment through stream and river channels which increases stream braiding, wetland formation, and riparian zone productivity, reduces catastrophic flooding, and regulates summer base flows. Removing beavers (and their dams) can result in mass movements of fine sediment and uncontrolled floods that erode stream beds and banks and lead to channel incision (Kelsey & West 1998; Butler & Malanson 2005). The loss of beavers from aquatic ecosystems in the Pacific Northwest has reduced the stability and diversity of structural aquatic habitat, decreased local water tables, and reduced the width and diversity of riparian vegetation all with negative consequences for native salmonids (Hessburg & Agee 2003; Demmer & Beschta 2008).
- *Mining* – River channels and floodplains have been mined for several types of materials throughout the history of Euro-American settlement. Many Oregon rivers supported (and some still support) instream sand and gravel mining operations that reduced channel stability, degraded spawning gravels, and simplified aquatic structural habitat (IMST 2002a). Placer mining¹² that occurred during the 19th and early 20th centuries affected structural habitat and water quality through the removal of riparian vegetation and channel substrates (Wissmar *et al.* 1994; Wohl 2005). Heavy metals such as mercury were also commonly used in placer mining and these contaminants persist in many historical mining locations (Wissmar *et al.* 1994). Removing sediment from channels and banks decreased channel stability, reduced channel volume, increased flood frequency, and perpetuated erosion or channel aggradation downstream of the mining site (Wissmar *et al.* 1994; Wohl 2005; Hessburg & Agee 2003). Affected river channels are slow to recover a stable form because fine sediment erosion and deposition of dredge spoils onto the floodplain limits riparian vegetation productivity that might stabilize river banks and facilitate recovery. The cumulative effects of these operations on salmonid habitats in Oregon are not well documented, but the effects of some large-scale operations still persist in Oregon (Wissmar *et al.* 1994; Hessburg & Agee 2003).

¹²Removal of minerals (commonly gold) deposited in alluvial sand and gravel of rivers and valley floors using hydraulic methods (e.g., washing, dredging).

SECTION 1.52: SPATIAL PERSPECTIVES ON SALMONIDS IN OREGON'S URBAN AND RURAL-RESIDENTIAL AREAS

Section 1.521: Contemporary Factors that Influence Large Spatial Extents

The effects of development are intermixed with contemporary anthropogenic changes that affect larger spatial extents (Allan 2004). Aquatic ecosystem responses integrate all these changes. Consequently, any rehabilitation, monitoring, or land use planning efforts require consideration of the larger landscape context. In the Pacific Northwest there are many external pressures that might affect aquatic ecosystem capacity for salmonid recovery in rural-residential and urban lands (e.g., land use activities in other portions of the basin, commercial fisheries harvest, invasive species, hydropower, fish hatcheries, climate change). The following two sections summarize the effects of dams and climate change to illustrate how such factors might affect salmonid populations in developed lands. Dams and climate change were selected to represent one case (i.e., dams) where effects are well-documented and one case (i.e., climate change) where there is great uncertainty in the potential future impact on salmonid populations. Selection of these two examples is not meant to indicate that they are any more or less important than other factors mentioned in this report.

DAMS: Stanford *et al.* (1996) considered dams the most all-encompassing cause of river alterations. Dams serving a variety of functions (water storage, flood control, hydropower, recreation) have been constructed on streams and rivers throughout Oregon. Several authors (e.g., Ruckelshaus *et al.* 2002) have provided extensive reviews on the effects of large dams on salmonid movements. While restricted movement is an issue for salmonids in many parts of Oregon, dams also affect river hydrology, channel morphology, and structural habitat in downstream reaches (Sedell & Froggatt 1984; Taylor 1998; IMST 2002b; Gammon 2005; Gregory *et al.* 2007) that pass through developed areas. For example, in the Willamette River basin there are 13 federally operated dams and at least 300 private dams (Hughes *et al.* 2005c) that regulate the nature, timing and magnitude of river flows, (reviewed by Gregory *et al.* 2007) and shape the ecological setting in which hydrologic alterations driven by developments operate.

Dams reduce variation in river flows by storing water during high runoff events and releasing water during low runoff periods (Gregory *et al.* 2007). Flow alterations affect downstream water quality by modifying the water temperature regime (lower temperatures in early spring; higher in late summer/fall) and can result in downstream reaches exceeding temperature criteria determined for various salmonid life history stages (Gregory *et al.* 2007; Angilletta *et al.* 2008). In unregulated rivers, seasonal floods shape stream channels by replenishing coarse sediments and instream wood (Welcomme 1979; Minshall 1988; Junk *et al.* 1989; Stanford *et al.* 1996; Poff *et al.* 1997). Dams contribute to channel incision by preventing the downstream movement of coarse and fine substrates. River channel incision results in head cutting and further incision of their tributaries, thereby isolating channels from their floodplains and riparian vegetation. Such streams and rivers have reduced structural complexity, and reduced capacity to accommodate flow fluctuations. By changing natural flow regimes, dams alter the mechanisms by which rivers and streams produce in-channel and off-channel habitats essential for supporting aquatic biological diversity (Hughes *et al.* 2005a, b, c). Consequently, any goals for rehabilitation of the local flow regime requires consideration of this context and may benefit from coordination with ongoing rehabilitation efforts aimed at larger spatial extents (e.g., Gregory *et al.* 2007).

CLIMATE CHANGE: There is broad consensus among the scientific community that the Pacific Northwest climate is undergoing a warming trend that will likely continue throughout the 21st century (Mote *et al.* 2003; Battin *et al.* 2007; ISAB 2007a; Climate Impacts Group 2009). However, there is significant uncertainty regarding the timing and magnitude of climate changes affecting the Pacific Northwest, particularly in predicting variations in timing, intensity and frequency of local precipitation patterns (Gibson *et al.* 2005; Battin *et al.* 2007). Despite this uncertainty, several authors have independently predicted that future climate changes could affect hydrology and water quality in ways that are unfavorable for spawning, incubation, and rearing of several salmonid species (Gibson *et al.* 2005; Crozier & Zabel 2006; Preston 2006; Battin *et al.* 2007; Ficke *et al.* 2007; Rieman *et al.* 2007; Climate Impacts Group 2009). While climate change models consistently predict negative consequences for Pacific Northwest salmonids, the likelihood, timing, and magnitude of effects vary across independent modeling efforts and currently are not well quantified (Preston 2006). Changes consistently predicted by independent modeling efforts include:

- Increased proportion of precipitation falling as rain;
- Increased peak flows and rain-on-snow events during winter months;
- Reduced snow packs;
- Earlier snowmelt and peak spring runoff;
- Reduced base flows during summer and fall months;
- Increased water temperatures; and
- Increased duration of warmer water temperatures.

The volume and timing of streamflows have strong influences on water quality, aquatic ecosystem condition, and water availability for various land uses (Poff *et al.* 1997; Gibson *et al.* 2005). A change in the prevailing form of winter precipitation (i.e., from snow to rainfall) and reduced summer streamflows will have diverse implications for water resource management and the potential to increase conflict among competing water uses including municipal, industrial, agricultural, and environmental uses (Meyer *et al.* 1999; Houston *et al.* 2003; Whitely Binder 2006).

Houston *et al.* (2003) projected freshwater withdrawals in several western US states (Washington, Oregon, California, Idaho) to 2050 and predicted that human population growth will increase demands on freshwater resources. Between 1960 and 1995 the human population in Pacific Coast states nearly doubled and freshwater withdrawals for public and domestic uses increased by 76% (Houston *et al.* 2003). If per capita water use remains constant in Oregon, demands for domestic uses were projected to increase by 65% between 2000 and 2050. Similarly water demands made by industrial and commercial interests in Oregon were projected to increase by 59% between 2000 and 2050 (Houston *et al.* 2003). These increased demands on freshwater resources will be partially offset by an estimated 6% reduction in water withdrawals made for agricultural uses, the largest source of water withdrawals in Oregon. Despite this reduction in agricultural withdrawals, projections that aggregate all uses (agricultural, industrial, commercial, public, domestic) indicate substantial net increases in demand for water resources in all Pacific Coast states (Houston *et al.* 2003). By 2050, total demands for freshwater resources in Oregon were projected to increase by 10% over withdrawals made in 2000 (Houston *et al.* 2003). This

increase could have significant ecological effects depending on sources used to meet the increasing need. For example, Dole & Niemi (2004) investigated potential effects of future land and water use on surface water resources in the Willamette River basin (models projected a doubling of the 1990 human population by 2050). All of the alternative futures modeled indicated that by 2050 northern parts of the Willamette River basin would experience severe water shortages and that modeled conservation actions were not sufficient to protect ecologically important instream flows.

Jenerette & Larsen (2006) modeled the sensitivity of urban water footprints (the area from which water used by municipalities is drawn) to changes in water availability caused by climate change and conservation measures aimed at increasing instream flows. Model results indicated that reductions in local water supplies available for municipal uses increased the area required for many cities to meet increasing demand for water resources (Jenerette & Larsen 2006). Many Oregon cities hold 'senior' water rights that, if exercised, would allow priority use of surface water resources by municipalities (Dole & Niemi 2004). If increasing demands for water resources cause municipalities to exercise these rights, water use by users holding 'junior' water rights would be restricted (Dole & Niemi 2004). In Oregon, water rights held by state agencies for instream uses are typically junior to many older water rights and restrictions on instream uses could change the distribution of instream flows in watersheds affected by development. Scenarios modeled by Dole & Niemi (2004) indicated that such an outcome was unlikely in the Willamette River basin because surface water resources in the mainstem Willamette River and the storage capacity provided by dams were sufficient to meet the demands of municipalities serving a growing population. However, the effects of senior water rights held by municipalities may become an important consideration in watersheds where conditions like those in the Willamette River basin do not exist.

The potential for interaction between climate change and land use change creates uncertainty about how the combined effects of these two phenomena will affect aquatic ecosystems (Gibson *et al.* 2005; Nelson & Palmer 2007; Pyke & Andelman 2007). Land use change has well-documented effects on aquatic ecosystems that could be exacerbated by climate change (Nelson & Palmer 2007; Pyke & Andelman 2007). Watersheds where streamflows are regulated by dams, for example, may not be affected by changes in the timing of peak flows. However, if such watersheds also experience drier conditions, demands on the water supply could reduce low flows and increase water temperatures beyond what might be caused by climate change alone (Gibson *et al.* 2005). In a recent review addressing the interactive effects of land use and climate change on aquatic ecosystems, Pyke & Andelman (2007) concluded that future land and water resource management actions present opportunities to mitigate some undesirable effects of climate change on aquatic ecosystems. The challenges facing Oregon's land and water resource managers include increasing demands on water resources, variability in natural climatic conditions, habitat requirements of endangered species, and uncertainty in future water supplies. Consequently, decisions regarding the use of water resources will become increasingly complex and will require informed input from scientists and stakeholders to meet these challenges.

Section 1.522: Regional Impacts of Human Population Centers

Much of Oregon's energy, water, and material use, and waste generation occur on the small fraction of land area occupied by urban developments (Pratt *et al.* 2000). Consequently, urban areas draw on resources well beyond their boundaries and can contribute to the degradation of resources at multiple scales including river basins, regions, and continents. For example, Portland lies within the Willamette River basin but obtains a significant portion of its domestic water supply from the Bull Run watershed, which lies outside the Willamette River basin. The system of dams and reservoirs in the Bull Run watershed significantly alter streamflows, water temperature regimes, and aquatic biota (including four threatened salmonid species) of both the Bull Run and Sandy Rivers (NMFS 2006b).

The resources required to support a population center can be quantified using *ecological footprint* analysis (Rees & Wackernagel 1996; Folke *et al.* 1997; Wackernagel *et al.* 2001, 2002; Rees 2003; Venetoulis *et al.* 2004). For example, in 1998 the Seattle region in Washington (including Tacoma and Bremerton) covered approximately 2,066 sq. mi. and was inhabited by 3.4 million people (Luck *et al.* 2001). The estimated land area required to support this population was 1,313 sq. mi. for combined domestic and agricultural water uses, 23,822 sq. mi. for food production, and 86,602 sq. mi. for carbon resources (e.g., wood products, petroleum; Luck *et al.* 2001). Thus, the 1998 Seattle metropolitan area required approximately 54 times more land area than the physical space occupied by its residents. This estimate of the Seattle ecological footprint is most likely smaller than the actual footprint because such analyses do not comprehensively quantify all human impacts (Rees 2000). In the Pacific Northwest, the extent of urban impacts on salmonid populations is also directly linked to consumption of the energy produced by dams that have several well-documented effects on salmonid movements and habitats. In addition to Oregon's urban areas putting demands on Oregon resources outside of UGBs, the world market also consumes many of these same resources (e.g., timber, salmonids, crops, livestock).

The ecological footprints of individual urban areas depend on both their population size and per capita consumption rate (Wackernagel *et al.* 2001, 2002; Venetoulis *et al.* 2004), as well as their geographic locations and competition for resources with adjacent cities (Luck *et al.* 2001). Shrinking household occupancy and increasing home size may also cause ecological footprints to increase because of decreased efficiency in the use of goods and services (Liu *et al.* 2003; see Section 1.43 of this report). Programs and policies designed to manage natural resources and associated landscapes, including the Oregon Plan, are more likely to be effective when they address impacts to resources needed to meet the consumptive demands of developed areas for water, energy, wood, food, and waste disposal.

Section 1.523: Land Use Patterns

Fish are found throughout watersheds, but the composition of fish assemblages¹³ changes with location and species richness increases with river size (Fausch *et al.* 1984). Reeves *et al.* (1998, 2002) documented that the number of species and the total number of fish increased in coastal Oregon rivers as they moved downstream from the headwaters. Similar patterns have been described in other areas of the Pacific Northwest (e.g., Li *et al.* 1987; McGarvey & Hughes 2008). This pattern is attributed to increasing habitat diversity (pools, riffles, backwaters,

¹³Assemblage refers to subsets of a community that share common ancestry (e.g., fish, bird, and insect assemblages).

overflow areas, floodplains) as slopes become more level and streams become less constrained by the surrounding landscape. Overlain on varying patterns of aquatic diversity are intensive land cover alterations associated with development that modify ecological processes at multiple spatial scales (Borgström *et al.* 2006; Cumming *et al.* 2006).

Statewide, decisions about how to manage Oregon's salmonid populations and their habitats rest with various individual land owners; watershed councils; local, state and federal agencies; elected policy makers; and federal, state, local and tribal governments (Hanna 2008). For example, a Chinook salmon migrating through the Columbia River basin to spawning habitat in northern Idaho traverses as many as 17 separate jurisdictions managed by federal, state, tribal and local governments (ISAB 2005; Hanna 2008). The jurisdictions of individual agencies and organizations that make decisions about the management of salmonid populations are spatially fragmented. In any given location, decisions about the management of salmonid populations (e.g., commercial and sport harvest, fish passage, hatchery production, habitat protection) or actions that affect populations (e.g., irrigation withdrawals, hydropower production) may be made by multiple entities with overlapping jurisdictional boundaries (Hanna 2008).

Embedded within such basin-wide jurisdictional complexities, developed landscapes constitute a heterogeneous and dynamic complex of land use types such as green spaces, transportation corridors and built areas each owned and managed by a different individual or entity (Alberti *et al.* 2003; Borgström *et al.* 2006; Kaye *et al.* 2006). The complex mix of land owners, of jurisdictional boundaries, and of land-use policies that exist over relatively small spatial extents in developed lands poses a challenge for the effective management of salmonid populations. Compared to other land uses (e.g., agriculture, forestry), developed landscapes undergo intensive, long-term, and often permanent conversions that limit management options. Remaining green spaces are commonly expected to serve multiple purposes (e.g., recreation, stormwater management, wildlife habitat) that necessitate tradeoffs (e.g., public safety, accessibility) and limit the functionality of such areas in watershed-scale land use planning (Borgström *et al.* 2006). Numerous land owners with competing interests for the ecosystem services provided by rivers inevitably require trade-offs that may lead to conflict when the protection of such services is at issue (Hanna 2008).

Even though urban areas occupy a relatively small area of the landscape, their position can lead to disproportionately larger effects on salmonids or fish assemblages. Compared to other land uses, urban areas often occupy critical locations in Oregon's watersheds. Towns and cities are commonly located along streams and rivers at lower elevations and often at their confluences (Figures 1-1 and 1-2). As such, they influence both local habitat in the lowlands and movement of fishes upstream and downstream. Migration barriers, alteration of physical habitat, and degradation of water quality at critical points along river networks have the potential to limit the abundance and distribution of salmonids throughout an entire watershed.

Streams within developed areas are commonly perceived at local scales otherwise known as stream reaches. At this scale, streams might traverse a neighborhood or section of town and integrate a series of habitats (e.g., glides, riffles, and pools) that support differing fish assemblages. Local residents have the majority of their direct interaction with rivers, aquatic organism, and riparian and aquatic habitat rehabilitation projects in such locations. Consequently, the stream reach provides numerous opportunities for education and community involvement. However, the hydrological, water quality, and fish passage factors that often limit fish assemblages in developed areas are most likely operating at watershed (Fitzpatrick *et al.*

2005) and river basin scales. Effectively addressing aquatic ecosystem impairments caused by rural-residential and urban developments may require actions taken at several spatial scales and maintained for variable lengths of time. Because management actions take place in larger political, economic, and cultural contexts, the boundaries of management jurisdictions may not match those of important ecological processes (Hanna 2008). When the scale of management is not aligned with the scale (spatial and/or temporal) at which ecological processes or disturbance regimes operate, actions intended to protect natural resources may be ineffective (Borgström *et al.* 2006; Cumming *et al.* 2006). Management barriers of this type may be fairly common in developed landscapes because of the high diversity and fragmented distribution of land owners and land uses (e.g., Borgström *et al.* 2006). Such difficulties present a significant challenge for integrating developed lands into watershed-scale recovery efforts aimed at Pacific Northwest salmonid species.

Science Question 1: How does urbanization alter aquatic ecosystems and what are the implications for salmonid rehabilitation?

Urban and rural-residential development involves a diverse collection of actions that transforms natural ecosystems into highly altered landscapes. The suite of aquatic ecosystem changes that accompanies development have been reviewed by several authors (e.g., Paul & Meyer 2001; Brown *et al.* 2005b; Walsh *et al.* 2005b; Chin 2006; Kaye *et al.* 2006). In this review, the IMST summarizes changes most relevant to Pacific Northwest aquatic ecosystems with an emphasis on how these alterations affect native aquatic biota, particularly salmonids.

Streams, rivers and estuaries capable of supporting healthy salmonid populations contain a range of environmental attributes that meet the physiological and behavioral requirements of salmonids throughout their complex life cycles (Table 1-5). These environmental attributes typically reflect the historical conditions under which salmonid populations evolved unique sets of adaptations (i.e., life histories) that maximize their survival (Miller & Brannon 1982; Bjornn & Reiser 1991; Groot & Margolis 1991; Thorpe 1994; Quinn & Myers 2004). The spatial scales over which necessary environmental attributes are distributed are species specific. For example, chum salmon complete the freshwater stages of their life cycle over much smaller spatial scales than Chinook salmon (Figures 1-2 through 1-8 and Table 1-5 in Section 1.0). As a result, habitat alterations stemming from development may affect individual salmonid species differently.

IMST has identified four key pathways (hydrology, physical habitat, water quality, fish passage) through which urban and rural-residential developments alter aquatic ecosystems (Figure 2-1). IMST's intent in this review is to provide a general perspective of the importance of these factors to the goals of the Oregon Plan. While each pathway is addressed separately in this report, it is important to keep in mind that they occur simultaneously and exhibit strong interdependency at multiple spatial and temporal scales (King *et al.* 2005; also see reviews by Paul & Meyer 2001; Walsh *et al.* 2005b). In particular, the combined changes in hydrology, water quality, fish passage, and physical habitat ultimately lead to changes in aquatic biota, including salmonids (Figure 2-1). Because these pathways influence one another, and because the abiotic factors linking these pathways to aquatic ecosystem change are numerous, the specific mechanisms that underlie aquatic ecosystem impairments are not easily isolated and may vary with location or time of year. Effective rehabilitation of salmonid habitat in urban and rural-residential areas requires watershed-scale consideration of all pathways and their interactions (e.g., Booth *et al.* 2004; Walsh *et al.* 2005b).

Stormwater and wastewater are two major products of urban and rural-residential development that contribute to alterations in hydrologic processes, physical habitat, water quality, and fish passage. To highlight the importance of these two factors and to reduce repetition throughout this report, the following sections summarize the challenges stormwater and wastewater present to aquatic ecosystem functions in Oregon's streams, rivers and estuaries.

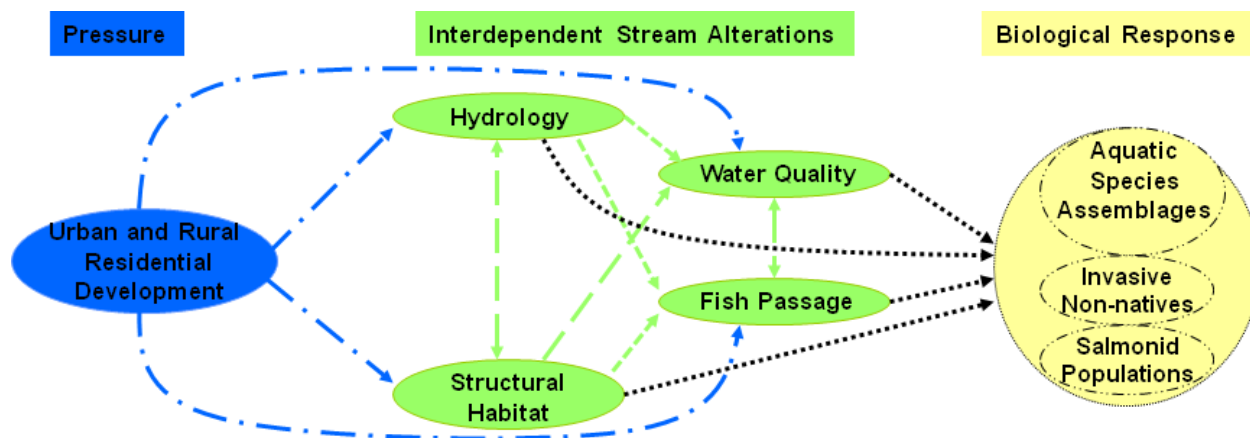


Figure 2-1. The pathways by which urban and rural-residential development alter aquatic communities and the condition of salmonid habitat and populations. Dashed/dotted (blue) arrows indicate direct effects of development on four key components of aquatic ecosystems (green). Dashed (green) arrows depict interactions among components, and dotted (black) arrows represent the influence of the altered ecosystem components on aquatic biota.

Section 2.0: Stormwater

Urban and rural-residential development causes profound changes to the pathways, volume, timing, and composition of stormwater runoff (Paul & Meyer 2001; Konrad & Booth 2005; Walsh *et al.* 2005b). These changes have diverse and persistent consequences for aquatic ecosystems that can extend throughout entire watersheds (Walsh *et al.* 2005a, 2005b). The State of Washington identified stormwater as a major cause of impairment in salmonid streams flowing through developed areas (GSRO 1999; ISP 2003). The extent of aquatic ecosystem impacts is strongly influenced by development pattern and stormwater infrastructure design (Dietz 2007; Walsh 2000; Walsh *et al.* 2005a). The suite of watershed-scale perturbations associated with changes in stormwater runoff includes physical, chemical, and biological changes.

Physical Changes: Development activities, that remove vegetation, compact soil, and/or create pavement and roofs, increase watershed imperviousness to precipitation. Consequently, the fraction of precipitation routed to surface runoff increases, triggering higher peak streamflows, the possibility of lower base flows, and greater flow variability (see Section 4.0 of this report). Disturbed vegetation and soil, and increased surface runoff, work in combination to alter watershed sediment budgets, which can produce a number of stressors for many aquatic organisms. These effects alter stream hydraulics, channel complexity, and channel morphology in ways that impair physical habitat (see Section 5.0 of this report) required by native aquatic biota.

Chemical Changes: Pollutants carried by stormwater runoff are a significant threat to freshwater resources (USEPA 1995). Water running over paved surfaces and through storm drains often bypasses soil and riparian vegetation that can buffer acidity, filter, and break down pollutants before they enter streams (Gresens *et al.* 2007). Stormwater frequently contains automotive

products (i.e., gasoline, oil, and antifreeze), metals, pesticides, road and airport deicers, fertilizers, and contaminated sediments (USEPA 2002b; Paul & Meyer 2001; Nielson & Smith 2005). Many heavy metals and pesticides are highly toxic to aquatic organisms and can alter the biotic communities of rivers and estuaries (Graves *et al.* 2004). Even at relatively lower rural-residential land use densities, untreated substances enter surface waters with negative consequences for aquatic biota (see Section 7.6 of this report).

Biological Changes: The changes in stormwater runoff associated with development can alter hydrologic processes, water quality, and physical habitat in ways that are not only detrimental to aquatic life but are also disproportionate to their land area (see reviews by Paul & Meyer 2001; Allan 2004; Booth 2005; Brown *et al.* 2005b; Walsh *et al.* 2005b). Numerous studies relating macroinvertebrate indices or fish assemblage composition to measures of urbanization typically show deteriorating conditions as urbanization increases (see Section 8.0 of this report). At the landscape scale, fish assemblages become increasingly homogeneous¹⁴ as development increases. This pattern is in part due to the physical habitat impairments associated with stormwater runoff. Increased stormwater runoff can limit salmonid population productivity or persistence by reducing survival, altering behavior, slowing growth, or delaying transitions between different developmental stages (see Section 8.3 of this report).

Section 2.1: Stormwater Management

Early efforts to manage stormwater typically used drainage infrastructure to move excess runoff away from people, structures, and transportation systems directly into streams that served as stormwater channels (Walsh 2000; Carter & Rasmussen 2006; Zheng *et al.* 2006). Extensive flooding, water quality impairments, and environmental damage caused by older stormwater management techniques motivated a shift in management emphasis from simply conveying excess water to also protecting receiving waters (Jones *et al.* 2005). To better address stormwater-related issues, the US Congress amended the Clean Water Act (CWA) in 1990 and 1999 to include Phases I and II of the National Pollutant Discharge Elimination System (NPDES) stormwater control programs (USEPA 2005). The NPDES requires that stormwater be managed to the ‘maximum extent practicable.’ The Phase I program requires NPDES permits for large municipalities that have populations of 100,000 or more. The Phase II program extends permit requirements to smaller communities (<100,000 residents) that fall under the US Census Bureau’s definition of an urbanized area, referred to as small *municipal separate storm sewer systems* (MS4s).

In communities operating under NPDES permits, the Oregon Department of Environmental Quality (ODEQ) requires that stormwater be managed under programs that address illicit discharge, construction site runoff, and post-construction management of stormwater in new developments and re-developed areas. Stormwater regulations apply to all construction sites disturbing more than one acre (0.4 ha), industrial sites, and MS4s. Entities managing municipal systems are responsible for establishing a stormwater management program that follows specific treatment requirements and also maintains compliance with Oregon’s *total maximum daily load* (TMDL) process currently implemented by the ODEQ.

¹⁴ A shift to more uniform species assemblages and communities across the landscape, with a reduction of unique assemblages.

Smaller developments (i.e., with populations under 50,000) in Oregon that are not contiguous with urban areas demarcated by the US Census Bureau have not, historically, been required to apply for NPDES Phase II permits. Some of Oregon's cities with 20,000 or more residents that are currently not required to manage stormwater under the NPDES system include Albany, Grants Pass, McMinnville, Newberg, Redmond, Roseburg, and Woodburn (Oregon Environmental Council 2007). These cities address water quality impairments attributed to stormwater runoff under Oregon's TMDL process (Benninghoff 2009 pers. comm.¹⁵) which is implemented when water bodies no longer meet water quality standards developed for temperature, bacteria, and various pollutants (i.e., water bodies on the state 303d list).

The CWA also requires monitoring and regulation of all non-point source pollution (including stormwater) and ODEQ has recently dedicated additional resources to this end (ODEQ 2007). Due to the ubiquity of non-point pollution sources in urban and rural-residential developments, it will be years before Oregon realizes a comprehensive non-point pollution management program in developed areas (ODEQ 2007). Until then, the effects of non-point source pollution on aquatic ecosystems may rival or exceed those of point source pollution generated by developments (Line *et al.* 1997; Paul & Meyer 2001; USEPA 2002b).

The city of Portland provides a useful example of the challenges posed by stormwater management in Oregon cities that are experiencing rapid growth. Portland straddles five watersheds that collectively receive 80–100 billion gallons of precipitation annually. Twenty billion gallons of that precipitation are converted to stormwater runoff. By 2040, continuing development is predicted to increase this volume by roughly 10% (2.2 billion gallons; Vizzini 2007 pers. comm.¹⁶). Currently Portland's stormwater is conveyed through 568 miles of storm sewers and 861 miles of combined storm and sanitary sewers either to wastewater treatment facilities (see Section 3.0 of this report) or directly to the Willamette River and Columbia Slough. As Portland continues to grow, increasing stormwater volumes will strain the limits of this conveyance system. To ease the increasing demands on its stormwater management infrastructure, Portland is implementing initiatives that will encourage property owners to manage stormwater onsite rather than routing it to the sewer system. Initiatives include programs to disconnect stormflow from storm sewers (e.g., through downspout disconnections and installations of bioswales and rain gardens), to educate the public on stormwater-related issues and to facilitate the development of a local marketplace based on stormwater management¹⁷.

¹⁵ Benjamin Benninghoff, Oregon Department of Environmental Quality, Portland, Oregon, personal communication, March 28, 2009.

¹⁶ Vizzini D (Portland Bureau of Environmental Services) Presentation given at the Urban Ecology Research Consortium Symposium (Jan. 22, 2007), Portland State University.

¹⁷ For details visit <http://www.portlandonline.com/BES/index.cfm?c=44048>. Accessed November 22, 2010.

Key Findings–Stormwater:
<ul style="list-style-type: none"> • In communities operating under NPDES permits, ODEQ requires that stormwater point-sources be managed under programs that address illicit discharge, construction site runoff, and post-construction management of stormwater in new developments and re-developed areas.
<ul style="list-style-type: none"> • Entities managing municipal systems are responsible for establishing a stormwater management program that follows specific treatment requirements and also maintains compliance with Oregon's <i>total maximum daily load</i> (TMDL) process currently implemented by the ODEQ.
<ul style="list-style-type: none"> • In Oregon, some smaller cities that are not contiguous with urban areas demarcated by the US Census have not historically been required to apply for NPDES permits. These cities address water quality impairments attributed to stormwater point-sources under Oregon's TMDL process which is implemented when water bodies no longer meet water quality standards developed for temperature, bacteria, and various pollutants.
<ul style="list-style-type: none"> • It may be many years before Oregon realizes a comprehensive non-point pollution management program in developed areas.

Section 3.0: Wastewater

Urban wastewater reaches aquatic ecosystems from both point sources and non-point sources. Point source pollution comes from discrete conveyances (e.g., treated sewage drained through pipes), typically derived from domestic or industrial infrastructure. Non-point source pollution originates from diffuse sources such as stormwater runoff or improperly functioning septic systems. Wastewaters derived from rural-residential and urban areas contribute a variety of pollutants to aquatic ecosystems including personal care products, pharmaceuticals, fire retardants, excess nutrients and property maintenance chemicals (see Section 7.6 of this report). Industrial facilities produce comparatively large volumes of wastewater that often contain sewage and potentially toxic pollutants such as solvents and organochlorines (Anderson *et al.* 1996; Fuhrer *et al.* 1996; Wentz *et al.* 1998; Morace 2006). In stream or river reaches, where wastewater effluent is a substantial proportion of the flow, resulting water quality impairments can have negative consequences for aquatic biota (see Sections 7.6 and 8.0 of this report).

Section 3.1: Wastewater Management

In Oregon's urban areas, municipal wastewater treatment facilities process domestic¹⁸ and some types of industrial wastewater¹⁹. Some urban areas also have treatment facilities designed solely for industrial wastewater management. Treatment of domestic wastewater is a multistage process (Keller 1999; USEPA 2004b). *Primary treatment* involves screening large particulates from

¹⁸ Domestic wastewater includes wastewater from toilets, sinks, tubs, showers, and washing machines used in residences, businesses, and industries.

¹⁹ The following summary of how wastewater is managed in Oregon is based in part on personal communications with Ranei Nomura, Oregon Department of Environmental Quality, Portland, Oregon, May 20, 2010.

incoming wastewater then separating the remaining fine particulates by allowing them to settle out of suspension within quiet tanks or ponds. *Secondary treatment* uses aerobic and anaerobic bacteria to metabolize fine particulate and dissolved organic waste products that remain after primary treatment is completed. Secondary treatment also involves disinfecting water with chlorine, ozone, or ultraviolet light. Finally, *tertiary treatment* is used to remove or neutralize specific pollutants that pass through secondary treatment processes, such as excess nutrients, heavy metals, and organic compounds. Examples include air stripping to remove ammonia or chelating chemicals to remove nutrients and metals (Ragsdale 2007). Primary and secondary treatments are required in all of Oregon's municipal wastewater treatment facilities that discharge effluent into surface waters. In the northern Willamette River basin, several specialized facilities also use more expensive tertiary procedures. Industrial wastewater treatment processes vary depending on the type of industry producing the waste. For example, screening of large particulates (primary treatment) may not be required if they are not present in industrial wastewaters or disinfection may not be required when there is no human sewage in the wastewater.

The ODEQ currently administers two permit programs to regulate the discharge of treated wastewater to surface or ground waters (Table 3-1). The NPDES permits were established under the CWA and Water Pollution Control Facilities (WPCF) permits were established under Oregon's state waste discharge permit law. WPCF permits are used to regulate wastewater discharges that have the potential to negatively impact groundwater. The CWA requires state regulatory agencies with NPDES permitting authority (e.g., ODEQ) to ensure that wastewater treatment facilities comply with federal regulations adopted by USEPA and state water quality standards approved by the USEPA. Federal regulations typically set minimum treatment requirements that integrate the best available treatment technologies with economically feasible treatment options. State water quality standards set specific criteria that are necessary to protect beneficial uses of surface and ground waters²⁰. Beneficial uses include aquatic organisms and their habitats, recreational activities such as boating and swimming, and drinking water. The number of individual NPDES and WPCF permits issued by ODEQ (Table 3-1) indicate that surface and ground waters in Oregon could receive a substantial volume of treated wastewater. Many of these facilities currently operated by NPDES permit holders are discharging below their design capacity and can treat more wastewater. It is likely that discharge will increase as Oregon's human population continues to grow.

An NPDES permit limits the amount of monitored pollutants that can be discharged to surface waters by permit holders. This regulation applies to pollutants that have water quality standards set by the State of Oregon²¹. NPDES permits require that the concentration of a monitored pollutant present in wastewater effluent be reduced when the discharged effluent is likely to exceed state water quality standards for the pollutant of concern. If the pollutant concentration in wastewater effluent is at a level that meets state water quality standards, then further treatment to reduce the concentrations of that pollutant is not required. When a water body receiving wastewater effluent fails to meet state water quality standards, ODEQ performs a thorough analysis of point source wastewater and nonpoint source inputs as part of a TMDL analysis.

²⁰ For details on beneficial uses of surface waters in Oregon see: <http://www.deq.state.or.us/wq/standards/uses.htm>. Accessed May 20, 2010.

²¹ For up-to-date lists of regulated water pollutants see <http://www.deq.state.or.us/WQ/standards/standards.htm>. Accessed May 11, 2010.

TMDL analyses define how much of each monitored pollutant a river or stream can receive and still meet water quality standards²².

Table 3-1. Numbers of active discharge permits issued under the NPDES and WPCF programs administered by ODEQ*.

	Eastern Region	Northwest Region	Western Region	Statewide
NPDES INDIVIDUAL PERMITS	75	111	188	374
Major Domestic	9	17	23	49
Major Industrial	3	7	9	19
Major Stormwater	0	4	2	6
Minor Domestic	31	35	88	154
Minor Industrial	31	46	53	130
Minor Stormwater	1	2	13	16
WPCF INDIVIDUAL PERMITS	290	213	356	859
Domestic	74	15	53	142
Industrial	28	8	12	48
Stormwater	0	1	0	1
Onsite	188	189	291	668
ALL	365	324	544	1233

* Data were obtained at from ODEQ staff (Ranei Nomura, ODEQ, personal communication, May 5, 2010). For complete descriptions of permit categories, see the ODEQ Water Quality Permit Program website at <http://www.deq.state.or.us/wq/wqpermit/permitfaqs.htm>. Accessed on November 22, 2010..

ODEQ requires that NPDES permit holders adequately operate and maintain treatment facilities, monitor effluent discharges for concentrations of specified pollutants, and report findings to ODEQ on a regular basis. To help public agencies comply with their permit requirements, ODEQ uses its Clean Water State Revolving Loan Fund. The program for this fund was enacted in 1987 through amendments to the Federal Water Pollution Control Act. In Oregon, the fund provides low-cost loans for planning, designing, or constructing various water pollution control activities conducted by public agencies. Oregon's public agencies have made extensive use of this resource. ODEQ has loaned more than \$800 million since its program was established in 1990. For the 2010 fiscal year (July 1, 2009 – June 30, 2010) ODEQ made \$96 million available for projects aimed at improving water quality.

WPCF permits are designed to protect groundwater and comply with drinking water standards. For example, approximately one third of the WPCF permits issued by ODEQ regulate underground injection systems that involve the discharge of several types of wastewater below

²² For information on the analyses that have been done to date, visit ODEQ's website at <http://www.deq.state.or.us/WQ/TMDLs/basinlist.htm>. Accessed December 30, 2010.

ground. Underground injection systems are commonly used by cities or counties that do not operate municipal stormwater treatment facilities or by private businesses that are not connected to municipal sewer or stormwater systems. Because underground injection systems discharge wastewater effluent directly into the ground, they have the capacity to introduce pollutants to groundwater that can subsequently enter surface waters such as streams, rivers, or wetlands. Permit holders discharging treated wastewater effluent into below-ground structures such as sumps, drywells, or drain fields are required to monitor effluents and ensure that the wastewater discharge will not pollute groundwater²³.

Because of Oregon's permit regulations, wastewater treatment facilities in Oregon have generated a considerable amount of monitoring data on the quality of treated wastewater discharged into the environment. Published reports tend to be case studies of "best available technologies." For example, Ragsdale (2007) reported that advanced tertiary treatment reduced total suspended solids and total phosphorous at two Portland-area wastewater treatment facilities. Presently, not all of the monitoring data reported to ODEQ is stored in an easily accessible electronic format. Much of the data collected by NPDES permit holders operating in Oregon is held in regional ODEQ offices in hard copy format. In 2004 ODEQ developed an electronic discharge monitoring database system (known as DMS or Discharge Monitoring System) to track monitoring data from its permittees and has been able to consistently enter data from "major"²⁴ NPDES permittees into this database since 2006.

Many rural-residential communities throughout Oregon rely on septic systems for wastewater treatment (e.g., Mitchell & Harding 1996; ODEQ 2004; Hinkle *et al.* 2007), which are regulated by ODEQ issued WPCF permits. Similar to municipal treatment plants, septic systems use settling tanks and bacteria to separate and metabolize organic waste. The resulting liquids flow from septic tanks to subterranean drain fields which diffuse the remaining wastes through surrounding soils (USEPA 2004b). Where soil drainage is adequate, septic systems can be a safe, cost-effective means to treat wastewater. However, in locations where clay, sand, or shallow soils are common, water tables are high, or flooding occurs frequently, septic systems can discharge incompletely treated or untreated wastewater into local ground or surface waters (Keller 1999; USEPA 2004b).

Section 3.2: Wastewater-related Issues Important to Aquatic Ecosystems

Specific water quality impairments resulting directly from wastewater effluent cannot be identified because the primary literature on urban water quality (e.g., Sonoda *et al.* 2001; Carle *et al.* 2005; Atasoy *et al.* 2006) fails to discriminate the effects of wastewater effluent from those of other urban influences, such as stormwater runoff. Other considerations related to municipal wastewater treatment facilities and septic systems also make it very difficult to draw generalizations about the proportion of ecosystem impairment that is a direct result from wastewater.

²³ For additional information on the use and regulation of underground injection systems see <http://www.deq.state.or.us/wq/uic/uic.htm>. Accessed 21 May, 2010.

²⁴ 'Major' permittees are generally domestic treatment plants with design flows equal to or greater than 1 million gallons per day and larger industrial treatment plant in specified industrial categories.

Several Oregon cities route wastewater and stormwater to treatment facilities through the same set of pipes, referred to as a *combined sewer system*. Combined sewer systems can discharge untreated sewage and stormwater directly into rivers in what is termed a *combined sewer overflow* if stormwater exceeds the capacity of sewage lines and treatment facilities. The number of chemicals identified in wastewater treatment facility effluent and combined sewer overflows ranges up to 200 (Ritter *et al.* 2002) but the timing and magnitude of events that trigger combined sewer overflows make it difficult to generalize about the quantity of contaminants that actually reach receiving waters. The combined sewer system serving Portland, for example, discharged six billion gallons of combined sewer overflow into the Willamette River and Columbia Slough in 1990²⁵. Between 1980 and 2001, all but two of Oregon's 31 communities that operate combined sewer systems modified their facilities to reduce the frequency of combined sewer overflows²⁶. Two Oregon communities (Portland and Astoria) are still working with ODEQ to meet regulatory standards for combined sewer overflow events. To date, Portland reduced combined sewer overflow discharge to 2.1 billion gallons in 2006 and further system modifications are scheduled for completion in 2011; Astoria is scheduled to complete corrections by 2022 (ODEQ 2001a).

Biological contaminants and nutrients from poorly functioning septic systems can be a source of non-point pollution in rural-residential areas (Mitchell & Harding 1996; Conn *et al.* 2006; Swartz *et al.* 2006; Hinkle *et al.* 2007; Squillace & Moran 2007). As part of a cooperative effort to understand if and how groundwater resources are affected by septic tanks, the USEPA, US Geological Survey, ODEQ, and the Deschutes County Environmental Health Division developed the *La Pine National Demonstration Project* (La Pine Project). The La Pine Project assessed how septic systems are affecting groundwater within southern Deschutes County (Oregon) (Hinkle *et al.* 2005, 2007, 2009). Hinkle *et al.* (2005, 2007, 2009) tested both septic and groundwater samples, and found that groundwater samples contained high levels of septic-derived nitrate (NO₃; 1% of sites exceeded USEPA maximum contaminant level standards). In addition nine organic compounds including pesticides and pharmaceuticals were found at concentrations lower than those measured in septic water (Hinkle *et al.* 2005). Researchers working in other areas where large numbers of septic systems are used in Oregon (e.g., Mitchell & Harding 1996) and throughout the US (e.g., Conn *et al.* 2006; Swartz *et al.* 2006; Squillace & Moran 2007) have also documented septic derived substances moving into groundwater. These findings have raised concerns about how contaminated groundwater may be contributing to surface water quality impairments in the Deschutes and Little Deschutes Rivers (Williams *et al.* 2007).

It is difficult to draw generalizations about how septic systems affect surface water quality for two interrelated reasons. First, the infiltration rate of septic contaminants depends on local soil and hydraulic parameters; the same contaminants will not always pose equal risks to groundwater quality in different areas (Mitchell & Harding 1996; Hinkle *et al.* 2005). Second, it is unclear to what degree groundwater contaminants transfer to streams and rivers (Hinkle *et al.* 2005; Gaddis *et al.* 2006). Groundwater-surface water interactions are extremely dynamic and variable (e.g., Ellis *et al.* 2007; Keery *et al.* 2007), making it difficult to predict when septic

²⁵ Portland Bureau of Environmental Services, <http://www.portlandonline.com/bes/index.cfm?c=31030>. Accessed November 22, 2010.

²⁶ Regulations allow combined sewer overflows during 5-year return (winter), 10-year return (summer), or larger, storm events (Richard Santner, Oregon Department of Environmental Quality, Portland, Oregon, personal communication). Note that a 5-year return storm event, for example, has an exceedence probability in a given year of 20%, i.e., the average length of time between such events is five years (McCuen 1998).

leakage will pose a significant threat to aquatic biota within a given basin. It is likely though that high groundwater tables will facilitate septic contaminant percolation into surface waters (Kalbus *et al.* 2006). Using data from the 1990 US Census²⁷, IMST estimated the number of septic units in Oregon. Assuming the fraction of households with septic systems (29.3%) remained constant between 1990 and 2005, a rough estimate of the current number of household septic systems in Oregon is 456,000. Given the estimated and increasing number of septic systems operated in Oregon, water quality impairment stemming from malfunctioning septic systems is a legitimate concern warranting further investigation (Paul & Meyer 2001; USEPA 2002b; Mueller & Spahr 2006).

Key Findings-Wastewater:

- The numbers of individual NPDES permits issued by ODEQ indicate that surface water and groundwater in Oregon could receive a substantial volume of treated wastewater.
- The number of chemicals identified in wastewater treatment plant effluent and combined sewer overflows ranges up to 200, but the timing and magnitude of events that trigger combined sewer overflows make it difficult to draw generalizations about the quantity of contaminants that actually reach receiving waters.
- NPDES and WPCF permit regulations set limits on the amount of monitored pollutants that can be discharged to surface waters by permit holders. These regulations only apply to pollutants that have water quality standards set by the State of Oregon.
- Rural-residential communities throughout Oregon rely on septic systems for wastewater treatment. Biological contaminants and nutrients from poorly functioning septic systems can be a source of non-point pollution in rural-residential areas. It is likely that high groundwater tables and porous soils will facilitate septic contaminant percolation into surface waters. Given the estimated and increasing number of septic systems operated in Oregon, water quality impairment stemming from failed septic systems is a legitimate concern.

²⁷ Data available at http://factfinder.census.gov/home/saff/main.html?_lang=en. Accessed November 22, 2010. The 2000 and 2010 Census did not include wastewater information so only 1990 data could be included here.

Sections 4 to 8: Aquatic Ecosystem Processes Altered by Urban and Rural-residential Development

Sections 4 through 7 review how hydrology, physical habitat, water quality, and fish passage can be affected by urban and rural-residential areas. IMST reviews the factors and mechanisms responsible for changes to aquatic ecosystem condition in urban and rural-residential areas, and the nature, timing, and magnitude of these changes. In Section 8, IMST concludes Science Question 1 by summarizing the comprehensive effects of aquatic ecosystem alteration on aquatic communities, particularly algae, macroinvertebrate and fish assemblages, and salmonid populations.

Section 4.0: Hydrology

Hydrologic processes shape rivers and estuaries by moving water, wood, and sediments, which create and maintain conditions that support aquatic biota including salmonids (Poff & Ward 1989; Jay & Simenstad 1996; Poff *et al.* 1997; Borde *et al.* 2003; Konrad & Booth 2005; Beechie *et al.* 2006; Poff *et al.* 2006a). Within any watershed, several hydrologic pathways route precipitation toward runoff, groundwater, or the atmosphere. Partitioning of precipitation among these hydrologic pathways, in part, shapes the local hydrologic regime which for rivers is typically characterized by the source, magnitude, timing, frequency, duration, seasonality, and rates of change of high and low flows (Poff *et al.* 1997).

Within the Pacific Northwest, regional differences in climate and geology exert significant controls over the natural hydrologic regimes of streams, rivers, and estuaries (Figure 4-1; Poff 1996; Benke & Cushing 2005; Beechie *et al.* 2006; Sanborn & Bledsoe 2006). For example, watersheds west of the Cascades receive 75–80% of their precipitation from large winter fronts that generate peak flows from November to March (Redmond & Koch 1991; Good 1999, 2000; Colbert & McManus 2003; Kentula & DeWitt 2003). Many streams and rivers in central and eastern Oregon are heavily influenced by snow melt or short duration, but intense, summer thunderstorms. Consequently, peak flows east of the Oregon Cascade Mountains can occur during the winter, spring, or summer months (Sanborn & Bledsoe 2006). Throughout Oregon, the timings of winter peak and of summer low flows correlate strongly with local geology (Tague & Grant 2004).

Hydrologic pathways that are altered by urban and rural-residential development lead to changes in the natural hydrologic regimes (e.g., Poff *et al.* 2006a) which can have profound consequences for aquatic ecosystems and the salmonids that depend on them (Konrad & Booth 2005; Walsh *et al.* 2005b). Across the US, broad physiographic regions or ecoregions show different hydrologic responses to development (Konrad & Booth 2005; Poff *et al.* 2006a). These different responses highlight the importance of incorporating a landscape context (e.g., climate, geology, and land use history) when evaluating either the effects of development along Oregon's rivers and streams or the potential for rehabilitating hydrologic regimes in these systems (Konrad & Booth 2005). For example, within the Willamette River basin (western Oregon) the hydrologic response to urbanization and associated water quality impacts occur within the context of river basin-scale hydrologic regulation resulting from the operation of numerous dams (Gregory *et al.* 2007).

Climate also plays a major role in watershed hydrology and climate change has the potential to intensify or reverse the hydrologic effects of development (Claessens *et al.* 2006). General

circulation model projections consistently predict both warmer temperatures and changes in seasonal precipitation patterns in the Pacific Northwest during the 21st century. Warmer winter temperatures are projected to reduce snow pack levels, which would result in higher winter streamflows. Precipitation is projected to increase during winters, further augmenting winter streamflow levels. In summer periods, however, precipitation is projected to decrease, leading to lower streamflows (Payne *et al.* 2004, Markoff & Cullen 2008). Therefore, climate change may influence the type and timing of precipitation and have important effects on future snow packs and streamflows (Hamlet & Lettenmaier 1999; Leung & Wigmosta 1999; Miles *et al.* 2000; Mote *et al.* 2003; Payne *et al.* 2004; ISAB 2007a) and salmonids (Battin *et al.* 2007) throughout the Pacific Northwest.

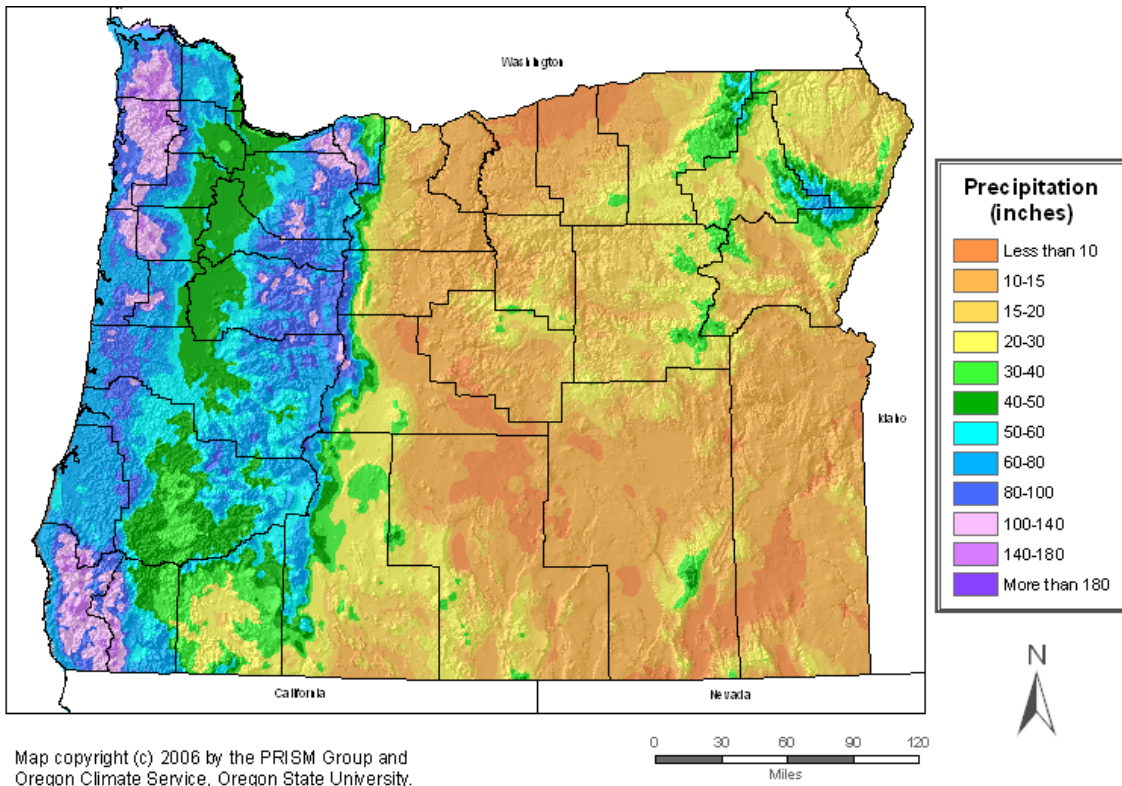


Figure 4-1. The average annual precipitation for Oregon calculated from 1971-2000. Source is the Oregon Climate Service, <http://www.ocs.oregonstate.edu/index.html>. Accessed on April 22, 2009.

Section 4.1: Factors and Mechanisms that Alter Hydrology in Urban and Rural-residential Areas

This section emphasizes changes in the timing and magnitude of streamflow, the linkage of streamflow to other physical and biological processes, and the importance of these processes in shaping salmonid habitats. Hydrologic interactions with channel conditions are discussed in Section 5.1 on physical habitat.

SECTION 4.11: IMPERVIOUS SURFACES

Within undeveloped lands, infiltration rates and water storage capacity are strongly influenced by soil characteristics; soil characteristics are determined by parent materials, climate, topography, biota and age (Gerrard 1981). The extent and distribution of soil infiltration capacity depend on how the mineral component of soils are leached by precipitation, soil particle size and heterogeneity (i.e., the relative composition of sand, silt and clay), and differ among regions with varying physical and biological characteristics (Hillel 1980). In intact forests and grasslands, rainfall not intercepted by vegetation infiltrates soils; after infiltration, soil water is mostly either withdrawn by vegetation or released groundwater.

One hallmark of development is the increased imperviousness of watersheds to precipitation. Construction of impervious surfaces, including pavement (e.g., roads, sidewalks, parking lots), roofs, and compacted soils, decreases infiltration and increases surface runoff directly routed to surface waters (Figure 4-2; Dunne & Leopold 1978; Paul & Meyer 2001; Booth 2000; Konrad & Booth 2005; Walsh *et al.* 2005a). The hydrologic effects include both faster stream response times and higher peak flow events, which are referred to as the “flashiness” of the stream. However, the fraction of impervious area that is created by development within a watershed and the hydrologic consequences of the impervious surface are context-dependent. Some studies conducted in the Pacific Northwest and elsewhere suggest that the degree of flashiness may be a function of watershed scale. Smaller watersheds tend to show flashier responses than larger watersheds. In some cases larger urbanized watersheds do not show changes in streamflow characteristics at all, presumably because of storage or flood control reservoirs and other landscape modifications that might increase water storage in the basin (Clark 1999; Chang 2007; Brown *et al.* 2009).

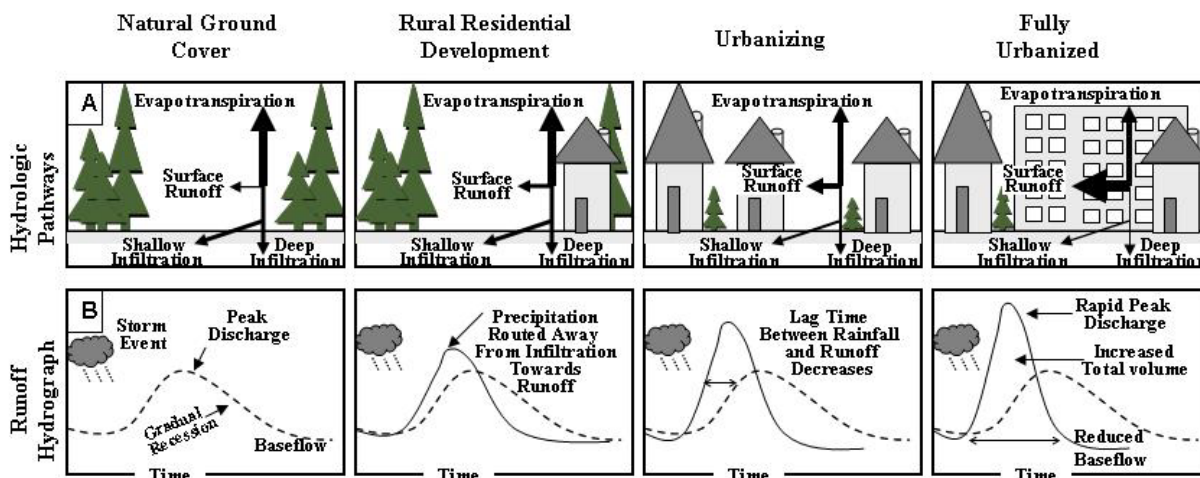


Figure 4-2. Hypothetical changes in precipitation routing among hydrologic pathways with increasing imperviousness area in watersheds undergoing urbanization. Arrow thickness represents the proportion of water taking each respective route but the relative proportions may change depending on climate, forest type, or other site specific factors. B. Comparative differences in the timing and magnitude of surface runoff from a single storm event and dry season base flows in undeveloped, developing, and developed watersheds. Dashed lines represent the predevelopment hydrograph while solid lines show changes in the hydrograph at progressive stages of development. Figure is modified from USEPA (1993) and Arnold & Gibbons (1996).

Because developed landscapes contain significant quantities of impervious surfaces, various measures of impervious area are commonly used to characterize the extent and intensity of development (Table 1-1) and to guide land use planning (Schueler 1994; Arnold & Gibbons 1996; Lee & Heaney 2003; Walsh *et al.* 2005a). In the Pacific Northwest, estimates of watershed-scale *total impervious area* (TIA) range from <5% in undeveloped watersheds (e.g., Reinelt *et al.* 1998) to 54% in the Columbia Slough watershed (City of Portland 2005). Site-level TIA associated with particular developed land uses (e.g., residential, commercial, industrial) can vary considerably depending on parcel dimensions and spatial arrangement of construction within parcels (e.g., Stone 2004; Stone & Bullen 2006). As a result, residential zoning and land use regulations, typically applied to individual parcels, can have significant control over watershed- and regional-scale imperviousness (See Section 9.2 of this report).

The connectivity between impervious surfaces and streams has important implications for the hydrology of rivers and estuaries in developed watersheds (Lee *et al.* 2006; Konrad & Booth 2005; Walsh *et al.* 2005a). With respect to aquatic ecosystem condition, the distinction between TIA and *effective impervious area* (EIA, the fraction of TIA with direct hydrologic connections to streams) has demonstrated importance (Hatt *et al.* 2004; Taylor *et al.* 2004; Walsh 2004; Newall & Walsh 2005). Gutters, drains, and stormwater sewers effectively bypass the infiltration capacity and time delays in natural soil systems and reduce the time required for surface runoff to enter streams, rivers and estuaries.

SECTION 4.12: CHANGES IN VEGETATION, INTERCEPTION, AND EVAPOTRANSPIRATION

Interception of precipitation by vegetation plays a significant role in local hydrologic processes because the complex surfaces of plants delay precipitation from reaching the ground and route a significant fraction of precipitation to evapotranspiration (Figure 4-2). In forested areas, interception can range from 10 to 50% of annual precipitation depending on forest structure (e.g., tree species, tree size, epiphyte load, deciduous vs. evergreen foliage) and the timing, form, and intensity of precipitation (Waring & Running 1998). Removal of native upland and riparian vegetation during rural-residential and urban construction, followed by replanting with smaller, often non-native, species may affect annual interception and subsequently evapotranspiration. In a long-term study of 51 watersheds in the eastern US, Dow & DeWalle (2000) documented decreased watershed-scale evapotranspiration where urban land cover increased more than 10% over the study period. Overall, reducing interception and evapotranspiration rates increase the proportion of water traveling through watersheds as surface runoff (Sanders 1986) and the rate at which precipitation is converted to runoff. This reduction in interception and evapotranspiration rates intensifies the damaging effects of impervious surfaces and stormwater (Dow & DeWalle 2000; Xiao & McPherson 2002).

American Forests (2001) conducted a landscape analysis of the Willamette and lower Columbia River regions to determine how forest cover had changed between 1972 and 2000. Findings from this analysis relevant to Oregon's aquatic ecosystems were:

- Across the region, light tree canopy cover increased from <20% to 75% of the land area while areas of heavy (natural) tree cover declined by 56%;
- Tree cover within urban areas (i.e., Albany, Beaverton, Corvallis, Eugene, Portland, Salem, Tualatin, and Wilsonville) declined from 21% to 12%; and
- Tree loss resulted in an estimated 7.2 billion gallon increase of stormwater production per peak storm event (2-year return, 24-hour storm event²⁸).

In a similar analysis of the Puget Sound region (Washington), American Forests (1998) found that tree cover loss and associated increases in impervious surfaces between 1972 and 1996 resulted in a 35% increase in stormwater production. Throughout the Pacific Northwest, loss of forest cover on low-elevation private forestland is expected to accelerate in the near future where these properties are converted to rural-residential developments (Stein *et al.* 2005).

SECTION 4.13: WATER WITHDRAWALS AND TRANSFERS

Rural-residential and urban development of landscapes diverts water resources toward residential, recreational, landscaping irrigation, commercial, and industrial uses, including waste processing facilities. Data collected at the county level (Table 4-1) illustrate these water withdrawal/transfer imbalances across Oregon. For example, both Multnomah and Washington counties have small within-county water withdrawals given their population sizes, while adjacent Clackamas County has comparatively large water withdrawals.

²⁸ A 2-year return, 24-hour storm event is a storm of 24 hour duration with such magnitude (i.e. rainfall depth) that it has an exceedence probability in a given year of 50%; i.e., the average length of time between such events is two years (McCuen 1998).

The magnitude of water removal from and transfer into watersheds for human uses can influence streamflow in rural-residential and urban waterways, particularly during drought periods. For example, several major cities in the Portland (Oregon) metropolitan area import a significant portion of their municipal water supplies from the Bull Run watershed, which lies outside the Willamette River basin. This diversion of water significantly reduces streamflow in both the Bull Run and Sandy Rivers with negative consequences for several threatened salmonid species (NMFS 2006b). Similarly, the Tualatin River water is used heavily for municipal purposes during the summer months but several major cities within this watershed also import water from the Bull Run watershed. Such water transfers may in part explain increases in both summer flows and annual runoff to precipitation ratios observed as urban development in the Tualatin watershed increased between 1976 and 2000 (Chang 2007). Additionally, increases of water transfer into urban systems can result in negative consequences for the urban streams receiving that additional water, as discussed in more detail in the Section 7.0 of this report.

Municipal and other water withdrawals from rivers that feed Oregon's estuaries produce poorly understood hydrologic effects. Reduced freshwater flows have the potential to alter sediment transport and delta morphology (Jay & Simenstad 1996). When summer freshwater flows into estuaries fall below historical levels, the freshwater/saltwater interface at the tidal front travels farther upriver (Good 2000). The ecological consequences of such changes for salmonids and their predators, competitors, and prey are unknown.

For the period 2000 to 2050, Houston *et al.* (2003) projected freshwater withdrawal increases in Oregon of 65% for public and domestic uses and 59% for industrial and commercial uses. Increasing demands on water resources imposed by population growth and increasing development pose significant threats to aquatic biota. Climate changes that reduce water quantity and increase summer stream temperatures will likely exacerbate these issues in many parts of Oregon (ISAB 2007a).

Table 4-1. Water withdrawn for public supply in Oregon counties in 2000. Public supply refers to water withdrawn by public and private water suppliers that provide water to at least 25 people or have a minimum of 15 connections (for domestic, commercial, industrial, or thermoelectric-power use).

Oregon County	Population in 2000 ¹	Surface Water Mgal/Day ¹	Ground Water Mgal/Day ¹	Total Mgal/Day ¹
Baker	16,741	2.50	0.63	3.13
Benton	78,153	5.71	0.12	5.83
Clackamas ²	338,391	167.22	6.53	173.75
Clatsop	35,630	9.13	0.00	9.13
Columbia	43,560	3.46	2.67	6.13
Coos	62,779	5.08	2.48	7.56
Crook	19,182	0.00	1.45	1.45
Curry	21,137	2.02	0.81	2.83
Deschutes	115,367	6.54	15.17	21.71
Douglas	100,399	5.82	0.00	5.82
Gilliam	1,915	0.00	0.29	0.29
Grant	7,935	2.27	0.60	2.87
Harney	7,609	0.00	2.06	2.06
Hood River	20,411	2.91	0.24	3.15
Jackson ²	181,269	38.71	0.46	39.17
Jefferson	19,009	2.69	0.40	3.09
Josephine	75,726	5.29	0.18	5.47
Klamath	63,775	0.02	9.96	9.98
Lake	7,422	0.33	1.85	2.18
Lane ²	322,959	35.30	22.39	57.69
Lincoln	44,479	4.32	0.47	4.79
Linn	103,069	11.88	0.48	12.63
Malheur	31,615	2.96	2.60	5.56
Marion ²	284,834	76.89	8.61	85.50
Morrow	10,995	2.31	2.76	5.07
Multnomah ³	660,486	1.10	9.42	10.52
Polk	62,380	2.78	1.84	4.62
Sherman	1,934	0.00	0.43	0.43
Tillamook	24,262	2.32	1.41	3.73
Umatilla ²	70,548	14.92	10.56	25.48
Union	24,530	0.00	3.72	3.72
Wallowa	7,226	0.82	0.14	0.96
Wasco	23,791	1.28	0.90	2.18
Washington ³	445,341	23.14	3.03	26.17
Wheeler	1,547	0.13	0.23	0.36
Yamhill	84,992	7.31	3.56	10.87

¹ Population data are from US Census Bureau (2003). Water withdrawal data are from US Geological Survey District Water Use Program (Oregon) http://or.water.usgs.gov/projs_dir/or007/or007.html (accessed February 15, 2007).

² The top five counties (Clackamas, Jackson, Lane, Marion, and Umatilla) for combined surface water and groundwater withdrawals.

³ Counties (Multnomah and Washington) with low total water withdrawals for their population size.

SECTION 4.14: CHANNELIZATION AND FLOOD CONTROL

River and estuary channelization is frequently done to “improve” lands for agricultural, residential, and industrial land uses (IMST 2002b). Oregon’s larger rivers and estuaries have been channelized to make them navigable for shipping and transportation (Cortwright *et al.* 1987; Benner & Sedell 1997; NMFS 2007). Channel modifications can protect buildings and roads from localized flooding and erosion, accelerate storm runoff conveyance, and facilitate draining floodplain wetlands. Some channelization projects have been designed specifically to minimize the space occupied by a channel and maximize the amount of real estate available for development (reviewed in Riley 1998). As a result, habitat for aquatic organisms is severely degraded or lost completely. Channelization also has large implications for stream geomorphology and physical habitat modification, as discussed in Section 5.2 of this report.

Actions commonly taken to channelize rivers and estuaries include:

- Removing wood, sandbars, and rocks that form channel constrictions;
- Installing bank stabilization structures such as revetments, riprap, and seawalls for flood and erosion control;
- Disconnecting sloughs, alcoves, side-channels, and chutes through the installation of dikes and levees that confine streamflow to a single channel; and
- Straightening meanders to speed water transport through the channel.

The Willamette River, which flows through Oregon’s largest urban areas, has been highly modified with numerous bank stabilization structures. Gregory *et al.* (2002b) estimated that approximately 26.5% of Willamette River mainstem miles have revetments on one or both banks. Between Eugene and Newberg (Oregon) many of these structures function to prevent soil erosion from agricultural and forested lands. However, both the number of revetments and the percentage protecting developed lands increase considerably along the river miles between Newberg and the Willamette’s confluence with the Columbia River (Gregory *et al.* 2002b; Table 4-2). Although rivers were originally channelized and revetments placed primarily for navigation and the protection of agricultural lands, revetments are increasingly associated with developed lands.

Table 4-2. Percentage of revetments along the Willamette River (Oregon) designed to protect municipal and rural-residential land uses.

Land Use Adjacent to Bank Stabilizing Structures (Revetments) ¹			
Willamette River Reach	Number of Revetments	Percent Municipal or Rural-residential	Percent Agricultural, Forestry, Bare Land
Columbia Confluence to Newberg	138	64	26
Newberg to Albany	117	26	74
Albany to Eugene	113	22	78

¹ Data from Gregory *et al.* (2002b).

Channelization is often undertaken as a means of local flood control, but it can contribute to increased flood levels by reducing the amount of overbank storage (i.e., floodplain storage; Woltemade 1994). Storm runoffs accumulate rapidly and produce higher and more frequent flood peaks compared to stream channels that remain connected to wetlands and side channels capable of absorbing floodwaters. For example, the lower 15 miles of Johnson Creek, a tributary of the Willamette River in Portland were heavily channelized during the 1930s to control flooding (Johnson Creek Watershed Council 2003). Impervious surfaces constructed since the 1940s have increased the peak runoff volumes in Johnson Creek by 30%. As a result of increased impervious area Johnson Creek regularly overflows its banks and floods several residential areas in Portland (Johnson Creek Watershed Council 2003; Chang 2007).

SECTION 4.15: WETLAND LOSS AND ALTERATION

Many of Oregon's urban and rural-residential areas are located along lowland aquatic ecosystems that serve important hydrologic and ecological functions (reviewed by IMST 2002b). Development in these ecosystems isolates, fragments, and eliminates wetlands (Holland *et al.* 1995; Thom *et al.* 2001) reducing their ability to collect and redistribute flood flows, recharge groundwater aquifers, store water for slower release, and provide rearing and overwintering habitat for fish and wildlife, particularly coho and Chinook salmon.

Gregory *et al.* (2002a) estimated that almost 95% of Willamette Valley wetlands present in 1851 were converted to other land cover types by 1990. Willamette Valley wetlands continue to disappear (Daggett *et al.* 1998; Bernert *et al.* 1999) despite environmental regulations established during the 1970's to prevent future wetland loss. Net wetland loss occurring between 1981 and 1994 in the Willamette Valley was estimated to be 10.6 sq. mi. (Bernert *et al.* 1999) and 9.9 sq. mi. (Daggett *et al.* 1998) in independent assessments. For this period, the fraction of lost wetland area converted to urban development was estimated at six percent (0.64 sq. mi.; Bernert *et al.* 1999) or 9% (0.90 sq. mi.; Daggett *et al.* 1998), while the wetland area converted to rural-residential development was estimated at 15% (1.49 sq. mi.; Daggett *et al.* 1998). The balance of lost wetland area was converted to agriculture or other land uses (Daggett *et al.* 1998).

Within the Portland metropolitan UGB, 40% of wetlands existing in 1982 were lost by 1992 (Kentula *et al.* 2004). Similarly, 6% of wetlands remaining within the Portland metropolitan UGB in 1992 were lost by 1998. Kentula *et al.* (2004) also found that impervious surfaces increased the magnitude of water level fluctuations and reduced floodwater retention capacity of small (< 5 acres) wetlands within the Portland metropolitan UGB. Hydrologic alterations also shifted the majority of remaining wetlands from riverine (within a river channel) to types with consistently deep water levels (ponds) that are atypical of the Portland region (Kentula *et al.* 2004). Consequently, altered hydrology and ecological function in remaining wetlands reduce their capacity to support native biota (Kentula *et al.* 2004).

As rural-residential and urban development increases, the quantity and quality of wetland habitat available to salmonids can be expected to deteriorate. Across Oregon, urban and rural-residential land cover and development rates are highest in western Oregon, particularly the Willamette Valley (Azuma *et al.* 2002, 2004, 2009). It is reasonable to assume that wetland loss will also result from human population growth and development in other areas of Oregon. Rural-residential and urban development have been identified as a threat to agricultural lands (Meyer & Turner 1992; Ramankutty *et al.* 2002; Burcher & Benfield 2006) which, while highly altered,

still have the capacity to provide some wetland habitat. Conversion of agricultural lands to urban and rural-residential uses may reduce the potential for rehabilitating these lands to benefit water quality, fish, and wildlife.

Section 4.2: Nature, Magnitude, and Timing of Hydrologic Changes

Studies conducted worldwide document the hydrologic changes that accompany development activities such as those described above (Konrad & Booth 2005; Walsh *et al.* 2005a; Chin 2006). In this section, IMST summarizes research on the nature, magnitude, and timing of these changes, with emphasis on available information from the Pacific Northwest. Changes to hydrologic routing commonly observed in developed landscapes include changes in *surface runoff* (quantity and timing), as well as changes in *groundwater recharge* and *stream base flow*.

SECTION 4.21: CHANGES IN SURFACE RUNOFF AND INFILTRATION CAPACITY

Landscape alterations that accompany development drive fundamental changes in the timing, magnitude, and nature of surface runoff and flood events in developed watersheds (Konrad & Booth 2005; Walsh *et al.* 2005b). Impervious surfaces increase the runoff component of local hydrologic regimes (Figure 4-2). Using data from 40 monitoring sites across the US, Schueler (1994) found that the fraction of precipitation volume routed to surface runoff (i.e., the runoff coefficient) increased directly with an increase in watershed imperviousness. This finding was later corroborated in a review by Shuster *et al.* (2005), who reported the median runoff coefficient increased to above 80% on highway monitoring sites where imperviousness was at a maximum. Vegetation alteration and surface leveling prior to construction and wetland loss exacerbate the reduced infiltration capacity of the land surface. Wetland loss also reduces water storage potential and increases the rate at which water moves through watersheds (Thom *et al.* 2001). Ultimately, water that may otherwise take hours, days, or weeks to move through the soil reservoir flows rapidly over hardened surfaces and enters streams in short, intense pulses.

Increased imperviousness and associated drainage structures alter the timing of surface runoff in two ways:

- *lag time* between peak precipitation and peak runoff (i.e., the time it takes rainfall to become runoff) decreases, causing streamflow to rise more rapidly during storms; and
- duration of *peak runoff* decreases resulting in more rapid recession of streamflow after storms.

Because increased imperviousness decreases infiltration, a larger proportion of precipitation becomes runoff. As a result, the magnitude of surface runoff changes as both the volume of individual runoff events and frequency of bank-full flow events increase compared to undeveloped watersheds. Because many Pacific Northwest soils have naturally high infiltration capacity, the increase in surface runoff due to development is often greater than increases observed in other geographic regions (Booth & Jackson 1997). The net result of changes in streamflow timing and magnitude are surface runoffs that are larger in volume, that enter stream channels more rapidly, and that reach bank-full volumes more frequently compared to undeveloped watersheds (Figure 4-2). Streams flowing through developed watersheds are often described as 'flashy' (Booth *et al.* 2004; Konrad & Booth 2005), a characteristic associated with

increased streamflow, reduced infiltration within the stream channel and flood plain, and a larger fraction of precipitation exiting watersheds as surface runoff (Paul & Meyer 2001; see Section 5.1 of this report for additional information on the consequences of such changes). Diminished infiltration can also convert wetlands that are consistently flooded into seasonal wetlands that dry out during the summer (Thom *et al.* 2001). Because the majority of runoff exiting a watershed is simply shifted from infiltration to surface flow, development may not affect annual (or longer term) streamflow (Konrad & Booth 2002). In watersheds where vegetation alterations affect evapotranspiration patterns, or where water transfers into or out of the watershed occur, annual streamflow may either increase or decrease depending on the watershed-scale water balance (Konrad & Booth 2005; Chang 2007).

While the reach-scale effects of impervious surfaces can be severe, contributions of increased surface runoff to watershed-scale stream degradation also depend on watershed size, development intensity, development placement within the watershed, and the efficiency with which runoff is routed from impervious surfaces to streams (Walsh *et al.* 2005a). Burges *et al.* (1998) found that surface runoff ranged from 12 to 30% of annual precipitation in a forested Puget Sound (Washington) lowland watershed, while surface runoff ranged from 44 to 48% of annual precipitation in a nearby watershed with 30% TIA. Using reach-scale data, Poff *et al.* (2006a) found that Pacific Northwest watersheds with 15 to 30% urban land cover had decreased high flow duration, increased flashiness, and annual flood peaks 22 to 84% greater than those in undisturbed watersheds. The magnitude of change in hydrologic behavior was larger in the Pacific Northwest than other physiographic regions in the US (Poff *et al.* 2006a). For example, a flashiness index (Sanborn & Bledsoe 2006) comparison between undisturbed and urbanized watersheds showed that developed Pacific Northwest watersheds were more flashy than comparable watersheds in southeastern and southwestern US regions (Poff *et al.* 2006a).

Information on the net effect of development outside UGBs on watershed hydrology is sparse. However, simply removing forest cover during rural-residential development is known to decrease evapotranspiration and increase streamflow (Grimmond & Oke 1986; Dow & DeWalle 2000; Claessens *et al.* 2006). Data from rural-residential developments in Washington indicate that reduced infiltration rates resulting from lawns and pastures on hobby farms (as reported by Booth *et al.* 2002), and suburban landscaping (Konrad 2003) are sufficient to significantly increase streamflow. Similarly, Burns *et al.* (2005) compared the hydrologic response of suburban watersheds in northern New York with 6.2% and 11.1% TIA to an undeveloped watershed and documented respective increases in peak discharge of 42% and 300%.

The nature of surface runoff changes can depend on the spatial patterning of rainfall relative to the location of development and naturally impervious landscape features within a river basin (Smith *et al.* 2005). For example, Hollis (1975) used data from several studies to examine the general relationship between flood size and impervious surface area effects. Hollis (1975) found that the total volume of stormwater increased with increasing flood size and recurrence interval, but the fraction of stormwater generated by impervious surfaces decreased. Hollis's (1975) observations could be explained by soils becoming saturated during prolonged storms and exhibiting hydrologic behavior similar to impervious surfaces (Chin 2006). Increased surface runoff from saturated soils may manifest more rapidly on thin soils associated with lawns and other landscaping in developed areas (Konrad 2003; Alberti *et al.* 2007). Research results from

the *Baltimore Ecosystem Study*²⁹ (Maryland) indicate that, in addition to TIA, both antecedent soil moisture and land surface heterogeneity explain variation in the fraction of precipitation that becomes runoff during discrete storm events (Smith *et al.* 2005) and support conclusions drawn by Hollis (1975). However, Smith *et al.* (2005) also demonstrated that an efficient drainage network structure can diminish the hydrologic effects of various landscape characteristics, thus highlighting the importance of hydrologic connectivity between impervious surfaces and streams noted by Walsh *et al.* (2005a).

The general hydrologic response of arid and semi-arid aquatic ecosystems to rural-residential and urban development is understudied relative to more mesic regions and warrants increased investigation. In arid regions, natural hydrologic regimes exhibit high spatial and temporal variability in the form, timing, and magnitude of precipitation. As a result, their hydrologic response to precipitation can be episodic and varied (Gray 2004a). Thus, hydrologic change associated with urbanization in more arid climates is likely to be difficult to predict compared to mesic climates (Chin & Gregory 2001). In undeveloped semi-arid climates, vegetation is relatively sparse, soils are shallow, and overland flow can be the predominant route of precipitation to streams (NRC 2002). In semi-arid areas where a high percentage of precipitation naturally exits watersheds as surface flow, the proportional increase in surface flow resulting from development may be small compared to what would occur in mesic areas experiencing similar levels of development (Konrad & Booth 2005). However, increasing urbanization around streams that are already naturally flashy may cause significant increases in peak flow (Chin & Gregory 2001).

Conversely, inter-watershed water transfers and development of municipal and industrial wastewater treatment facilities that discharge effluent directly into river channels can convert naturally ephemeral or intermittent streams into perennial systems. In many arid regions, treated wastewater effluent may make up the majority of flow during periods of low precipitation leading to serious water quality issues (Brooks *et al.* 2006). This can also occur in relatively humid regions when cities discharge wastewater effluent to small streams during periods of low flow.

SECTION 4.22: CHANGES IN GROUNDWATER RECHARGE AND BASE FLOW

The base flow (or non-storm flow) of many Pacific Northwest rivers is derived primarily from groundwater. Leopold (1968) and Harbor (1994) predicted that increased imperviousness should decrease base flow because an increased proportion of precipitation is routed away from groundwater towards surface runoff (Figure 4-2). Channelization and associated wetland drainage can also reduce water tables and affect surface flows (Thom *et al.* 2001). Observations of groundwater and low streamflow reductions associated with increasing urbanization support Leopold's (1968) and Harbor's (1994) predictions (Klein 1979; Simmons & Reynolds 1982; Ku *et al.* 1992; Barringer *et al.* 1994; Rose & Peters 2001; Fitzpatrick *et al.* 2005).

However, other studies of streamflow responses to urban development present conflicting findings, indicating that urbanization does not affect baseflows consistently. Poff *et al.* (2006a) found reduced minimum streamflows at the reach-scale associated with greater than 15 to 30%

²⁹ The Baltimore Ecosystem Study is one of 26 LTER (Long-term Ecological Research) programs established by the National Science Foundation. See <http://www.beslter.org/>. Accessed on October 12, 2010.

urban land cover in the Pacific Northwest but also documented regional differences in the minimum flow response to increasing urban land cover. Konrad & Booth (2002) found that while winter (wet season) base flows in western Washington streams declined in response to urban development, minimum annual 7-day streamflow showed inconsistent results. They concluded that poor infiltration reduces shallower subsurface water stores that feed winter base flows more than deeper groundwater recharge that supports summer base flows. Others have documented that leaky water and sewer lines (e.g., Lerner 1986, 1990, 2002) can actually increase base flows in urban developments. In urban areas, irrigation used for landscape plants, gardens, and lawns provides additional input to the water balance (Grimmond & Oke 1986) and perhaps contributes to groundwater and to base flow. Brandes *et al.* (2005) analyzed 25 years of streamflow data from six watersheds undergoing urbanization and four reference watersheds in the Delaware River basin (Pennsylvania and New Jersey) and found that watershed geology, location of development within a watershed, and anthropogenic water transfers were more useful in explaining base flow patterns than impervious surface estimates. This inconsistency in response of base flow patterns to increasing impervious surface area (or other indices of development) may be scale-dependent (Brandes *et al.* 2005), but clearly more investigation is needed in this area.

Key Findings: Hydrology	
	<ul style="list-style-type: none"> • Impervious surfaces and soil compaction decrease infiltration and increase surface runoff that is directly routed to surface waters. Residential zoning and land use regulations can affect watershed- and regional-scale imperviousness.
	<ul style="list-style-type: none"> • Removing native vegetation during construction, and replacing with smaller, non-native species, can reduce interception and evapotranspiration rates and increase the fraction of stormwater that reaches impervious surfaces.
	<ul style="list-style-type: none"> • Many of Oregon's developments reduce the ability of wetlands to collect and redistribute flood flows, recharge groundwater aquifers, store water for slower release, and provide rearing and overwintering habitat for fish.
	<ul style="list-style-type: none"> • Changes to hydrologic routing commonly observed in developed landscapes include changes in surface runoff as well as changes in groundwater recharge and stream base flow. The hydrologic effects include faster stream response times to precipitation, higher and shorter peak flow events, and potentially reduced base flows.
	<ul style="list-style-type: none"> • Contributions of increased surface runoff to watershed-scale stream degradation depends on watershed size, development intensity, development placement within the watershed, and the efficiency with which runoff is routed from impervious surfaces to streams.
	<ul style="list-style-type: none"> • The general hydrologic response of arid and semi-arid aquatic ecosystems to development is understudied relative to more mesic regions and warrants increased investigation.
	<ul style="list-style-type: none"> • Climate change will play a major role in watershed hydrology and has the potential to intensify the hydrologic effects of development. Increasing demands on water resources imposed by human population growth pose significant threats to aquatic biota. Climate changes that reduce water quantity and increase summer stream temperatures will likely exacerbate these issues in many parts of Oregon.

Section 5.0: Riparian and Aquatic Physical Habitat

Physical habitat influences the abundance and distribution of organisms. In aquatic environments, physical habitat variables include channel substrate size, channel complexity and cover, riparian vegetation structure, and the degree and type of channel-riparian interaction. Physical processes that work in combination to create a wide variety of riparian and physical habitats include (Montgomery & Buffington 1998):

- Timing and magnitude of streamflow,
- Wood and sediment supply, transport and deposition,
- Stream bank and bed erosion, and
- Channel migration.

The spatial and temporal complexity of physical habitat conditions formed by these processes provide elements critical to salmonid persistence. Rural-residential and urban development can significantly modify the processes that link aquatic ecosystems to the surrounding landscapes and lead to physical habitat deterioration by altering hydrology, riparian vegetation, and river channel structure.

Section 5.1: Factors and Mechanisms that Alter Physical Habitat in Developed Areas

This section emphasizes the effects of development on stream condition from a physical structure (i.e., channel stability, substrate, large wood) viewpoint. This means that reach-scale characteristics of physical habitat will often be emphasized within the text. Whenever possible, the IMST attempts to put these reach-scale changes and their local effects on salmonids in the context of the larger terrestrial and aquatic landscape.

SECTION 5.11: HYDROLOGIC MECHANISMS

Hydrologic processes interconnect strongly with processes that shape physical habitat in streams, with each continuously responding to changes in the other. Unless stream channels are naturally constrained by bedrock or some similar means, they will make dynamic adjustments in response to changes in flow regime and sediment supply imposed by development (Dunne & Leopold 1978; Booth & Henshaw 2001; Bledsoe 2002). Streamflows carrying sediment and large wood interact with channel beds and banks to shape channel form (Schumm 1971; Dunne & Leopold 1978; Beschta 1985; Beschta & Platts 1986). Stream type and mode of sediment transport play significant roles in determining stream response to altered hydrology. Consequently, hydrologic changes are important forces driving channel readjustment in developed landscapes (Walsh *et al.* 2005b). Changes in channel morphology can in turn become mechanisms for further local hydraulic change (Figure 2-1; Poff *et al.* 2006a).

Rural-residential and urban developments alter watershed hydrology in several ways (see Section 4.1 of this report). Impervious surfaces in developed watersheds create surface runoff that is larger in volume, enters stream channels more rapidly, and reaches bank-full volumes more frequently compared to undeveloped watersheds. Stormwater detention facilities cannot fully

mitigate changes in surface runoff volumes; to reduce peak discharges, they extend the duration of flows at or just below bank full volumes, which can have the effect of inducing channel erosion (Booth & Jackson 1997; Brown & Caraco 2001; Bledsoe 2002). Intentional channelization, whether for commerce, bank stabilization or flood control purposes, increases channel capacity, stream power, and the potential for channel erosion and flooding downstream (Simon & Rinaldi 2006). Reduced channel and physical habitat complexity are almost universal consequences of increased flashiness and channelization that accompany development (Walsh *et al.* 2005b; Poff *et al.* 2006a).

Riparian vegetation adds channel complexity and bank stability directly from roots or indirectly as large wood when trees fall into streams. Hydrologic changes alter interactions between streams and adjacent riparian areas in ways that can remove established riparian vegetation and/or prevent re-colonization or regeneration of riparian plants in riparian zones (Booth 1991). Many riparian plant species are adapted to the hydrologic patterns of flood and drought in undeveloped landscapes. Thus, hydrologic alterations can affect the extent and structure of riparian vegetation communities that establish and grow along riverbanks in developed watersheds. For example, black cottonwood (*Populus trichocarpa*) and willow (*Salix* spp.) seed germination and establishment requires bare mineral soil deposition and slow flow recession following floods (Dykaar & Wigington 2000; Amlin & Rood 2002; Karrenberg *et al.* 2002). Fierke & Kauffman (2005) found that new black cottonwood regeneration along the Willamette River (Oregon) was limited to low areas experiences annual flooding and scouring.

SECTION 5.12: UPLAND DISTURBANCE

Construction activities mechanically disturb large quantities of soil, thereby increasing erosion and watershed sediment yields (i.e., hillslope erosion; Wolman & Schick 1967; Keller 1999; Paul & Meyer 2001). Areas disturbed by construction can have soil erosion rates 2 to 40,000 times greater than pre-disturbance rates and annually produce ~80 million tons of sediment that enter US waters (Harbor 1999). Compacted soils have reduced infiltration rates and subsequent increased surface runoff across these soils leads to increased erosion (Leopold 1968; Keller 1999). Road building is another key source of sediment delivered to waterways (Waters 1995).

The increase in erosion rates caused by construction and the amount of sediment transported to surface waters depends on watershed size and development intensity. Based on 100 published studies conducted worldwide over the past 50 years, sediment production in urbanizing watersheds tends to increase 2- to 10-fold (Chin 2006). In western Washington, Nelson & Booth (2002) documented nearly a two-fold increase in watershed-scale sediment erosion in the urbanizing Issaquah River basin (144 km²) while only 0.3% of the watershed area was under construction. During the later stages of urbanization when construction activities subside, impervious surfaces, compacted surfaces, landscaping, and stormflow detention and treatment can limit sediment mobilization and reduce sediment delivery rates (Paul & Meyer 2001; Chin 2006; Poff *et al.* 2006a).

SECTION 5.13: RIPARIAN VEGETATION REMOVAL

Salmonid and steelhead population declines in the Pacific Northwest have been attributed, in part, to lost and reduced riparian functions (Beschta 1997). Riparian ecosystems are zones of dynamic interaction between aquatic and terrestrial ecosystems that exert significant influence over streamflow dynamics, instream habitat structure, and interactions among stream channels and off-channel habitat (Gregory *et al.* 1991). As a result, aquatic ecosystem condition is strongly associated with the condition of riparian vegetation (Stoddard *et al.* 2005; Paulsen *et al.* 2008). For example, intact riparian areas facilitate channel floodplain interactions that provide important off-channel rearing areas for juvenile salmonids (Sommer *et al.* 2001).

The spatial distribution and structural characteristics of riparian vegetation vary within and across physiographic regions in Oregon. Riparian vegetation is influenced by site and watershed characteristics including stream size, channel gradient, plant community composition, disturbance regimes, interactions among channels, and subsurface water movement (Anderson *et al.* 2004; Everest & Reeves 2007). Consequently, the minimum area of undisturbed riparian vegetation required to preserve riparian ecological function is variable depending on site and watershed characteristics. In general, riparian vegetation contributes to:

- Stream bank formation,
- Stream bank stabilization,
- Large wood contributions,
- Channel complexity maintenance,
- Stream temperature modification from shade,
- Organic litter contributions that fuel aquatic food webs,
- Terrestrial food sources (e.g., leaf litter, insects) for aquatic organisms, and
- Sediment and nutrient filtration from stream inputs.

Riparian areas are ecologically critical for maintaining healthy aquatic ecosystems, but they also tend to be valuable real estate properties and development often results in the restructuring or total loss of riparian vegetation (Ozawa & Yeakley 2007). In the greater Portland metropolitan region, approximately 51% of riparian buffers along the 775 stream miles within the UGB were developed by 1998 (Ozawa & Yeakley 2004). In portions of the Columbia River basin, important to ESA-listed salmonid populations, riparian areas affected by urban and agricultural development were significantly narrower than riparian areas in forest or shrub/grassland landscapes (i.e., 30 m vs. 70 m median width, respectively; Fullerton *et al.* 2006).

Riparian deforestation is often identified as an important driver of the aquatic ecosystem response to development (Figure 5-1; e.g., May *et al.* 1997; Booth 2005; Hook & Yeakley 2005; McBride & Booth 2005). May *et al.* (1997) estimated that when TIA exceeded 40%, approximately 40% of riparian buffers no longer provided ecological benefits to streams draining small Puget Sound (Washington) watersheds (Figure 5-1). McBride & Booth (2005) attributed heterogeneous physical habitat condition in moderately urbanized areas, in part, to intactness of the local riparian buffer. Similarly, Hook & Yeakley (2005) concluded that near-stream riparian buffers were important for maintaining water quality in Johnson Creek (Portland, Oregon). However, riparian habitat loss covaries with several other factors making it difficult to isolate

riparian alterations as a direct cause of aquatic ecosystem impairment (Ourso & Frenzel 2003; Walsh *et al.* 2005b). For example, road crossings, that interrupt otherwise intact riparian buffers, create points where stormwater can bypass routing and detention facilities and flow directly into streams, thus degrading physical habitat (McBride & Booth 2005). The importance of riparian area continuity along streams has been documented by others (reviewed by Fullerton *et al.* 2006), but the minimal lengths and widths of contiguous riparian buffers required to maintain aquatic communities will likely vary with environmental characteristics such as stream size, topography, parent materials and climate factors.

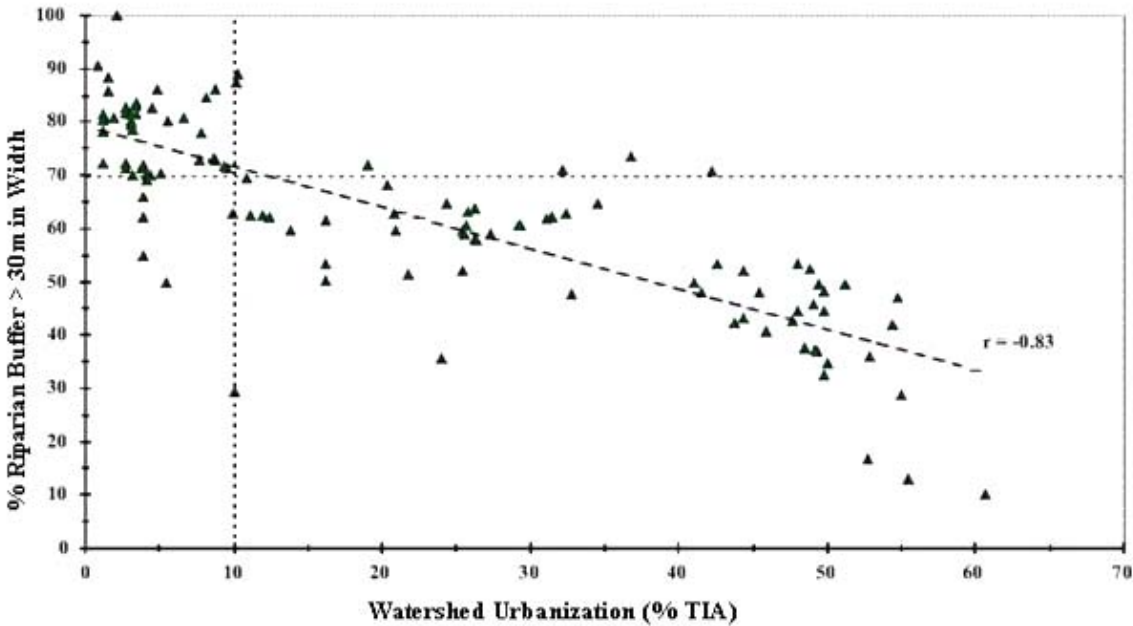


Figure 5-1. The relationship between riparian buffer width and total impervious area (TIA) in small Puget Sound lowland streams. Horizontal and vertical dashed lines highlight sites where 70% or more of riparian buffers were more than 30m wide and watershed TIA was less than 10%. The original authors used horizontal and vertical dashed lines to demarcate both the size of riparian buffers required by sensitive area ordinances in Puget Sound (Washington) and the level of watershed urbanization where most riparian buffer widths fell below this minimum size (i.e., 100–150 ft or 30 m). IMST feels that the vertical and horizontal lines should not be interpreted as implicit thresholds, as the existence of thresholds in this context has been the subject of considerable debate. Figure reproduced from May *et al.* (1997) with permission from the Center of Watershed Protection (Ellicott City, Maryland).

SECTION 5.14: DIRECT INSTREAM MODIFICATION OF PHYSICAL HABITAT

Restructuring river and stream channels can increase stream power, decrease channel complexity, and increase within-channel erosion. These modifications intensify the effects of altered hydrology and sediment delivery from upland sources (Jacobson *et al.* 2001). The removal of riparian vegetation and large wood, channelization, bridge construction, and channel dredging each result in significant channel erosion (Booth 1991; Waters 1995; Keller 1999).

Section 4.0 described several channel modifications that straighten rivers and confine flow to a single channel. This section reviews several additional ways that human activity directly alters aquatic physical habitat in developed areas including:

- Overwater structures,
- Dredging,
- Wood removal,
- Aggregate removal, and
- Estuary diking and filling.

Overwater Structures – Pilings, wharfs, and bridges can affect aquatic physical habitat structure. The level of disturbance created by these structures ranges from small changes associated with bridges constructed in rural-residential and urban settings to major habitat alterations associated with harbor development in large cities (Fresh *et al.* 2005; NMFS 2007). In small rivers, overwater structures can narrow channel width and create catch points for sediment and debris that increase resistance to flow. In estuaries, shade from overwater structures negatively affects eelgrass (*Zostera* spp.) beds and substrate disturbance disrupts epibenthic fauna³⁰ (Glasby 1999; Shafer 1999; Simenstad *et al.* 1999; Haas *et al.* 2002; Southard *et al.* 2006; NMFS 2007). Individual structures in rivers and estuaries can also modify riparian vegetation, stream bank structure, channel substrate composition, channel depth, and light contrasts (Simenstad *et al.* 1999; Carrasquero 2001; Kemp *et al.* 2005; Southard *et al.* 2006; NMFS 2007; Toft *et al.* 2007) in ways that may:

- Influence salmonid migratory behavior,
- Alter salmonid prey distributions and densities,
- Increase habitat overlap between salmonids and their predators, and/or
- Increase salmonid predator concentrations.

While individual structures may not cause significant impacts, the cumulative effects of numerous structures on river and estuary habitats can lead to fish assemblage changes (Jennings 1999; Simenstad *et al.* 1999; Carrasquero 2001; Haas *et al.* 2002; Southard *et al.* 2006).

Dredging – Material removal from channels, or dredging, is commonly done to increase channel depth or width and to reduce stream meandering (USFWS 2006; Wallick *et al.* 2009). Because urban areas are centers for commerce, major rivers are often dredged to develop and maintain navigable channels and ports for ships. In Oregon, the lower section of the Willamette River between Swan and Sauvie Islands, referred to as “Portland Harbor,” is routinely dredged to maintain a shipping channel 300 ft wide and 40 ft deep (Weston 1998). Dredging also occurs in eleven urban estuaries along the Oregon coast. Eight of the estuaries are designated by DLCDC for shallow draft development³¹ and dredged when the bottom is at 22 ft or less while the remaining three estuaries are designated for deep draft development³² and dredged to maintain depths

³⁰ Organisms living on the surface of bottom sediments in streams, rivers, or estuaries.

³¹ Nehalem Bay, Tillamook Bay, Depoe Bay, Siuslaw River, Umpqua River, Coquille River, Rogue River, Chetco River.

³² Columbia River, Yaquina Bay, Coos Bay.

greater than 22 ft (Cortwright *et al.* 1987; Good 1999). Dredging, together with altered flow and sediment regimes, has reduced the area of the Columbia River estuary by 20% (Fresh *et al.* 2005). Dredging can significantly increase channel capacity and gradient, triggering unintended changes in channel morphology throughout a watershed or river basin including upstream degradation (head cutting), downstream aggradation (filling), and bank instabilities throughout, as well as disconnecting the main channel from adjacent wetlands (Good 1999; Simon & Rinaldi 2006).

Large Wood Removal – During the 19th and 20th centuries, large wood was frequently removed, or snagged, from streams and estuaries to increase river navigability. In smaller channels, large wood and log jams were removed because they were perceived as barriers to migrating salmonids. These actions greatly reduced wood abundance in channels and wetlands of large rivers and estuaries of the Pacific Northwest (Collins *et al.* 2002; Wing & Skaugset 2002; Hood 2007). Snagging is still a common practice in rural-residential and urban areas (Larsen *et al.* 2004). Bridges and culverts tend to accumulate wood that must be removed to maintain these structures. Where streams run through parks and near homes, wood is likely to be removed to reduce the risk of accidents during recreational use of waterways. The removal of wood from channels in streams and estuaries decreases hydraulic roughness (i.e., channel structures that slow water velocity) which can increase flow velocities, stream power, peak discharge, and channel incision (Good 1999; Simon & Rinaldi 2006). Reductions of in-channel wood also decrease the abundance and surface area of pool habitat and channel refuges in streams and estuaries (Montgomery *et al.* 1995; Collins *et al.* 2002) required by salmonids (e.g., Montgomery *et al.* 1999).

Aggregate Removal – Sand and gravel are mined from waterways and floodplains for use in building and road construction, pipeline bedding, drainage areas (e.g., leach fields in septic systems), industrial applications (e.g., glass manufacturing, foundry operations, abrasives), and landscaping. River substrates are often preferred over upland sources because moving water physically abrades sediments removing weaker materials and naturally grades, sorts, and rounds the sediments. Demand for mined sand and gravel is often greatest where there is a convenient, economical mode of transport such as barges, and/or nearby markets, like urban areas (OWRRI 1995). Within Oregon, the majority of permitted aggregate mining operations are in the Willamette Valley followed by the Umpqua River basin. According to Kondolf (1994) mining river sediments can alter aquatic physical habitat by affecting:

- Habitat quantity (e.g., when river flow captures floodplain mining pits),
- Channel geometry (e.g., width-to-depth ratios),
- Channel gradient (when channels are deepened and straightened),
- Channel stability, and
- Channel incision rates.

Estuary Diking and Filling – Historical conversion of estuarine swamps and salt marshes to agricultural land through diking and draining accounts for most of the habitat loss in Oregon estuaries (Good 1999; IMST 2002b). However, recent and historical development of Oregon tidelands has also contributed to estuarine habitat loss (Cortwright *et al.* 1987; Good 1999,

2000). For example, urban and industrial development has reduced tidally influenced habitat in Coos Bay (Oregon) (Hoffnagle & Olson 1974; Borde *et al.* 2003), but the quantity of salmonid habitat lost to development coast-wide has not been estimated.

Estuaries are composed of hydrologically interconnected habitats that are especially important to juvenile salmonids (Cortwright *et al.* 1987; Good 1999, 2000). The fry of some salmonid species (particularly chum and Chinook) rear in the upper reaches of estuaries for several weeks and follow tidal fluctuations as they acclimate to the increased salinity of seawater (Groot & Margolis 1991; Thorpe 1994; Bottom *et al.* 2005). As juvenile salmonids mature, they move into deeper, more saline channels, mudflats, and eelgrass bed habitats in the lower estuary prior to migrating into the ocean (Groot & Margolis 1991; Thorpe 1994; Miller & Sadro 2003; Hosack *et al.* 2006). Filling tidelands in upper and lower estuary reaches to create urban and rural-residential properties, as well as armoring estuary shorelines to protect these properties, can destroy, fragment, and disconnect habitats necessary for the rearing, acclimation, and smoltification of salmonid juveniles (Good 1999, 2000; Borde *et al.* 2003; Bottom *et al.* 2005; Fresh *et al.* 2005; Rice 2006).

Section 5.2: Nature, Timing, and Magnitude of Physical Habitat Changes

Changes in salmonid habitat resulting from development range from minor effects to near complete loss of useable fish habitat. This section evaluates the nature, timing, and magnitude of change in aquatic habitat with respect to:

- Channel morphology,
- Channel and streambank stability,
- Large wood and other organic inputs, and
- Substrate siltation and coarsening.

The general direction of change in physical habitat caused by development is frequently documented, but the timing and magnitude of such changes are not well documented. The latter are more difficult to summarize because river channels continue to evolve in response to changing water flows, wood delivery and transport, and sediment loads, and may take decades to reach dynamic equilibrium (e.g., Henshaw & Booth 2000). When development and redevelopment activities are continuously occurring, stream channels may never reach a dynamic equilibrium (Chin 2006). The magnitude of change is partially dependent on the spatial pattern and sequence of landscape alterations as well as the underlying parent geology and hydrologic regime (Montgomery 1999; Henshaw & Booth 2000; Poff *et al.* 2006a, b). The direction and magnitude of change are also dependent on when measurements are made relative to the stage of development; streams may be aggrading or eroding, contracting or enlarging, and the magnitude of change may be increasing or decreasing over time (Chin 2006).

SECTION 5.21: CHANNEL MORPHOLOGY

Fluctuations in stream channel morphology reflect a dynamic equilibrium between erosion caused by bank full flows and more gradual delivery and stabilization of materials from upstream and terrestrial upslope areas. As a result, stream velocity, stream gradient, and the amount, type and size of sediment transported by the stream exert strong controls over stream channel dimensions (Bledsoe & Watson 2001b). Long-term changes in sediment budgets and flow regimes associated with development cause channel morphology to change until it arrives at a dynamic equilibrium structure that accommodates the modified conditions (Dunne & Leopold 1978; Booth 1990; Montgomery & Buffington 1997; Paul & Meyer 2001; Chin 2006). Morphological alterations typically observed include changes in channel depth, incision rate, width, sinuosity, number and size of point bars, and patterning of pools and riffles (Paul & Meyer 2001).

Periods of active construction disturb large quantities of soil and increase watershed sediment yields (Wolman & Schick 1967; Keller 1999; Paul & Meyer 2001). Channels undergo a series of erosional stages when sediment loads are delivered to streams experiencing increased flood frequencies, water volumes, and velocities, leading to an imbalance between sediment delivery and the stream's ability to transport sediment (Figure 5-2; reviewed in Paul & Meyer 2001; Chin 2006; Simon & Rinaldi 2006). An accumulation of excess sediment in river channels (aggradation) can reduce channel capacity and increase the number of flood events (Paul & Meyer 2001) that deposit sediment on stream banks and elevate bank heights above predisturbance levels. The magnitude of channel aggradation depends on watershed and stream size relative to the amount and location of development.

During the latter stages of urbanization, impervious surfaces cover soils and greatly reduce the supply of channel forming materials such as sediment and large wood. As hydrologic alterations stemming from increased impervious area intensify, stream channels begin to enlarge and destabilize riparian vegetation (May *et al.* 1997; Bledsoe & Watson 2001a; Bledsoe 2002; Konrad & Booth 2002; Simon & Rinaldi 2006). Stream channels typically enlarge through lateral erosion, bed erosion, and/or less often overbank deposition (Henshaw & Booth 2000). Depending on channel slope and geology, enlarging channels may incise up to several meters below their predevelopment bed levels (Booth 1990), or split into multiple (braided) channels winding between new gravel bars formed by increased sediment inputs (Booth & Henshaw 2001). Channel incision and widening limit interaction between streams and their floodplains, minimizing the potential benefits of riparian areas (Roy *et al.* 2006).

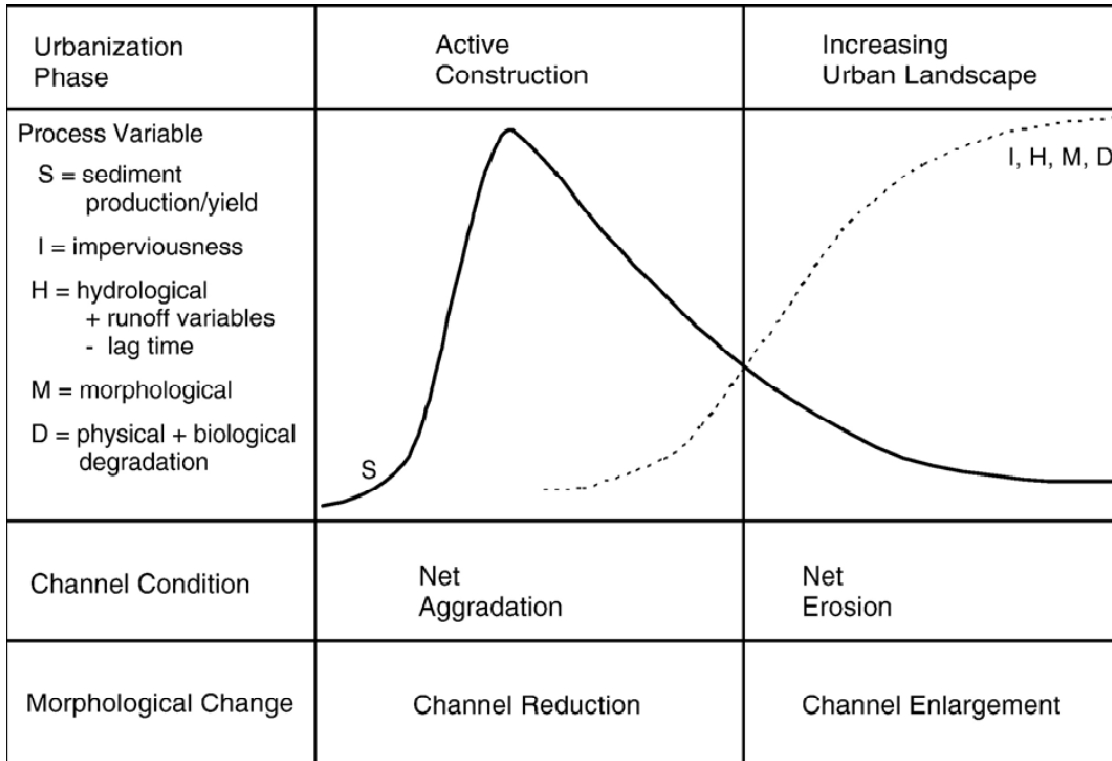


Figure 5-2. General phases of urbanization with associated process changes, channel conditions, and morphological adjustments. Curves are approximated to indicate trends but could exhibit considerable variation among variables depending on the hydrologic and geomorphic context within any particular watershed. Figure reproduced from Chin (2006) with permission from Elsevier B.V.

As channels enlarge, they become capable of containing stormflow events of increasingly larger volumes and the likelihood of floods overtopping stream banks decreases (Klein 1979; Booth 1991). Additional bank-full discharge events are a major source of channel erosion and can result in higher and steeper streambanks that are susceptible to mass failure events (Bledsoe & Watson 2001b; Simon & Rinaldi 2006). At this point, the majority of sediment transported by the stream comes from within-channel sources as opposed to hillslope erosion (Trimble 1997). Accelerated channel erosion can become a significant sediment source for downstream reaches (Simon & Rinaldi 2006) and can propagate the effects of development beyond the reach scale. Depending on the extent and intensity of development, it is not uncommon for channel alterations to migrate up and downstream of rural-residential and urban areas (Booth & Henshaw 2001; Simon & Rinaldi 2006).

Several studies have documented the magnitude of change in channel morphology with increasing development. Chin (2006) found that channels tended to enlarge to 2 to 3 times their original size in humid and temperate environments. Hammer (1972) studied 78 small watersheds near Philadelphia (Pennsylvania) and found that channel cross sectional area increased by a factor of 2.2 for impervious area associated with houses, and ranged up to a factor of 6.8 for impervious area associated with commercial buildings, row and apartment houses, factories,

airport runways, shopping centers, and parking lots. In King County (Washington), Booth & Reinelt (1994) observed an average channel widening of 0.6m (17%) along urban streams where native vegetation was significantly altered or removed.

As stream channels deepen and widen in response to development, other physical characteristics change as well. The pattern of aquatic habitat diversity (pools, riffles, runs) also changes as streams undergo the hydrologic and physical changes that accompany development (Paul & Meyer 2001). Booth & Reinelt (1994) evaluated fish habitat quality in two urbanizing Puget Sound (Washington) watersheds by measuring pool to riffle ratios and channel roughness and diversity; then rated habitat quality as excellent, good or degraded. Habitats rated as excellent or good generally were located in watersheds with less than 6% impervious area. Degraded habitat was first encountered in watersheds with 8% or more effective impervious area and most degraded habitat occurred in reaches with 10% or greater effective impervious area.

Overall, the rate and magnitude of changes in channel morphology depend on development type, watershed size, topographical relief, climate, geology, sediment sources, and land use history (Booth & Henshaw 2001; Paul & Meyer 2001). The sediment production (construction) phase can last months to years depending on the type of development. If and when sediment yields decline, channels may require several decades to adjust before they reach a dynamic equilibrium (Chin 2006). This assumes, of course, that the channel form was in dynamic equilibrium prior to development. Bledsoe & Watson (2001a) suggested that stream channels draining smaller, more permeable watersheds are more likely to exhibit a greater erosive response to development. However, because the primary controlling factors are significant watershed-scale characteristics and processes that operate over variable timeframes, the relationship between the rate and magnitude of channel response and measures of development (e.g., TIA) is highly variable (Henshaw & Booth 2000; Anderson *et al.* 2004) and varies along the length of the effected channel (Gregory *et al.* 1992; Paul & Meyer 2001).

Limited research in arid environments suggests that river responses to urbanization occur rapidly over short distances but are variable (Chin 2006). Many ephemeral streams naturally carry large suspended sediment loads and experience high spatial and temporal variability in precipitation inputs. Consequently, channel morphology may undergo rapid and less predictable responses to development that may also be more isolated because of the localized nature of rainfall (Chin 2006). Additional research is required to better understand the effects of development on aquatic physical habitat in Oregon's arid environments.

SECTION 5.21: CHANNEL AND STREAMBANK STABILITY

Streambank and channel stability are subjective concepts because their nature is inherently dynamic. Streambank erosion is a natural part of dynamic stream channels, particularly alluvial channels that are not constrained by bedrock and are composed of material transported from upstream reaches. For the purposes of this section, 'stable' streambanks and channels are those that show no continued, directional change in response to development.

The relationship between development and channel stability is complex and depends on flow regime changes, riparian vegetation condition, floodplains, and the intrinsic stability of the stream type (Bledsoe & Watson 2001a, b; Sudduth & Meyer 2006). Riparian vegetation is an important stream bank stabilizer and contributes to the maintenance or re-establishment of

channel stability by reducing erosion along both stream banks and streambeds and by dissipating stream power, especially during floods (Everest & Reeves 2007). Channel widening is linked to channel instability and mass wasting events. Widening streams and rivers gradually undercut their banks until the overhanging material collapses into the channel, thereby causing additional increases in sediment delivery from within the channel (Neller 1988; Ritter *et al.* 1995). Once stream channel capacity increases to the point where increasingly large peak flows are fully contained, the former floodplain no longer functions to dissipate flood energy. In this situation, stream channels may become unstable (Booth & Jackson 1997; Simon & Rinaldi 2006).

Forest retention can play an important role in channel stability. Booth *et al.* (2002) reported that 65% forest retention was required to maintain 2-year discharges below the 10-year modeled discharge. Similarly, May *et al.* (1997) found that streambed erosion became evident when TIA ranged from 10-30% and that streambanks generally were unstable when TIA exceeded 30% in Puget Sound lowland watersheds. Booth & Jackson (1997) characterized a large number of stream channels in Washington and related channel stability to percent EIA and surface runoff in their respective watersheds (Figure 5-3). Nearly all channels classified as 'stable' were in watersheds with less than 10% EIA. Conversely, most channels classified as 'unstable' were in watersheds with more than 10% EIA. Channels also tended toward instability when actual 2-year discharge exceeded the 10-year discharge modeled for each stream. This discharge benchmark generally occurred when EIA exceeded 10%, and mirrors Bledsoe's (2002) finding that channel stability depends on the frequency of moderate flow events and the distribution of stream power along weak points in the channel. While these findings suggest TIA or EIA thresholds at which significant changes in channel characteristics occur, there is considerable debate on the existence and applicability of thresholds in these systems.

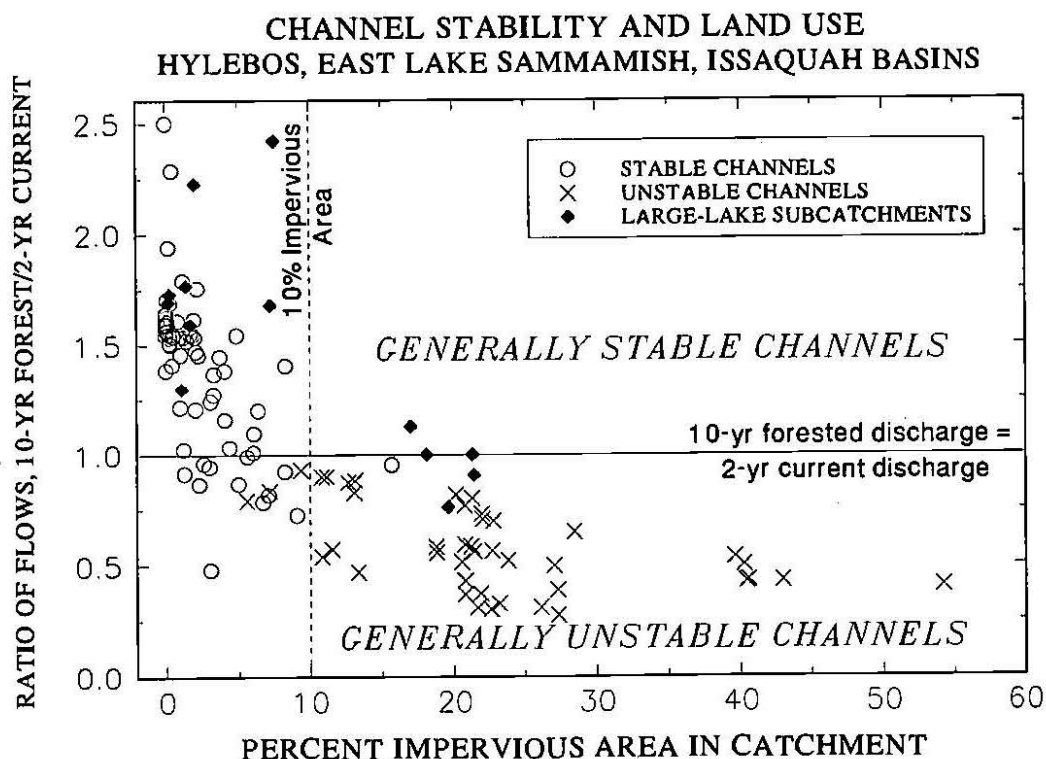


Figure 5-3. Channel stability as a function of surface runoff and EIA. These results are for basins dominated by glacial till soils and with no stormwater mitigation in the Hylebos, East Lake Sammamish, and Issaquah basins in western Washington. The vertical axis represents the ratio of modeled 10-year discharge for a forested basin to the current two-year discharge and gives an index of hydrologic change. When this ratio equals one (horizontal line), the 2-year current discharge equals the 10-year modeled discharge. Channel stability appears to consistently decline as this ratio decreases and EIA increases. IMST feels that the vertical and horizontal lines should not be interpreted as implicit thresholds, as the existence of thresholds in this context has been the subject of considerable debate. Reproduced from Booth & Jackson (1997) with permission from John Wiley and Sons.

SECTION 5.13: LARGE WOOD AND OTHER ORGANIC MATTER INPUTS

Large wood, particularly coniferous, is a key structural component influencing channel dynamics and aquatic habitat complexity in Pacific Northwest rivers, streams, and estuaries. The abundance, size, and abundance of individual large wood pieces influence the capacity of instream wood to form and maintain complex aquatic physical habitat. The importance of individual large wood pieces generally increases with increasing piece size (Bilby 1984; Bisson *et al.* 1987; Bilby & Ward 1989). Long, large diameter pieces trap additional materials, and change the streamflow dynamics and channel morphology (Collins *et al.* 2002). Many of the following functions served by large wood are of critical importance to the maintenance of salmonid habitat (Meehan *et al.* 1977; Bisson *et al.* 1987, 1988; Maser *et al.* 1988; Gregory *et al.* 1991; Hicks *et al.* 1991; Reeves *et al.* 1993; Montgomery *et al.* 1995, 1996; Beechie & Sibley 1997; Bilby & Bisson 1998; McIntosh *et al.* 2000):

- Dissipation of streamflow energy,

- Regulation of sediment storage and transport,
- Streambank protection and stabilization,
- Pool, riffle, and gravel bar formation, and
- Habitat diversity created by cover and channel complexity.

Large wood in streams, rivers, and estuaries comes from riparian and upslope areas. Large wood derived from riparian areas typically enters streams through windfall or stream bank erosion while more episodic landslides or debris torrents deliver wood from upslope sources. Periods of high water may subsequently transport large wood downstream from its entry point. Research conducted in western Oregon and Washington has shown that the majority of large wood (both number of pieces and volume) in a specific stream reach typically originates from windfall or erosion of local riparian forests (Keller & Swanson 1987; McDade *et al.* 1990; McGreer & Andrus 1992).

Several mechanisms associated with development reduce potential wood recruitment into streams. Past and current wood removal activities associated with development contribute to declines in large wood (May *et al.* 1997). As channels adjust to altered sediment budgets and flow regimes, increased stream power can flush remaining and newly recruited wood from the channel. Channel straightening and bank armoring reduces large wood recruitment by preventing rivers from laterally eroding their banks and floodplains (Collins *et al.* 2002). Levee construction, overbank deposition, and channel incision that isolate rivers from their floodplains also reduce the potential for rivers to recruit wood from forested floodplains (Roy *et al.* 2005). Finally, sources that resupply large wood to stream channels are reduced or lost as development encroaches on riparian forests (May *et al.* 1997; Finkenbine *et al.* 2000; Ourso & Frenzel 2003). Ultimately, the loss of large wood from river channels and estuaries decreases habitat complexity and intensifies the effects of channelization.

Wing & Skaugset (2002) found that land ownership and forest age were important predictors of large wood volume and size of structurally important logs in western Oregon streams. Their analysis indicated that rivers flowing through rural-residential developments contained significantly less wood than those in forested areas. In Puget Sound lowland streams, large wood abundance is 1 to 2 orders of magnitude below abundance estimates from the period prior to Euro-American settlement (Collins *et al.* 2002). In these streams, smaller, non-coniferous pieces that decay more rapidly dominate contemporary wood recruitment. Poor wood recruitment rates limit the number of 'key' logs large enough to initiate and stabilize wood jams (Collins *et al.* 2002). Finkenbine *et al.* (2000) found that British Columbia (Canada) streams flowing through landscapes with greater than 10% TIA contained minimal quantities of large wood unless substantial riparian buffer zones were present. Similarly, May *et al.* (1997) found that declines in both the size (>0.5m diameter) and quantity of large wood were correlated with increasing TIA (Figure 5-4). Parallel measures of salmonid rearing habitat (pool area, pool size, pool frequency) showed that the loss of large wood was associated with impairment of habitats important to salmonid populations (May *et al.* 1997). While the contribution of development to large wood reductions was not explicitly quantified, watersheds with TIA estimates below 5% and relatively intact upstream riparian buffers tended to contain the highest frequencies and volumes of large wood (May *et al.* 1997). This is consistent with conclusions drawn by Gregory *et al.* (1991) that intact, mature riparian forests are key to maintaining in-stream large wood.

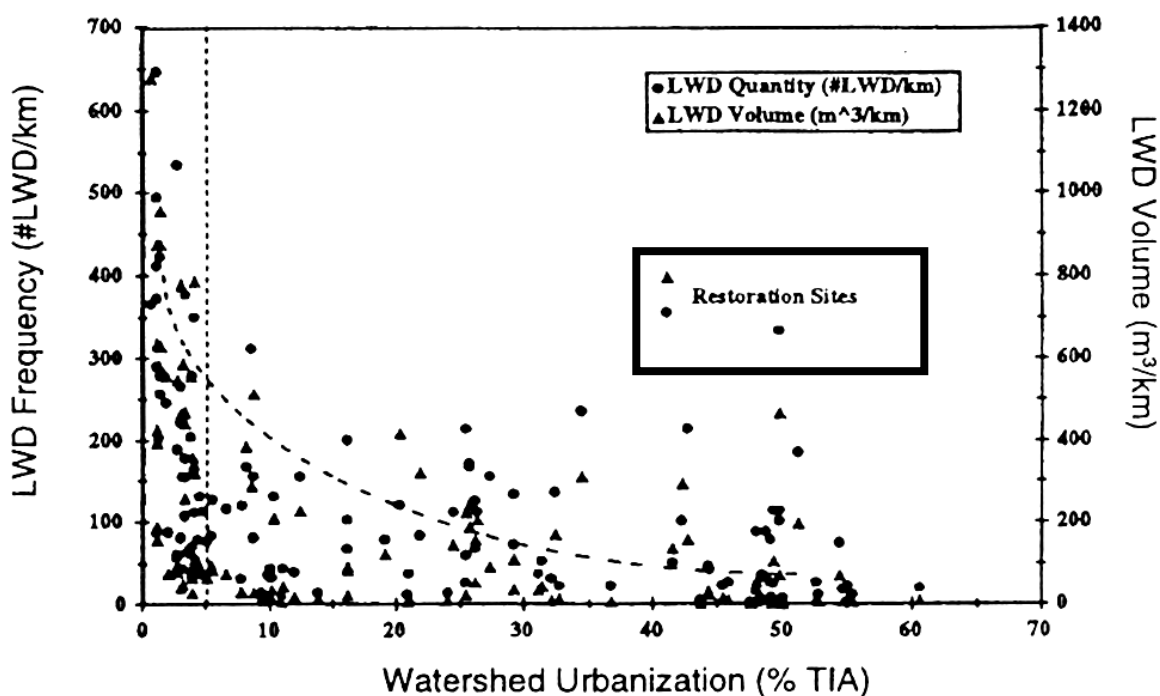


Figure 5-4. Large wood in streams in relation to total impervious area in the watershed. The vertical line highlights the finding that the amount of large wood (number of pieces or volume) in streams is highly variable even at low levels of TIA, but only sites with TIA below 5% had the highest large wood frequency. IMST feels that the vertical line should not be interpreted as an implicit threshold. May *et al.* (1997) attributed variation in large wood amounts to legacy effects of past timber harvest in some watersheds. Data points that fall within the inset box ($n=3$) received habitat restoration treatments. Figure reproduced from May *et al.* (1997) with permission from the Center for Watershed Protection (Ellicott City, Maryland).

SECTION 5.14: SUBSTRATE SILTATION AND COARSENING

Hydrologic and geomorphic processes that sort and deposit gravel and fine sediments maintain channel substrate structure. May *et al.* (1997) estimated that ecologically significant increases in the percent of fine sediment may occur when upstream TIA exceeded 20%. Excess fine sediments can cover streambeds, fill spaces between coarse substrate materials, and increase substrate embeddedness (Wolman & Schick 1967; Klein 1979). Therefore, the texture and complexity of channel substrates change in response to altered sediment budgets and flow regimes in developed areas (Paul & Meyer 2001). Despite efforts to control sediment from construction and other ground disturbances, sedimentation is frequently cited as a cause of river impairment in the US (USEPA 2002b, 2006c; Stoddard *et al.* 2005; Paulsen *et al.* 2008). Channel substrates may remain in this condition as rivers respond to increased sediment loads.

In the absence of fine sediments, bed coarsening can occur. As construction continues and new impervious surfaces are created, upslope sediments stabilize, and high streamflows and bank-full flows increase which flush fine sediments from streams and leave larger materials in the streambed (Konrad *et al.* 2005). This process, when localized, is referred to as scouring and can occur over short periods, generally in response to stormflows (Simon & Rinaldi 2006). The long-

term effects of repeated scouring, however, may not be fully evident for decades (Finkenbine *et al.* 2000; Chin 2006). In King County (Washington) the annual number of streamflow events likely to result in scouring was 5- and 11-fold higher in watersheds with 18% and 37% TIA (respectively) compared to forested watersheds (Bledsoe & Watson 2001a). While not reported in detail, May *et al.* (1997) found lowland stream channels that were lacking large wood and had gradients of more than 2% to be more susceptible to stream scour than their undeveloped counterparts. Finkenbine *et al.* (2000) observed reduced amounts of fine substrate material in southwest British Columbia (Canada) streams recovering from the construction phase of urbanization. In a more arid climate, intense summer stormwater discharges flushed fine sediments from the Provo River (Utah) and coarsened stream substrates (Gray 2004a).

Key Findings: Aquatic physical habitat

- Reduced channel and physical habitat complexity are frequent consequences of development. Physical habitat alterations common to urban streams include enlarged channels, eroding banks, excess fine sediment over otherwise coarse streambeds, reduced riparian vegetation and large wood, all of which diminish physical aquatic habitat complexity.
- Construction activities can increase erosion and watershed sediment yields. Changes in sediment budgets and flow regimes associated with development can cause significant changes in channel morphology.
- Accelerated channel erosion can become a significant sediment source for downstream reaches and can propagate the effects of development beyond the reach scale.
- Activities that restructure channels include the installation of pilings, wharfs, and bridges, channel dredging, large wood removal, aggregate removal, bank armoring, and diking and filling in estuaries. Restructuring channels in rivers and estuaries can increase stream power, decrease channel complexity, and increase within-channel erosion.
- Riparian deforestation is often identified as an important factor influencing how aquatic ecosystems respond to development.
- Several mechanisms associated with development reduce potential wood recruitment into streams and the loss of large wood from river channels and estuaries decreases habitat complexity and intensifies the effects of channelization.
- The direction and magnitude of changes to physical habitat depend on the type of stream channel affected, the age of the development, and the spatial pattern and sequence of landscape alterations.

Section 6.0: Fish Passage through Urban and Rural-residential Areas

Movement is a key feature of all salmonid life histories and salmonids exhibit a variety of movements across different spatial and temporal scales. Distances traveled by salmonids range from occasional forays among stream reaches to extensive marine and riverine migrations that traverse entire watersheds and river basins (Quinn 2005). There is an extensive literature documenting the range in salmonid movement distances (Gowan *et al.* 1994; Fausch & Young 1995; Baxter 2002; Rodriguez 2002). Large and small-scale salmonid movements are mediated by differences in body size, physical and physiological requirements of different life stages, different habitat requirements of each life stage, and spatial heterogeneity and connectivity among required habitats (Schlosser 1995). The timing and timeframe over which salmonids make characteristic movements is a product of species-specific life histories and individual differences evolved to maximize survivorship and reproductive success in variable environments.

Movement allows salmonids access to habitats that meet their physiological needs and their requirements for spawning, rearing, and refuge (Schlosser 1995; Pess *et al.* 2002; Rosenfeld *et al.* 2002; Neville *et al.* 2006a; Isaak *et al.* 2007). Travel among habitats is required throughout the lifespans of individual fish. Depending on the species, variable distances separate these habitats. The spatial proximity of distinct habitats and ease of travel among them affects survivorship by controlling the energy required to move between habitats and the predation risk incurred during travel (Dunning *et al.* 1992; Schlosser 1995). Similarly, uninhibited access to functionally similar habitats (e.g., rearing habitat) in different locations allows a population, particularly juveniles, to feed and seek refuge over a broader area and may reduce density-dependent mortality rates (Schlosser 1995). In sum, effective fish passage allows:

- Migrating adults full access to high-quality spawning habitat, resulting in broadly distributed progeny;
- Juvenile access to stream, off-channel, and estuary habitats for rearing;
- Uninhibited downstream movement of smolts as they migrate to the ocean; and
- Fish access to upstream and downstream refuges as chemical, physical, and biological habitats fluctuate.

Fish passage barriers can disrupt landscape-scale habitat connectivity in several ways with varying consequences for population persistence and resilience (Dunning *et al.* 1992; Schlosser 1995; Dunham *et al.* 2003). From a genetic perspective, barriers to movement can disrupt critical dispersal pathways thus isolating populations from one another. Resulting gene flow restriction subsequently erodes genetic variability within populations because incoming migrants no longer offset the processes of genetic drift and inbreeding (Slatkin 1985; Neraas & Spruell 2001; Wofford *et al.* 2005; Neville *et al.* 2006b). If the affected species exhibits metapopulation dynamics (Hanski & Gilpin 1991; Rieman & Dunham 2000), fish passage barriers can also result in local extinctions by altering various demographic and genetic processes (Hanski 1996, 1999). Metapopulations are composed of independent but interconnected populations (of the same species) that occupy a variable number of spatially separate habitat patches at any time (Hanski & Gilpin 1991; Rieman & Dunham 2000). Metapopulations are dynamic and involve movement among habitat patches such that empty patches can be recolonized after populations have gone

extinct. A metapopulation persists when a balance exists between the extinction and recolonization of the constituent populations within the patch network (Harrison 1991). To achieve such a balance, individual fish must be able to move through corridors between patches within the geographical area occupied by the metapopulation. Fish passage barriers that block dispersal corridors sever interconnections among habitat patches, eliminating the opportunity for recolonization following extinction events (Hanski 1996; Rieman & Dunham 2000; Dunham *et al.* 2003).

For salmonids that undertake long-distance marine or riverine migrations, habitat connectivity is synonymous with fish passage across entire watersheds or river basins. Rivers must be barrier free for their entire lengths between estuaries or river mainstems and spawning areas (adult upstream migration), and between rearing areas and estuaries or river mainstems (juvenile or adult downstream migration). Thus, both resident and migratory salmonids require the freedom to move among stream reaches that contain habitat suitable for different behaviors (feeding vs. spawning), high and low flow refuges, and life stages (juvenile vs. adult). For all salmonids, life history variation results in species-specific differences in barrier passage ability (Myers *et al.* 2006) and varying consequences for landscape-level fragmentation caused by fish passage barriers (Sheer & Steel 2006). Barrier-free waters are also critical for many non-salmonid fish that migrate long distances in rivers, such as lampreys, sturgeons, suckers, and minnows.

Section 6.1: Factors and Mechanisms that Alter Fish Passage in Developed Areas

Across the Pacific Northwest, instream barriers (e.g., culverts, dams) are known to block anadromous fish access to entire basins and have resulted in basin-wide extirpations (Lichatowich 1999; Beechie *et al.* 2006; Sheer & Steel 2006). These barriers also fragment salmonid populations, limiting gene flow, reducing genetic diversity (Neraas & Spruell 2001; Wofford *et al.* 2005), potentially reducing population persistence through landscape scale disturbances (Schlosser 1995), and ultimately increasing extinction risk. Urban and rural-residential developments along streams, rivers and estuaries in Oregon contain an assortment of fish passage barriers that may prevent salmonids from reaching habitats for feeding, rearing, acclimating, and spawning. This section describes the degree to which rural-residential and urban developments prevent or hinder salmonids from reaching critical habitats.

Decreased fish passage in developed landscapes results from several human mediated actions that create both physical and physiological barriers including:

- Inadequate or excessive streamflow and velocities,
- Culverts and other in-stream structures,
- Dams,
- Streams piped underground,
- Artificial lighting,
- Noise, and
- Poor water quality.

Streamflows – Sufficient streamflow is an obvious requirement for salmonid movement. Reduced flows can block or delay movement (Myers *et al.* 2006) and increased peak flows can increase mortality by sweeping eggs or fish downstream during critical periods of salmonid life cycles. As discussed in Section 4.0 of this report, both of these hydrologic conditions result from rural-residential and urban development. In some cases, flows may be adequate for fish passage through pre-disturbance stream channels, but water in channels reshaped by development may flow at depths insufficient or velocities excessive for fish migrations.

Culverts – Culverts and similar devices create a pervasive salmonid habitat connectivity problem throughout all land uses in Oregon (GAO 2001; Heller & Sanchez 2005; Sheer & Steel 2006). Several aspects of culvert design result in obstructed fish passage (Bates *et al.* 2003; Clarkin *et al.* 2005). Examples include high water discharge points or shallow plunge pools, high water velocity and turbulence within the culvert, inadequate depth within the culvert, obstructions within or at the upstream end of the culvert, or water flow under or around the culvert. In addition to the high density of road crossings, the hydrologic regime changes that accompany development can intensify channel degradation around culverts, increasing the likelihood that these structures will become fish passage barriers (Bates *et al.* 2003).

Dams – Hydropower dams create well documented fish passage problems (e.g., Ruckelshaus *et al.* 2002 and references therein). In the Pacific Northwest, hydropower projects service the energy demands of a growing population and their environmental effects are part of the ecological footprint of development. More directly linked to urban and rural-residential areas however, are smaller dams that impound public water supplies. Few of these dams incorporate effective fish passage structures. As a result, fish are blocked from accessing miles of habitat both upstream and downstream of these dams. Ironically, habitat upstream of these barriers typically is high quality because of efforts to ensure that public water supply watersheds are relatively undisturbed.

Streams Piped Underground – Probably the most thorough aquatic alteration practiced during the development of older urban areas was piping streams underground (e.g., Metro 1999). This involved diverting long segments of streams from their natural channels into pipes to route the water to larger waterways. In these piped streams, inadequate streamflow (depth, velocity) and other obstructions (e.g., length, lack of light) severely limit or prevent fish passage. Ecological functions in the piped reaches have also been largely eliminated and several authors have suggested that extensive underground piping of headwater streams can alter hydrology, water quality and nutrient cycling in downstream river reaches (e.g., Alexander *et al.* 2007; Freeman *et al.* 2007; Meyer *et al.* 2007; Wipfli *et al.* 2007). The net result is lost access to upstream habitats required by migratory fish, lost habitat in the portion of the stream system that is underground, and alterations to habitat and aquatic species assemblages in downstream reaches.

Artificial Lighting – In laboratory, artificial stream, and field experiments (Cedar River, Washington), Tabor *et al.* (2004) reported that intense light at night may inhibit sockeye salmon fry migration and may increase predation by freshwater sculpins (*Cottus* spp.) as the fry slow or stop their outmigration until light conditions are more favorable. The overall effect, most likely localized, on sockeye salmon fry could not be fully assessed. It is not known how intense artificial lighting associated with development and transportation corridors may affect other salmonid species.

Noise – There is some concern that excess noise generated by anthropogenic sources (e.g., active bridge and pier construction, pile driving, traffic noise) might affect the health or survival of fishes by causing hearing loss or altering ecologically important behaviors (Song *et al.* 2008). The few studies conducted on this phenomenon show results ranging from damaged auditory structures and prolonged hearing loss to unaffected auditory structures and temporary hearing loss. These differences may be specific to individual fish species or to the water depth or noise amplitude used in different experiments (reviewed by Song *et al.* 2008). However, no research has addressed whether noise in the auditory range of fish could constitute a temporary or permanent barrier to fish migration or might otherwise alter the migratory behavior of either juvenile or adult fish.

Poor Water Quality – Water quality is an important attribute of dispersal and migration routes. High turbidity, excessive temperatures, low levels of dissolved oxygen, and pollutants effectively block movement by presenting physiological and olfactory challenges to fish (Myers *et al.* 2006). Water quality is discussed in Section 7.0 of this report, and will not be discussed further in this section.

Section 6.2: Nature and Magnitude of Fish Passage Changes in Oregon

The timing and magnitude in which passage barriers block fish movements among critical habitats vary in biologically important ways. Complete barriers block all fish movements throughout the year regardless of flow velocity and volume. Temporal barriers block all fish movements some of the time and can delay upstream or downstream movements of adults or juveniles depending on streamflow. Partial barriers block only some fish (e.g., smaller individuals or species) some or all of the time and can be among the most difficult to identify as barriers during inventories and assessments such as those conducted on culverts (Clarkin *et al.* 2005).

The degree to which Oregon's salmonid populations are limited by fish passage barriers associated with rural-residential and urban areas is poorly documented. Complete barriers formed by some dams are obvious. For example, the City of Portland constructed the Headworks Dam in 1922 to increase the municipal water supply from the Bull Run River. The dam is known to block approximately 37 miles of salmon and steelhead habitat (Taylor 1998). The magnitude of cumulative passage impacts from temporal and partial barriers of broadly distributed culverts, underground piping, and water quality are more difficult to estimate. Within the Willamette and lower Columbia River basins, Sheer & Steel (2006) identified 1,491 complete fish passage barriers blocking access to 9,277 stream miles, approximately 42% of historic stream habitat. These barriers prevent anadromous fish from reaching 40% of streams with gradients suitable for steelhead, 60% of streams with habitat in good condition, and 30% of streams draining watersheds dominated by coniferous land cover. Not surprisingly, the largest proportional lengths of blocked habitat occur in watersheds where large hydroelectric dams are present (Sheer & Steel 2006).

Many fish passage barriers are clustered near roads in areas that contain most of Oregon's rural-residential and urban developments (i.e., lower elevations and within floodplains). The high road density in rural-residential and urban areas increases the likelihood that culverts and other structures restrict or slow salmonid movements through developments. Between 1996 and 1999,

ODFW and ODOT conducted a collaborative survey of state and county owned roads in Oregon and evaluated over 5,500 culverts for their potential to pose barriers to fish passage (Mirati 1999). The surveys did not include roads owned by private (e.g., forestlands, residential property), federal³³, or city entities (Mirati 1999). Fish were not able to pass through approximately 52% (~2,870) of the inventoried culverts. Oregon's coastal and upper Willamette Valley regions have the majority of examined culverts (38% and 33% respectively) and identified barriers (50% and 27% respectively)³⁴. The IMST was not able to determine the degree to which these roads and fish passage barriers were associated with rural-residential and urban developments in Oregon.

Metro³⁵ (Oregon) conducted a culvert survey in 1999 and 2000 in an area roughly within the urban growth boundary and found 1,500 culverts that had not been documented in other survey efforts, including the collaborative effort by ODFW and ODOT. One hundred fifty (150) or 10% of these act as complete barriers to fish movement (Metro 2002). The IMST was not able to locate similar data for other urban areas in Oregon.

Within the city of Portland, 41 miles of streams (18% of the 227 stream miles) are known to be piped underground (City of Portland 2004). These alterations are most numerous in tributaries on the eastern side of the Willamette River, but also include streams on the western side (Metro 1999). The entire lower Willamette River watershed is estimated to contain 182 miles of piped streams but the proportion of total stream miles is unknown because historical stream location and piping records are incomplete (City of Portland 2004). The IMST was not able to locate data on piped streams or otherwise lost habitat in other developed areas in Oregon, but it is logical to assume that the problem is similar in areas that were established and urbanized over timeframes similar to Portland (e.g., Salem, Eugene, Roseburg, Medford, Coos Bay).

Together, culverts, piped streams, and similar development practices have eliminated approximately 400 stream miles from the Portland-Metro region (Metro 1999). The degree to which these streams supported salmonids is unknown. Given the wide distribution of salmonids in other streams in the Portland-Metro region, however, it is likely these eliminated streams did support salmonids, both directly by providing habitat and indirectly as conduits for water and energy to downstream locations used by salmonids.

³³ The US Bureau of Land Management and US Forest Service estimated that as of 2001, as many as 5,500 road-associated culverts blocked fish passage on public lands in Oregon and Washington.

³⁴ Data available at <http://www.dfw.state.or.us/fish/passage/inventories.asp>. Accessed on December 26, 2010.

³⁵ Metro (<http://www.oregonmetro.gov>) is the elected government responsible for managing a regional urban growth boundary encompassing 25 cities and more than 60 special service districts within Washington, Multnomah and Clackamas counties (Oregon).

Key Findings: Fish passage

- Urban and rural-residential developments along streams, rivers and estuaries in Oregon contain an assortment of fish passage barriers that may prevent salmonids from reaching habitats for feeding, rearing, acclimating, and spawning.
- Decreased fish passage in developed landscapes may result from inadequate or excessive streamflow and velocities, culverts and other in-stream structures, dams, piped streams, artificial light, excessive noise, or poor water quality.
- The degree to which Oregon's salmonid populations are limited by fish passage barriers associated with rural-residential and urban areas is poorly documented. Complete barriers are formed by some dams used to store municipal water supplies. However, the magnitude of cumulative passage impacts resulting from broadly distributed culverts, piped streams, and water quality barriers are more difficult to estimate.
- Estimates from the Portland Metro region indicate that fish barriers formed by culverts and streams piped underground may be extensive throughout Oregon's urban areas, but similar information for these other areas were not located.

Section 7.0: Water Quality

Since the US Congress passed the Clean Water Act (CWA) in 1972, significant progress has been made in identifying and reducing point source pollution discharges into US surface waters (Beasley & Kneale 2002; Mrazik 2006). However, the USEPA recently assessed approximately one fifth of the nation's waters and found that 39% do not meet state-level water quality standards (USEPA 2002b; GAO 2004). In a survey of the coastlines and estuaries of the conterminous US, USEPA (2004a) reported that 60% of the near coastal surface area failed to attain reference conditions³⁶ for water quality and 24% failed for sediment chemistry. Following a survey of all wadeable streams in the conterminous US, the USEPA (2006c; Paulsen *et al.* 2008) concluded that 67% of the total stream length failed to attain reference conditions. Among the limited number of water quality variables measured, streams with excess nitrogen, phosphorus, and fine sediments were most often associated with biological assemblages in poor condition.

Many waters remain impaired by non-point pollution sources that are difficult to identify and control (NRC 1992; USEPA 1996; Carpenter *et al.* 1998; Wentz *et al.* 1998; Beasley & Kneale 2002; ODEQ 2004; Brett *et al.* 2005a, b; Carle *et al.* 2005; Atasoy *et al.* 2006; Mrazik 2006). Between 1991 and 2001, the USGS National Water-Quality Assessment Program (NAWQA; Hamilton *et al.* 2004) characterized water quality in 51 major river basins draining approximately half of the US land area. The following major findings were most relevant to rural-residential and urban developments.

- Surface and groundwater contamination is widespread in urban areas.

³⁶ Reference conditions reflect the range of natural variability characterized from or thought to represent an ecosystem under least-disturbed conditions.

- Without exception streams and groundwater in areas with significant urban development contained a complex mixture of nutrients, trace elements, pesticides, volatile organic compounds, and the chemical breakdown products of these constituents.
- Breakdown products were found as frequently as their parent contaminants.
- New products that have the potential to become water contaminants in urban environments are approved for use each year.
- Many contaminant concentrations varied seasonally, with long periods of low or undetectable levels punctuated by short periods of high concentration.
- Organochlorine compounds no longer in use (e.g., DDT, PCBs³⁷) were detected in 95% of fish tissue samples collected at urban sites and exceeded tissue concentrations determined to be protective of wildlife at 75% of urban sites.

In Oregon, 13,937 stream miles monitored by ODEQ fail to meet one or more water quality standard while only 5,687 miles met all standards (Oregon Progress Board 2000)³⁸. Where urban lands dominated the 5-mile radius surrounding a stream monitoring site, water quality rankings fall in the poor or very poor range (Figure 7-1; Oregon Progress Board 2000). Data from four Oregon river basins indicated that while many pollutants are discharged primarily from point sources, non-point sources contribute a majority of the pollutants that exceed Oregon's water quality standards (Oregon Water Progress Board 2000). While the non-point contributions of individual urban areas vary, they can pose a significant threat to water quality (NRC 1992; USEPA 1996; Oregon Progress Board 2000; Brett *et al.* 2005a, b; Atasoy *et al.* 2006).

³⁷ Polychlorinated biphenyls are a class of organic compounds that includes over 200 closely related chemical compounds with variable toxicities.

³⁸ Oregon contains approximately 114,500 linear miles of rivers and streams, only a small fraction of which are monitored by ODEQ (Oregon Progress Board 2000).

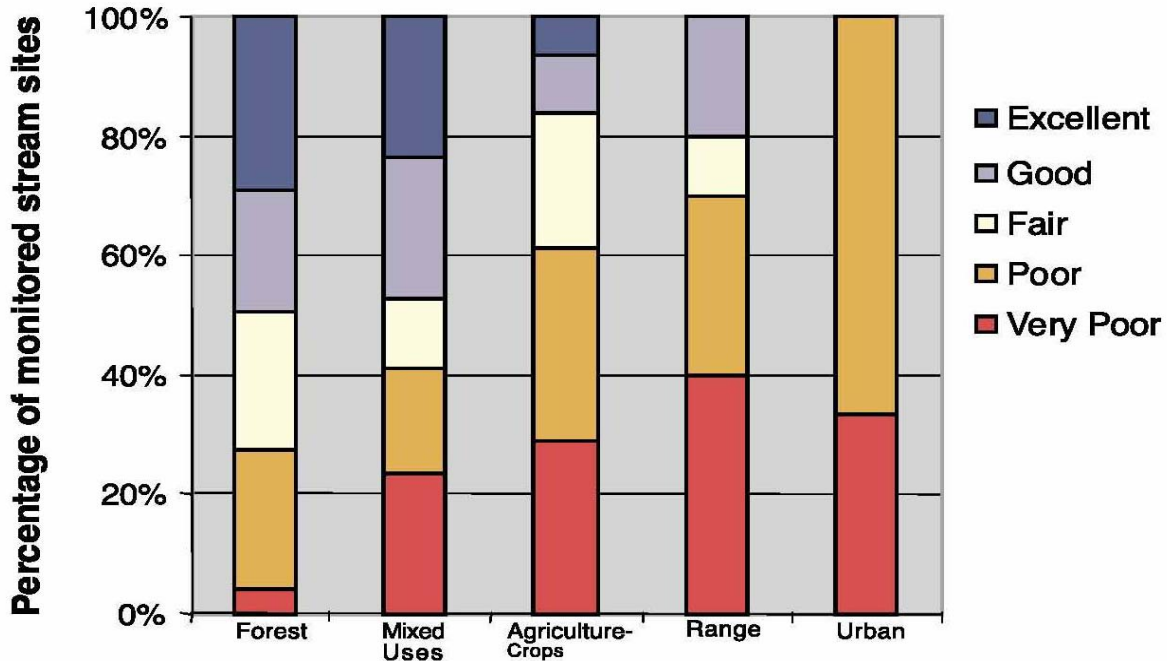


Figure 7-1. The relationship between water quality and adjacent land use in Oregon. Water quality, measured using the Oregon Water Quality Index, integrates information on temperature, dissolved oxygen, biochemical oxygen demand, pH, nutrients, total solids, and fecal coliform bacteria. Land use categories are based on dominant land use within a five-mile radius of the monitoring site. Streams in Oregon's urban areas typically have water quality problems related to temperature and dissolved oxygen. Additionally, some streams are adversely affected by oxygen demanding wastes (measured as biological oxygen demand) and by excess nutrients, usually phosphorous and nitrogen. Figure reproduced from the Oregon State of the Environment Report (Oregon Progress Board 2000).

Section 7.1: Sources of Variation in Water Quality Response to Development

Several mechanisms operating in rural-residential and urban developments increase the likelihood of water quality impairment (Figure 7-2). The diversity and quantity of nutrients and compounds (e.g., fertilizers, pet waste, wastewater effluent, increased erosion) available for transfer to streams increase dramatically with development. In rapidly growing areas, runoff from construction sites can be a significant sediment source despite control measures. Chemicals toxic to fish and other aquatic biota originate from a variety of point and non-point sources. The density of point sources and the volume of effluent they produce increase as urban populations grow. Removal and disturbance of riparian vegetation reduce the capacity of riparian areas to sequester pollutants and sediments before they reach streams. Stormwater runoff across impervious surfaces transfers pollutants directly to streams and estuaries, bypassing soils and remaining vegetation that could otherwise filter, sequester, and break down potential water contaminants.

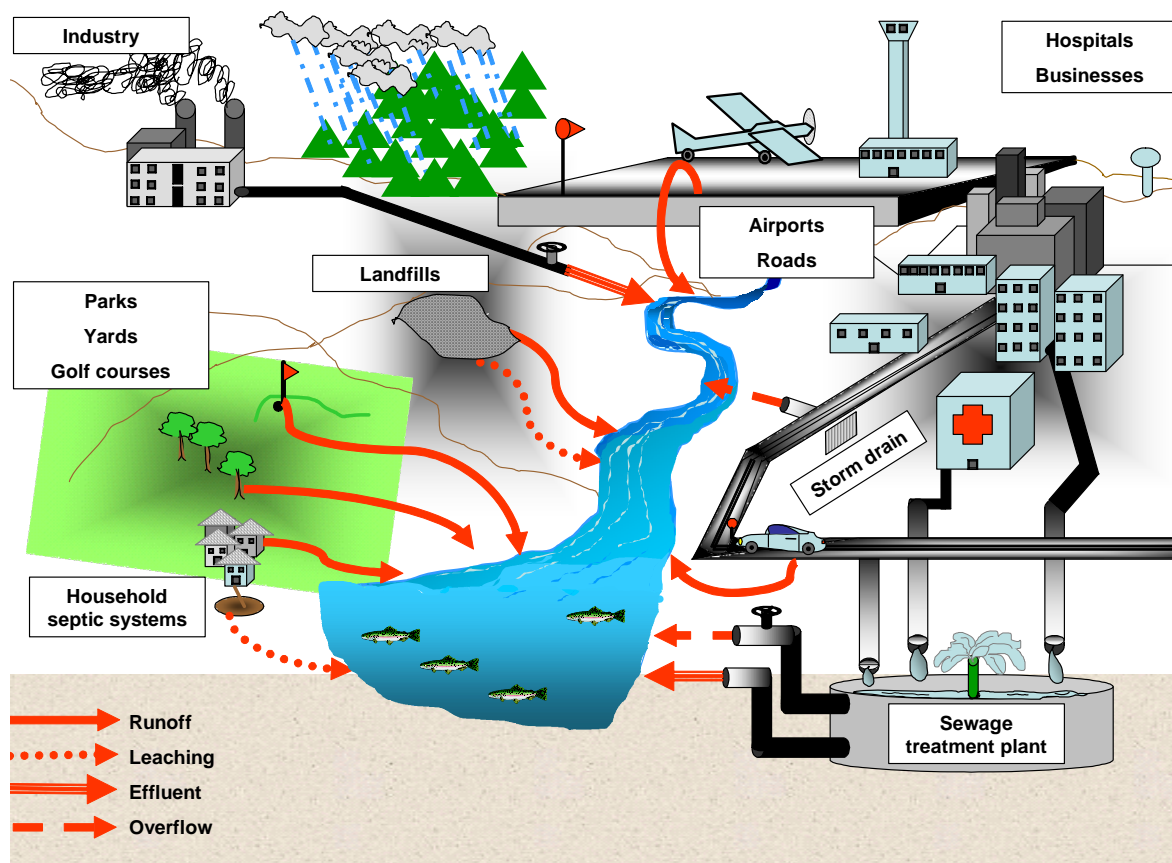


Figure 7-2. A generalized schematic showing sources of pollutants in the urban landscape. Note that the figure is not drawn to scale and that the potential pollutant contributions by each category are not drawn proportionately to the relative size of impact.

Quantifying the association between specific elements of water quality and rural-residential or urban land uses is difficult because water quality parameters are affected by various natural and anthropogenic factors (Coulter *et al.* 2004). Natural features (e.g., topography, geology, climate, hydrology, soils) underlying developments control concentrations of naturally occurring substances that may be considered contaminants when they exceed ‘background’ levels (Hamilton *et al.* 2004). Natural features also affect how contaminants are transported from land to water and create variability in how contaminants accumulate in different environments. Stream discharge can play a major role in the magnitude of pollutant concentration in surface waters (Lehrter 2006). Small streams respond rapidly to storm events resulting in contamination peaks that rise and fall rapidly compared to larger rivers, which maintain lower contaminant concentrations for longer periods of time (Hamilton *et al.* 2004). Surface water is typically more vulnerable to contamination than groundwater which is somewhat protected by overlying substrates that filter contaminants and where relatively long residence times may allow some chemicals to degrade or disperse. Consequently, it may take decades for groundwater to show impairments (Hamilton *et al.* 2004); once contaminated, however, groundwater is extremely difficult to decontaminate. Groundwater may be more vulnerable in areas with permeable soils or

areas where groundwater pumping lowers water tables, induces surface water infiltration, and thus transports surface contaminants to groundwater (Hamilton *et al.* 2004). This amount of natural variability can cause water quality to fluctuate within single rainfall events, seasonally, annually, or over variable intervals, depending on location (geographic, surface, or subsurface). Connecting changes in water quality to specific land uses requires that long-term trends be distinguished from natural fluctuations. The historical data required for such analyses are lacking in many areas of the Pacific Northwest (Hamilton *et al.* 2004).

The intensity, type, and distribution of development also introduce variability in the nature and magnitude of water quality degradation. Schiff & Benoit (2007) found that their integrative water quality index was most strongly associated with impervious surface area, highlighting the role impervious surfaces play in delivering non-point pollution to streams. Similarly, Atasoy *et al.* (2006) found that a 1% increase in effluent discharges from point sources had a much smaller impact on total phosphorus, nitrogen, and suspended solids than a comparable increase in land uses that generate non-point source pollution. However, the percentage of impervious surface cover associated with measurable water quality impairment ranges from 4–5% (May *et al.* 1997) to 10–12 % (Klein 1979; Wang *et al.* 2000). Much of the variation observed in the relationship between impervious surfaces and water quality depends on the quantity of non-point contaminants washed from impervious surfaces, connectivity between impervious surfaces and streams, how well riparian buffers shield streams from non-point source pollution (Ourso & Frenzel 2003; Hatt *et al.* 2004), and on previously existing land uses such as agriculture and mines (ODEQ 2006; see Section 1.41 of this report).

The stage of development also introduces variability in the water quality response. The types and quantities of contaminants that enter streams when undeveloped lands are converted to residential uses (i.e., new construction) can be qualitatively different from contaminants derived from subsequent uses of converted land. Former agricultural lands may have pesticides and associated metals in the soil, groundwater, and sediments (e.g. in drainage ditches) at concentrations above acceptable risk levels (as defined in Oregon Revised Statute 465.315; ODEQ 2006). Atasoy *et al.* (2006) found that both land conversion and developed land use increased total phosphorus and total nitrogen loadings in North Carolina streams. In their study, only land conversion (i.e., new construction) increased total suspended solids (despite unspecified standard control practices). New construction also had a larger effect on total phosphorus than existing developments (Atasoy *et al.* 2006), possibly because phosphorus binds to fine sediments. Carle *et al.* (2005) found that water quality variation was best explained by development type, connectivity to city stormwater and wastewater systems, and development density, indicating that older, densely developed neighborhoods and younger, low-density suburban developments contribute to water quality impairment in different ways.

The pattern in which different pollutants accumulate and move into streams is also variable and dependent on seasonality of rainfall. Many pollutants (e.g., suspended solids, various nutrients, metals) follow a ‘first flush’ pattern where runoff generated early in a rainfall event transports most of the total pollutant load and is the most contaminated (Lee *et al.* 2002). Quantitative definitions of this phenomenon generally identify a fraction of the total pollutant load (e.g., >50%) that occurs in an initial fraction (e.g., 25%) of storm event runoff (Flint & Davis 2007). In climates like that of the Pacific Northwest where rainfall occurs during distinct seasons, the first flush concept can also apply to the rainfall season (i.e., the earliest storms transport the majority of the available pollutant loads). During a first flush event, a disproportionately high quantity of

pollutants discharge into surface waters but individual pollutants exhibit variable peak loads within and among storm events (Chang & Carlson 2005; Flint & Davis 2007). In an analysis of 38 storm events in 13 separate urban watersheds, Lee *et al.* (2002) found that the contaminants dominating first flush events depended on both land use (i.e., residential vs. industrial) and analysis method and that first flush intensity increased as watershed size decreased and rainfall intensity increased. Within a given storm event, some pollutants may also undergo a 'second flush,' defined as flushing of 50% of the total pollutant load in any 25% portion of the runoff volume beyond the first 25% (Lawler *et al.* 2006; Flint & Davis 2007). Monitoring designs for municipal stormwaters are unlikely to detect the highest pollution loads if sampling designs do not account for first and second flush phenomena.

The following sections summarize the effects of development on several water quality parameters including suspended sediment and turbidity, nutrients, water temperature, dissolved oxygen, and toxic pollutants. Concluding remarks on the responses of aquatic biota, including salmonids to changes in water quality and the potential for rehabilitation of water quality follow these sections.

Section 7.2: Suspended Sediment and Turbidity in Urban and Rural-residential Areas

In this section, IMST describes the factors and mechanisms that alter suspended sediment and turbidity as well as the nature, timing, and magnitude of suspended sediment and turbidity changes in surface waters affected by development.

SECTION 7.21: FACTORS AND MECHANISMS THAT ALTER SUSPENDED SEDIMENT AND TURBIDITY

Sediments transported by streams and rivers serve integral roles in many ecosystem processes to which salmonids are adapted. Periodic flooding, associated with increased erosion of sediments, delivers and sorts gravel required for salmonid spawning. Sediment loads commonly reflect the location, quantity, and composition of sediment sources found throughout the contributing watershed. Geology, vegetation cover, landscape topography, and weather conditions determine erosion patterns of sediment, ranging from fine (e.g., clay, silt) to coarse (e.g., gravel, cobble) from upland slopes and stream channels. Once sediments enter a stream, many factors influence whether they remain suspended within the water column or are deposited, including particle size, channel gradient, water velocity, and the total sediment load carried by the stream. Fine sediments that remain suspended can be particularly damaging to aquatic organisms and even low-level accumulation of fine sediments in stream beds can reduce salmonid spawning success and alter fish and macroinvertebrate assemblages (Bryce *et al.* 2008, 2010). Water-borne clay and silt influence numerous aspects of water quality when they bind to phosphorus and toxic contaminants (e.g., heavy metals) and facilitate transport of these substances to streams (Brett *et al.* 2005a; Lawler *et al.* 2006; Li *et al.* 2006).

Turbidity, a measure of light transmission through water, is an important water quality variable (Lawler *et al.* 2006). Increasing turbidity reduces light penetration through water and, consequently, photosynthetic productivity that forms the basis of many aquatic food webs (reviewed by Henley *et al.* 2000). Through its relation to light suppression, turbidity can

influence the biological oxygen demand and dissolved oxygen available in streams (see Section 7.5). Many factors influence turbidity including suspended sediments, water chemistry, terrestrial plant debris, and aquatic microorganisms (Lloyd 1987; Henley *et al.* 2000). Water containing excess fine sediment is highly turbid. In combination, increased suspended sediment and turbidity can lead to population and community-level changes in aquatic ecosystems (Lawler *et al.* 2006).

Urban and rural-residential development increases both suspended sediment and turbidity through multiple pathways with numerous detrimental effects on salmonids and other aquatic biota (Paul & Meyer 2001; Opperman *et al.* 2005; Lohse *et al.* 2008). Direct influences are most obvious when land-clearing and construction activities mechanically disturb large quantities of soil (Wolman & Schick 1967; Keller 1999; Paul & Meyer 2001; Atasoy *et al.* 2006). Manipulation of the stream channel during development also increases suspended sediment concentrations. Removal of riparian vegetation and large wood, channelization, bridge construction, and dredging can cause significant stream channel erosion (Booth 1991; Waters 1995; Keller 1999). Road networks that expand along with rural-residential and subsequent urban development are a chronic source of fine sediment delivery to streams (Carter *et al.* 2003). Indirect influences are a function of hydrologic and physical habitat changes that accompany development (see Sections 2.31 and 2.32 of this report). For example, channelization and bank stabilization confine rivers and streams to a single channel, diminishing sediment filtration and storage by riparian zones (see Section 2.32 of this report). None of these factors operate in isolation and instead act in a cumulative manner with other land uses to increase sediment erosion and, consequently, to increase suspended sediment and turbidity.

SECTION 7.22: NATURE, TIMING, AND MAGNITUDE OF SUSPENDED SEDIMENT AND TURBIDITY CHANGES

Sediment eroded from the landscape is one of the most ubiquitous non-point source pollutants affecting surface water quality (Nelson & Booth 2002). Few studies have estimated the magnitude of sediment generated by development in Oregon. In Fanno Creek (primarily located in southwestern Portland, Oregon), runoff from urban and industrial lands can contribute as much as 2.5 million pounds of sediment annually (ODEQ 2001b). A 1997 study commissioned by Oregon's Governor found that, on a per acre basis, urban sites in the Willamette River basin contributed the greatest fraction of suspended sediment to the river (GAO 1998). Research conducted elsewhere demonstrates that total suspended solid (TSS) concentrations and turbidity vary considerably with development. In rapidly developing Issaquah Creek (western Washington), Nelson & Booth (2002) estimated that channel erosion associated with urban development increased watershed-wide sediment production by 20%, with an additional 12% increase contributed by other urban impacts including construction, road surface erosion and sediment production from residential and commercial areas.

In contrast, Brett *et al.* (2005a) found little association between urban land cover and either TSS or turbidity in 17 Seattle (Washington) area watersheds. Burcher & Benfield (2006) found that TSS concentrations were significantly lower in North Carolina suburban developments compared to other land uses. A common explanation for such observations is that watersheds contribute increased sediment loads to streams during the construction phase of development, but TSS concentrations decrease relative to predisturbance conditions after impervious surfaces cover

potential sediment sources (Finkenbine *et al.* 2000; Atasoy *et al.* 2006). For example, Carle *et al.* (2005) found that low TSS concentrations in North Carolina streams were associated with impervious surface area connections to stormwater sewer systems (as measured by effective impervious area or EIA) in older sections of the city of Durham where new construction was limited. In new developments, high TSS concentrations were attributed to erosion from construction sites, despite application of stormwater regulations (Carle *et al.* 2005).

Discrepancies among studies characterizing the relationship between development and TSS concentrations or turbidity may result from differences in study approach or methodology, type of disturbance, disturbance duration, disturbance proximity to stream, watershed size, vegetation characteristics, climate, or geography (Nelson & Booth 2002; Coulter *et al.* 2004). In mixed-use watersheds (e.g., urban, agricultural, undeveloped) the percentage of different land use types is important because they differ in their non-point source pollution contributions, particularly suspended sediments (Coulter *et al.* 2004). Given the discrepancies among available research results, IMST, in the text below, characterizes the nature, magnitude, and timing of sediment and turbidity changes in relation to 1) the development phase, 2) a single storm event, and 3) timing in the annual cycle.

During Development – Development initiates or modifies a number of sediment producing processes including construction site erosion, road surface erosion, and channel-bank erosion (Nelson & Booth 2002). As discussed in Section 2.0, new construction triggers substantial changes in sediment supply and annually produces ~ 80 million tons of sediment that enters US waters (Harbor 1999). Results from 100 published studies, conducted worldwide over the past 50 years, show that sediment production in urbanizing watersheds can increase from 2- to 10-fold during the initial phases of development (Chin 2006).

While there is abundant information on the amount of sediments entering aquatic ecosystems, only a few studies have documented a direct linkage between residential or commercial construction and changes in measured TSS or turbidity in surface waters. Monitoring conducted during 1997 by the City of Portland (2006) showed that construction sites release large amounts of sediment. One monitored site released more than three times the amount of TSS in a single storm event compared with that released by a reference site over the course of a year, which helped trigger Portland to develop and implement new city codes and develop an erosion control manual to better control erosion during construction. Olding *et al.* (2004) found that during moderate to large rainfall events, stormwater management facilities operating in sites with new construction had TSS discharge 2 to 3 times higher than identical facilities operating in more stable watersheds.

Many studies have documented how altered sediment budgets and hydrology typically contribute to channel erosion (Paul & Meyer 2001; Nelson & Booth 2002; Chin 2006) which then becomes a source of increased TSS concentrations and turbidity in downstream reaches. This is particularly true in valley-bottom channels that are easily eroded and susceptible to channel enlargement from increased discharge (Nelson & Booth 2002). Development may result in decreased surface erosion rates once impervious surfaces cover large areas, but hydrologic changes stemming from development also increase sediment loads delivered downstream by increasing channel erosion. For example, in a southern California watershed with 50% urban

cover, Trimble (1997) estimated that 67% of total sediment production came from channel-bank erosion within San Diego Creek.

During a Storm Event – Schiff & Benoit (2007) reported that turbidity and TSS concentrations fluctuate by orders of magnitude during individual storm events. Lawler *et al.* (2006) characterized turbidity dynamics in a United Kingdom headwater stream (Tame River, a tributary of the Thames River) after rainfall events and found that TSS concentrations increased as individual storms progressed and throughout storm events sequences. Similarly, Flint & Davis (2007) found that suspended solids frequently exhibited a second flush that contained higher sediment loads than the first flush from the same storm. Lawler *et al.* (2006) attributed increasing turbidity within a storm event to suspended solids from either combined sewer overflows or more distant sediment sources arriving at monitoring sites during latter stages of the storm. These authors interpreted higher turbidities during successive storms as evidence that sustained supplies of suspended solids can exist in some urbanized systems. In an arid ecosystem (Provo River, Utah), Gray (2004a) observed that larger summer storms generated TSS flushing events with poor water quality conditions persisting up to 12 hours. Storms of smaller magnitude did not alter water quality parameters beyond the natural range of variation for the stream (Gray 2004a). Sansalone & Cristina (2004) and Cristina & Sansalone (2003) described storm event flushing of TSS and total dissolved solids as flow limited. In other words, higher flow events (per unit drainage area) exhibited a ‘front-loaded’ first flush while low flow events flushed particulate matter more consistently over time.

Throughout the Annual Cycle – The annual timing of sediment movement into streams is dependent on hydrology, rainfall patterns, and timing of sediment producing activities such as construction. In undisturbed watersheds of western Oregon, the first one or two large rainfall events in the fall are likely to transport much of the sediment that enters streams during any given year (GAO 1998). In contrast, urban runoff can transport sediment to streams at any time of year (ODEQ 2001b). Most of the sediment flushed from urban surfaces consists of fine particles that bind to both urban-generated and natural (or background) pollutants. To prevent these pollutants from reaching surface waters, many municipalities and stormwater districts often detain urban runoff to allow sediments to settle out of the water column. As a result, much research attention has been focused on documenting TSS flushing behavior and efficiency of settling ponds under variable rainfall conditions at different locations (e.g., Comings *et al.* 2000; Bledsoe 2002; Hossain *et al.* 2005; Bäckström *et al.* 2006; Birch *et al.* 2006; Li *et al.* 2006; Kang *et al.* 2007). Of particular interest are sediments washed from road surfaces because they are smaller than those typically trapped by stormwater detention structures, and are more likely to transport nutrients, metals and toxic contaminants to streams (Li *et al.* 2006). In their study, Li *et al.* (2006) found that two-compartment settling tanks, when capturing and retaining the first 20% of runoff volume, could remove 40% of the total particulate load. In another study, Birch *et al.* (2006) found TSS retention by a pond next to a roadway during storms varied from below 0 (i.e. the pond was a source of TSS) to as high as 93%, depending on rainfall conditions. Resuspension and flushing of sediment during storm events can be a confounding factor, reducing the effectiveness of stormwater detention structures (Norton 2008). As many of these studies document both highly variable TSS concentrations entering stormwater detention structures and highly variable TSS removal efficiency (e.g., Bäckström *et al.* 2006; Birch *et al.* 2006; Li *et al.*

2006) it is difficult to draw any general conclusions of expected retention ranges for TSS relevant to developments in Oregon.

Key Findings: Sediments

- Urban and rural-residential development increases both suspended sediment and turbidity through land-clearing and construction activities, manipulation of the stream channel, and removal of riparian vegetation.
- None of the factors affecting sediments operate in isolation. Instead they act in a cumulative manner with other land uses to increase sediment erosion, and consequently, to increase suspended sediment and turbidity.

Section 7.3: Nutrients in Urban and Rural-residential Areas

In this section, IMST describes the factors and mechanisms that alter nutrient concentrations and the nature, timing, and magnitude of nutrient changes in streams, rivers, and estuaries affected by development.

SECTION 7.31: FACTORS AND MECHANISMS THAT ALTER NUTRIENT CONCENTRATIONS

Rural-residential and urban developments function as nutrient sources worldwide (Kaye *et al.* 2006). Because nitrogen (N) and phosphorus (P) frequently become pollutants in aquatic ecosystems affected by development, IMST's review focuses primarily on these nutrients. In ecosystems that are not limited by light, the availability of N and P is a strong determinant of photosynthetic rates, plant growth, and biomass production of organisms that form the foundation of food webs. When developed landscapes supplement nutrient delivery to surface and ground waters, phytoplankton and aquatic plant production (including nuisance and toxic algal blooms) can increase dramatically. This process known as eutrophication is a common cause of surface waters failing to meet CWA water quality standards (USEPA 1996, 2002b; Brett *et al.* 2005a) and is strongly associated with poor biological condition (as reflected in macroinvertebrate assemblages) in streams nationwide (Paulsen *et al.* 2008).

Anthropogenic nutrient sources (particularly landscaping fertilizers, septic fields, detergents in municipal wastewater effluent, and commercial and industrial discharges) increase the total amount of N and P available for transport to streams (Bowen & Valiela 2001; Brett *et al.* 2005a, b; Atasoy *et al.* 2006). The nutrient form (e.g., ammonium vs. nitrate and nitrite for N) and magnitude of increase depend largely on patterns of septic tank discharge, wastewater treatment technologies, fertilizer use, and atmospheric deposition including automobile exhaust (reviewed in Bowen & Valiela 2001; Paul & Meyer 2001; Bernhardt *et al.* 2008). Nitrates are easily leached from the soil and transported to groundwater (p. 167, Novotny 1995). Based on the US National Stormwater Quality Database³⁹, freeways produced the largest concentrations of

³⁹ Database only included land uses in developed areas. Agriculture was not included.

ammonia and total Kjeldahl N in stormwater, industrial sources accounted for the largest concentrations on nitrate and nitrite, whereas residential areas had the largest concentrations of total N (Bernhardt *et al.* 2008)⁴⁰.

Soluble forms of P are also transported to streams as wastewater from septic, municipal, commercial, and industrial sources as well as atmospheric deposition (e.g., Schuster & Grismer 2004; Brett *et al.* 2005b). Phosphorus applied as fertilizer is commonly bound to sediment particles (p. 166, Novotny 1995), therefore processes that accelerate erosion and increase suspended sediment transport to streams also increase particulate P transport (Brett *et al.* 2005b). After entering surface waters, the size of the sediment particle to which the P is attached determines how fast the particulate P settles out of the water column or remains suspended (i.e., organic matter, clays, silts) where the P is biologically available to aquatic plants (Brett *et al.* 2005b; Ellison & Brett 2006). Many early studies linked increased total P to particulate-bound nutrients mobilized during stream bank erosion and movement of in-stream sediments (reviewed by Paul & Meyer 2001). Based on the US National Stormwater Quality Database, industrial sources accounted for the largest concentrations of orthophosphate⁴¹ in stormwater, while residential areas had the largest concentrations of dissolved and total P (Bernhardt *et al.* 2008).

In intact terrestrial ecosystems, riparian and upland vegetation can play a significant role in capturing and sequestering excess nutrients from stormwater runoff or floodwaters. However, extensive manmade drainage and flood control systems effectively bypass the beneficial services of soil microbes and vegetation present in riparian and upland areas (Brett *et al.* 2005a; Cadenasso *et al.* 2008). Impervious surfaces accumulate deposits of various N and P compounds which are then washed directly into waterways rather than entering the soil where they can be removed by plant and microbial processes (Coats *et al.* 2008). Bypassing vegetated areas decreases opportunities to capture and remove N and P from stormwater runoff before it enters rivers, streams, and estuaries.

SECTION 7.32: NATURE, TIMING, AND MAGNITUDE OF NUTRIENT CHANGES

Stream water concentrations of both N and P tend to be higher in developed landscapes than in areas of lower population density, although higher concentrations can be found in streams in close proximity to specific agricultural and horticultural uses such as row crops and container nurseries (Paul & Meyer 2001). During nationwide monitoring of surface waters, USGS (2001) found that more than 70% of sampled urban streams exceeded minimum nutrient levels determined by USEPA to limit nuisance aquatic plant growth. Research conducted within and beyond the Pacific Northwest has documented increased P concentrations (up to five times beyond 'natural' or reference levels) associated with urban development (Wahl *et al.* 1997; Sonoda *et al.* 2001), impervious surface patch size (Carle *et al.* 2005), and wastewater effluent (Fisher *et al.* 2000; Coulter *et al.* 2004). Analysis of urban runoff of the Tualatin River basin (western Oregon) indicated that P concentrations in runoff usually exceed background P

⁴⁰ Ammonia (NH₃) is a form of nitrogen that can easily be lost from the soil through vaporization or leaching. In the soil, bacteria convert ammonia into nitrites (NO₂) which are toxic to plants. Other bacteria oxidize nitrites into nitrate (NO₃) which is readily used by plants. Nitrate is easily leached from the soil and can lead to eutrophication of surface waters. Total Kjeldahl N is the amount of nitrogen in organic substance determined by the Kjeldahl method of acid digestion. Total N is the amount of both organic and inorganic nitrogen.

⁴¹ Orthophosphate is an inorganic form of phosphorus readily available for plant uptake in the environment.

concentrations⁴² in tributaries of the Tualatin mainstem (ODEQ 2001b). In the Seattle (Washington) area, Brett *et al.* (2005b) found that streams draining urban dominated watersheds had, on average, 110% and 40% higher P and N concentrations (respectively) compared to streams draining forested watersheds. In Portland (Oregon), Hook & Yeakley (2005) found higher N concentrations in streams draining a small urban watershed than streams draining forested watersheds, but the urban stream concentrations were lower than streams in agricultural systems.

While the above studies have shown increased nutrient loads associated with developed areas, it is difficult to determine whether the increased nutrient loads are more attributable to higher inputs, reduced nutrient retention, or both. One approach is to quantify the degree to which nutrient availability increases in developed landscapes. For example, fertilizer application to residential landscaping constitutes a significant source of excess nutrients that varies considerably according to individual landowner preferences. Survey results reported by Nielson & Smith (2005) indicated that the majority (64%) of respondents in the Tualatin River basin (western Oregon) fertilize their lawns 2 to 3 times per year, a fertilizer frequency in excess of that advised by yard care specialists. However, the degree to which these nutrients are later transferred to streams is unknown.

The type of wastewater treatment used within a development (i.e., septic tank systems vs. municipal treatment facilities) also influences the magnitude of nutrient inputs to aquatic ecosystems. ODEQ (2001b) reported that total P levels in the Tualatin River (western Oregon) were greatly reduced when wastewater treatment plants increased their total P removal capabilities and implemented best management practices such as stormwater treatment, street sweeping, and educational programs. While this is encouraging, treated sewage effluent does constitute a significant nutrient source in other Pacific Northwest locations. For example, in western Washington, Inkpen & Embry (1998) reported that treated effluent contributes 22% of the N load in the Puyallup River and 15% of the P load in the Snohomish River. During summer drought seasons, municipal water discharge can constitute a significant fraction of instream flow that can result in seasonal increases in nutrient concentrations in affected streams (Brooks *et al.* 2006; Kaye *et al.* 2006).

Septic systems also contribute nutrients to ground and surface waters. In a comparison of developed North Carolina watersheds, Carle *et al.* (2005) found that developed lands outside city limits contributed higher total N and total P loads to streams than developed areas serviced by municipal wastewater treatment. Similarly, Hatt *et al.* (2004) found that septic tank densities strongly influenced N concentrations in streams of Melbourne, Australia. In Cape Cod (Massachusetts), Cole *et al.* (2006) used a stable isotopic form of N to determine the effect of land use on N loading in groundwater. Higher isotopic N concentrations found in urban watersheds were attributed to increased wastewaters from septic systems (Cole *et al.* 2006). In La Pine (Oregon), N isotope data indicated that septic tank effluent was the main source of nitrate in shallow groundwater in the area, whereas naturally occurring sedimentary organic matter was the main source of ammonia found in deep groundwater⁴³ (Hinkle *et al.* 2007). Steffy

⁴² Natural P loadings from groundwater in the Tualatin River basin are high and were taken into account in the background concentrations determined by ODEQ (2001c).

⁴³ Groundwater from the La Pine (Oregon) discharges into the Deschutes and the Little Deschutes Rivers but the amount of septic related nitrate entering surface waters was not determined in this study (Hinkle *et al.* 2007) or in others examining nutrient loading in the aquifer.

& Kilham (2004) analyzed stable isotopic forms of N to determine the degree to which aquatic food webs accumulated N derived from anthropogenic sources in developed landscapes. Stable isotope signatures revealed that for all trophic levels analyzed, N from anthropogenic sources was up to 10% greater than that observed in minimally disturbed systems. Sampling sites in close proximity to residential septic tank systems exhibited the highest anthropogenic N levels, leading Steffy & Kilham (2004) to conclude that improperly functioning septic systems contributed large amounts of anthropogenic N to aquatic ecosystems.

The distribution and number of landscape features that retain nutrients may also serve as important regulators of the nutrient loads delivered to surface waters. Developments can eliminate areas and create discrete areas that retain and remove significant quantities of N (i.e., denitrification). For example, stormwater detention ponds, ditches, gutters, and lawns all have the capacity to accumulate and retain water, N, and organic matter long enough for microorganisms to convert the forms of N typically used by aquatic plants to nitrogen gas (Kaye *et al.* 2006). Evidence supporting this contention comes from observations of stream N inputs that were lower than expected given the quantities of N accumulated on hydrologically linked impervious surfaces (e.g., Hope *et al.* 2004; Grimm *et al.* 2005) and high rates of denitrification in stormwater retention basins (Zhu *et al.* 2004). These processes, however, do not remove P although stormwater detention ponds may sequester it by adsorption to sediments and uptake by plants. While these features of developed landscapes may reduce or retain nutrients, it remains unknown to what degree these vegetated features will decrease nutrient inputs into Oregon waterways because most storm runoff occurs during the fall and winter when many plants become dormant (Grimm *et al.* 2008; Pickett *et al.* 2008).

Reduced nutrient retention within streams may play a significant role in increasing nutrient concentrations downstream of developments (Kaye *et al.* 2006). Stream ecosystems provide important connections among surrounding ecosystems including terrestrial uplands, groundwater, lakes, and downstream recipient ecosystems such as larger rivers, freshwater wetlands, and coastal estuaries. Nutrient retention within any given stream reach reduces nutrient transport to downstream ecosystems. Highly engineered stormwater drainage structures and altered channels accelerate downstream nutrient transport, reduce physical habitat heterogeneity that supports aquatic biota capable of direct nutrient uptake, disconnect channels from floodplains capable of sequestering nutrients, and therefore decrease in-stream nutrient retention (Kaye *et al.* 2006). Grimm *et al.* (2005) found that as stream structure declined in heavily urbanized areas of the arid southwestern US, longer stream lengths were required for biotic uptake of fixed amounts of N to occur. Similarly, Gibson & Meyer (2007) found that both N and P uptake rates in the Chattahoochee River (Georgia) were much lower than uptake rates measured in less heavily modified streams resulting in transport of anthropogenic nutrients many kilometers downstream. Gibson & Meyer (2007) also found that adsorption of P to suspended sediment temporally slowed downstream transport as sediments settled, but this effect was thought to be only temporary because sediment-bound P is readily mobilized during subsequent high-flow events.

In summary, the above evidence indicates that development not only increases the amount of nutrient available for delivery to streams, but also changes the degree to which streams and surrounding riparian and upland landscapes retain nutrients (Kaye *et al.* 2006). The comprehensive nature of these changes and their influences on nutrient loads in aquatic

ecosystems adjacent to or downstream of developed lands has received little research attention in the Pacific Northwest.

Key Findings: Nutrients
<ul style="list-style-type: none"> • Stream water concentrations of both nitrogen and phosphorus tend to be higher in developed landscapes than in areas of lower population density.
<ul style="list-style-type: none"> • Development not only increases the amount of nutrients available for delivery to streams, but also changes the degree to which streams and surrounding riparian and upland landscapes retain nutrients.
<ul style="list-style-type: none"> • It is difficult to determine whether increased nutrient loads observed in aquatic ecosystems affected by development are more attributable to higher inputs or to reduced retention, although both factors clearly contribute.
<ul style="list-style-type: none"> • During summer drought seasons, municipal water discharge can constitute a significant fraction of instream flow that can result in seasonal increases in nutrient concentrations in affected streams.

Section 7.4: Water Temperature in Urban and Rural-residential Areas

In this section, IMST describes the factors and mechanisms that alter water temperature and the nature, timing, and magnitude of water temperature changes in streams, rivers, and estuaries affected by development.

SECTION 7.41: FACTORS AND MECHANISMS THAT ALTER WATER TEMPERATURE

Salmonids require relatively cold water during most life history stages and can experience both lethal and sublethal effects from elevated water temperature (reviewed in McCullough 1999, McCullough *et al.* 2001; IMST 2004; Table 7-1). Temperature governs both development rate and survival of salmonid eggs and alevins (Murray & McPhail 1988; McCullough *et al.* 2001; Nelitz *et al.* 2007). Spawning activity (i.e., redd excavation, egg deposition, and fertilization) may cease if water temperatures are not favorable (McCullough *et al.* 2001; Sauter *et al.* 2001). Temperature cues often initiate seaward migrations of juvenile salmonids (Roper & Scarnecchia 1999; Achord *et al.* 2007), as well as the return of sexually mature adults (McCullough *et al.* 2001; Sauter *et al.* 2001). Altered temperatures can interfere with adult migration by advancing or delaying it (Quinn & Adams 1996; Cooke *et al.* 2004; Goniea *et al.* 2006), by creating thermal barriers to upstream movement (Alabaster 1988; Quinn *et al.* 1997), and by inducing stress-related infection and mortality (Macdonald *et al.* 2000; Rand *et al.* 2006; Newell *et al.* 2007). Other temperature-mediated mechanisms that affect salmonid growth and survival include disease and parasite resistance, competitive ability, and predation risk (Brett 1956; Poole *et al.* 2001, 2004; Nelitz *et al.* 2007). Given the mechanistic links between water temperature and salmonid health, it is not surprising that temperature is a key determinant of salmonid distribution and abundance throughout the Pacific Northwest, at both river reach (Nielsen *et al.*

1994; Tiffan *et al.* 2006) and river basin scales (Li *et al.* 1994; Torgersen *et al.* 1999; Ebersole *et al.* 2001; Sauter *et al.* 2001).

Table 7-1. Estimates of temperature ranges at or above which various life-history stages of Pacific Northwest salmon and bull trout are likely to experience adverse effects. Ranges include important variation within and among salmon species. Most salmonids are commonly observed at summer habitat temperatures ranging from 50°F to 63°F (10°C to 17°C), with the exception of bull trout that are more commonly observed at summer habitat temperatures ranging from 43°F to 54°F (6°C to 12°C). Table adapted from Poole *et al.* (2001).

Life-History Stage	Temperature Response	Anadromous Salmon Temperature Range	Bull Trout Temperature Range
Adult Migration	Blocked	70-72°F (>21-22°C)	N/A
Adult Migration	Cued	N/A	50-55°F (10-13°C)
Spawning	Initiated	45-57°F (7-14°C)	<48°F (<9°C)
Egg Incubation	Optimal	43-50°F (6-10°C)	36-43°F (2-6°C)
Smoltification	Suppressed	>52-59°F (>11-15°C)	N/A
Adult Survival	Lethal (one week exposure)	>70-72°F (>21-22°C)	N/A
Juvenile Survival	Lethal (one week exposure)	>73-75°F (>23-24°C)	>72-73°F (>22-23°C)

The pathways by which rural-residential and urban land uses influence stream temperatures are complex and often interconnected making it difficult to determine the importance of individual factors (Figure 7-3; IMST 2004). Water temperature is a function of heat load, stream discharge, and water volume. Therefore, streams become more susceptible to temperature changes when flows and/or volumes are low and/or heat energy sources are abundant (Poole & Berman 2001; IMST 2004). In the Pacific Northwest, stream temperatures can naturally exceed those optimal for salmonid spawning and rearing, particularly during periods of summer drought (Poole *et al.* 2001, 2004). Under these conditions, additional warming caused by anthropogenic effects can be particularly stressful for salmonids and other biota adapted to cold water.

A diverse set of mechanisms have the potential to increase heat inputs to streams and rivers in rural-residential and urban areas. Industrial and municipal facilities discharge significant volumes of heated wastewater into Oregon's streams and rivers on an annual basis (see Section 3.0 of this report). Constructed surfaces such as pavement and rooftops absorb more heat than vegetated surfaces and can absorb enough heat to alter the climate in developed landscapes, a phenomenon termed "heat island effect" (e.g., Voogt & Oke 2003; Arnfield 2003; Souch & Grimmond 2006). Water flowing over these heated surfaces picks up excess heat and can become a significant non-point source of thermal pollution when routed to streams (Nelson & Palmer 2007). Because of the low levels of rainfall that occur during summer months in Oregon, it is unclear whether the heating of storm flows over impervious areas in Oregon cities

significantly affects stream water temperatures. Detention ponds, designed to regulate the rate and volume of stormwater flow through developed areas also increase stream temperature (Galli 1990). These individual heat sources influence temperatures immediately downstream to varying extents and contribute to the cumulative heat load received by streams. Dams and reservoirs associated with municipal drinking water supplies can also alter the temperatures of streams outside urban

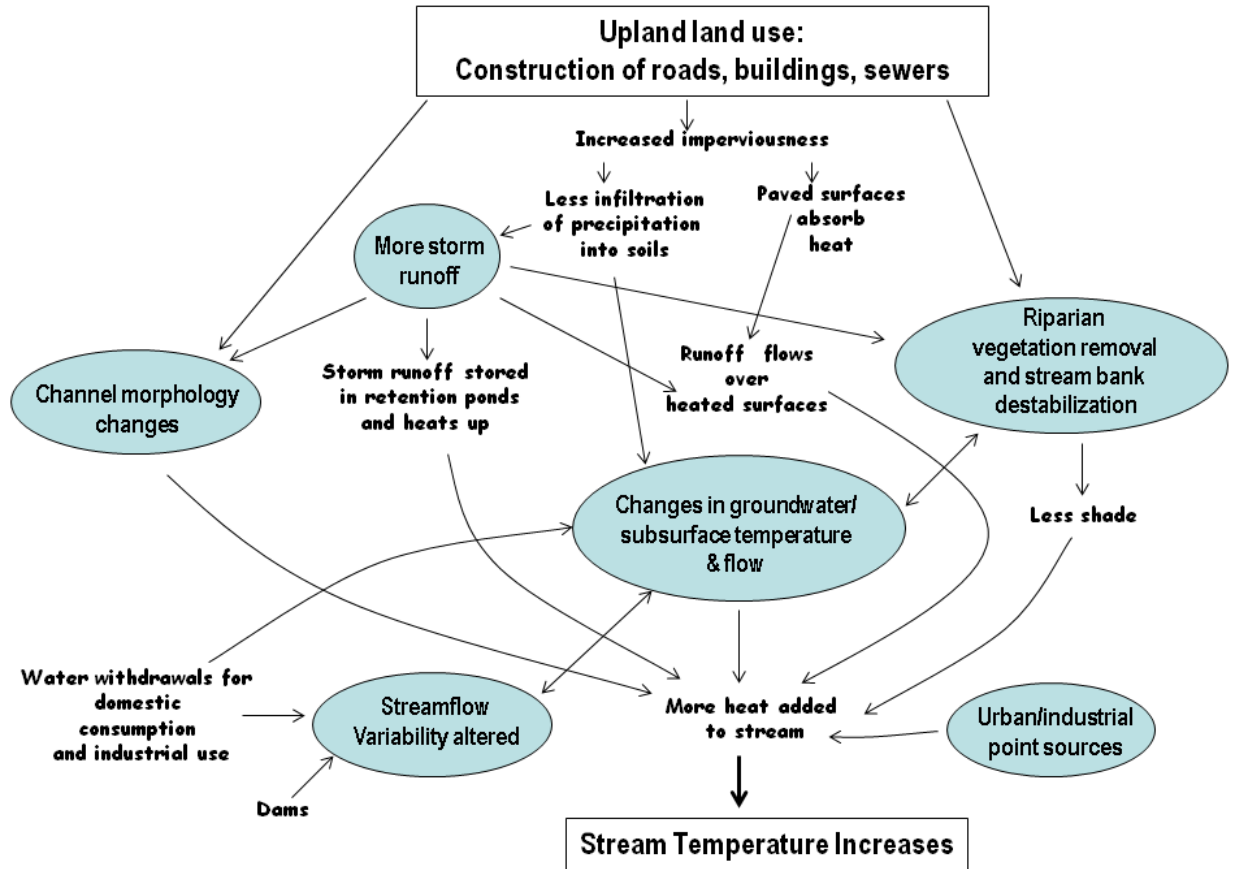


Figure 7-3. Hydrologic and physical habitat factors associated with developed landscapes that influence stream temperature variability. Habitat factors are shown in shaded ellipses. For detailed information on these influences, see IMST (2004).

growth boundaries. For example, dams on the Bull Run River, constructed to regulate water supply to the Portland metropolitan area, release water that is cooler than unregulated temperatures in early summer and warmer than ambient temperatures in late summer (ODEQ 2005; NMFS 2006b).

Riparian vegetation can directly affect stream temperatures by intercepting short-wave radiation during the day and insulating the stream from long-wave radiation loss at night. Through evapotranspiration, vegetation reduces air temperatures by converting sensible heat to latent heat (McPherson 1994). In addition, riparian vegetation also partially controls channel morphology,

streamflow, groundwater connectivity, infiltration and percolation rates, wind speed, humidity, and soil temperature, all of which influence stream temperature (reviewed in IMST 2004). As a result, removal of riparian vegetation, a common consequence of development (Ozawa & Yeakley 2007), influences stream temperatures via numerous mechanisms.

Channel morphology, particularly width and depth, influences the amount of heat gained or lost from a stream (reviewed in Poole & Berman 2001; IMST 2004). Wider channels have more stream surface area available to exchange radiant and atmospheric heat energy and are less effectively cooled by riparian forests. As channel depth decreases, solar radiation penetrates a larger fraction of the water volume and influences heating and cooling rates (Nelson & Palmer 2007). As watersheds undergo development, channel dimensions often change in ways that lead to increased stream temperatures.

Groundwater contributions to flow are an important factor in determining stream temperature (reviewed in Poole & Berman 2001). Groundwater, insulated from daily and seasonal temperature fluctuations, exhibits relatively stable temperatures that buffer stream temperatures when groundwater constitutes a large proportion of flow. Groundwater influences on surface water temperatures are particularly strong near their input site. Groundwater can also form pockets of cold water that create reach-scale thermal heterogeneity (reviewed in Jones & Mulholland 2000) and constitute important habitat features for cold-water biota including salmonids (Poole *et al.* 2001, 2004; Ebersole *et al.* 2003). Depending on watershed geology and stream channel structure, two sources of groundwater can influence stream temperature (Poole & Berman 2001). Water flowing along shallow pathways below river channels and riparian zones (referred to as hyporheic⁴⁴ groundwater) exchanges with surface waters over relatively short timeframes (e.g., minutes to months). Water stored in deep aquifers (phreatic groundwater) also exchanges with surface flows but typically over longer intervals.

Hydrologic alterations that reduce groundwater discharge to streams can increase stream temperature and reduce reach-scale temperature heterogeneity, thus reducing habitat available to aquatic organisms that require cooler temperatures (reviewed in Poole & Berman 2001; IMST 2004). Movement of hyporheic groundwater is a function of streamflow variability, stream channel pattern, and streambed complexity (reviewed in Poole & Berman 2001), all of which are altered by development. In Oregon, high flows and floods occur during the winter and spring months when water temperatures are at their coldest. Recharge of hyporheic groundwater during these periods may create an important source of cold water that buffers stream temperatures during sensitive baseflow periods (Poole & Berman 2001). River channelization confines flow and limits river-floodplain interactions that recharge shallow groundwater sources, thus reducing groundwater discharge during baseflow. Channel modifications such as straightening, diking, dredging, and armoring focus stream energy toward the center of the channel further reducing channel heterogeneity, leading to channel incision and, disruption of hyporheic flow when it is present (Hancock 2002). Removing large wood also decreases streambed complexity and can reduce hyporheic groundwater exchange in some streams.

Disturbance and removal of upland vegetation typically decreases infiltration of precipitation inputs through the soil, limits deep aquifer recharge, increases delivery of fine sediments that clog channel substrates and restrict hyporheic exchange, and alters the timing, volume, and

⁴⁴ The hyporheic zone is the region in streambed and bank sediments where exchange between surface and ground waters may occur.

magnitude of peak flows that shape channel morphology (see Section 4.0 of this report). When reduced infiltration and percolation limits groundwater aquifer recharge, reduced summer baseflows can lead to elevated stream temperatures in some urban streams (Finkenbine *et al.* 2000).

Municipal water withdrawals from both shallow and deep groundwater sources reduce flow in nearby streams and rivers, thus concentrating heat energy and increasing stream temperature. If the withdrawn water is returned to the stream, it is likely in the form of heated industrial or wastewater effluent and adds to the stream's overall heat load (Kinouchi 2007; Kinouchi *et al.* 2007). Approximately 70% of Oregon residents, including 90% of residents in rural developments, use groundwater as their primary water source (Bastasch 2006). Human population growth will certainly increase the demands made on Oregon's groundwater resources, particularly under the constraints imposed by a changing climate (Houston *et al.* 2003). Increasing use of groundwater resources has the potential to reduce streamflows and increase stream temperatures (Dole & Niemi 2004; ISAB 2007a, b; See Section 4.2 of this report).

SECTION 7.42: NATURE, TIMING, AND MAGNITUDE OF WATER TEMPERATURE CHANGES

Hydrologic and physical habitat changes, as well as point and non-point pollution sources that accompany development, can alter the timing and amount of heat energy and/or water delivered to aquatic habitats and strongly influence temperature fluctuations in these environments (Figure 7-3; Poole & Berman 2001). Stream temperature changes include increases in the maximum and decreases in the minimum daily and seasonal temperatures (Poole & Berman 2001). The likelihood that environmental changes associated with development will lead to stream temperature changes varies depending on reach- to basin-scale characteristics including riparian vegetation context, landscape position (e.g., headwaters vs. mainstem), stream size, and watershed geology.

Compared to undeveloped watersheds, research focusing on changes in stream temperatures in rural-residential and urban streams is limited (Krause *et al.* 2004; Nelson & Palmer 2007). Models used to predict the stream temperature response to development provide valuable information on the how altered physical habitat and hydrologic regimes affect stream temperature, and highlight the importance of riparian shade and channel width (e.g., LeBlanc *et al.* 1997; Krause *et al.* 2004; Nelson & Palmer 2007). However, interpreting conclusions drawn from these modeling efforts requires caution because the models do not include important point source thermal discharges (e.g., stormwater sewers or wastewater treatment effluent) known to increase stream temperature in developed landscapes.

LeBlanc *et al.* (1997) identified riparian shading, groundwater discharge, and stream width as variables that have the potential to influence stream temperature. In general, LeBlanc *et al.* found that stream temperature increased as riparian canopy density decreased and channel width-to-depth ratios increased, but results varied depending on stream orientation on the landscape (e.g., north to south). The magnitude of temperature change increased when development also reduced base flow discharge and groundwater exchange with the stream (LeBlanc *et al.* 1997). Krause *et al.* (2004) found that the combined effects of reduced riparian shade, increased channel width, and increased stormwater runoff temperature associated with high-density development produced the largest changes in mean daily stream water temperature. Nelson & Palmer (2007) integrated empirical relationships between land use and stream temperature into a model used to

predict stream temperature change in a rapidly urbanizing watershed. The proportion of deforested land, particularly within riparian areas, was identified as an important variable explaining increased temperature.

In areas that receive substantial spring and summer precipitation, stormwater flow over heated pavement may be a source of heat to streams. For example, Wang *et al.* (2003b) observed a positive linear relationship between summer maximum water temperature and the amount of connected impervious area across 39 sites in Wisconsin and Minnesota. In Maryland, Nelson & Palmer (2007) found that high runoff events generated by localized summer storms caused surges in stream temperature (+ 3.5°C on average but ranged to > 7°C) that persisted for up to 3 hours. In contrast, Booth *et al.* (2001) found that urbanization caused only minor elevation of summer stream temperature in King and Snohomish counties (western Washington) and attributed this result to the combined effects of groundwater baseflow sources and infrequent summer precipitation. IMST is unaware of any studies that examined whether runoff passing over paved surfaces contributes significantly to stream heating in Oregon basins. Little precipitation falls in Oregon when air temperatures are high, indicating that results may be similar those of Booth *et al.* (2001); however, future changes in climate may alter this precipitation pattern (Hamlet & Lettenmaier 1999; Leung & Wigmosta 1999; Miles *et al.* 2000; Mote *et al.* 2003; Payne *et al.* 2004; Claessens *et al.* 2006).

Research carried out in Japan demonstrated that wastewater from municipal treatment plants can constitute a large proportion of the anthropogenic heat delivered to streams and can drive significant stream temperature increases over extended periods of urban development (Kinouchi *et al.* 2007). As the number and density of residences increase in a development, both the volume and temperature of wastewater generated by residential use can increase. Kinouchi (2007) demonstrated that increases in temperature and volume of water generated by residential uses increased the annual mean temperature of wastewater generated by municipal treatment plants in Tokyo, Japan by 5.5°C over four decades. In general, the effects of municipal treatment plant wastewater on stream temperature depend on the temperature and volume of wastewater discharged and on the flows and volumes of the receiving stream.

A few studies have documented the cumulative magnitude of water temperature change resulting from rural-residential or urban development. Scientists evaluated the water quality of six urban areas across Oregon using ODEQ's Water Quality Index (Figure 7-1; Oregon Progress Board 2000)⁴⁵. In Medford (southwest Oregon), Eugene-Springfield (western Oregon), Bend (central Oregon), and La Grande (eastern Oregon) water temperature ranked "poor". Portland (western Oregon) temperature trends were good or unclear. Temperature trends were potentially declining in quality in many western Oregon watersheds including the Clackamas River, Fanno Creek, Willamette River, and Columbia Slough (Oregon Progress Board 2000). Water quality data collected by the City of Portland (2004) and ODEQ (2001b) indicate that the cumulative effects of development both increase heat loading and reduce flow in urban streams, resulting in summer stream temperatures that often exceed those required by salmonids (Table 7-1).

When a water body in Oregon fails to meet state water temperature standards, ODEQ performs a thorough analysis of point and nonpoint sources of increased heat loading as part of a TMDL

⁴⁵ Bend, Coos Bay, Eugene-Springfield, La Grande, Medford, and Portland Metropolitan Area. These cities were selected because they represent different ecoregions, sizes, densities, and socio-economic populations.

analysis⁴⁶. In the Tualatin River watershed (western Oregon), approximately 12% of the land is used for urban and rural-residential developments (ODEQ 2001b). Stream temperature modeling for this watershed, carried out as part of the TMDL process, has indicated that with minimal anthropogenic heat sources, 98% of the stream network would be below a maximum daily temperature threshold of 64°F (17.8°C)⁴⁷ (ODEQ 2001b). Of the total heat loading that occurs during critical summer months, 41% is derived from natural background sources, 52% from anthropogenic non-point sources and 7% from point sources. Fifteen industrial and municipal facilities permitted to discharge heated effluents into the river contribute the 7% of total summertime heat loading attributed to point sources. The temperatures of effluent discharged by individual facilities ranges from 66°F (19°C) to 88°F (31°C). Effluents discharged by two wastewater treatment facilities (Durham and Rock Creek) contribute disproportionately to the point source heat loading for the Tualatin River. For example, the Rock Creek Wastewater Treatment Plant discharged water at 72°F (22°C)⁴⁸ into a reach with an average temperature of 65°F (18°C). The discharge increased the average river temperature 1.5°F (0.83°C) for almost a mile downstream (ODEQ 2001b).

ODEQ (2001b) attributed non-point source anthropogenic heat loading (52% of the total heat loading) to increased solar radiation along stream reaches where riparian vegetation has been disturbed or removed, thus reducing stream shading. Solar radiation loads derived from anthropogenic disturbance ranged from 44% along the mainstem Tualatin River (Oregon) to between 88% and 99% in Tualatin tributaries. These data mirror findings by Booth *et al.* (2001) that changes to the riparian canopy have the most direct influence on summertime stream temperatures in the heavily developed Puget Sound (Washington) lowlands. These data also corroborate modeling results that identify riparian condition as a key mechanism in the stream temperature response to development (LeBlanc *et al.* 1997; Krause *et al.* 2004; Nelson & Palmer 2007). Riparian vegetation condition is highly correlated with a suite of variables that collectively regulate stream temperature including stream bank erosion, channel stability, and channel width. Therefore, it is not surprising that riparian condition and increased solar radiation exposure are frequently identified as important factors in the stream temperature responses to development.

Key Findings: Stream temperature

- Rural-residential and urban land uses can influence stream temperature by increasing effluents discharged from industrial and municipal facilities and detention ponds, dams, reservoirs and water withdrawals associated with municipal drinking water supplies.
- Rural-residential and urban land uses can directly and indirectly influence stream temperature by removing riparian vegetation, modifying channel morphology, and reducing groundwater discharge.

⁴⁶ For an additional example of the TMDL process in Oregon see the ODEQ (2007) factsheet *Reducing Temperature in the Willamette Basin* at http://www.deq.state.or.us/wq/pubs/factsheets/willamette/07wq000_temperature.pdf. Accessed May 25, 2010.

⁴⁷ Tualatin subbasin temperature standards (ODEQ 2001c) mandate that no measurable surface water increase resulting from anthropogenic activities is allowed in salmonid rearing streams where water temperatures exceed 17.8°C (64°F) or salmonid spawning streams where water temperatures exceed 12.8°C (55°F).

⁴⁸ Measurements taken July 27, 1999 (ODEQ 2001c).

Section 7.5: Dissolved Oxygen in Urban and Rural-residential Areas

In this section, IMST describes the factors and mechanisms that alter dissolved oxygen concentrations and the nature, timing, and magnitude of dissolved oxygen changes in streams, rivers, and estuaries affected by development.

SECTION 7.51: FACTORS AND MECHANISMS THAT ALTER DISSOLVED OXYGEN CONCENTRATIONS

Dissolved oxygen (DO) dynamics are a major determinant of aquatic community species composition. All salmonids and many other fish species require more than 5 mg O₂/L to survive. The amount of DO present in a body of water reflects a balance among:

- Oxygen production via photosynthesis;
- Diffusion of oxygen between water and the atmosphere;
- Oxygen solubility that decreases with increasing temperature and elevation;
- Chemical reactions that require oxygen creating a chemical oxygen demand; and
- Oxygen consumed by respiration of plants and animals including decomposition of organic matter by microorganisms that creates biological oxygen demand.

Dissolved oxygen dynamics in aquatic ecosystems are complex and depend on interactions among these physical, chemical, and biological processes. Mechanisms that alter DO concentrations in rural-residential and urban streams include water temperature changes, effluents from municipal and industrial wastewater-treatment facilities, leaks and overflows from sewage lines and septic tanks, stormwater runoff, and decaying aquatic plants that have undergone rapid biomass production due to excess nutrient availability. Water temperature can affect DO in two ways. First, higher water temperatures reduce the amount of oxygen that can remain dissolved in the water⁴⁹. Second, the rates of biological and chemical processes consuming oxygen increase with higher temperatures. Metabolic rates of aquatic organisms also increase as temperatures rise, thus increasing their oxygen requirements during periods of decreased oxygen solubility and availability (Brett 1964; Matthews & Berg 1997).

Biological processes strongly influence DO concentrations. Photosynthesis increases the supply of DO and consumes carbon dioxide and bicarbonate. Respiration and decomposition of plant biomass decrease DO concentrations and release carbon dioxide. When elevated nutrient concentrations support excessive growth of algae and other aquatic plants, daytime photosynthesis and nighttime respiration of plants can cause DO concentrations to have larger diurnal fluctuations (Smith *et al.* 1993; Gordon *et al.* 2005). In many water bodies, DO concentrations may not meet water quality standards (see ODEQ 2001b, 2005 for examples) because of excessive algae growth and respiration. In these streams, DO concentrations supersaturate during the day and rapidly decline at night. As a result, ODEQ monitors chlorophyll *a* concentrations (desired is <15µg/L) to determine when algal growth may cause DO problems (ODEQ 2001b).

⁴⁹ For example, the maximum DO concentration (100% saturation) in freshwater at sea level is 14.6 mg O₂/L at 0°C (32°F), but the maximum DO concentration under identical conditions at 20°C (68°F) is only 9.1 mg O₂/L (Colt 1984).

Aquatic microorganisms can decompose organic solids in the water column or on the bottom of streams. Sources of organic matter vary and include natural sources such as leaf litter, or anthropogenic sources such as stormwater runoff, effluent from wastewater treatment facilities, algal detritus from algae blooms stimulated by excess nutrient availability, and soil erosion (ODEQ 2001b). For example, in some cities, sewer networks allow stormwater runoff already loaded with pollution from urban surfaces to mix with large volumes of urban wastewater during storm events. This mixture of stormwater and raw sewage can be discharged directly into streams and rivers when storm flows exceed the sewer network capacity.

While Oregon cities have greatly reduced the frequency of wastewater overflow events (see Section 3.0 of this report), they still occur. The organic matter that enters rivers during combined sewer overflows can dramatically increase the amount of oxygen consumed by microorganisms (i.e., biological oxygen demand) downstream of the plume, thus depleting DO available to aquatic biota as long as the organic material remains (Even *et al.* 2004). Microorganisms also convert ammonia (originating in wastewater overflows or treatment plant effluent; ODEQ 2001b) to nitrite and nitrate (referred to as nitrification), a biological process that requires oxygen.

Compared to decomposition in the water column and nitrification, decomposing sediments may remain a DO sink for much longer periods after pollution discharges cease because sediments that settle out of the water column decompose slowly. Consequently, organic-containing sediments delivered by stormwater runoff or combined sewer overflows may trigger DO deficiencies long after the rain event that delivered the sediment to the river has ended.

Some toxic substances can reduce DO concentrations in streams. The USEPA estimated that 40 million liters of aircraft deicing and anti-icing fluids are discharged annually to receiving waters in the US (USEPA 2000c). Portland International Airport (Oregon) has released deicing fluids into the Columbia Slough and Columbia River but has also made efforts to better contain this runoff (GAO 2000). Glycols, which constitute the majority of aircraft deicing formulations, have high chemical oxygen demand and can cause significant DO reductions when they enter streams through stormwater runoff (Corsi *et al.* 2006). Low DO levels can also alter water chemistry in ways that accelerate the release of phosphorus and toxic chemicals, such as heavy metals, from sediments and prevent the detoxification of ammonia (a substance directly toxic to aquatic organisms) by oxygen requiring microorganisms.

SECTION 7.52: NATURE, TIMING, AND MAGNITUDE OF DISSOLVED OXYGEN CHANGES

Wang *et al.* (2003a) compared in-stream metabolic activities between an urban and an agricultural stream and found that the urban stream was always heterotrophic (consuming DO) compared to the agricultural stream that was periodically autotrophic (producing oxygen). Their research did not identify the likely causes of this difference. Similarly, Rodriguez *et al.* (2007) identified an inverse relationship between DO in estuaries of the northeastern US and total urban area.

Urban stormwater runoff and combined sewer overflows are common sources of low DO concentrations and high rates of oxygen consumption. Water quality monitoring at 83 sites distributed across the US regularly recorded depleted DO concentrations in urban areas, particularly during periods of wet weather (Keefer *et al.* 1979). Heaney *et al.* (1980) reviewed research results on DO downstream of urban areas and concluded that approximately one-third of the sites exhibited lowest DO concentrations after storms. Pitt (1979) also demonstrated that

stormflows to streams and rivers increased biological and chemical oxygen consumption rates (i.e., biological and chemical oxygen demand). Impacts of urban stormwater can last much longer than the duration of a single storm. Pitt (1995) later documented a lag between rainfall and peak oxygen demand; 10 to 20 days after a storm event, oxygen demand increased to levels 5- to 10-fold greater than those observed in the initial 1 to 5 days after the storm event.

Low DO concentrations in the mainstem Tualatin River (Oregon) and many of its tributaries have led ODEQ to list them as water quality impaired (ODEQ 2001b). Unacceptable DO levels typically occur during the late summer and early fall months and result from increased temperature, low flows, algal detritus, and high oxygen demand of river sediments. In most cases, the oxygen sink created by sediments, exacerbated by increased temperatures, is a significant contributor to oxygen depletion.

Key Findings: Dissolved oxygen

- Mechanisms that alter dissolved oxygen concentrations in rural-residential and urban streams include water temperature changes, effluents from municipal and industrial wastewater-treatment facilities, leaks and overflows from sewage lines and septic tanks, stormwater runoff, and decaying aquatic plants that have undergone rapid biomass production due to excess nutrient availability.
- Urban stormwater runoff and combined sewer overflows are common sources of low oxygen concentrations and high rates of oxygen consumption. Unacceptable DO levels typically occur during the late summer and early fall months and result from increased temperature, low flows, algal detritus, and high oxygen demand of river sediments.

Section 7.6: Toxic Pollution in Urban and Rural-residential Areas

In this section, IMST describes the types, origins, and potential impacts on aquatic biota of anthropogenic-derived toxic chemicals entering Oregon's waterways. Toxic contaminants create complex problems for aquatic organisms and have important implications for natural resource managers. Because of this, the following section on toxic contaminants departs from the format of previous report sections so that biotic responses to toxic contaminants can be presented in greater detail than the general responses discussed later in this report.

SECTION 7.61: ORIGINS, PREVALENCE AND DIVERSITY OF CONTAMINANTS ASSOCIATED WITH DEVELOPMENT

Some contaminants originate from a few significant sources. In the US, widespread use of the volatile organic compound methyl *tert*-butyl ether (MTBE) as a gasoline additive contaminated ground and surface waters in many communities, stimulating legislation to restrict or ban its use in several states⁵⁰ (and potentially nationwide⁵¹; Hamilton *et al.* 2004; Moran *et al.* 2005). Atmospheric deposition of coal combustion and industrial waste incineration products are a major source of mercury contamination in many ecosystems (Hamilton *et al.* 2004; Peterson *et al.* 2007).

Other pollutants originate from numerous low-level sources that make significant contributions when considered in total. Copper is a common pollutant in urban stormwater runoff and can originate from some building materials, wood preservatives, pesticides, and vehicle brake pads (Beasley & Kneale 2002). Several pesticides are widely used to maintain landscaping, therefore numerous public or privately owned land parcels can act as sources for these water contaminants. Herbicides such as 2,4-D and glyphosate were detected in a large proportion of water samples collected between 2000 and 2005 in the Clackamas River basin (western Oregon) (Carpenter *et al.* 2008).

Legacy compounds are substances that were manufactured and in use for years or decades and are now banned, but continue to pollute Oregon's aquatic ecosystems (Wentz *et al.* 1998; Ebbert *et al.* 2000; ISAB 2007b; LCREP 2007). The manufacture and use of polychlorinated biphenyls (PCBs) in the US was banned in 1979 but these materials still occur in streams and estuaries (King *et al.* 2004), including those associated with urban areas along the Willamette River (Black *et al.* 2000). King *et al.* (2004) concluded that urban areas bordering the Chesapeake Bay may still contain active sources of PCBs and pointed to the need for further research into historical and contemporary storage and delivery of these chemicals to surface waters and sediments.

Every year, new compounds are approved by regulatory agencies for use in the US. Guidelines for general water quality or aquatic life criteria are not required for many of these compounds prior to their approval for use (Ebbert *et al.* 2000; LCREP 2007; Carpenter *et al.* 2008). For example, more than 100 point sources legally discharge effluent containing unregulated contaminants directly into the lower Columbia River estuary (LCREP 2007). Up to 200 different

⁵⁰ June 2004 USEPA bulletin EPA-420-B-04-009 titled *State Actions Banning MTBE (Statewide)*. <http://www.epa.gov/mtbe/420b04009.pdf>. Accessed on October 7, 2010.

⁵¹ March 2004 USEPA bulletin EPA420-F-00-010 titled *Control of MTBE in Gasoline*. <http://www.epa.gov/otaq/consumer/fuels/mtbe/f00010.htm>. Accessed on October 7, 2010.

chemicals have been identified in wastewater treatment plant effluent and combined sewer overflows (Ritter *et al.* 2002). The paucity of information regarding the occurrence of these contaminants in the environment or their effects on aquatic organisms clouds our understanding of their effects on aquatic ecosystems. Several sources identify compounds that fall into this information gap as *emerging contaminants* (e.g., Ritter *et al.* 2002; Brooks *et al.* 2006; Ellis 2006; ISAB 2007b; LCREP 2007). Emerging contaminants are not always newly created or approved compounds. This term also applies to substances recently recognized as unregulated and potentially significant water pollutants, even though they may have been present in runoff and wastewater for decades. For example, pharmaceuticals, some of which act as endocrine disruptors⁵², have been discharged into surface and ground waters for many years but efforts to survey and study them as pollutants have only recently begun (Ritter *et al.* 2002). It is the perception of the IMST that many, if not most, of the potentially toxic substances are not included in water quality analyses. This presents a further difficulty in assessing urban contaminants in surface and ground waters.

Emerging contaminants identified by various authors include the following examples.

- 1) There may be as many as 6 million different *pharmaceuticals and personal care products*, collectively known as PPCPs, commercially available worldwide. The development of new PPCPs and use of existing PPCPs increases annually (Kolpin *et al.* 2002; Ritter *et al.* 2002; Cui *et al.* 2006; Brooks *et al.* 2006; Ellis 2006). Examples of human and veterinary pharmaceuticals found in wastewater effluent include analgesics such as ibuprofen, antibiotics, anti-inflammatories, psychiatric drugs, lipid regulators, beta-blockers, x-ray contrast media, steroid estrogens and other hormones, and miscellaneous chemicals such as caffeine. Examples of personal care products include antiseptics, detergents, antibiotics, bioactive food supplements, cosmetics, fragrances, insect repellent, and sunscreen.

These substances primarily enter aquatic ecosystems when treated wastewater is discharged into receiving waters (Ritter *et al.* 2002; Ellis 2006). Synthetic estrogen originating from birth control pills, for example, is essentially untouched by sewage treatment (Parrott & Blunt 2005). Few generalizations can be made regarding modes of action or risk to aquatic organisms because these compounds range widely in chemical structure. While the environmental effects of many PPCPs have not been studied, there is a growing body of evidence indicating that some classes of substances (e.g., estrogenic compounds) pose significant threats to aquatic organisms (Santos *et al.* 2010).

- 2) Polybrominated-diphenyl-ethers (PBDEs) are widely used as flame retardants in various textiles, plastics, foams, and fire extinguishers. PBDEs leach from the plastics, electronics, and textiles in which they are used (de Wit *et al.* 2002). These compounds may enter surface and ground waters through treated wastewater and septic field effluent (Rayne *et al.* 2003; Elliott *et al.* 2005; ISAB 2007b; LCREP 2007). Another source of environmental contamination may be industrial facilities that either manufacture PBDEs and other flame retardants or use them in the manufacturing of other consumer products (de Wit *et al.* 2002). PBDEs have been isolated from tissues of aquatic organisms and their terrestrial predators residing in urbanized estuaries with increasing incidence and at

⁵² Endocrine disruptors are substances foreign to an organism that act like hormones and that stop the production or block the transmission of hormones in the body.

higher concentrations. Rayne *et al.* (2003) sampled mountain whitefish (*Prosopium williamsoni*) from portions of the Columbia and Kootenya Rivers (British Columbia, Canada) between 1992 and 2000 and documented a 12-fold increase in PBDE concentrations in whitefish tissues over this period. PBDEs are similar to PCBs in terms of their environmental persistence, chemical behavior, and immunotoxicity (Table 7-2; de Wit 2002; Morace 2006; LCREP 2007). Concern over public health and environmental effects of these contaminants caused both the Washington⁵³ and Oregon⁵⁴ state legislatures to ban some PBDEs beginning in 2011.

- 3) Some forms of polycyclic aromatic hydrocarbons (PAHs) are considered emerging contaminants. PAHs comprise a large group of natural and anthropogenic organic compounds and are present in creosote, asphalt, soot, roofing tar, crude oil, gasoline, and diesel fuel (Reynaud & Deschaux 2006; LCREP 2007). Anthropogenic PAHs probably enter surface waters via creosote treated structures, industrial effluent, episodic fuel spills, and runoff containing petroleum products and sediment-bound PAHs that have accumulated on impervious surfaces. PAHs arise from numerous sources in developed landscapes and are considered to be ubiquitous in aquatic ecosystems (Meador *et al.* 1995; van Metre *et al.* 2000). However, the transport, fate, and effects of PAHs in aquatic ecosystems requires additional research.
- 4) Nanomaterials are a diverse group of chemical compounds smaller than 100 nm in size that exhibit unique, size-dependent properties (Guzmán *et al.* 2006). It is anticipated that nanomaterials will be widely used in many applications in technology and industry (Dahl *et al.* 2007). There is concern with potential environmental impacts of nanomaterials that recently have become more ubiquitously manufactured and distributed, including their potential for toxicity to fish (Teuten *et al.* 2009). Laboratory-based experiments have demonstrated toxicity of several nanomaterial compounds in vertebrate organisms (reviewed by Guzmán *et al.* 2006). The behavior of manufactured nanomaterials in natural environments has been raised as a concern for this rapidly developing technology (Guzmán *et al.* 2006; Dahl *et al.* 2007). Limited research is currently underway to determine the potential for nanomaterials to become environmental contaminants (e.g., Harper *et al.* 2008).
- 5) Several chemicals used in the manufacture of plastics and personal care products have received increasing attention in surveys for water contaminants. Two examples of such contaminants include bisphenol A and a class of compounds called phthalates. Otherwise known as plasticizers, these chemicals are used to manufacture plastic products such as toys, food containers, medical devices, and vinyl (particularly polyvinyl chloride or PVC) used in flooring and wall coverings and similar products (see Oehlmann *et al.* 2009; Clara *et al.* 2010; and references cited therein). Phthalates are also used to carry fragrances and modify the consistency of personal care products such as nail polish (OEC 2007; Oehlmann *et al.* 2009). Because plastics have become a ubiquitous feature of human societies, plastic debris continuously enters natural ecosystems, is disposed of in landfills, or simply remains in use (Barnes *et al.* 2009). Plasticizers can enter aquatic

⁵³ <http://www.watoxics.org/issues/pbde/legislative-update>. Accessed on July 24, 2008. For a summary of proposed and passed legislation related to PBDE bans in the US and elsewhere, see <http://www.ewg.org/node/26976>. Accessed on September 18, 2008.

⁵⁴ <http://www.leg.state.or.us/09reg/measpdf/sb0500.dir/sb0596.en.pdf>. Accessed May 4, 2010.

ecosystems via waste water effluent generated during manufacturing processes or by leaching directly from finished products that contain them (Oehlmann *et al.* 2009; Teuten *et al.* 2009; Clara *et al.* 2010). Phthalates and bisphenol A have been detected repeatedly in several sources that reach surface waters including rainwater, treated and untreated wastewater, sediments, leachates from landfills, and stormwater (Oehlmann *et al.* 2009; Clara *et al.* 2010 and references therein). These chemicals resemble hormones that animals produce naturally (e.g., estrogen) thus they can disrupt a number of reproductive, developmental and physiological processes in animals that ingest or absorb them (Oehlmann *et al.* 2009). In a recent review of available data Oehlmann *et al.* (2009) concluded that both phthalates and bisphenol A have the potential to adversely affect the reproductive biology of wild fish populations. However, few population-level studies have been conducted and population-level responses to such contaminants remain a knowledge gap.

SECTION 7.62: FACTORS AND MECHANISMS THAT CONTRIBUTE TOXIC POLLUTANTS TO AQUATIC ECOSYSTEMS

Surface and groundwater contamination by toxic substances is widespread in developed areas (USGS 1999, 2001; Paul & Meyer 2001; Allan 2004). The diversity of potential contaminants continually increases as new industrial and commercial products and materials are developed and approved for use (Hamilton *et al.* 2004). A thorough review of all known toxic contaminants released within developed areas or their effects on aquatic life is beyond the scope of this report. Instead, IMST provides an overview of toxic inputs, a summary of the diversity of toxic contaminants detected in aquatic ecosystems affected by development, and a description of how contaminant loads accumulate in and distribute throughout aquatic ecosystems. Specific contaminants discussed reflect the availability of published information. Examples of known toxic effects on fishes and food webs and a discussion of the scientific limitations that hinder toxic pollution management are presented in Section 8.1 of this report.

Streams in or Near Developed Areas – In urban and rural-residential areas, numerous point and non-point sources release contaminants into nearby surface and ground waters (Figure 7-2). The following bulleted list provides some specific examples:

- Residential households contribute pesticides, cleaning supplies, pharmaceuticals, personal care products, and other toxic chemicals such as paint, wood preservatives, solvents and various petroleum products (Beasley & Kneale 2002; Ritter *et al.* 2002). Septic systems release chemical contaminants even when these systems are operating properly (Swartz *et al.* 2006; Hinkle *et al.* 2009; ISAB 2007b).
- Impervious surfaces associated with transportation corridors accumulate metals, petroleum compounds, automotive fluids, dioxins, and deicing salts. Stormwater transports these compounds into waterways (Beasley & Kneale 2002; Ritter *et al.* 2002; USEPA 2002b; ISAB 2007b). Airports, even small facilities, apply large quantities of deicing and anti-icing fluids (Corsi *et al.* 2006) releasing glycols and potentially toxic additives into aquatic ecosystems as part of stormwater runoff (Fisher *et al.* 1995; Hartwell *et al.* 1995; Pillard 1995; Cornell *et al.* 2000).

- Outdoor common areas such as golf courses and parks are often maintained using mixtures of herbicides and pesticides (Paul & Meyer 2001).
- Hospitals, extended care facilities, nursing homes, universities, and other civic services contribute a broad array of chemicals associated with research and testing activities, as well as cleaning agents, pharmaceuticals, personal care products, and solvents (e.g., Kummerer 2001).
- Building materials release toxic contaminants as they age. For example, roofing materials are a considerable source of metal contamination (Beasley & Kneale 2002; Ritter *et al.* 2002). Building maintenance often involves application of preservatives that kill degrading organisms (e.g., moss, fungi). Commercial products used for these purposes often contain metals (e.g., zinc) or pesticides that are highly toxic to aquatic organisms.
- Industries contribute a broad array of chemical solvents used in manufacturing and metals are released during waste incineration (Wentz *et al.* 1998; Tanner 2002; Morace 2006). Deposition of particulates from industrial emissions onto impervious surfaces can contaminate stormwater that flows across these surfaces before entering streams and rivers (Beasley & Kneale 2002; Ritter *et al.* 2002). Some industries use large volumes of water for processing and then discharge contaminated effluent to surface waters (Wentz *et al.* 1998).
- Water treatment plants receive contaminants from households, businesses, universities, hospitals, and landfills and route them to surface or ground waters when containment is inadequate or if treatment procedures do not remove toxic substances (Kolpin *et al.* 2002).
- Landfills and hazardous material storage sites (e.g., petroleum products⁵⁵) can release contaminants when containment methods fail (Ritter *et al.* 2002).

Streams outside of Developed Areas – Developed areas can also influence the delivery of toxic contaminants such as fire retardants to surface waters in more remote locations. The number of rural-residential areas in fire-prone ecosystems has been increasing in the western US. These areas have also been associated with increases in wildfire frequency and the overall acreage burned (Sturtevant & Cleland 2007; Syphard *et al.* 2007; White *et al.* 2009). Syphard *et al.* (2007) documented an association between housing density and the size and frequency of human-caused fires in California, with the largest increase in fire frequency being associated with intermediate levels of human disturbance. The effect of fire disturbance and fire retardants on aquatic ecosystems is an active area of research,⁵⁶ but there is little documentation of their cumulative effects on aquatic ecosystems in and around rural-residential developments. Streams flowing through areas burned by wildfires can experience increased water temperatures, reduced dissolved oxygen concentrations, increased loads of naturally occurring toxic compounds (e.g., ammonia) and changes in pH (Crouch *et al.* 2006). Fine fire residues (e.g., ash) can clog the

⁵⁵For examples see ODEQ fact sheets on the Leaking Underground Storage Tanks Program at <http://www.deq.state.or.us/pubs/factsheets.htm#LUST>. Accessed on December 27, 2007.

⁵⁶ See February, 2008 decision on aerial application of fire retardant by the US Forest Service, http://www.fs.fed.us/fire/retardant/Aerial_Application_of_Fire_Retardant.pdf. Accessed on October 10, 2008.

respiratory structures of aquatic organisms and result in negative post-fire effects on aquatic ecosystems (Giménez *et al.* 2004; Crouch *et al.* 2006).

Many retardants used to fight wildfires are ammonium-based formulations that release toxic compounds such as ammonia or cyanide as they break down in the environment (Buhl & Hamilton 2000; Giménez *et al.* 2004). While these compounds break down rapidly and do not bioaccumulate, retardants delivered in or near streams at high concentrations may require significant dilution (e.g., 100-1,750 times for rainbow trout) before they are no longer toxic to aquatic organisms (Gaikowski *et al.* 1996; Buhl & Hamilton 2000; Crouch *et al.* 2006). Limited evidence indicates that accidental delivery of aerially applied fire retardants (e.g., because of erratic winds or poor visibility) to streams and rivers may impair water quality and impose lethal or sublethal effects on aquatic organisms (Buhl & Hamilton 2000; Boulton *et al.* 2003; Giménez *et al.* 2004). Buhl & Hamilton (2000) documented several incidents during the 1990's where the accidental application of fire retardants to streams resulted in fish kills in the John Day River basin (eastern Oregon). Some of these fish kills affected thousands of individual organisms, including hundreds of anadromous steelhead trout (Buhl & Hamilton 2000). Given the potential consequences to aquatic ecosystems posed by fire and fire control strategies, increasing fire frequency in areas undergoing rural-residential development may present risks of unknown magnitude to nearby salmonid populations.

SECTION 7.63: ROUTES OF ENTRY INTO AND RETENTION IN FISH

The chemical properties of toxic pollutants determine how organisms encounter pollutants, how they enter fish bodies, and how they persist and concentrate in fish bodies. Several factors, including the following, make these determinations an exceptionally complex discussion:

- The great diversity of chemical contaminants;
- The considerable variation in solubility of these compounds;
- The wide variation in degradation and transformation rates of different chemicals;
- Differences in geology and water chemistry within and between river systems;
- Differing physiologies and anatomies of fishes;
- Inter-developmental stage differences in fishes;
- Differences in behavior between species and life history stages of fishes;
- Variation in aquatic biota between and within river, stream and estuary systems; and
- Variation of environmental variables through time and between locations, in particular changes in water temperature, pH, sunlight, and hydrologic regimes.

There are two main types of aquatic pollutants, those that are water-soluble (such as salts, minerals, and some metals) and those that are fat (lipid)-soluble (such as PCBs, DDTs⁵⁷, and many other organic pesticides and pharmaceuticals). Solubility properties play a major role in whether individual compounds circulate in the water column or are adsorbed onto sediment

⁵⁷ The abbreviation 'DDTs' denotes the insecticide DDT and its common breakdown products (e.g., DDE).

(Jones *et al.* 2001; Schowanek & Webb 2002). Water-soluble compounds tend to reside in the water column until they degrade. In contrast, lipid-soluble compounds are repelled by water molecules. This chemical behavior increases the rate at which lipid-soluble toxics bind to sediments, slows their environmental degradation (e.g., photolytic or microbial), and increases their persistence in aquatic environments (Ritter *et al.* 2002). Contaminants adsorbed onto microparticles may become distributed throughout the water column which can increase a fish's exposure to the contaminants.

Contaminants generally enter the bodies of fish through their gills during normal gas exchange with the water or with food (Tyler & Jobling 2008). It is also possible for toxic chemicals to be transferred from maternal sources into eggs and into surviving progeny. Once in the bloodstream, toxic effects occur until circulatory, liver, and kidney functions excrete, detoxify, metabolize, or otherwise make the toxic compounds inactive or until the fish dies. Some toxic chemicals (e.g., copper) may only contact a few external cells, but still have severe effects on the behavior or physiology of fish. For example, the receptor neurons that control salmonid olfaction (smell) operate in direct contact with the aquatic environment. Damage to these sensitive cells from contact with copper impairs salmonid sensory perception and affects many ecologically important behaviors such as migration and predator avoidance (Table 7-2).

Both lipid-soluble and water-soluble toxic compounds accumulate in fish bodies. At certain high-energy requiring life stages or during other periods of increased activity, such contaminants or their metabolites could be redistributed as fat reserves are metabolized or other changes in metabolism change the biochemical nature of the fish's body tissues, thereby exposing individuals to elevated risk of toxic effects (Milston *et al.* 2003; Debruyne *et al.* 2004; Svendsen *et al.* 2007). Consequently, some toxics may have little to no biological effect until they are concentrated and then more rapidly released from compartments where they were stored. Certain life stages of fishes are more sensitive to contaminants than others. These tend to be stages of transition, such as during early development or reproduction (Rosenthal & Alderdice 1976). Importantly for salmonids, the smoltification stage (when juveniles migrate to the ocean) can also be very sensitive to toxics (Misumi *et al.* 2005).

Bioaccumulation can occur as prey species that have consumed and retained toxic compounds are subsequently consumed by predators that store toxic compounds at even higher tissue concentrations. Lipid-soluble substances tend to bioaccumulate; whereas, water-soluble contaminants generally do not (Ritter *et al.* 2002). However, some metals (e.g., mercury; Peterson *et al.* 2007) and most organic chemicals have the potential to bioaccumulate. Through this process, contaminant concentrations can increase in a predator's tissues well beyond concentrations measured in surrounding waters or sediments, with the highest concentrations and most severe biological effects found in top predators. The level of exposure depends on how concentrated contaminants are in the water, sediments, and prey, and the volume of each that associates with the predator (e.g., food abundance or gill water contact).

SECTION 7.64: DETERMINING TOXICITY AND SETTING CRITERIA TO PROTECT AQUATIC LIFE

The USEPA sets numeric criteria on chemical concentrations that can be present in surface waters without harming aquatic life. Criteria currently exist for approximately 150 contaminants⁵⁸ but most emerging toxic chemicals lack such criteria. Current information on how toxic contaminants affect aquatic organisms comes, for the most part, from the following four general areas of research and monitoring:

- Acute toxicity lab tests of known contaminants on the time until death of individuals of selected species;
- Chronic toxicity tests of the effects of contaminants on the growth, behavior, and development of test organisms;
- Documenting toxic compounds within the tissues of fish and other aquatic organisms; and
- Correlating toxic chemical loads or documented exposure with negative, sub-lethal effects.

Traditional approaches used to assess contaminant toxicity in aquatic organisms present difficulties for translating individual responses measured in laboratory settings to population-level effects in natural environments. Environmental concentrations of many toxic contaminants are typically below those necessary to complete informative laboratory tests. For example, typical toxicity testing approaches are often insufficient to evaluate the chronic, low-dose exposure typical of many pharmaceuticals and personal care products in aquatic environments (Ellis 2006). This problem occurs because of lack of agreement on appropriate end points to measure, the most sensitive species to test, or the life histories that should be tested, as well as which chemical compounds and complexes to focus on. The need for multiple biological endpoints in toxicity sampling is illustrated by Liney *et al.*'s (2006) research on the fish species *Rutilus rutilus*. Liney *et al.* (2006) exposed early-life stages of *R. rutilus* to prolonged, low doses of municipal effluent and found that genotoxic (affects DNA molecules) and immunotoxic (affects the immune system) effects occurred at much lower doses than doses required to induce changes in the reproductive system.

A Mixture of Contaminants in Aquatic Ecosystems – Developed land uses introduce a diverse array of contaminants to aquatic ecosystems. Kolpin *et al.* (2002) detected multiple pharmaceuticals, hormones, and other organic wastewater contaminants (median = 7 contaminants per sample with a high of 38 contaminants in one water sample) in water samples collected from 139 streams in 30 states. PPCPs, alone, include hundreds of chemicals used for different purposes and with differing chemical activities and environmental persistence. Their ecological effects are largely unknown. The diversity of potential contaminants, particularly PPCPs, increases continually as new products and materials are developed, approved for use (Hamilton *et al.* 2004), manufactured, and purchased by consumers. Method development to detect these compounds in the environment lags far behind the introduction of new contaminants (Jørgensen & Halling-Sørensen 2000). In addition, water quality assessments do not generally

⁵⁸ For detailed information on national water quality criteria for the protection of aquatic organisms visit: <http://www.epa.gov/waterscience/criteria/aqlife/#guide>. Accessed on December 27, 2010.

consider chemical breakdown products or metabolites of parent contaminants. This lack of information makes it difficult to determine actual contaminant loads received by aquatic ecosystems. Pharmaceutical substances are particularly toxic to fish because they are designed to target physiological responses in people. Fish are sensitive to PPCPs because they are vertebrates and vertebrate responses to pharmaceutical compounds provide information to predict physiological effects in fish. However, predicting physiological effects caused by other toxic compounds that were not designed with a targeted vertebrate response can be much more problematic.

Synergistic Toxicities and Additive Effects in the Environment – Streams, rivers, and ground waters contain contaminant mixtures that vary in composition and concentration (Sandahl *et al.* 2005). Mixtures of contaminants are likely to produce synergistic⁵⁹ toxicities (Laetz *et al.* 2009) making it difficult to evaluate the cumulative toxicity of the mixtures. However, little information exists about potential additive⁶⁰, synergistic, or antagonistic⁶¹ effects that may occur in complex contaminant mixtures because most toxicity research focuses on single compounds (Kolpin *et al.* 2002; Sparling & Fellers 2007; Carpenter *et al.* 2008).

The following studies provide information about the cumulative effects of toxicant mixtures. These studies were carried out using contaminant concentrations representative of those commonly experienced by aquatic organisms. Many of the contaminants used in these studies have been found in Oregon (e.g., Wentz *et al.* 1998; Ebbert *et al.* 2000; Fresh *et al.* 2005; ISAB 2007b; LCREP 2007).

- DDT and its breakdown products may exert both endocrine disrupting and immunotoxic effects and may add to the effects of other estrogenic contaminants that alter the reproductive physiology of Pacific Northwest salmonids (Fresh *et al.* 2005 and references cited therein).
- Laetz *et al.* (2009) found that mixtures of organophosphate and carbamate insecticides (e.g., malathion, carbaryl) resulted in additive and synergistic effects on coho salmon nervous system function by inhibiting enzyme activity.
- The herbicide atrazine has been shown to act synergistically with organophosphate insecticides (e.g., diazinon) thereby increasing the toxicities of these substances to aquatic organisms (Anderson & Lydy 2002; Jin-Clark *et al.* 2002; Anderson & Zhu 2004).
- In toxicity tests using an aquatic midge (*Chironomus tentans*), Anderson & Zhu (2004) demonstrated that the toxicity of structurally different organophosphate insecticides increased up to 10-fold in the presence of atrazine.

⁵⁹ The combined effect of two or more contaminants on an organism is greater than the sum of the individual contaminant effects.

⁶⁰ Two or more contaminants in a mixture share a common mode of action and show an effect that is a function of their combined concentration.

⁶¹ The combined effect of two or more contaminants on an organism is less than the sum of the individual contaminant effects.

Table 7-2. Acute and sub-lethal¹ effects of various contaminants on Pacific Northwest salmonids. Contaminants included in this table represent general classes frequently detected in waters affected by rural-residential and urban development and that often exceed criteria established for the protection of aquatic life. Documented effects were typically caused by contaminant concentrations commonly detected in surface waters in the Pacific Northwest.

Ecological Effect	Contaminant Type ²	Common Sources ³	Specific Effects	Biological Level Documented	Selected References
Growth; Development	PCBs	Legacy; Contaminated sediments	Disrupted thyroid function	Individual adult lake trout	Brown <i>et al.</i> 2004
	PAHs	Creosote, asphalt, soot, roofing tar, crude oil, gasoline, and diesel fuel	Reduced biomass, lipid stores	Individual juvenile Chinook salmon	Meador <i>et al.</i> 2006
	PPCPs (e.g., detergents)	Treated wastewater effluent	Reduced growth; Inhibited smoltification; Abnormal reproductive development	Individual Atlantic salmon	Arsenault <i>et al.</i> 2004; Madsen <i>et al.</i> 2004
Sensory; Neurological; Behavioral	Copper	Vehicle exhaust and brake wear; Stormwater transport	Rapid and persistent olfactory impairment; Behavioral processes affected (e.g., migration; predator avoidance)	Individual juvenile coho, chum & Chinook salmon; rainbow trout; Laboratory experiments	Hansen <i>et al.</i> 1999a, b; Baldwin <i>et al.</i> 2003; Sandahl <i>et al.</i> 2004, 2006, 2007; McIntyre <i>et al.</i> 2008
	Organic pesticides: (e.g., insecticides, herbicides, fungicides)	Non-point source transfer from residential and commercial landscaping, right of way maintenance	Reduced neurological enzyme activity; Olfactory impairment; Diverse physiological and behavioral processes affected (e.g., homing; reproductive cues; predator avoidance; swimming speed)	Individual Atlantic, coho & Chinook salmon; rainbow & brown trout	Moore & Waring 1996; Waring & Moore 1997; Scholz <i>et al.</i> 2000, 2006; Jarrard <i>et al.</i> 2004; Sandahl <i>et al.</i> 2004, 2005, 2006, 2007; Jaensson <i>et al.</i> 2007; Tierney <i>et al.</i> 2006a, b, 2007, 2008
Reproductive	Synthetic estrogen (e.g., pharmaceuticals, pesticides and their metabolites)	Treated wastewater effluent	Inhibited testicular growth; Reduced male fertility; Vitellogenin production; Feminization of male fish; Direct negative population level effects	Individual male rainbow trout; fathead minnow	Purdom <i>et al.</i> 1994; Jobling <i>et al.</i> 1996; Schultz <i>et al.</i> 2003; Thorpe <i>et al.</i> 2003; Lahnsteiner <i>et al.</i> 2006; Kidd <i>et al.</i> 2007
	PPCPs (e.g., detergents)	Treated wastewater effluent	Vitellogenin production; Altered hormone production & hormone receptor synthesis; Abnormal reproductive development	Individual Atlantic salmon; rainbow trout; sockeye salmon	Harris <i>et al.</i> 2001; Luo <i>et al.</i> 2005; Bangsgaard <i>et al.</i> 2006

¹Sub-lethal effects are those that alter essential behavior or reduce overall health in ways that can reduce productivity of salmonid populations.

²PCBs – polychlorinated biphenyls; PAHs – polycyclic aromatic hydrocarbons; DDTs – dichloro-diphenyl-trichloroethane and its degradation products (e.g., DDE); PPCPs – pharmaceuticals and personal care products.

³Common sources include those identified in rural-residential and urban environments. Additional, sometimes more significant, sources may also exist outside of developed areas.

Table 7-2 *continued*. Acute and sub-lethal¹ effects of various contaminants on Pacific Northwest salmonids.

Ecological Effect	Contaminant Type ²	Common Sources ³	Specific Effects	Biological Level Documented	Selected References
Immunological	PCBs; PAHs	Legacy; Creosote, asphalt, soot, roofing tar, crude oil, gasoline, and diesel fuel	Immune suppression; Increased disease susceptibility and mortality	Individual juvenile Chinook salmon; Arctic charr	Arkoosh <i>et al.</i> 1998a, b; Maule <i>et al.</i> 2005
	DDTs	Legacy	Long-term immune suppression	Individual juvenile Chinook salmon; Cellular	Milston <i>et al.</i> 2003; Misumi <i>et al.</i> 2005
	PAHs	Creosote, asphalt, soot, roofing tar, crude oil, gasoline, and diesel fuel	Immune suppression	Numerous fish species, including salmonids	Reynaud & Deschaux 2006
Direct Toxicity	Organochlorine pesticides (e.g., Endosulfan)	Insecticide products; Likely transported in stormwater	Nervous system stimulant	Many fish species including salmonids	Gormley & Teather 2003; Wan <i>et al.</i> 2007

¹Sub-lethal effects are those that alter essential behavior or reduce overall health in ways that can reduce productivity of salmonid populations.

²PCBs – polychlorinated biphenyls; PAHs – polycyclic aromatic hydrocarbons; DDTs – dichloro-diphenyl-trichloroethane and its degradation products (e.g., DDE); PPCPs – pharmaceuticals and personal care products.

³Common sources include those identified in rural-residential and urban environments. Additional, sometimes more significant, sources may also exist outside of developed areas.

Toxicity effects have only been determined for a very small fraction of contaminants that may affect aquatic organisms. Laboratory and field-based studies tend to focus on the sensitivity of a few select species to a limited number of contaminants thus ignoring the heterogeneous physiological, predatory, and competitive responses of natural populations. Laboratory toxicity tests also tend to be of short duration, while wild fishes may be exposed to these substances for prolonged periods, often at varying doses, as either discharge of the contaminant into the environment or the volume of recipient waters changes through time (Davis *et al.* 1999; Spromberg & Meador 2006). Consequently, data on the effects of chronic exposure also are lacking for many chemicals and organisms, making ecologically relevant inferences difficult to make (Fent *et al.* 2006).

Setting Criteria to Protect Aquatic Life – The paucity of available information limits the ability to determine protective criteria for aquatic organisms for many of the potentially toxic contaminants and their breakdown products found in waters affected by development (Hamilton *et al.* 2004). Another dilemma for establishing toxicity criteria is that some chemicals may not have biological or environmental threshold effect levels. For example, PPCPs that act as endocrine disruptors and mimic or inhibit action of hormones (Norris 2000; Ellis 2006) may not have a ‘no-effect level’ (Sheehan *et al.* 1999). Recent research on the effects of copper on

salmonid olfactory function also indicates that very low copper concentrations cause cellular damage (Sandahl *et al.* 2007). Also, the biology of fish may not be sufficiently understood to allow recognition of a detrimental effect. For example, understanding the highly relevant process of salmonid smoltification is confounded by the fact that there are no clear anatomical, physiological, or behavioral indicators for when smoltification begins or ends (Stefansson *et al.* 2003).

Even if water quality testing methods kept pace with the production and release of new potentially-toxic contaminants, it is extremely expensive to monitor concentrations and behavior of all the new substances entering developed watersheds. However, the limited information gained from toxicity testing and field monitoring for toxic compounds clearly indicates that contaminants pose serious threats to aquatic organisms including salmonids by affecting reproductive physiology, sensory organs, growth, and development (Table 7-2; Morace 2006). Resolution of these issues is a significant challenge facing efforts to protect water quality in rural-residential and urban areas.

SECTION 7.65: NATURE, TIMING, AND MAGNITUDE OF TOXIC POLLUTION

Urban and rural-residential land uses introduce a diverse array of contaminants to aquatic ecosystems. Not surprisingly, water quality assessments conducted by the USGS NAWQA program (e.g., Hamilton *et al.* 2004; Gilliom *et al.* 2006) and other efforts have documented widespread contamination of streams and groundwater in urban areas. Surveys conducted throughout the Pacific Northwest (Anderson *et al.* 1996; Wentz *et al.* 1998; Ebbert *et al.* 2000; Tanner 2002; Fresh *et al.* 2005; Morace 2006; LCREP 2007; Peterson *et al.* 2007; Carpenter *et al.* 2008) have detected several contaminant types in freshwater and estuarine ecosystems affected by development including:

- Pesticides,
- Fossil fuel byproducts,
- PAHs,
- PBDEs,
- Metals,
- Pharmaceuticals,
- Personal care products, and
- Legacy pollutants (e.g., PCBs; DDTs).

Groundwater surveys also detected various volatile organic compounds (primarily solvents and fuel additives) in up to 80% of shallow monitoring wells beneath urban lands (Wentz *et al.* 1998; Ebbert *et al.* 2000). In Oregon, the cities of Bend, Coos Bay, Eugene-Springfield, La Grande, Medford, and Portland have problems with leaking underground petroleum storage tanks resulting in sites ranked as hazardous by ODEQ (Oregon Progress Board 2000).

Pollutant mixtures that include parent compounds and their breakdown products are common in developed watersheds (Jones *et al.* 2001; Hamilton *et al.* 2004). This is evident in the following results from water quality surveys conducted in the Pacific Northwest and nationwide:

- In a two-year, nationwide survey across 30 states (including Oregon), Kolpin *et al.* (2002) sampled 139 streams susceptible to toxic contamination from human, industrial, or agricultural wastewater and found the following:
 - 86% of pharmaceuticals, hormones and other organic wastewater contaminants tested for were detected at low concentrations;
 - PPCPs were detected in approximately 40% of the 139 streams samples, with 80% of the contaminated streams containing steroids and various non-prescription drugs;
 - Detergent breakdown products, plasticizers, and steroids were found to contribute almost 80% of the total measured concentrations, in over 60% of stream samples; and
 - 75% of streams sampled had more than one organic wastewater contaminant detected (median of seven, maximum of 38).
- For eight urban US streams (including one in Portland, Oregon) surveyed for 75 pesticides, Hoffman *et al.* (2000) determined that 46% of samples contained more than one insecticide currently in use, and 61% of samples contained more than one herbicide currently in use.
- Fifteen percent of urban stream samples collected during NAWQA surveys contained up to 10 different volatile organic compounds and 23% of urban stream samples contained 10 or more pesticides (Hamilton *et al.* 2004).
- Urban streams in King County (Washington) contained 23 of 98 pesticides screened for during water quality surveys (Ebbert *et al.* 2000; Hamilton *et al.* 2004).
- Streams draining mostly urban lands along the Willamette River (Oregon) contained 25 pesticides along with high sediment concentrations of lead, silver, zinc, and cadmium (Wentz *et al.* 1998).

Tissue samples taken from aquatic organisms contain many of the contaminants detected in water and sediment samples, for example:

- In sub-estuaries throughout the Chesapeake Bay (eastern US), PCBs, heavy metals, and other organic contaminant concentrations in fish tissues correlated with the amount of developed land within the watersheds discharging to the estuary (Comeleo *et al.* 1996; King *et al.* 2004).
- In the Puget Sound (Washington), mean concentrations of PAHs, PCBs and fluorescent aromatic compounds were significantly higher in the stomach contents, livers, and bile of juvenile Chinook salmon from an urbanized estuary than in fish from an undeveloped estuary (Arkoosh *et al.* 1998b; Meador *et al.* 2002).
- Mean PCB concentrations in Chinook salmon bred at hatcheries in the Puget Sound (Washington) ranged up to 2.5 times higher than Chinook salmon bred in coastal hatcheries. Fish from the more developed areas of southern Puget Sound had the greatest PCB concentrations (Missildine *et al.* 2005).

- Johnson *et al.* (2007a) measured contaminant concentrations in tissues and stomach contents of coho and Chinook salmon from several Pacific Northwest estuaries and found that Chinook salmon collected from industrial and urbanized estuaries carried the largest contaminant loads. DDTs and PCBs concentrations in the stomach contents and tissues of juvenile Chinook salmon migrating through the Columbia River estuary were among the highest levels recorded to date (Johnson *et al.* 2007a, b; LCREP 2007).
- In Oregon, juvenile salmon sampled from the lower Willamette River and Columbia River estuary contained PBDE concentrations higher than any others measured in the Pacific Northwest (LCREP 2007; Sloan *et al.* 2010).

The following water quality surveys detected contaminant concentrations either exceeding those determined to be protective of aquatic life or experimentally determined to cause harm to aquatic organisms.

- Arkoosh *et al.* (1998b) sampled juvenile Chinook salmon from both a non-urban Puget Sound estuary and an urban estuary where fish were exposed to organic contaminants (PAHs, PCBs) and tested their immunocompetence by exposing them to a common marine pathogen (*Vibrio anguillarum*). Fish from the urban estuary showed higher susceptibility to the pathogen and increased mortality after exposure.
- Nearly all the urban streams sampled during NAWQA surveys contained at least one pesticide in current use at concentrations that exceeded guidelines established to protect aquatic life (Hamilton *et al.* 2004; Gilliom *et al.* 2006).
- Aquatic-life protection criteria were exceeded by the insecticides chlorpyrifos, diazinon, malathion, and parathion in a national comparison of 8 urban streams (including one in Portland, Oregon). Diazinon exceeded water quality protection criteria in 17% of samples (Hoffman *et al.* 2000).
- In Sacramento and Stockton (California), 80% of urban water samples contained chlorpyrifos, and 85% of samples contained diazinon at concentrations exceeding water quality protection criteria set by the California Department of Fish and Game (Bailey *et al.* 2000).
- From 2000 to 2005 in the Clackamas River basin (Oregon), pesticide yields were highest in streams draining urban and industrial lands (compared to agricultural and forested lands), with concentrations of some pesticides (diazinon, chlorpyrifos, azinphos-methyl, DDE) exceeding USEPA and ODEQ criteria for protecting aquatic life (Carpenter *et al.* 2008).
- The following findings were reported for a range of salmonid stocks in the Columbia River estuary:
 - Copper concentrations were detected at levels experimentally shown to inhibit salmonid olfaction (Baldwin *et al.* 2003; Sandahl *et al.* 2007; LCREP 2007).
 - Sediment concentrations of PAHs, PCBs, and DDTs exceeded state or federal sediment quality guidelines. PCBs, PAHs, DDTs, and PBDEs tissue levels in juvenile salmonids approached concentrations determined to be detrimental to their health (Fresh *et al.* 2005; LCREP 2007).

- Pharmaceuticals and personal care products tested for, including some suspected endocrine disruptors, were widespread. Positive tests for vitellogenin⁶² in the tissues of juvenile fish rearing in the Columbia River estuary indicated exposure to endocrine disruptors (LCREP 2007).
- The USEPA (Hayslip *et al.* 2006) measured contaminants (arsenic, cadmium, DDT and its breakdown products, lead, mercury, selenium, and zinc) in the tissues of fish collected from more than 200 randomly selected sites throughout Oregon and Washington estuaries and found the following:
 - In 3.3% of the sampled estuary area, fish tissues contained four chemicals at concentrations exceeding criteria determined to be harmful to fish.
 - In 11.1% of the sampled estuary area, fish tissues contained three chemicals at concentrations exceeding criteria determined to be harmful to fish.
 - In 38.9% of the sampled estuary area, fish tissues contained two chemicals at concentrations exceeding criteria determined to be harmful to fish.

Most of the information available on aquatic pollutants addresses toxic metals and persistent organic contaminants such as PCBs and DDTs. Many contaminants detected in Pacific Northwest waters do not have established aquatic-life protection criteria (Morace 2006) and little is known about the toxicological effects of many of these substances. Other contaminants simply go undetected because they are not screened for during water quality assessments.

Determining the Quantities of Toxic Contaminants that Enter Aquatic Ecosystems – Assessing actual toxic pollutant loads derived from developed landscapes is problematic compared to documenting the diversity of contaminants entering aquatic ecosystems. Pesticides are probably the best understood in this regard. Oregon currently allows the use of 771 active pesticide ingredients in more than 11,000 different products (Carpenter *et al.* 2008). Nonagricultural uses account for ¼ to ⅓ of the total pesticide use in the US (Hoffman *et al.* 2000; Paul & Meyer 2001). Residential areas receive a significant fraction of these compounds (Figure 7-1) and urban application rates tend to be higher (per unit area) than rates documented for agricultural lands (Hoffman *et al.* 2000).

The type and concentration of contaminants found in urban waters may mirror their use and disposal in the surrounding landscape. For example, the active ingredients in insecticide products most frequently purchased in home and garden stores (e.g., the insecticides diazinon⁶³, carbaryl, chlorpyrifos, and malathion) are frequently detected in streams draining urban basins nationwide (USGS 1999; Coupe *et al.* 2000; Ebbert *et al.* 2000; Ritter *et al.* 2002; Hamilton *et al.* 2004; Gilliom *et al.* 2006). The USGS (1999) found that some urban streams contain higher concentrations of these household and garden insecticides than agricultural streams contain farm pesticides. However, limited information exists on the spatial and temporal release patterns of many substances (including pesticides) in urban landscapes and the fraction of these

⁶² Vitellogenin is an egg-yolk protein precursor not normally present at detectable levels in male fish. Tests for this protein are used to assess exposure of male fish to estrogenic contaminants.

⁶³ The USEPA banned residential use of diazinon in 2004;

<http://www.epa.gov/pesticides/factsheets/chemicals/diazinon-factsheet.htm#5>. Accessed on July 18, 2008.

contaminants transported to surface and ground waters (Coupe *et al.* 2000; Hoffman *et al.* 2000; Paul & Meyer 2001).

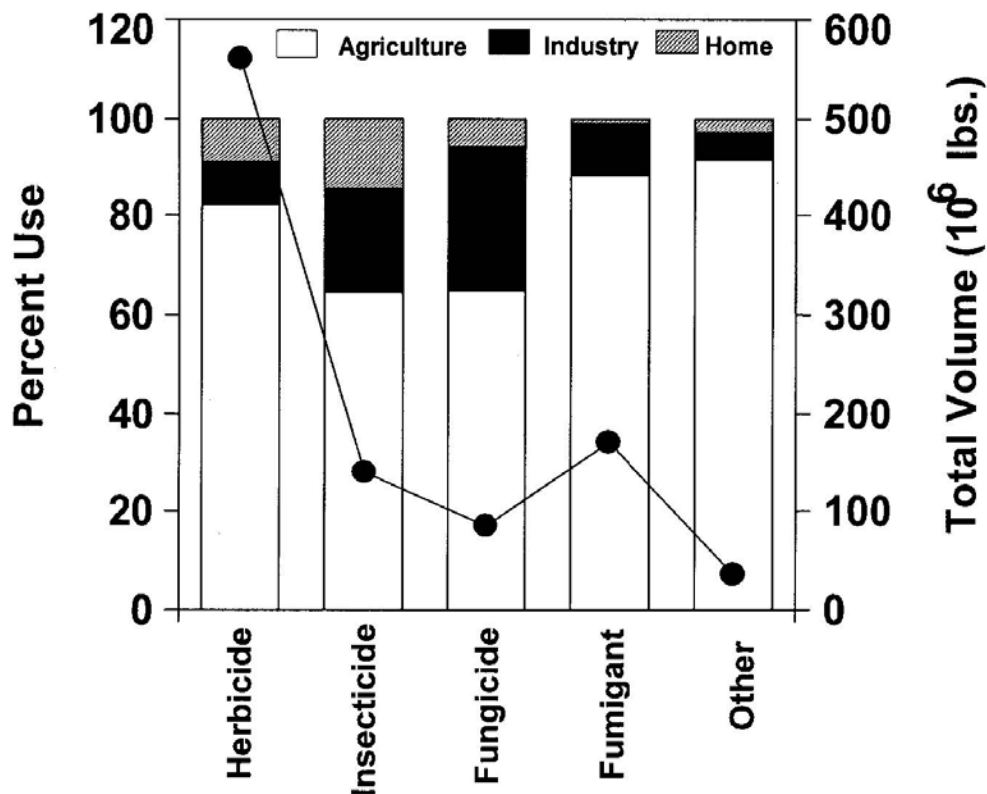


Figure 7-1. Relative use of various pesticides in agriculture, industry, and residential lands in the US. Stacked bars represent percent use and black dots represent total volume. IMST feels that the dots representing total volume should not be connected by the line. Figure reproduced from Ritter *et al.* (2002) with permission from Taylor & Francis Ltd.

Changes in Toxic Contaminants in Developed Landscapes – The spatial and temporal distributions of many contaminants that have been detected in surface waters in the Pacific Northwest are not adequately documented (Wentz *et al.* 1998; Ebbert *et al.* 2000; ISAB 2007b; LCREP 2007). Contaminant concentrations in surface and ground waters depend not only on the quantity released into the surrounding environment, but also on the timing of use, frequency and magnitude of stormwater runoff, and physical and chemical properties of the receiving environment (Hamilton *et al.* 2004). Once released, contaminants move through different environmental paths (e.g., atmosphere, soil, water, wastewater) where they are subjected to microbial, chemical or photolytic processes that modify their concentrations, chemical forms, behaviors, and/or toxicities (Jones *et al.* 2001; Ritter *et al.* 2002; Schowanek & Webb 2002). Contaminants may react with other substances already present and undergo chemical modifications or they may simply break down into alternate chemical structures. Various features in the landscape sequester and concentrate contaminants for variable periods of time.

Detention ponds can sequester heavy metal and hydrocarbon contaminants adsorbed to stormwater sediments (Datry *et al.* 2004; Bäckström *et al.* 2006; Birch *et al.* 2006; Lee *et al.* 2006). Urban estuaries accumulate toxic contaminants from adjacent stormwater runoff and wastewater discharge, as well as from upstream sources (Good 1999; Fresh *et al.* 2005; Lee *et al.* 2006).

The amount of time contaminants persist in the environment depends on their chemical structure and behavior. Some contaminants break down rapidly once they enter surface waters but degradation rates depend on environmental conditions such as temperature or pH. In contrast, metals persist indefinitely and cycle through the environment without breaking down (Ritter *et al.* 2002), although their oxidation states vary depending on aqueous conditions. Some contaminants (e.g., PAHs, dioxins) adsorb onto sediments and break down slowly over time or degrade into breakdown products that can be as toxic as the parent compound. Other contaminants are more water soluble and are broken down more quickly through microbial activity or photolytic degradation. Absorption onto sediment reduces contaminant concentrations in ambient waters but creates an environmentally persistent contaminant source that can degrade water quality whenever sediments are disturbed (Faulkner *et al.* 2000; Beasley & Kneale 2002).

The temporal patterning of contaminant release in watersheds undergoing development is dependent on specific patterns of residential, commercial and industrial land use and the length of time different land uses have been present in a watershed. For example, water quality degradation in the Columbia River estuary likely began with the onset industrialization. Today, the estuary receives contaminants from over 100 point sources in addition to non-point sources from cities like Astoria and Portland in Oregon and Vancouver and Longview in Washington (Fresh *et al.* 2005; LCREP 2007). The contaminant loads contributed by individual sources also change through time. Human usage rates determine the availability of many contaminants such that their release into aquatic ecosystems ranges from episodic to nearly continuous. Wentz *et al.* (1998) found that pesticide concentrations in the Willamette River varied seasonally. Hoffman *et al.* (2000) surveyed eight urban streams and documented carbaryl and diazinon concentrations that frequently exceeded aquatic life criteria during spring and summer months.

The proportional contribution of point sources to pollution loads experienced by aquatic ecosystems depends on the fraction of total flow they contribute to a water way. Ritter *et al.* (2002) reported that the proportions of different point-source pollutants varied considerably throughout the year in 47 Ontario (Canada) urban centers. The fraction of streamflow made up by stormwater was larger during wet weather while the fraction made up by wastewater treatment plant effluents (13 % during wet weather) ranged up to 80% during dry weather (Ritter *et al.* 2002). In a study of water quality of rivers draining to the North Sea, Neal & Robson (2000) found that in rivers affected by urban and industrial development, contaminants with higher water solubility tended to occur in higher concentrations during summer months when low flows reduce the capacity for rivers to dilute pollution. In contrast, contaminants with low solubility or those that bind to sediments exhibit higher concentrations during the winter months when higher flows mobilize sediments (Neal & Robson 2000). An extreme example of this occurred in the Pacific Northwest when a 100-year flood event in 1996 mobilized sediments and associated legacy contaminants in the Columbia and Willamette Rivers. The DDE concentrations in the water column increased to at least 5 times that of the level determined to be protective of aquatic life and in some cases were detected for the first time in some areas (Fresh *et al.* 2005).

Wastewater treatment plants, even those using tertiary treatment processes, do not adequately remove many compounds thought or known to act as endocrine disruptors (e.g., PAHs, personal care products, pharmaceuticals). Consequently, treated effluent acts as a point source for these contaminants (Brooks *et al.* 2006; Conn *et al.* 2006; Belgiorno *et al.* 2007). Kolpin *et al.* (2002) found that concentrations of urban-derived pharmaceuticals were greatest during the low-flow months and undetectable during high-flow months. Brooks *et al.* (2006) estimated that, throughout the US, 23% of treated effluents are released into streams where the effluent dilution factor is less than 10 fold; this fraction increases from 23% to 60% during low flow conditions. In systems where wastewater treatment effluent makes up a dominant portion of flow during part or all of the year, pollutants that pass through treatment processes are a considerable concern. It is technologically feasible for municipal sewage treatment plants to remove pharmaceutical and other toxic compounds, yet this is not done in the US. New technology demonstration projects for this purpose are underway at two municipalities in the United Kingdom (Huo & Hickey 2007). However, the economic costs and benefits of such treatment techniques are unknown.

Over extended periods, clear patterns in the deposition of persistent contaminants can be determined. To document temporal changes of contaminant concentrations in rapidly urbanizing watersheds, the USGS (NAWQA) analyzed sediment layers in urban lakes across the nation (Hamilton *et al.* 2004). Sediment concentrations of tightly regulated or banned contaminants (e.g., lead, DDTs, PCBs) have declined in response to management actions taken to control release of these substances into the environment (Hamilton *et al.* 2004). For example, in a Texas lake lead concentrations peaked in sediments from the late 1960s and declined by about 70% in strata representing periods after the elimination of leaded gasoline. In contrast, nickel concentrations have nearly doubled since 1930 (Beasley & Kneale 2002). Many contaminants, including byproducts from asphalt and fossil fuel combustion (e.g., PAHs), copper, zinc, lead, and chromium have increased in concentration, mirroring increased automobile use in cities and highlighting the importance of impervious surfaces as non-point pollution sources (Mielke *et al.* 2000; Davis *et al.* 2001; Paul & Meyer 2001; Beasley & Kneale 2002; Hamilton *et al.* 2004).

Key Findings: Toxic contaminants
<ul style="list-style-type: none"> • Surface and groundwater contamination by toxic substances is widespread in and near developed areas. Streams, rivers, and ground waters contain contaminant mixtures that vary in composition and concentration that are likely to produce synergistic toxicities.
<ul style="list-style-type: none"> • Some toxic contaminants originate from a few significant sources while others originate from numerous low-level sources that make significant contributions when considered in total.
<ul style="list-style-type: none"> • Substances banned from manufacture and use for years or even decades continue to pollute Oregon's aquatic ecosystems.
<ul style="list-style-type: none"> • Every year, regulatory agencies approve new compounds for use in the US. Guidelines for general water quality or aquatic life criteria are not determined for most of these compounds prior to their release into surface and ground waters. The paucity of information regarding the occurrence of these contaminants in the environment or their effects on aquatic organisms clouds our understanding of water quality in aquatic ecosystems.
<ul style="list-style-type: none"> • Traditional approaches to assessing contaminant toxicity in aquatic organisms present difficulties for translating individual responses measured in laboratory settings to population-level effects in natural environments. Little information exists about potential additive, synergistic, or antagonistic effects that may occur in complex contaminant mixtures because most toxicity research focuses on single compounds. Data on the effects of chronic exposure also are lacking for most chemicals and organisms, making ecologically relevant inferences difficult.
<ul style="list-style-type: none"> • Development of chemical analysis methods for environmental detection of the diversity of potential contaminants that enter aquatic ecosystems or their chemical breakdown products lags far behind the introduction of these compounds, particularly pharmaceuticals and personal care products (PPCPs).
<ul style="list-style-type: none"> • Most contaminants detected in Pacific Northwest waters do not have established aquatic life protection criteria. Other contaminants simply go undetected because they are not screened during water quality assessments.
<ul style="list-style-type: none"> • Many water quality surveys conducted in the Pacific Northwest detected contaminant concentrations either exceeding those determined to be protective of aquatic life or experimentally determined to cause harm to aquatic organisms.
<ul style="list-style-type: none"> • The spatial and temporal distributions of most contaminants that have been detected in surface waters in the Pacific Northwest are not adequately documented.

Section 8.0: Biological Responses of Aquatic Ecosystems to Urban and Rural-residential Development

This section integrates key findings from preceding sections of this report then summarizes what is currently known about how rural-residential and urban developments affect benthic algal and macroinvertebrate assemblages⁶⁴, fish assemblages, and salmonid populations. The previous sections documented how rural-residential and urban developments affect hydrology, physical habitat, water quality, and habitat connectivity (fish passage). These alterations occur simultaneously and exhibit strong interdependency at multiple spatial and temporal scales (King *et al.* 2005; Paul & Meyer 2001; Walsh *et al.* 2005b; Figure 2-1). Collectively these changes impair habitat required by salmonids and other native aquatic biota (e.g., Poff *et al.* 1997; Konrad & Booth 2005) and contribute to the phenomenon referred to as the 'urban stream syndrome' (see below; Meyer *et al.* 2005; Walsh *et al.* 2005b). Several key points from the earlier sections are repeated here for the reader's reference.

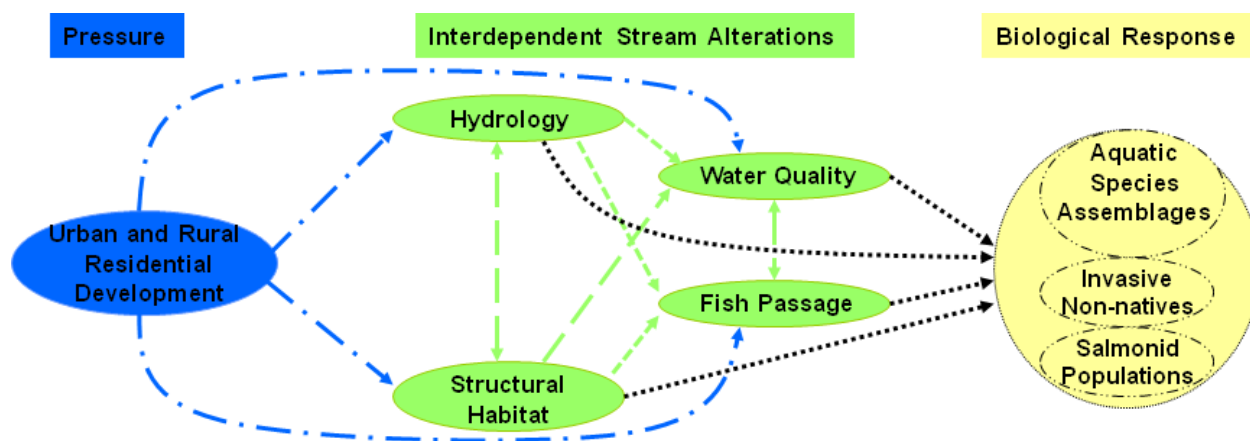


Figure 2-1. The pathways by which urban and rural-residential development alter aquatic communities and the condition of salmonid habitat and populations. Dashed/dotted (blue) arrows indicate direct effects of development on four key components of aquatic ecosystems (green). Dashed (green) arrows depict interactions among components, and dotted (black) arrows represent the influence of the altered ecosystem components on aquatic biota. This figure was first presented on page 39 of this report.

The following are integrated key findings from preceding report sections describing how rural-residential and urban development affects aquatic ecosystems in the Pacific Northwest⁶⁵:

- Rural-residential and urban developments modify processes that link surrounding landscapes to aquatic ecosystems.

⁶⁴ Following Fauth *et al.* (1996), the term assemblage refers to major taxonomic groups within a community (e.g., fish, bird, and insect assemblages). Fauth *et al.* (1996) use the term community to refer to all biota in an ecosystem.

⁶⁵ Because these concepts are discussed in detail earlier in the report, supporting references are not repeated in this summary.

- The volume and chemical composition of stormwater runoff derived from developments have diverse and persistent consequences that can extend throughout entire watersheds and are a major cause of impairment in streams flowing through developed areas. Negative effects of stormwater will increase as human populations and their ecological footprints grow.
- Increasing demands on water resources posed by human population growth and increasing development are significant threats to freshwater ecosystems. Predicted climate changes suggest that water quantity will be reduced and summer stream temperatures will be increased over the next several decades, which could exacerbate these issues in many regions of Oregon.
- Hydrologic responses to development (e.g., increased flashiness, reduced base flow) and changes in physical aquatic habitat (e.g., channelization) can increase channel capacity, stream power, channel erosion, and downstream flooding.
- Vegetation removal from riparian and upland areas and soil disturbance associated with development can increase both the proportion of water that travels through watersheds as surface runoff and the amount of sediment delivered to streams, rivers, and estuaries, while decreasing riparian cover. This combination of actions decreases habitat complexity, impairs water quality, and intensifies the effects of channelization.
- Riparian habitat loss deprives aquatic ecosystems of numerous ecological functions (e.g., buffering water temperatures, reducing erosion, recruiting large instream wood, detoxifying contaminants, sequestering nutrients) that regulate water quality, create physical habitat complexity, and supply nutrients for aquatic food webs.
- Direct modification of in-stream physical habitat (e.g., overwater structures, channel, dredging, wood and aggregate removal) intensifies the effects of altered hydrology and sediment delivery from upland sources.
- Improved wastewater treatment technologies produce progressively cleaner effluent; however, septic systems failures, combined sewer overflows, and large volumes of treated wastewater effluent generated by developments are significant sources of heat energy, organic contaminants, personal care products, pharmaceuticals, and nutrients that enter ground waters, streams, rivers and estuaries.
- For many pollutants, non-point sources contribute much of the pollution entering streams, rivers and estuaries and pose a major threat to water quality.
- The intensity, type, age, distribution of development, and pattern in which individual pollutants move through watersheds introduce variability in the nature and magnitude of water quality degradation.
- Highly engineered stormwater drainage structures and altered channels decrease nutrient retention in streams, wetlands, and riparian areas.
- Physical and physiological barriers impede fish passage within rural-residential and urban areas, but the degree to which these structures limit Oregon's salmonid populations is not well documented.

Section 8.1: Linking Assemblage and Population-level Changes to Development

The numerous physical, chemical, and biological factors in aquatic ecosystems that can be altered by development have direct and indirect effects on aquatic organisms. Because these factors are numerous and highly interdependent, it is extremely difficult to isolate individual mechanisms responsible for changes in aquatic species assemblages or populations. At any given time, combinations of various physical and chemical habitat impairments can affect the structure and dynamics of aquatic organism populations. Changes in the population dynamics of individual species subsequently affects the structure of species assemblages in aquatic ecosystems. Aquatic biota responses to development also likely depend on physiographic context (e.g., channel and watershed geomorphology, climate, sediment supply).

Selecting variables useful for characterizing potential assemblage or population-level responses to development is complex for several reasons. First, suites of factors act on assemblages and populations simultaneously. Impervious surfaces, for example, can generate 'flashy' pulses of increased flow that not only alter disturbance patterns but also pulse increased toxic contaminant, sediment, heat, and nutrient loads through aquatic ecosystems. Second, the importance of any individual factor in limiting the survival or productivity of aquatic organisms likely varies across time and space. In the Pacific Northwest, the effects of altered hydrology may be stronger during the rainy winter months while water quality impairments (e.g., temperature, dissolved oxygen, toxic contaminants) may be more important during summer low flow periods. Finally, different factors interact in poorly understood ways and possibly produce additive, synergistic, or antagonistic effects on populations or assemblages that are difficult to predict. For species with complex life histories (e.g., multiple life stages with different habitat requirements) responses measured at the individual level or within a single life stage may not translate clearly to population-level changes that are easily measured or monitored (e.g., productivity and abundance). Consequently, simply documenting physical or chemical changes in habitat does not necessarily provide accurate prediction of assemblage or population-level effects.

In the following text box, toxic contaminants are used to highlight the difficulty inherent in linking population- or assemblage-level responses to specific stressors and mechanisms. However, many of the general issues raised also arise when trying to identify the mechanisms that underlie population or assemblage-level responses to changes in hydrology, habitat structure, or other water quality variables associated with development. The effects of development on aquatic ecosystems can be evaluated in experimental streams (Angermeier & Karr 1984; Warren 1971) or by using appropriate survey designs in urban streams (Brown *et al.* 2009; Hughes *et al.* 2004; Roni *et al.* 2008; Pont *et al.* 2009). ODEQ recently published a collaborative study in the Willamette River basin using data from multiple sources and was able to identify major stressors in urban areas such as elevated water temperatures, poor riparian conditions, and unstable streambeds, and related those stressors to macroinvertebrate and fish assemblages (Mulvey *et al.* 2009). However, such studies are expensive, time consuming, and must be repeated in many different areas before broader trends can be accurately characterized. The absence of a clear understanding of such mechanisms means that it is also difficult to predict the effects of alternative development strategies on aquatic organisms in specific locales. The shortage of sufficient data indicates the need for more information on population-level and assemblage-level responses to development in a wide range of ecological settings.

Toxic Contaminants: An example of linking assemblage or population changes to development

Toxic contaminants provide a useful example of the difficulties associated with connecting any particular aspect of development to changes in fish populations or aquatic organism assemblages. Information on the identity of toxic substances, their concentrations in water, sediment, food organisms, or fishes, and the direct or indirect risks they pose to aquatic organisms is only available for a tiny fraction of the thousands of toxic chemicals present in aquatic ecosystems. Depending on their physiology, different aquatic species may exhibit variable responses to the same toxic compounds at different times. Endocrine disrupting chemicals often have non-linear dose-response relationships and affect vertebrate nervous, immune and reproductive systems rather than the typical endpoints of growth or mortality affected by other toxic compounds. The information available on specific responses of individual aquatic organisms to toxic exposure may not extend to all life history stages of the species that have been tested. Demographic characteristics of natural populations may mask or magnify physiological effects that are measurable in individuals (Spromberg & Meador 2006). As a result, high mortality may have little effect on population growth rates for some species, while other species may exhibit population-level effects stronger than what might be predicted from traditional toxicity studies. Tests do exist for traditional toxic compounds, whole effluents, and hormonal activity (Colborn *et al.* 1993; 1996), but the numbers of tests needed make such research an expensive and labor intensive undertaking.

Variable contaminant behavior influences the degree of aquatic organism exposure (Ritter *et al.* 2002). A study of ten common pharmaceuticals including ibuprofen, the anti-epileptic drug carbamazepine, and the anti-parasitic drug ivermectin found that environmental persistence varied widely (Löffler *et al.* 2005). Individual contaminants exhibit variable toxicities depending on environmental characteristics such as water temperature, pH, and salinity (LCREP 2007). For example, trace metal chemistry varies in response to pH, reactions with other inorganic or organic substances, water hardness, carbon dioxide concentrations, and biological processes. Many contaminants move into surface waters along non-point pathways and their presence in surface waters depends on use and climatic and hydrologic conditions in a watershed (Sandahl *et al.* 2005). Contaminant pulses may only last a few hours, and prolonged toxicity depends on the persistence of individual contaminants (Sandahl *et al.* 2005). Toxics may remain stationary if they bind to rapidly settling sediments, or be dispersed far from the point of entry by flowing waters. Mobile organisms can also disperse toxics to locations far from where exposure occurred (e.g., Krümmel *et al.* 2003, 2005; O'Toole *et al.* 2006).

Life-history characteristics of aquatic species determine the extents of their exposure to toxic contaminants (Sandahl *et al.* 2005; Spromberg & Meador 2006). This raises concerns for extending the results of toxicity studies to species with different life histories (Spromberg & Meador 2006). Point sources and sediment settling patterns can create contaminant 'hot spots' that affect aquatic organisms differently depending on the habitat preferences of individual species, populations, or life stages (e.g., Fresh *et al.* 2005). Pacific salmonids vary in their spatial and temporal use of various freshwater and estuarine habitats. The migratory nature of fish, even those normally considered 'resident', confounds our ability to determine when and where individuals may be exposed to contaminants. Migrating fish may experience limited exposure as they move through contaminated areas, while resident fish or fish with longer freshwater or estuarine rearing periods may endure repeated exposure to short-term pulses and long-residence contaminants for weeks, months, or years (Sandahl *et al.* 2005). More sensitive life-history stages (i.e., early developmental, juvenile, and smolt stages; McNabb 1999; Finn 2007) may experience relatively longer exposure periods to various contaminants. For example, out-migrating juvenile Chinook and coho salmon experience widespread exposure to chemical contaminants as they move through Pacific Northwest estuaries, particularly deep draft estuaries with extensive urban development (e.g., Columbia River, Yaquina Bay, Coos Bay) (Morace 2006; Johnson *et al.* 2007a; LCREP 2007). However, Johnson *et al.* (2007a) found that Chinook salmon had whole body contaminant concentrations (PCBs, DDT, PAHs, and organochlorine pesticides) 2 to 5 times higher than corresponding measures from coho salmon. These differences likely reflect variability in residence time, habitat use, and feeding behavior while in the estuary.

Section 8.2: Assemblage-level Responses to Development

In this section, IMST describes the response of assemblages (algal, macroinvertebrate, fish) and populations (salmonid) to anthropogenic changes in urban and rural-residential streams, rivers, and estuaries.

SECTION 8.21: NON-NATIVE SPECIES INTRODUCTION AND ESTABLISHMENT

Developed areas have high rates of non-native species introductions that allow some species to establish self-sustaining populations (Moyle & Light 1996b; Richardson 2000; Witmer & Lewis 2001). A few of the species that become established may become invasive. Invasive species typically reproduce prolifically, disperse widely, and alter native species populations through several mechanisms including competition, predation, and hybridization. These species ultimately modify the structure and function of invaded ecosystems (Lee & Chapman 2001; Tickner *et al.* 2001; Lodge & Schrader-Frechette 2003; Oregon Invasive Species Council 2007). Certain biological and environmental characteristics increase the likelihood that some non-native species will successfully establish and become invasive in new environments. Habitat generalists tend to be more successful as are species that experience little control from diseases, predators, or competitors that would normally limit their reproduction and spread (e.g., Witmer & Lewis 2001; Kennish 2002). Habitat alterations and disturbances may make some sites more vulnerable to invasion and some native species more vulnerable to negative biotic interactions such as competition or predation (e.g., Witmer & Lewis 2001; Meador *et al.* 2003; Zelder & Kercher 2004; Ehrenfeld 2008). Habitat alterations thought to facilitate non-native species invasions include native vegetation removal, changes in water table depth, altered hydrologic flow and fire regimes, soil and water contamination, and changes to stream and river channel morphology. All these alterations can be caused by rural-residential and urban development.

People introduce non-native species into developed landscapes both intentionally and accidentally. Deliberate introductions tend to serve aesthetic, pest control, ecosystem rehabilitation, recreation, or culinary purposes (Table 8-1). State agencies and other entities purposefully stock non-native fish species in reservoirs, lakes, and streams for biological control or recreational fishing. In past decades, many of these non-native fish have naturalized and some have become invasive including common carp (*Cyprinus carpio*), smallmouth bass (*Micropterus dolomieu*), and largemouth bass (*M. salmoides*). Accidental introductions occur when non-native species escape human management or are transported to new locations by ships, planes, recreational boats and trailers, automobiles and trucks, equipment, clothing, luggage, or packaging for live food (Table 8-1). Some non-native organisms are released into new areas when people dump aquaria and non-native pets into natural areas and municipal water systems (Gertzen *et al.* 2008). Non-native disease agents (e.g., whirling disease, *Myxobolus cerebralis*) hitchhike with other introduced species when shipments of non-native plants and animals accidentally include non-native parasites or pathogens (Chapman *et al.* 2003).

At the reach scale, it is difficult to predict where non-native species will establish and spread (Moyle & Light 1996a; Meador *et al.* 2003; Marchetti *et al.* 2006; Ehrenfeld 2008). The incidence and abundance of invasive species does not always increase with increasing human disturbance, because species dispersal is random and unpredictable (stochastic), and because urban land use creates a heterogeneous landscape of microhabitats (Weaver & Garman 1994; Fierke & Kauffman 2006; Moyle & Marchetti 2006; Ehrenfeld 2008; Vidra & Shear 2008). At

Table 8-1. Examples of invasive, non-native species present in Oregon. Species listed were introduced fairly directly by rural-residential, urban, and industrial development¹ and activities related to those areas such as inter-continental commerce. Other species, such as Himalayan blackberry (*Rubus armeniacus*) are associated with developed areas but their introductions are contributed to other land uses such as agriculture and not included here.

Selected Species	Origin; Description	Introduction Pathway into Oregon	Oregon Regions; Habitats	Impact on Aquatic Ecosystems	Selected References
English ivy (<i>Hedera helix</i>)	Europe; ornamental vine	Portland ~1800s; planted into gardens; escaped via birds	Westside; Urban forests	Outcompetes native herbs in forest; Climbs and shades trees	Stoddard <i>et al.</i> 2005; Fierke & Kauffman 2006
Purple loosestrife (<i>Lythrum salicaria</i>)	Eurasia; ornamental herb	North America early 1800s; planted into ponds; escaped via water	Westside; Freshwater habitats	Outcompetes native aquatic plants	Uveges <i>et al.</i> 2002; Zedler & Kercher 2004
Smooth cordgrass (<i>Spartina alterniflora</i>)	E North America; saltmarsh grass	Wash. 1894; accidental import; San Francisco 1970; planted for restoration; Siuslaw ~1970; spread via ballast	Coastal estuaries; Mudflats	Invades eelgrass beds used by salmonid smolts; Changes hydrology of tidal creeks in mud flats	Callaway & Josselyn 1992; Osgood <i>et al.</i> 2003; Nugent <i>et al.</i> 2005; Zedler & Kercher 2004
Green crab (<i>Carcinus maenus</i>)	Europe; estuary crab	San Francisco 1989; accidental import; Oregon ~1997; spread via ballast	Coastal estuaries; Benthic	Feeds on mussels, urchins, barnacles; May alter prey base for salmonid smolts	Nugent <i>et al.</i> 2005; Boersma <i>et al.</i> 2006
Mudsnail (<i>Potamopyrgus antipodarum</i>)	New Zealand; freshwater snail	Snake River 1987, accidental via ships; spread via boats and equipment	Statewide rivers; Benthic	Outcompetes native invertebrates; Covers rocks and other substrates; May alter trophic dynamics that support fish	Nugent <i>et al.</i> 2005
Black bass (<i>Micropterus</i> spp.)	E North America; freshwater fishes	Willamette 1888; stocked for sport; Lake Oswego ~1923; spread via stocking and migration	Statewide rivers; Urban waters	Preys upon juvenile salmonids and other small fish	Hughes & Gammon 1987; Farr & Ward 1993; Gray 2004b; Bonar <i>et al.</i> 2005; Fritts & Pearson 2005
Common carp (<i>Cyprinus carpio</i>)	Asia; freshwater fish	Willamette and Columbia Rivers ~1880; stocked for food; spread via floods and migration	Statewide rivers; Urban waters	Eats roots; Increases turbidity	Gray 2004b; Schade & Bonar 2005; Moyle & Marchetti 2006; Rahel 2007
Mosquitofish (<i>Gambusia affinis</i>)	E North America; freshwater fish	North America ~1900; garden ponds for mosquito control; spread via stocking and floods	Statewide rivers; Urban waters	Eats insect larvae and small fish; Affects trophic dynamics that support fish	Gray 2004b; Schade & Bonar 2005; Rahel 2007
Whirling disease (<i>Myxobolus cerebralis</i>)	Europe; Parasite	Eastern North America ~1950; Oregon 1986; accidental via imported salmonid stocks	Statewide rivers; hatchery fish	infects salmonid species; invades brain causes erratic swimming or death	ODFW 2001; Nugent <i>et al.</i> 2005; Miller & Vincent 2008

¹More complete listings of invasive plants and animals that affect watersheds, riparian areas, or salmonids in Oregon are available through the Oregon Department of Agriculture (www.oregon.gov/ODA/PLANT/WEEDS/), Oregon Invasive Species Council (www.oregon.gov/OISC/), and Oregon Sea Grant (www.seagrant.oregonstate.edu/themes/invasives/). Websites accessed May 24, 2010.

the landscape scale, however, the relationship between development and invasion by non-native species may be more consistent (Riley *et al.* 2005). Leprieur *et al.* (2008) found that the invasiveness of non-native fish species was strongly and positively associated with gross domestic product, percent urban area, and population density. In California, non-native fish distributions were found to be highly and positively correlated with urbanization (Marchetti *et al.* 2004; Riley *et al.* 2005). In Oregon, pollution tolerant non-native fish species were found to be highly abundant in sections of the Willamette River most affected by development (Hughes & Gammon 1987; Wentz *et al.* 1998).

SECTION 8.22: BENTHIC ALGAL ASSEMBLAGES

Algae are photosynthetic organisms that strongly influence dissolved oxygen concentrations and provide a primary food source for aquatic ecosystems. Algal assemblages respond rapidly to changes in water quality and channel substrate. Consequently, bioassessments of aquatic ecosystems affected by development often include some type of algal assemblage characterization (Sonneman *et al.* 2001; Fore & Grafe 2002; Pan *et al.* 2004; Burton *et al.* 2005; Walker & Pan 2006; Weilhoefer & Pan 2006, 2007).

The species composition of algal assemblages can change quickly in response to development (Carpenter & Waite 2000; Pan *et al.* 2004; Walker & Pan 2006; Weilhoefer & Pan 2007). Assemblage changes are highly specific to region and type of disturbance (Fore & Grafe 2002; Potapova *et al.* 2005). The abundance of certain groups of benthic algal species increases as channel structures become simplified and sedimentation is increased. For example, cyanobacteria (or blue-green algae) and green algae can live attached to concrete in modified streams and some benthic diatoms can live in areas of high sedimentation (Carpenter & Waite 2000; Kennen & Ayers 2002; Burton *et al.* 2005). Other algal species respond to changes in water quality that follow development. For example, in the Willamette River basin (western Oregon), the abundance of filamentous green algae increased in wastewater sites with high phosphorus concentrations; cyanobacteria increased in turbid waters containing organic pollution; and diatom species composition shifted in response to increased nutrients in areas of high surface runoff (Carpenter & Waite 2000). In areas where high turbidity, heavy metals, herbicides, or sediment deposition impair water quality, overall algal biomass can decrease even in the presence of high nutrient concentration (Fore & Grafe 2002; ISAB 2007b). Algal species form the basis of many aquatic food webs and changes in algal assemblages have the potential to alter productivity and diversity of species that feed on them. The potential for changes in the trophic structure of aquatic communities in waters affected by development requires additional research.

SECTION 8.23: BENTHIC MACROINVERTEBRATE ASSEMBLAGES

Benthic macroinvertebrate assemblages are rich in species that exhibit diverse responses to changes in aquatic conditions related to various land uses, including urban and rural residential development. Macroinvertebrates provide a major food source for many fishes, including juvenile and resident salmonids, therefore salmonid productivity can be limited by reductions in macroinvertebrate biomass availability (Warren 1971; Hughes & Davis 1986).

Recent studies relating macroinvertebrate assemblage indices⁶⁶ in cool and coldwater streams to urbanization typically report deteriorating index scores as the percent of urbanization increased from 0 to 90% or the percent of impervious surfaces increased from 2 to 60% (Table 8-2) with no clear threshold effects (i.e., there were no levels of urbanization where there was a no-effect level or where assemblage indices began to decline sharply). Results from these studies also show considerable variation in the response indicator (e.g., Index of Biological Integrity (IBI)) at the lower levels of urbanization (e.g., Figure 8-1). Several authors have proposed the following explanations for observed patterns of variability in macroinvertebrate assemblage data:

⁶⁶ Most recent assessments of macroinvertebrate assemblage responses to development employ some sort of index (see Appendix A for detailed descriptions of commonly used indices).

- Single measures of development intensity may not capture all aspects of development that alter aquatic ecosystems (Karr & Chu 1999; Gresens *et al.* 2007).
- Inaccurate estimates of urbanization intensity may result in variability in the response, particularly at low levels of urbanization (Karr & Chu 2000; Tate *et al.* 2005).
- Greater mismatches between the extent of a disturbance and the extent of the response at lower levels of development (Wang *et al.* 2006) or failure to consider landscape ecology variables such as connectivity, proximity, and differing resolutions on predictor and response variables (Steel *et al.* 2010b). For example, Van Sickle *et al.* (2004) found that considering the condition of the entire upstream riparian corridor provided better fit with biological responses than either entire watershed or reach-scale land uses.

Table 8-2. Selected recent literature that reported deteriorating macroinvertebrate assemblage indices with increasing levels of urban development. Literature is restricted to studies published after 1990.

Indicator	Selected References
Index of Biological Integrity (multiple metrics; USEPA 2006c)	Horner <i>et al.</i> 1997; May <i>et al.</i> 1997; Karr & Chu 2000; Booth <i>et al.</i> 2001; Morley & Karr 2002; Stark & Maxted 2004; Cuffney <i>et al.</i> 2005; Limburg <i>et al.</i> 2005; Alberti <i>et al.</i> 2007; Rodriguez <i>et al.</i> 2007
Ephemeroptera, Plecoptera, Trichoptera (pollution intolerant species; Lenat & Penrose 1996)	Richards & Host 1994; Bryce & Hughes 2002; Morse <i>et al.</i> 2003; Ourso & Frenzel 2003; Wang & Kanehl 2003; Gray 2004a; Van Sickle <i>et al.</i> 2004; Carter & Fend 2005; Limburg <i>et al.</i> 2005; Riley <i>et al.</i> 2005; Voelz <i>et al.</i> 2005; Urban <i>et al.</i> 2006; Waite <i>et al.</i> 2008.
Hilsenhoff Biotic Index (pollution tolerant species; Hilsenhoff 1982)	Ourso & Frenzel 2003; Cuffney <i>et al.</i> 2005; Voelz <i>et al.</i> 2005

Others have attempted to improve the performance of predictive variables by relating integrated measures of development to assemblage level responses (McMahon & Cuffney 2000; Brown & Vivas 2005; Tate *et al.* 2005). These estimates integrate distinct types of information about complex development patterns and better account for the numerous aspects of urbanization that may affect aquatic ecosystems (Tate *et al.* 2005). As a result, they hold promise for improving our ability to predict macroinvertebrate assemblage responses to development, particularly at lower development intensities. For example, Alberti *et al.* (2007) reported that both the configuration and amount of development were significantly correlated with macroinvertebrate IBI scores.

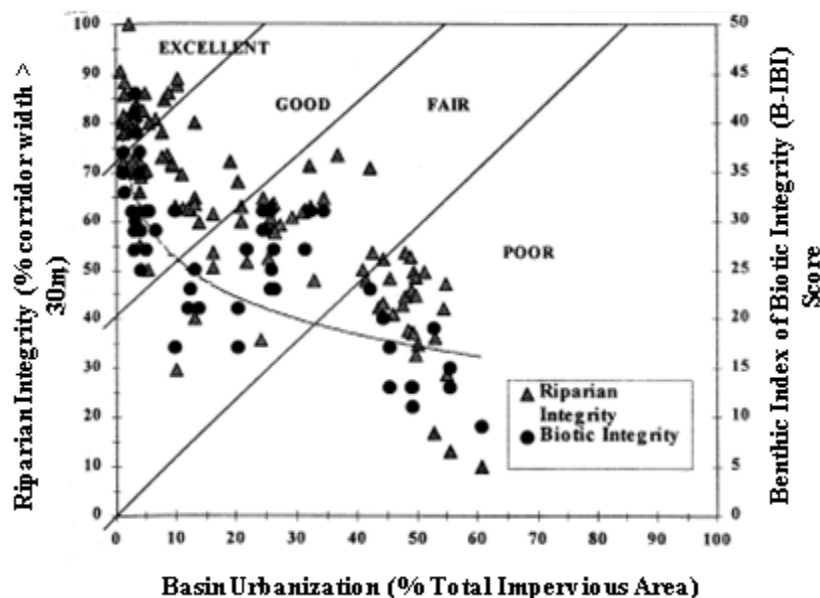


Figure 8-1. Relationship between urbanization and stream biota. Benthic index of biotic integrity (B-IBI) declines with increasing total impervious area, although the correlation is not as strong at lower impervious area. Figure also shows the potential benefits of riparian buffers in urbanizing watersheds. Reproduced from May & Horner (2000) with permission from American Water Resources Association.

SECTION 8.24: FISH ASSEMBLAGES

Fish assemblages respond differently in degree, and to different stressors, than macroinvertebrate assemblages (Yoder & Rankin 1995; USEPA 2000b; Stoddard *et al.* 2005). Therefore, measuring corroborative assemblage changes for macroinvertebrates and fishes can provide complementary evidence of development impacts, and the temporal and spatial scale of those impacts, than either assemblage provides alone (Plafkin *et al.* 1989; Stoddard *et al.* 2005; Davies & Jackson 2006). As for macroinvertebrates, various indices (e.g., IBIs) are commonly used to integrate fish assemblage data (Mebane *et al.* 2003; Hughes *et al.* 2004; Stoddard *et al.* 2005; Davies & Jackson 2006; Pont *et al.* 2006, 2009; Whittier *et al.* 2007a, b). Metrics for coldwater fish assemblages typically include number or percent of salmonids or anadromous fish.

Recent studies relating IBIs or other fish assemblage measures from cool and coldwater streams and rivers to the degree of urbanization consistently showed that the percent of salmonids, the ratio of salmon to trout, and IBI were reduced as the percent of urbanization increased from 0 to 78% or the percent of impervious cover increased from 1 to 78% (Table 8-3). As reported for benthic macroinvertebrates, there were no clear threshold effects found for fish and there was considerable variability found at low levels of development intensity (e.g., Figure 8-2).

Table 8-3. Selected recent literature that reported reduced fish assemblage and population indices with increasing levels of urban development.

Indicator	Selected References
Index of Biological Integrity	Wang <i>et al.</i> 2000, 2001, 2003c; Bryce & Hughes 2002; Drake & Pereira 2002; Mebane <i>et al.</i> 2003; Snyder <i>et al.</i> 2003; Van Sickle <i>et al.</i> 2004; Moerke & Lamberti 2006a; Matzen & Berge 2008; Meador <i>et al.</i> 2008
Percent Anadromous Fish	Limburg & Schmidt 1990, Wolter <i>et al.</i> 2000; Waite <i>et al.</i> 2008
Salmon Spawning and Productivity	Perkins <i>et al.</i> 1980; Scott <i>et al.</i> 1986; Moscrip & Montgomery 1997; Finkenbine <i>et al.</i> 2000; Pess <i>et al.</i> 2002; Regetz 2003; Bilby & Mollot 2008

At the landscape scale, fish assemblages become increasingly homogeneous⁶⁷ as development increases. This pattern is primarily due to the loss of endemic native species, physical habitat impairment, and increases in the abundance and distribution of fish species that are broadly distributed, generalists, or tolerant of poor conditions (e.g., Scott & Helfman 2001; Olden *et al.* 2006; Scott 2006; Light & Marchetti 2007; Smokorowski & Pratt 2007). For example, widely introduced and invasive fish species (e.g., common carp and mosquitofish (*Gambusia affinis*)) contribute to homogenization because their ranges are broad and continue to expand (Rahel 2000, Scott & Helfman 2001, Rahel 2007). Several non-native fish species⁶⁸ have become established and are proportionately more abundant in the Portland reach of the Willamette River (western Oregon) than elsewhere in that river (Farr & Ward 1993; Hughes & Gammon 1987; Hughes *et al.* 2005a, b, c; LaVigne *et al.* 2008). There is also considerable potential for Pacific Northwest fish assemblages to homogenize as urban development increases the occurrence or abundance of non-native aquatic vertebrates, especially if those non-natives are piscivores, such as largemouth or smallmouth bass (Gray 2004b; Bonar *et al.* 2005; Fritts & Pearson 2005; Schade & Bonar 2005).

Non-native fishes can alter native fish assemblages by introducing diseases and parasites, inhibiting native fish reproduction, increasing competition for resources, and increasing predation on native fish (Moyle *et al.* 1986; Baltz & Moyle 1993; Moyle & Light 1996a, b; (Kohler & Courtenay 2002; Marchetti *et al.* 2004). Non-native fishes also can alter habitat, the food web structure, and native fish gene pools (Kohler & Courtenay 2002). In a survey of 31 published studies, Ross (1991) found that native fish populations decreased (and sometimes disappeared) 77% of the time after non-native fish were introduced. Reed & Czech (2005) reported that non-native, invasive species were the second most common cause of fish endangerment in the US. Sanderson *et al.* (2009) estimated that the effects of non-native species on salmonid populations are comparable to those caused by hydropower, hatcheries, commercial harvest, and habitat factors.

⁶⁷ A shift to more uniform species assemblages and communities across the landscape, with a reduction of unique assemblages.

⁶⁸ For example, American shad, (*Alosa sapidissima*), smallmouth bass, largemouth bass, walleye (*Sander vitreus*), yellow perch (*Perca flavescens*), yellow bullhead (*Ameiurus natalis*), and common carp.

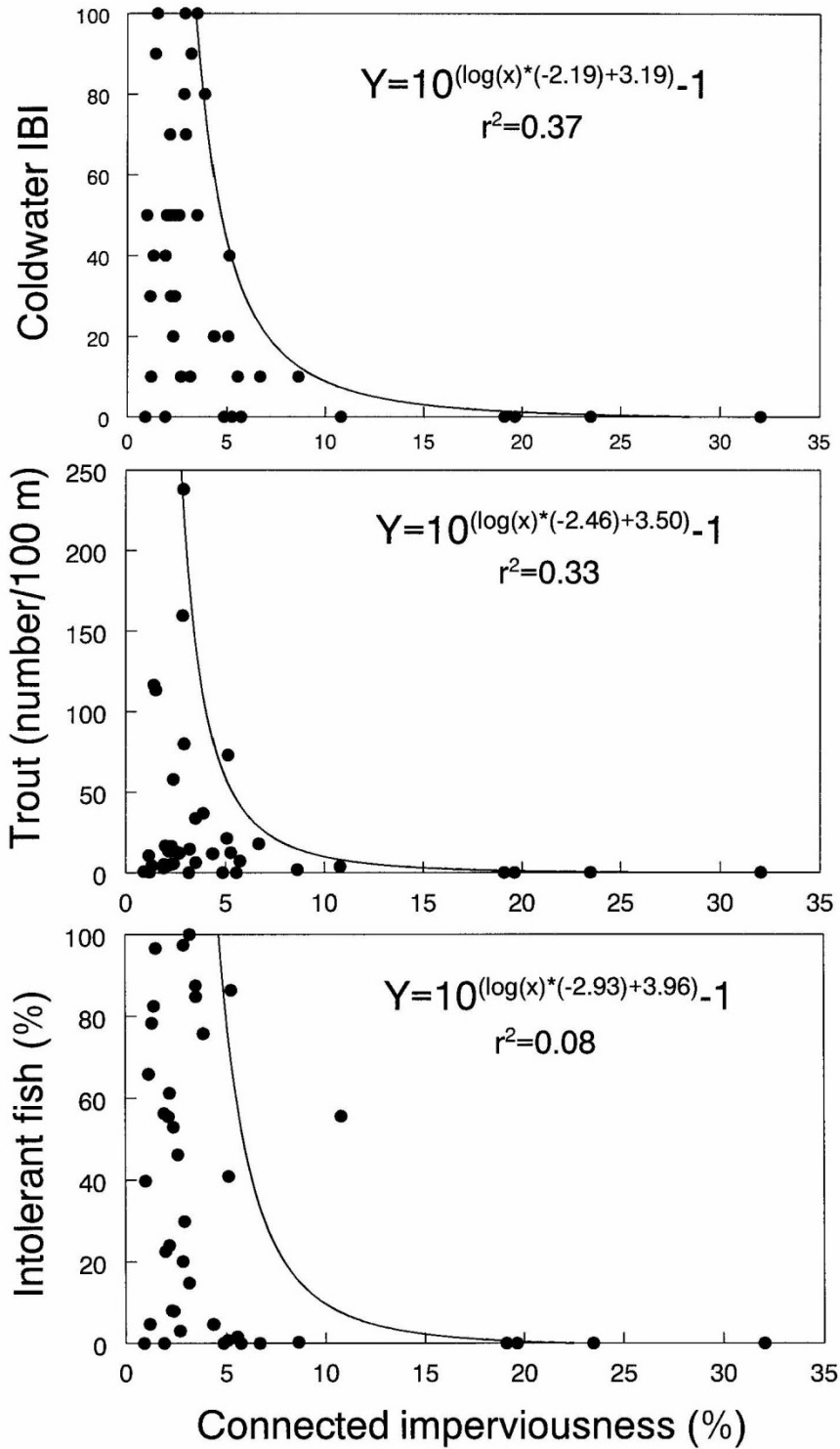


Figure 8-2. Relationships between connected imperviousness (EIA) and the index of biotic integrity (IBI), trout abundance, and percent intolerant fish in Wisconsin and Minnesota coldwater trout streams. Lines and equations on each graph represent 90% quantile regressions fit to the data using a negative exponential model. Figure reproduced from Wang *et al.* (2003b) with permission from the American Fisheries Society.

Because invasive fish are usually found in ecosystems that have already been altered, determining the independent impact of invasive fish on native fish assemblages is difficult (Moyle & Light 1996a; Moyle & Marchetti 2006). Warm-water adapted fish species may become more prevalent in aquatic assemblages as increasing temperatures compromise the reproduction, growth, and survival of common cold and cool-water species (Nelson & Palmer 2007). Temperatures that cause sub-lethal stress are an often overlooked but important component of water quality that can shift species assemblages toward species tolerant of warmer temperatures (Krause *et al.* 2004) and away from salmonids (Reeves *et al.* 1987; LaVigne *et al.* 2008; Sanderson *et al.* 2009).

Section 8.3: Salmonid Population-level Responses to Development

Because salmonids are a focus of this report, this section expands on the effects development can have on salmonids.

Urban and rural-residential developments are frequently located along streams, rivers, and estuaries. Anecdotal evidence, current observations of habitat preferences, historical land surveys, and canning records (Gresh *et al.* 2000) suggest that river reaches flowing through Oregon's urban centers once supported large numbers of salmonids (Groot & Margolis 1991; Stanford *et al.* 1996; Quinn 2005). In the Pacific Northwest, there is a growing understanding that aquatic habitat affected by existing development is important for salmonids (e.g., Pess *et al.* 2002; Regetz 2003; MacCoy & Blew 2005; Sheer & Steel 2006; Burnett *et al.* 2007; Bilby & Molloy 2008). Projections of future land use and land cover in Oregon's coastal mountains show increasing rural-residential and urban development within 328-foot (100-meter) buffers surrounding high quality coho and steelhead habitat, with more rapid development projected for coho habitat (Burnett *et al.* 2007).

Although many studies have characterized habitat preferences or habitat quality for salmonids, most research has associated habitat data collected at or below the stream-reach scale with measurements taken from individual fish. The few studies documenting salmonid population-level responses to development have characterized the presence or health of salmonid populations in relation to land use at the scale of watersheds or river basins. Key findings from these studies include:

- River basins in the Puget Sound (western Washington) region that experienced significant urban development between the 1940/50s and the 1980/90s also experienced salmon abundance declines higher than those in reference basins (Moscrip & Montgomery 1997).
- In the Snohomish River basin (western Washington) adult coho salmon abundance declined on lands converted to urban uses between 1984 and 1998 (Pess *et al.* 2002).
- In a comparison of 22 spring-summer Chinook salmon populations in Oregon, Washington, and Idaho, productivity was lowest in sub-watersheds with more urban land cover (Regetz 2003).
- In the Seattle (Washington) area between 1986 and 2001, coho salmon declined by 75% in index sites affected by development (Bilby & Molloy 2008).

- Also in the Seattle (Washington) area, 24% to 86% of adult coho salmon entering streams affected by urban development die before they spawn compared to approximately 1% in nearby forested streams (Bilby & Mollet 2008). The causes of these high pre-spawning mortality⁶⁹ rates remain under investigation but have been associated with road density (Sandahl *et al.* 2007; ISAB 2007b).
- In a study of 721 Toronto (Ontario, Canada) sites, salmonids declined rapidly as percent impervious cover increased from 0 to 10% and they tended to disappear when percent impervious cover exceeded 10% (Stanfield & Kilgour 2006; Stanfield *et al.* 2006).
- Stranko *et al.* (2008) reported that when areas were only slightly affected by urban development, salmonids disappeared from Maryland streams.
- In the Willamette Valley (western Oregon), the percent of fish assemblages composed of salmonids declined considerably in sites with high levels of urban development (Waite *et al.* 2008).

As discussed in-depth in Sections 4 through 7, development alters hydrology, water quality, physical habitat, and habitat connectivity in ways that not only are detrimental to salmonids and aquatic life in general but are also disproportionate to their land area (Paul & Meyer 2001; Allan 2004; Booth 2005; Brown *et al.* 2005b; Walsh *et al.* 2005b). The loss of spawning, rearing, or refuge habitats equates to reduced species abundance, production, and resiliency in the face of natural and anthropogenic disturbances. Development along lowland streams and estuaries may impose a limiting factor for populations of salmonid species such as chum salmon, coho salmon, and cutthroat trout that rely heavily on lowland habitat for spawning and rearing (Thorpe 1994; May *et al.* 1997; Burnett *et al.* 2007).

Hydrologic alterations and structures intended to stabilize stream banks often convert rivers from complex, multi-channel, meandering paths to simplified, narrow, deep channels that are disconnected from side channels, wetlands, and floodplains (Sedell & Froggatt 1984; Sedell *et al.* 1990; Benner & Sedell 1997). The interaction between active channels and floodplains during lateral channel migration and floods is an important process that creates habitat for salmonids (Amoros *et al.* 1987; Gregory *et al.* 1991). Urban and rural-residential land use actions (e.g., removing riparian and upland vegetation, channelization, bank armoring, inter-basin water transfers, dams, dikes) that alter upland, floodplain, and stream channel hydrology collectively contribute to the loss of habitat for salmonid spawning, rearing, migration, and protection from predators and adverse conditions

Removing riparian vegetation may decrease available habitat created and maintained by large instream wood and lead to increases in water temperatures, sediment inputs, and organic nutrient inputs to streams. Intact riparian areas perform several key functions that create and maintain salmonid habitat including supplying large wood to the stream channel, stream temperature regulation, stream bank stabilization, and regulation of organic nutrient and sediment inputs. Simplification of reach-scale temperature variability results in loss of coldwater refugia that allows organisms to avoid unfavorable temperatures over short periods, thus reducing habitat available for coldwater-adapted salmonids (Poole & Berman 2001). Increased temperature and

⁶⁹ Information available on the NOAA Northwest Fisheries Science Center websites: http://coastalstorms.noaa.gov/stormwater/index.php?option=com_content&task=view&id=8&Itemid=12 and <http://www.nwfsc.noaa.gov/research/divisions/ec/ecotox/movies/cohopsm.cfm>. Accessed on October 12, 2010.

nutrient inputs can cause rapid algal growth resulting in gas supersaturation during the day and substantial oxygen deficits at night, both of which stress salmonids.

Habitat connectivity is affected by fish passage barriers (e.g., dams, diversions, improperly placed and sized culverts, impaired water quality) that restrict or completely block upstream or downstream movement among critical habitats. This can eliminate mobile life history forms from upstream communities (Beechie *et al.* 2006; Neville *et al.* 2006a) and diminish the long-term persistence of populations that become spatially restricted in limited habitats (Wofford *et al.* 2005; Fausch *et al.* 2006).

The degree to which development affects any salmonid population depends on how the species uses habitats within the ecological footprint of a development. In addition to habitat loss, development may limit salmonid population productivity or persistence by:

- Reducing survival,
- Altering behavior, and,
- Altering reproduction, growth, and development.

SECTION 8.31: REDUCED SURVIVAL

Many aquatic ecosystem changes imposed by development affect salmonid survival. Acute lethal events may occur over short periods (e.g., seconds to days) in response to high water temperatures, low dissolved oxygen concentrations, or exposure to high concentrations of toxic substances that interfere with critical physiological functions (e.g., nervous system coordination). In contrast, chronic sub-lethal effects that reduce long-term survival may result from any hydrologic, physical habitat, connectivity, or water quality change that does the following:

- Interferes with normal growth or development;
- Suppresses normal immune function;
- Impairs normal adaptive behaviors (such as predator avoidance, social interactions or migration); or
- Interferes with reproductive development.

Much of the literature documenting salmonid survival in waters affected by development focuses on various water quality impairments. Salmonids require relatively cold water during most life history stages and can experience both lethal and sub-lethal effects from elevated water temperature (Table 7-1; reviewed in McCullough 1999, McCullough *et al.* 2001; IMST 2004). Reduced summer base flows resulting from either municipal water use or decreased groundwater recharge can induce stress-related infections and mortality by increasing water temperature, decreasing dissolved oxygen concentrations, and restricting fish movements to suboptimal locations (Macdonald *et al.* 2000; Rand *et al.* 2006; Newell *et al.* 2007). Elevated suspended sediment concentrations affect both juvenile and adult salmonids but juveniles are particularly vulnerable (Newcombe & MacDonald 1991; Servizi & Martens 1991). Many authors associate acute physiological effects of suspended sediment with gill damage, which causes respiratory impairment and leads to multiple secondary effects (e.g., Newcombe & Flagg 1983; Berg & Northcote 1985; Waters 1995). Suspended sediment effects are mediated by exposure duration

and concentration, with longer exposures and higher concentrations causing greater damage (Newcombe & MacDonald 1991; Servizi & Martens 1992; Newcombe & Jensen 1996). Suspended sediment effects in salmonids include abnormal blood chemistry, weight loss, increased susceptibility to bacterial infection, and death (Newcombe & MacDonald 1991; Waters 1995; Lake & Hinch 1999; Henley *et al.* 2000; Robertson *et al.* 2006).

Toxic contaminants can result in direct mortality or cause a variety of sublethal effects (Table 7-2; Arkoosh *et al.* 1998a). Studies conducted in several Pacific Northwest estuaries affected by development (e.g., McCain *et al.* 1990; Stein *et al.* 1995; Stehr *et al.* 2000) showed that migrating juvenile salmon were exposed to contaminant levels associated with reduced disease resistance and growth (Arkoosh *et al.* 1998a, b, 2001; Johnson *et al.* 2007a, b). Loge *et al.* (2005) estimated that exposure to toxic contaminants in the Columbia River estuary may cause mortality rates of 1.5 to 9% for juvenile Chinook salmon depending on habitat use. Juvenile salmon undergo a period of rapid growth and development and experience many physiological changes during the time they spend in estuaries. Therefore, contaminant exposure may significantly affect the long-term health and survival of these fish as they enter marine environments (Meador *et al.* 2002; Loge *et al.* 2005; Spromberg & Meador 2006; Johnson *et al.* 2007a).

SECTION 8.32: ALTERED BEHAVIOR

Salmonids will actively avoid waters with high suspended sediment concentrations (Bisson & Bilby 1982; Sigler *et al.* 1984; Henley *et al.* 2000; Robertson *et al.* 2007). Cederholm & Reid (1987) found that juvenile coho salmon avoided streams with >4 g/L suspended sediment. High sediment inputs can also bury riffle habitats that are essential for over-winter survival of juvenile salmonids (Bustard & Narver 1975; Hillman *et al.* 1987), and fill pools frequently used by multiple age-classes (Saunders & Smith 1965; Waters 1995), thereby forcing salmonids into sub-optimal habitats. Suspended sediment concentrations also influence foraging behavior and, consequently, growth (Henley *et al.* 2000; Bash *et al.* 2001). While this is generally a negative relationship, with higher suspended sediment concentrations leading to lower growth (Crouse *et al.* 1981; Sigler *et al.* 1984), the dynamic can be complex. Decreased predation risk in turbid waters (e.g., 0.02-0.18 g/L; Robertson *et al.* 2007) may allow juvenile salmonids to spend more time in open water, away from cover (Gregory 1993; Gregory & Levings 1998; De Robertis *et al.* 2003; Newcombe 2003; Korstrom & Birtwell 2006). Increased foraging time may be counteracted by diminished foraging success (i.e., rate of prey capture), leading to net energetic losses and decreased growth. Suttle *et al.* (2004) found that juvenile steelhead foraging success and growth were negatively associated with excess fine sediment because benthic invertebrate prey availability was reduced in highly embedded substrates. In general, streams, rivers and estuaries with elevated suspended sediment loads are less productive than systems with lower suspended sediment loads and are less likely to support large numbers of salmon and trout (Lloyd *et al.* 1987; Waters 1995).

Salmonids possess highly developed sensory systems that play a critical role in predator avoidance, kin recognition, spawning behavior, and migration timing and direction. Some salmonid sensory organs (e.g., olfactory receptor neurons) operate in direct contact with the aquatic environment putting them at risk of damage by water contaminants. Copper and several organophosphate pesticides have been found to impair salmonid olfactory nervous systems (Table 7-2), thus inhibiting their ability to detect chemical signals and respond appropriately.

The concentrations of copper and pesticides used in laboratory experiments generally reflect those detected in waters affected by development (e.g., the Columbia River estuary; Fresh *et al.* 2005). The effects of copper toxicity on the salmonid olfactory system occur rapidly, rendering fish unable to avoid continued copper exposure after the first few minutes (Baldwin *et al.* 2003). Recovery from copper exposure may require several hours to days or weeks depending on the level and length of exposure (Sandahl *et al.* 2007). Because these contaminants are common in stormwater runoff, salmonids can be exposed to repeated contaminant pulses over time.

SECTION 8.33: ALTERED REPRODUCTION, GROWTH, AND DEVELOPMENT

The documented effects of sewage effluents on fish include feminization and likely sterility of male salmonids as well as precocious maturation in females, again likely leading to functional sterility (Kime 1998; Matthiessen 1998; Matthiessen & Sumpter 1998; McNabb *et al.* 1999). Human birth control hormones are estrogenic endocrine disrupting compounds (i.e., they interfere with the normal action of an individual's hormonal system) that are not removed by sewage treatment facilities and are discharged into surface waters with treated wastewater. In terms of toxicity, even low exposure levels to reproductive hormones may have significant implications for salmonid populations (Kolpin *et al.* 2002; Cui *et al.* 2006 and references cited therein; Kidd *et al.* 2007). The breakdown products of detergents (nanophenols) are also mildly estrogenic. Research conducted in Great Britain (Kime 1998) first documented that detergent breakdown products pass through water treatment facilities and act as endocrine disruptors in trout reproduction. Additional experiments have also shown that downstream migration of Atlantic salmon (*Salmo salar*) smolts is delayed when fish are exposed during smoltification (Madsen *et al.* 2004).

Excess sedimentation caused by rural-residential and urban development can significantly reduce the quantity of available spawning habitat in affected streams (Lohse *et al.* 2008). Fine sediments can impair salmonid spawning and incubating habitat by limiting the delivery of dissolved oxygen to developing eggs and alevins, reducing waste product removal, or hindering fry emergence from redds. Galbraith *et al.* (2006) reported that when fine sediment concentrations reached 9 g/L, sockeye and coho salmon egg fertilization rates decreased by $\geq 80\%$. Sediments that settle out of the water column clog interstitial spaces in redds and trap salmonid eggs and alevins in oxygen-deprived environments (Bjornn & Reiser 1991; Waters 1995; Greig *et al.* 2005; Julien & Bergeron 2006; Lévassieur *et al.* 2006; Heywood & Walling 2007). High rates of pre-emergence mortality have been observed when fine sediments exceed 15 to 20% of spawning gravel weight (Quinn 2005). Chinook and steelhead egg survival decreased to 5% as fine sediment concentrations increased in a northern California stream (Meyer 2003). The survival and emergence of salmonid fry can be reduced by as much as 50% when fine particles make up more than 30% of spawning substrates (Kondolf 2000).

Altered water temperatures can interfere with adult migration by advancing or delaying it (Quinn & Adams 1996; Cooke *et al.* 2004; Goniea *et al.* 2006) and by creating thermal barriers to upstream movement (Alabaster 1988; Quinn *et al.* 1997). Spawning activity (i.e., redd excavation, egg deposition, and fertilization) may cease if water temperatures are not favorable (McCullough *et al.* 2001; Sauter *et al.* 2001). Temperature governs both development rate and survival of salmonid eggs and alevins (Murray & McPhail 1988; McCullough *et al.* 2001; Nelitz *et al.* 2007). Temperature cues often initiate seaward migrations of juvenile salmonids (Roper &

Scarnecchia 1999; Achord *et al.* 2007). Other temperature-mediated mechanisms that affect salmonid growth include disease resistance, competitive ability, and predation risk (Brett 1956; Poole *et al.* 2001, 2004; Nelitz *et al.* 2007).

There is limited information on the direct effects of altered hydrologic conditions on fishes in urban streams, rivers, and estuaries. The growth and swimming speed of blacknose dace (*Rhinichthys atratulus*) inhabiting urban streams in Baltimore (Maryland) had negative correlations with some aspects of urban development (i.e., impervious surface area) that can alter watershed hydrology (Nelson *et al.* 2003; Nelson *et al.* 2008). If such effects also occur in salmonids, hydrological modifications that follow development could reduce their growth and development.

Key Findings: Biological responses
<ul style="list-style-type: none"> It is inherently difficult to link assemblage- and population-level changes to specific (or combinations of) physical, biological, or chemical factors that have been altered by urban and rural-residential development. Few studies have documented salmonid-level responses to urbanization of watersheds.
<ul style="list-style-type: none"> Developed areas facilitate intentional and accidental introductions of non-native species. Introduced species may become invasive and can modify the ecological structure and function of native riparian and aquatic ecosystems.
<ul style="list-style-type: none"> Benthic algal assemblages can respond quickly to changes in water quality and sedimentation.
<ul style="list-style-type: none"> Algal species form the basis of many food webs and changes in assemblages have the potential to affect the trophic structure of aquatic ecosystems.
<ul style="list-style-type: none"> Macroinvertebrates provide a major food source for many fishes, including juvenile and resident salmonids; therefore salmonid productivity can be limited by reductions in macroinvertebrate biomass availability. Benthic macroinvertebrate assemblages are rich in species that exhibit diverse responses to changes in aquatic conditions related to various land uses, including urban and rural residential development.
<ul style="list-style-type: none"> At the landscape scale, fish assemblages become increasingly homogeneous as development increases because of the loss of endemic species, aquatic habitat impairment, and an increase in non-native fish.
<ul style="list-style-type: none"> Development may limit salmonid population productivity or persistence by reducing habitat quality, quantity, and accessibility; by reducing reproduction rates, survival, growth, and development at various life-stages; and by altering behavior such as foraging and migration.

Science Question 2 – How might Oregon accomplish the mission of the Oregon Plan in the face of an increasingly urbanized landscape?

In 1997, the State of Oregon established the Oregon Coastal Salmon Restoration Initiative Conservation Plan which later became the broader state-wide Oregon Plan for Salmon and Watersheds (i.e., the Oregon Plan). This mission of the Oregon Plan is to “*restore the watersheds of Oregon and to recover the fish and wildlife populations of those watersheds to productive and sustainable levels in a manner that provides substantial ecological, cultural and economic benefits*” (Oregon Revised Statute 541.405(2)(a)). The Oregon Plan focuses on factors that contribute to the decline of native salmonids and watershed health. While most measures and restoration actions have been focused on forest and agricultural resource lands, there is a growing recognition and effort to improve aquatic ecosystems and watersheds affected by urban and rural-residential areas. This section focuses on approaches to meeting the goals of the Oregon Plan that are unique to urban and rural-residential areas.

Section 9.0: Potential Contributions to the Oregon Plan

The potential for developed areas to contribute to the mission of the Oregon Plan should not be underestimated. Between 1950 and 2000, Oregon's human population increased 125% to 3.4 million residents and is projected to add another 1.5 million residents by 2030 (US Census Bureau 2005). Most of these new citizens will reside in urban areas (US Census Bureau 2003) located along streams, rivers, and estuaries that are important to the persistence and recovery of native salmonids, including a number of federally-listed species (see Section 1.31 of this report). Protecting or improving the condition of aquatic ecosystems within urban and rural-residential developments will help ensure that developed lands contribute to the persistence and recovery of salmonid populations across broader spatial scales. Unless proactive measures are taken to avoid or mitigate the effects of current and future development, however, it will be difficult to reverse or slow the impairment of aquatic habitat quality and function as Oregon's human population continues to increase.

In the literature previously reviewed by IMST (see Sections 2.0–7.0 of this report) and others (Paul & Meyer 2001; Allan 2004; Kaye *et al.* 2006), impaired water quality, degraded physical habitat, altered flow regimes, and blocked fish passage are commonly linked to the types of engineering and development practices used on developed lands, the patterns in which developments expand, the consumer products widely used in developed areas, and the trends in resource use and waste production on developed lands. Consequently, the outcomes of natural resource policies and management actions, such as the Oregon Plan, will be affected by the extent and location of rural-residential and urban development resulting from Oregon's future population growth (Kline *et al.* 2007; Bilby & Mollot 2008) and associated economic growth (e.g., Reed & Czech 2005).

In Science Question 2, IMST examines scientifically credible approaches to avoiding, minimizing, or mitigating the adverse effects of development with emphasis on concepts relevant to salmonid population persistence and recovery. The following sections provide:

- A review of futures analyses completed in the Pacific Northwest and the potential of such analyses to serve as planning tools.
- An overview of strategies and actions that could be used to guide the placement and construction of future developments in ways that are more protective of aquatic ecosystems.
- Selected examples of proactive measures underway in the Pacific Northwest.
- A summary of how the aquatic ecosystem response to developed land uses is currently monitored in Oregon.

Section 9.1: Futures Analysis as a Planning Tool

Minimizing aquatic ecosystem impairments while Oregon's human population and economy grow requires understanding where and how future development is likely to occur. Spatial models of future land use planning and socioeconomic trend data (e.g., past land use change, socioeconomic factors that drive land use change, contemporary housing and population trends) to characterize a range of landscape configurations possible under different policies, management actions, and development scenarios (Hulse *et al.* 2004; Kline *et al.* 2007). Such models are powerful tools for evaluating how land use policies and programs could drive the location and extent of future development (Kline 2005a, b). When model predictions of future land use configurations are made at appropriate spatial and temporal scales, they may also be used to predict potential consequences of different development scenarios on ecological processes, ecosystem condition, and the recovery or persistence of salmonid populations (Kline *et al.* 2007).

The accuracy of futures analyses depends on how well models represent the complex interactions among socioeconomic forces, changing landscapes, and ecological processes (Nilsson *et al.* 2003). Extrapolating aquatic ecosystem responses to future development requires the integration of multiple models parameterized with knowledge from diverse disciplines including economics, hydrology, geomorphology, and ecology (Nilsson *et al.* 2003). The capacity to construct and parameterize models that forecast ecological condition is limited by information gaps within each of these disciplines. Applying model results to natural resource management requires consideration of how socioeconomic trends and land use policies may change in the future (Kline *et al.* 2007; see Section 1.43 of this report). However, such changes are difficult to predict and can reduce the level of certainty associated with results from futures analyses.

In practice, efforts to model alternative futures are intended to demonstrate relative outcomes (as opposed to exact endpoints) of decisions made about the use of land and water resources (Baker *et al.* 2004; Burnett *et al.* 2007). Significant efforts have been made to model the location and density of future population growth and development in the Pacific Northwest and to characterize the implications of future land use change for aquatic and terrestrial habitat condition (Table 9-1). While the level of certainty associated with any individual extrapolation of aquatic ecosystem condition is low (e.g., Van Sickle *et al.* 2004), the majority of futures analyses conducted for Pacific Northwest landscapes indicate that future development could have moderate to severe consequences for riparian and aquatic habitat condition and aquatic biota (Table 9-1). These results mirror findings from a retrospective analysis of salmon distributions carried out in four river basins that drain to Puget Sound (Washington).

Table 9-1. Examples of Futures Analyses. These examples predict how human population growth and development may affect aquatic ecosystems in the Pacific Northwest.

Location	Spatial; Temporal Scale	Modeling Objectives Relevant to Natural Resource Management	Demographic Predictive Variable	Key Findings Relevant to Aquatic Ecosystem Management	Reference
Oregon	Willamette River Basin; 1850, 1990, 2050	Modeled future landscapes for three alternative development scenarios including current land use policies, a market-oriented approach, and prioritization of ecosystem protection and restoration. Endpoints evaluated included water availability, channel structure, riparian condition and fish species richness in the Willamette River; ecological condition of other streams; and terrestrial vertebrate populations.	Doubling of 1990 population by 2050	Continuation of current land use policies resulted in expansion of urban areas, but limited basin-wide effects on aquatic biota. Relaxation of current environmental policies had limited effects on aquatic biota primarily because most development occurred on land already highly modified by agricultural uses. Increased conservation measures significantly improved indicators of stream condition. Out of stream water uses increased by 40 to 60% under all three scenarios.	Baker <i>et al.</i> 2004
Oregon	Willamette River Basin; 1990 to 2050	Evaluated the impact of current approaches for water use on future water resource availability.	Doubling of 1990 population by 2050	A basin-wide approach is unnecessary for understanding many water management issues. Modest, comprehensive conservation efforts are insufficient for protecting instream flows. Increased urban water use does not seriously affect junior water right holders.	Dole & Niemi 2004
Oregon	Willamette River Basin; 1800's, 1990, 2050	Modeled future landscapes for three alternative development scenarios including current land use policies, a market-oriented approach, and prioritization of ecosystem protection and restoration. Endpoints evaluated included fish and aquatic invertebrate assemblages.	Doubling of 1990 population by 2050	Agricultural and urban land development occurring since the 1800's is associated with statistically significant reductions in the condition of aquatic biota. Conservation actions modeled have the potential to rehabilitate aquatic biota. Maintenance or relaxation of current environmental policies had limited effects on aquatic biota primarily because most development occurred on land already highly modified by agricultural uses.	Van Sickle <i>et al.</i> 2004
Oregon	Coastal Province; 1996 to 2096	Modeled the intrinsic potential for high quality rearing habitat for juvenile coho salmon and steelhead as a function of present and future landscape characteristics based on current land management policies.	Gravity Index (Kline <i>et al.</i> 2003)	Stream reaches with high intrinsic potential to support rearing habitat for coho salmon were disproportionately affected by developed land uses. Recovery of steelhead or coho populations likely depends on habitat improvements on private lands.	Burnett <i>et al.</i> 2007
Montana, Wyoming, Idaho	Greater Yellowstone Ecosystem; 1990-1999	Modeled affects of three rural-residential development scenarios on various habitat metrics, including riparian habitats.	Contemporary demographic trends	Rural-residential homes were more likely to be located in riparian habitats than what would be expected if new home constructions was distributed randomly.	Gude <i>et al.</i> 2007

Table 9-1, *continued*. Examples of Futures Analyses. These examples predict how human population growth and development may affect aquatic ecosystems in the Pacific Northwest.

Location	Spatial; Temporal Scale	Modeling Objectives Relevant to Natural Resource Management	Demographic Predictive Variable	Key Findings Relevant to Aquatic Ecosystem Management	Reference
Oregon: East of the Cascade Mountains	Northeast, Central, and Klamath regions analyzed separately; 2000 to 2025	<p>Predict extent and density of future development from known land use patterns and trends.</p> <p>Evaluate loss of forest, range and agricultural land to developments of varying density.</p> <p>Evaluate wildfire risk posed by future development.</p>	Modeled building counts and building count changes	<p>Data on past and current human population growth and land use trends may be insufficient to predict future development patterns.</p> <p>Spatial land use models should be used in conjunction with other economic data sources (e.g., increased tourism) to predict the probabilities and patterns of future development.</p> <p>Crook, Deschutes, Jefferson and northern Klamath counties are predicted to undergo the highest conversion of forest, range, and agricultural lands to more densely developed lands.</p>	Kline <i>et al.</i> 2007
California	Russian River Basin; 1994 to 2002; 2002 to 2010	Modeled the potential sediment response to land use change forecasts for agricultural, rural-residential and urban land uses.	Contemporary demographic and land use trends	<p>The total land area converted to rural-residential uses was greater than that converted to urban use.</p> <p>The location of future rural-residential development ranged into previously undisturbed areas more likely to contain high quality salmonid spawning habitats.</p> <p>Future increases in rural-residential development have greater potential to reduce the quantity and quality of existing salmonid spawning habitats.</p>	Lohse <i>et al.</i> 2008

Bilby & Molloy (2008) correlated changes in the spawning distribution of coho salmon with changes in land use that occurred between 1986 and 2001. Over this period, the portion of the study area covered by urban development increased from 7 to 13% and the area in rural-residential uses increased from 11 to 21% (Bilby & Molloy 2008). Coho salmon populations underwent rapid declines in the portions of the study area most affected by urban development.

As research in economics, hydrology, ecology, and other relevant disciplines fills critical knowledge gaps, the utility of futures analyses in evaluating and setting land use policies will increase. Ultimately, such analyses could become a very useful part of the routine toolset used by city-, county-, and state-level land managers (Baker *et al.* 2004). Such efforts are already underway in Oregon. The Metro regional government (northwestern Oregon), for example, modeled potential outcomes of four future growth patterns on land consumption and air quality (Metro 2000). More recently, resource managers in Benton County (western Oregon) completed a comprehensive analysis of future water demands (Benton County 2008). A significant effort currently underway to plan for Oregon's future water supply needs is the Oregon Water Supply and Conservation Initiative overseen by OWRD⁷⁰. The impetus and strategy for this initiative are detailed in the following section.

SECTION 9.11: PLANNING FOR OREGON'S LONG-TERM WATER SUPPLY NEEDS

The Oregon Progress Board (2000) has identified inadequate water supply as one of the major environmental challenges facing the state. Oregon water law allocates available water resources across users who hold water rights. At any given time, prioritization of water use is determined by a seniority system established by the date OWRD received a user's application for the water right, the amount of water allocated to individual water rights, and the actual amount of water available (Dole & Niemi 2004). Presently, available surface water resources are either fully- or over-appropriated during low flow periods (i.e., summer and fall months) and pressure on groundwater resources is growing in many areas (Oregon Progress Board 2000; ISAB 2007b; Snell & Colbert 2007; Figures 9-1 and 9-2). Because shallow groundwater aquifers connect with and supplement surface water flows, an increased use of groundwater resources has the potential to further reduce surface water supplies (Snell & Colbert 2007).

Human population growth will increase the demands made on Oregon's existing water resources, particularly in the face of a changing climate (Houston *et al.* 2003). Technological innovations that increase water use efficiency may help offset the need to develop additional water resources to meet future demands (Houston *et al.* 2003). However, with limited water resources available for new uses, conflicts between in-stream (e.g., salmonids, maintaining adequate streamflows) and out-of-stream uses will increase. Such conflicts have the potential to become divisive and can be expensive to resolve (Snell & Colbert 2007). Increasing demands on water resources will present significant challenges as resource managers and policy makers weigh difficult tradeoffs among competing social, economic, and ecological uses. Resolution of such challenges requires an understanding of future water availability, water demands, and social priorities on water use (Jenerette & Larsen 2006).

Of the 18 western US states, only Oregon and Alaska have no plan for meeting future water requirements (Snell & Colbert 2007). Several steps have been taken by the State of Oregon to

⁷⁰ http://www.wrd.state.or.us/OWRD/LAW/owsci_info.shtml. Accessed December 16, 2009.

identify and meet future water needs. The Oregon Governor created the Headwaters to Ocean⁷¹ initiative with the goal to identify priorities and strategies for meeting future water needs in Oregon. The Headwaters to Ocean advisory council recommended an approach that consists of initiating investments in long-term efforts to collect data for planning purposes and addressing short-term concerns related to current water supplies, water conservation, pollution control and prevention, monitoring water use, and ecosystem services. OWRD identified 5 key components in its Oregon Water Supply and Conservation Initiative⁷² including:

- Assessing statewide water demands;
- Inventorying sites with the potential to increase above- and below-ground water storage;
- Identifying opportunities for conservation of water resources;
- Conducting analyses of basin-wide water yields; and
- Providing financial support to local communities engaged in water supply planning.

The budget passed by the Oregon Legislature for the 2009-2011 Biennium included \$3.5 million for activities and investments related to water resource management including:

- Development of an integrated water resource management strategy to be cooperatively overseen by OWRD and ODEQ (House Bill 3369);
- Expenditures for infrastructure projects that will increase water conservation (e.g., aquifer storage and recovery); and
- Expenditures to meet future water supply needs (including those of fish and wildlife) while also protecting ground and surface water quality.

In addition, OWRD is currently seeking to develop a long-term water supply strategy and has recently implemented a survey to gather information that will aid in forecasting future water demands and supplies through 2025 and 2050 at the county or river basin level⁷³. OWRD is also currently administering a \$1.6 million grant program that supports research into the feasibility of various water conservation, reuse or storage sites or technologies⁷⁴.

⁷¹ <http://governor.oregon.gov/Gov/GNRO/14jan09-h2o-strategy-home-page.shtml>. Accessed December 16, 2009.

⁷² www.wrd.state.or.us; <http://www.wrd.state.or.us/OWRD/LAW/owsci.shtml#Updates>. Accessed December 16, 2009.

⁷³ Reports derived from this survey can be downloaded at http://www.wrd.state.or.us/OWRD/LAW/owsci_info.shtml. Accessed December 16, 2009

⁷⁴ http://www.wrd.state.or.us/OWRD/LAW/conservation_supply.shtml. Accessed December 16, 2009

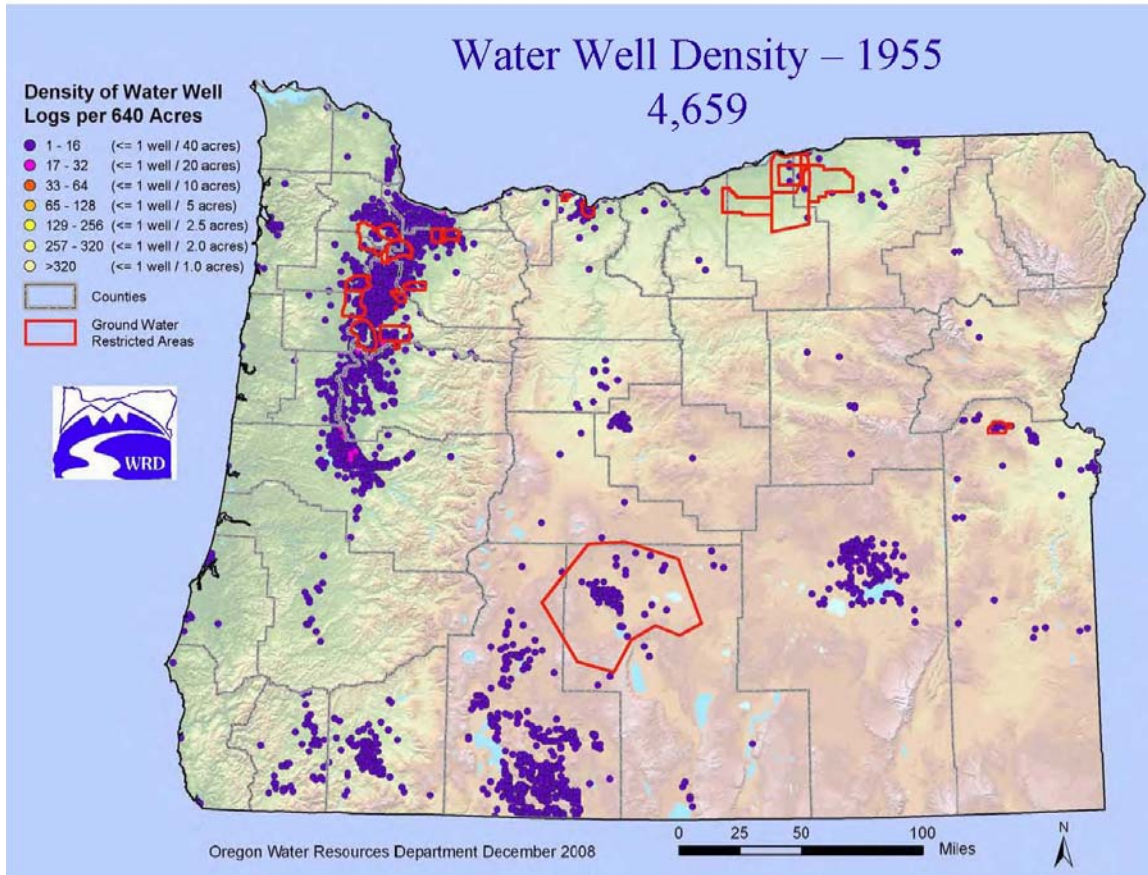


Figure 9-1. The density and distribution of permitted and exempt groundwater wells in Oregon during 1955. Figure is based on water well logs on file (excluding logs for well deepening, alteration, and abandonment) at the Oregon Water Resources Department OWRD. State regulations requiring that water well logs be submitted to OWRD for any new well construction or existing well modification were instituted in 1955. Only a few of the wells that existed prior to 1955 are represented in these figures. Groundwater restricted areas (depicted by red lines) represent areas with groundwater use restrictions, such as prohibition of new permits or, in some cases, restricted use of existing permits. In most cases, exempt uses are allowed in the restricted areas. Exempt uses include wells used for domestic purposes. These wells constitute a water right with a priority date but do not require the user to hold a permit from OWRD. Up to 15,000 gallons per day can be pumped from exempt wells. The amount of water actually withdrawn varies considerably among represented well localities. Figure provided by OWRD.

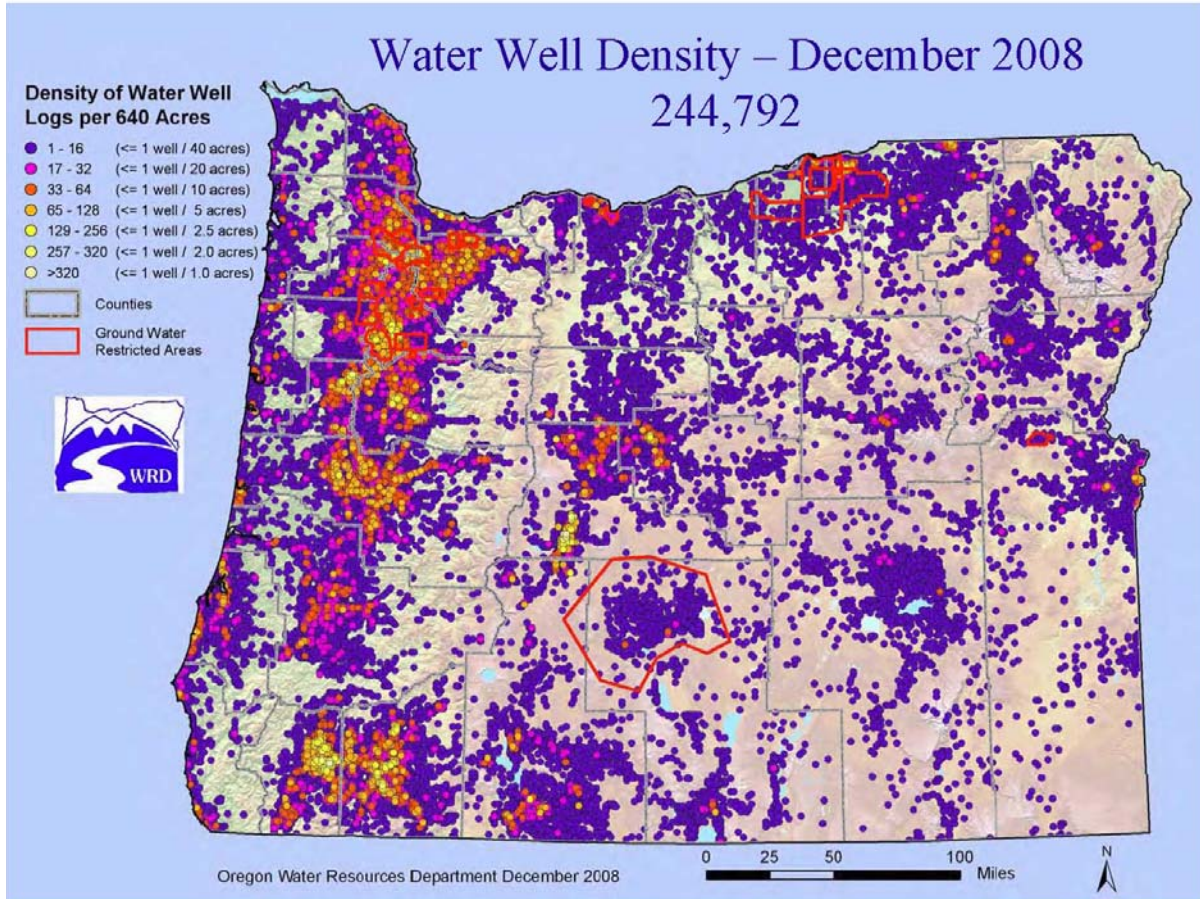


Figure 9-2. The density and distribution of permitted and exempt groundwater wells in Oregon during 2008. Figure is based on water well logs on file (excluding logs for well deepening, alteration, and abandonment) at the Oregon Water Resources Department OWRD. State regulations requiring that water well logs be submitted to OWRD for any new well construction or existing well modification were instituted in 1955. Only a few of the wells that existed prior to 1955 are represented in these figures. Groundwater restricted areas (depicted by red lines) represent areas with groundwater use restrictions, such as prohibition of new permits or, in some cases, restricted use of existing permits. In most cases, exempt uses are allowed in the restricted areas. Exempt uses include wells used for domestic purposes. These wells constitute a water right with a priority date but do not require the user to hold a permit from OWRD. Up to 15,000 gallons per day can be pumped from exempt wells. The amount of water actually withdrawn varies considerably among represented well localities. Figure provided by OWRD.

Key Findings: Futures analysis and planning

- Avoiding aquatic ecosystem impairments associated with future development requires understanding where and how future development is likely to occur.
- Spatial models of future land use (futures analyses) are powerful tools for estimating the location and extent of future development and for evaluating potential effects of different development scenarios on aquatic ecosystems. The science underlying futures analysis is an area of ongoing research and efforts to model alternative futures typically demonstrate relative outcomes, rather than exact endpoints, of different policies on land and water resource use.
- Individual model estimates of aquatic ecosystem condition have a low level of certainty; however, the majority of futures analyses conducted for Pacific Northwest landscapes indicate that future development could have moderate to severe consequences for riparian and aquatic habitat condition and aquatic biota.
- Oregon currently lacks an established long-term water management strategy but several initiatives have recently been undertaken to assess priorities and strategies for managing water sources in Oregon.

Section 9.2: What actions can be taken to protect salmonids in the face of a developing landscape?

This section describes a range of actions that could be taken to avoid or reduce the negative effects developments can have on aquatic ecosystems, or offset negative effects occurring in one location by investing in actions that avoid, mitigate, or remedy impacts elsewhere.

SECTION 9.21: AVOID FUTURE IMPACTS

The USEPA (2004c) recommends 75 proactive policies and actions that hold potential for avoiding the negative effects of development on aquatic ecosystems at both regional and site-level scales. Regional-level policies fall into the following categories (USEPA 2004c):

- *Discouraging development in strategic areas*: When communities inventory and clearly define areas they want to protect (e.g., headwaters, estuaries, wetlands, marshes, riparian corridors, and other lands with higher ecological value), development will shift to land with lower ecological value.⁷⁵
- *Environmental regulatory innovations including voluntary incentives*: The federal Clean Water Act (CWA) defines national water quality goals and standards and details procedural steps necessary to attain them. Individual states and tribes are given the authority to determine how they will meet federal standards outlined and enforced by the USEPA. Such delegated authority creates opportunity for state-level innovation in water

⁷⁵ For an example of how achieving such goals are being approached in Oregon, see the Riparian and Wetlands project underway (2009-2011) in Benton County. <http://www.co.benton.or.us/cd/riparian/advisory.php>. Accessed December 16, 2009.

quality and aquatic habitat management and can encourage cost-effective voluntary practices.

- *Education*: The effects of development on water resources are widespread and regulation alone has not proven effective in protecting aquatic ecosystems. Educating local officials, residents, business owners, developers, and other stakeholders on the many ways their actions affect aquatic ecosystems is critical to the success of the Oregon Plan.
- *Funding and fee structures*: Financial incentives are important tools for directing development in ways that protect aquatic ecosystems. Fees that reflect the true cost of water quality and physical habitat impairments caused by development encourage proactive actions (e.g., better stormwater control).

Site-level policies fall into the following categories:

- *Site planning*: Local governments focused on planning approaches that are compatible with protecting aquatic ecosystems can direct the location of new developments.
- *Strategies and technologies*: Site-specific strategies determine how developments function as livable places while also protecting aquatic ecosystems.
- *Education*: Outreach, training, and information about new development approaches and innovations can help encourage development patterns that protect aquatic ecosystems.
- *Ordinances and codes*: Ordinances and codes determine the type of development allowed at specific locations and advance standards to better manage water resources⁷⁶.

In the following sections IMST summarizes recent peer-reviewed literature relevant to many of the policies outlined by the USEPA (2004c).

SECTION 9.22: AVOID BUILDING IN SENSITIVE AREAS

While factors that impair aquatic ecosystem conditions are well documented (e.g., Paul & Meyer 2001; Allan 2004; Sections 2.0–7.0 of this report) comprehensive research on how best to protect streams and rivers from future development is still in its infancy and few examples exist for the effective conservation of freshwater ecosystems (Abell *et al.* 2007). Achieving a high level of conservation in river networks may require a hierarchical approach that incorporates freshwater protected areas (i.e., reserves similar to those used as conservation tools in terrestrial and marine ecosystems) into a mix of lands managed using ‘salmonid-friendly’ practices (Abell *et al.* 2007; Linke *et al.* 2008). The use of riparian buffer zones is a well-known strategy for protecting aquatic ecosystems adjacent to developed lands (e.g., Booth 2005). Some initiatives aimed at establishing freshwater protected areas are underway in the Pacific Northwest (e.g., North American Salmon Stronghold Partnership⁷⁷). Land acquisitions and similar conservation tools are also important components of many conservation plans in Oregon, including plans for

⁷⁶ Also see model ordinances to protect local resources: <http://www.epa.gov/owow/nps/ordinance/index.htm>; <http://www.lcd.state.or.us/>. Accessed December 16, 2009.

⁷⁷ http://www.wildsalmoncenter.org/programs/north_america/strongholds.php. Accessed December 16, 2009.

salmonid species (ODFW 2006). The following examples highlight programs that have either acquired land or directed development away from sensitive lands in Oregon.

- The **Metropolitan Greenspaces Program** (Metro & USFWS 2005) was jointly administered by the USFWS and Metro (northwestern Oregon) and involved stakeholders from non-profit organizations, local governments within Metro, and citizens. Metro is the elected government responsible for managing a regional urban growth boundary encompassing 25 cities and more than 60 special service districts within Washington, Multnomah and Clackamas counties. About 1.3 million people live within the approximately 400 sq. mi. (1036 sq. km) demarcated by the Metro UGB. The primary goal of the Metropolitan Greenspaces program was natural resource conservation implemented through natural area inventories, land acquisition, habitat restoration, environmental education, and public outreach. From 1991 through 2005 the program was funded by a \$135.6 million bond measure and other grants that allowed matching funds to be leveraged from federal agencies. The land acquisition component of the program resulted in the purchase of over 8,000 acres (3,237 ha) of high priority fish and wildlife habitat across the greater Portland Metro area. The program provides a nationally recognized example for conservation strategies implemented in and around urban areas.
- The Metro council of regional governments along with Clackamas, Multnomah, and Washington counties has initiated a process intended to shape the location and intensity of development occurring in the Portland metropolitan region between 2010 and 2060. Beginning in 2007 with Senate Bill 1011, the **Coordinated Reserves Work Program**⁷⁸ has resulted in proposals for a series of urban and rural reserves on lands currently outside the UGB for the Portland-Metro area. Under Oregon's land use laws, the UGB is intended to contain a twenty-year supply of developable land. Every five years Metro determines how much acreage is needed to meet the 20-year demand and expands the UGB accordingly. The Coordinated Reserves Work Program identifies urban reserves that contain lands suitable for future UGB expansions and urban development in advance of the 5-year UGB planning intervals. Rural reserves are intended to protect natural areas and features from development and to maintain lands for the production of agricultural and forest products. Proposed urban and rural reserves are being designed in compliance with Oregon's land use laws (e.g., DLCD Goals 5 and 6) and will undergo review by DLCD.
- The **West Eugene Wetland Partnership**⁷⁹ has acquired and protected a 3,000 acre (1,214 ha) complex of wetland and associated upland habitats through a combination of regulation, mitigation banking, land acquisition, restoration, and education. Since the early 1990's the Partnership has raised over \$20 million in state and federal funds for land acquisition and habitat restoration. The site also serves as a wetland mitigation bank for the city of Eugene and the surrounding area. City and county planners are also working to connect the wetland complex to other important natural resource sites acquired by the **Rivers to Ridges** program (Lane Council of Governments 2003). The

⁷⁸ <http://www.oregonmetro.gov/index.cfm/go/by.web/id=30155>, and http://library.oregonmetro.gov/files/reserves_work_program_overview_07-10-09.pdf. Accessed December 21, 2009

⁷⁹ <http://www.eugene-or.gov/portal/server.pt?open=512&objID=667&PageID=2543&cached=true&mode=2&userID=2>. Accessed December 17, 2009.

success of both the West Eugene Wetland Partnership and the Rivers to Ridges programs is credited in part to planners who engaged citizens, built a community vision for natural resource protection, and gained broad political support for protecting wetland resources.

Managing land use in ways that protect aquatic ecosystems requires consideration of lateral, longitudinal, and vertical connectivity (Linke *et al.* 2008). Because streams and rivers transport water, solutes, and sediments, distant land-use activities can affect water quality and physical habitat within reaches that might otherwise have high conservation value. Consequently, landscape features occurring over a broad area should be considered when determining the conservation value associated with protecting a particular river segment (Linke *et al.* 2008). The high mobility of many aquatic organisms also presents a difficult challenge for the design of freshwater protection strategies (Abell *et al.* 2007). Most salmonids have complex life histories that require several different habitats (e.g., spawning, rearing, refuge, and smolting) distributed over broad spatial extents (Table 1-5). This increases the likelihood that at least one of their critical habitats will fall outside of protected reaches.

Typically, land acquisition budgets are insufficient for covering costs associated with purchasing and managing all desirable lands. Only protecting inexpensive sites that have a low probability of being developed will exclude areas with high conservation value. Alternatively, focusing on high-priced lands that provide large conservation benefits will likely only protect a small area (Newburn *et al.* 2006). The selection of areas for protection can be accomplished with greater efficiency if the process occurs before surrounding areas begin to undergo development (Costello & Polasky 2004; Newburn *et al.* 2006). Land values and threats to sensitive species constantly change as developments expand and thus present moving targets for conservation (Armsworth *et al.* 2006). The dynamic forces of land supply and demand help determine land value. As a result, the purchase of land for conservation purposes changes land supply and may influence the monetary value of nearby parcels and alter the likelihood that these parcels will be developed (Armsworth *et al.* 2006). Ultimately such dynamics can influence the conservation benefits gained by protecting certain parcels.⁸⁰

Avoiding the effects of future development also requires identifying lands that can be developed with minimal consequences for aquatic ecosystems. Selecting sites for either protection or development involves striking a balance between conflicting conservation and economic interests such as the ecological value of a parcel, monetary value of a parcel, and the likelihood that a parcel will be developed within a defined period (Armsworth *et al.* 2006; Newburn *et al.* 2006). Polasky *et al.* (2008) analyzed the economic and biological tradeoffs of alternate land use scenarios on rural 'working' lands (i.e., outside of protected areas and UGBs) in the Willamette River basin (Oregon). Using spatially explicit models that integrated information on land use patterns, economic returns from alternate land uses, and the habitat requirements of terrestrial vertebrates, Polasky *et al.* (2008) identified land use patterns that maximized both economic gains and conservation benefits. Conservation of wetland habitats adjacent to the Willamette River between Eugene and Corvallis substantially increased conservation benefits at minimal economic cost. While their analysis focused on terrestrial vertebrates, riparian wetland conservation would also benefit aquatic organisms and these results highlight the advantages of

⁸⁰ For examples of how open space can influence home sale values in Oregon see Lutzenhiser & Netusil (2001) and Mahan *et al.* (2000).

considering the spatial arrangement of various land uses (i.e., agriculture, forestry and rural-residential) in land use planning (Polasky *et al.* 2008).

SECTION 9.23: ENGINEERING & BIOENGINEERING SOLUTIONS

Stormwater derived from developments has strong influences on hydrology and channel morphology of streams, rivers, and estuaries, and has been identified as a significant source of diffuse (non-point) pollutant loads entering surface waters (USEPA 2004c, 2005; Trauth & Shin 2005; Dietz & Clausen 2008; see Section 2.0 of this report). To address stormwater-related issues in medium and large municipalities, the US Congress amended the CWA in 1990 and 1999 to include Phase I & II NPDES stormwater control measures (USEPA 2005). Approaches used to manage and treat stormwater in Oregon cities typically include 'end of pipe' techniques (e.g., stormwater detention ponds) that convey stormwater to large management facilities for treatment before it enters surface waters (USEPA 2000a, 2007; Zimmer *et al.* 2007). Such techniques are intended to regulate peak stormflow rates and control some pollutants but do not address alterations to stormflow or bankfull flow duration that are known to cause aquatic ecosystem impairments (USEPA 2000a, 2007; Booth *et al.* 2004; Dietz & Clausen 2008; see Section 2.0 of this report).

Continuing development will increase the difficulties many municipalities face in meeting NPDES permit obligations and other water quality regulations such as TMDL requirements (USEPA 2007). This will also result in the continuing impairment of Oregon's aquatic ecosystems and will hinder efforts to rehabilitate urban and rural-residential streams. The USEPA strongly supports two alternative approaches aimed at improving stormwater management on developed lands. *Low impact development* (LID), also known as Green Infrastructure⁸¹, is a site design strategy composed of techniques that minimize site disturbance and impervious surface area, that reduce reliance on 'end-of-pipe' stormwater treatment facilities, and that preserve or mimic natural (i.e., predevelopment) hydrologic processes within the boundaries of individual developments (USEPA 2000a, 2005, 2007; Dietz 2007; Zimmer *et al.* 2007; Godwin *et al.* 2008). Smart growth is a framework for planning the spatial pattern and density of developments at regional, watershed and site-level spatial scales (Nickerson 2001; APA 2002; Palmer *et al.* 2002; USEPA 2001b, 2005, 2006a; NOAA 2009).

Section 9.231: Low Impact Development

The LID concept evolved out of best management practices designed to meet NPDES stormwater permit requirements (USEPA 2005). Many LID techniques were pioneered in the northeastern and northwestern US (USEPA 2007; Zimmer *et al.* 2007) and can be incorporated into both existing and new developments (USEPA 2000a; Hinman 2005; Godwin *et al.* 2008). The primary goals of LID designs are to reduce surface runoff, increase groundwater recharge, and increase evapotranspiration by strategic placement of numerous stormwater management applications (Table 9-2) throughout a development (USEPA 2000a, 2007; Hinman 2005; Dietz 2007; Zimmer *et al.* 2007; Dietz & Clausen 2008; Godwin *et al.* 2008). Relative to older and more typical current procedures, LID techniques used in new and existing developments have

⁸¹ See USEPA Managing Wet Weather with Green Infrastructure, http://cfpub.epa.gov/npdes/home.cfm?program_id=298. Accessed December 17, 2009

been shown to increase stormwater infiltration, improve stream hydrology, and reduce the amount of stormwater-associated pollutants that reach surface waters (e.g., UNH Stormwater Center 2010). LID techniques are directed towards controlling stormwater runoff at its source, as opposed to downstream locations. This requires preservation or restoration of hydrologic processes such as interception and infiltration, and of natural topographic features (McCuen 2003). Such actions can lower the pollutant load transferred to surface waters, reduce erosion, and contribute to the preservation or rehabilitation of the natural hydrologic regime (USEPA 2004a, 2005; UNH Stormwater Center 2010). The following LID strategies improve the hydrologic function within individual developments (McCuen 2003, USEPA 2000a, 2004c, 2005, 2006a):

- Maximizing stormwater retention at the parcel-level;
- Preserving or emulating natural hydrologic processes during the construction of hard surfaces;
- Protecting (as opposed to paving or filling) small permanent and intermittent streams and associated riparian buffers and wetlands; and
- Regulating the volume, timing, and velocity of stormwater flows at many points throughout a watershed rather than at few downstream locations.

Table 9-2. Low Impact Development Practices. Shown are different categories of low impact development practices, their use, and examples of each (adapted from USEPA 2007).

Low Impact Development Practice/Design	General Purpose	Examples
Conservation design	preserve open space and minimize disturbance of vegetation and soils in new developments or infill	clustered development; open space protection; reduced street and sidewalk widths; shared and shorter driveways
Infiltration practices	capture and infiltrate runoff into soil	infiltration basins and trenches; porous pavement; disconnected downspouts; rain gardens; vegetated roofs
Runoff storage practices	capture runoff from impervious surfaces and store for reuse or gradual infiltration	storage basins associated with parking lots, streets, and sidewalks; rain barrels and cisterns; depression storage
Runoff conveyance practices	route excess runoff from large storm events out of LID structures through structures that regulate flow velocity, volume, and timing	eliminate curbs and gutters; grassed swales; roughened channels and surfaces; long flow paths over landscaped areas; terraces and check dams
Filtration practices	filter runoff through media designed to capture pollutants	bioretention/rain gardens; vegetated swales; vegetated filter strips or buffers
Low impact landscaping	select landscaping features and plants to serve LID functions	native plants; drought tolerant garden and landscaping plants; convert turf to shrubs or trees; soil amendment

Compared to conventional stormwater management techniques, LID can be less expensive to implement, although the costs of long-term maintenance remain unclear (USEPA 2000a, 2007). Relevant organizations such as the Oregon Environmental Council⁸², the Metro regional

⁸² <http://www.oeconline.org/our-work/rivers/stormwater/stormwater-report>. Accessed December 29, 2009.

government⁸³, the Bureau of Environmental Services at the City of Portland⁸⁴, the Puget Sound Action Team (Hinman 2005), and Oregon Sea Grant (Godwin *et al.* 2008) provide extensive guidance on the use of LID techniques to control stormwater.

Effectiveness of LID Techniques – There is a growing body of literature on the effectiveness of LID⁸⁵. The majority of studies available assess individual LID practices (e.g., vegetated roofs, permeable pavement) at relatively small spatial scales. Research findings indicate that individual LID practices effectively reduce stormwater runoff and sequester many types of freshwater pollutants (reviewed by USEPA 2000a; Dietz 2007, UNH Stormwater Center 2010). Dietz & Clausen (2008) assessed stormwater runoff and pollutant loads derived from two adjacent Waterford (Connecticut) subdivisions constructed using traditional and LID techniques. This study provides a more realistic view of LID effectiveness because it measured stormwater at the scale of entire developments and integrated the effects of multiple stormwater control techniques. Stormwater runoff, runoff rates, and pollutant loads in the LID subdivision did not increase with impervious surface area and were similar to those measured in nearby forested watersheds representing predevelopment conditions (Dietz & Clausen 2008). Research addressing whether LID techniques can achieve the desired level of protection for aquatic ecosystems at the watershed scale is limited (Dietz 2007; USEPA 2007). Zimmer *et al.* (2007) modeled the ability of LID techniques to reduce the effects of development on watershed-scale hydrology and demonstrated that LID techniques improved hydrologic conditions in both new and existing developments.

Common barriers to the implementation of LID techniques include resistance to change, limited opportunities, limited funding, restrictions imposed by existing codes and rules, maintenance issues, and lack of government staff and resources to implement policies and programs (USEPA 2000a; Godwin *et al.* 2008). Because LID techniques must be broadly distributed throughout a development they often require implementation on private property which complicates maintenance issues (USEPA 2000a). Existing codes may also prevent city land managers from implementing alternative strategies (e.g., restrictions against disconnecting downspouts). Limited staff at planning and public works departments have difficulty keeping pace with permitting demands imposed by rapidly growing cities (Godwin *et al.* 2008).

The suite of LID techniques in use is continually evolving along with the need to evaluate the effectiveness of both existing and new techniques (Dietz 2007). Results from the collective body of research reviewed by IMST indicate that LID techniques can reduce, to varying degrees, the negative effects that developments have on nearby streams, rivers, and estuaries. Overall, more research is needed to determine if LID reduces the deterioration of aquatic ecosystems and to identify specific land use policies that will effectively manage future growth in ways that protect water resources and aquatic ecosystems (USEPA 2007).

⁸³ <http://www.oregonmetro.gov/index.cfm/go/by.web/id=24592>. Accessed December 29, 2009.

⁸⁴ <http://www.portlandonline.com/bes/index.cfm?c=31892>. Accessed September 1, 2010.

⁸⁵ See International Stormwater BMP database - <http://www.bmpdatabase.org/BMPPerformance.htm>; Water Environment Research Foundation - <http://www.werf.org/net/search.aspx>. Accessed December 21, 2009.

Section 9.232: Smart Growth

The principles underlying *smart growth* were drafted by a coalition of preservation, development, academic, and governmental organizations that comprise the Smart Growth Network (USEPA 2006a). The smart growth concept is based on a set of 10 land-use principles (USEPA 2001b; Trauth & Shin 2005) intended to guide the development of livable cities in ways that preserve natural hydrologic processes, improve water quality, and increase water quantity (McCuen 2003; USEPA 2005, 2006a). At regional and watershed scales, land use policies informed by smart growth principles direct development away from contiguous tracts of land intended to protect the ecological condition of aquatic and riparian ecosystems. Once the locations of future development have been determined, appropriate techniques for managing stormwater (e.g., LID practices) can be implemented within individual developments (USEPA 2000a, 2007).

The use of smart growth concepts in regional- and watershed-scale land use planning concentrates growth on smaller land areas (compared to traditional developments) and protects the condition of aquatic ecosystems (USEPA 2004c, 2007) by doing the following:

- Avoiding development near areas with high ecological value,
- Maximizing use of existing infrastructure,
- Concentrating future development in existing developments, and
- Regulating the quantity and distribution of impervious surfaces at the watershed level, rather than at the parcel or development level.

The USEPA has produced extensive guidance on smart growth including policy actions that provide an explicit framework for incorporating smart growth principles into land use planning at regional, watershed, or site-level scales (USEPA 2004c, 2005, 2007; Trauth & Shin 2005).

In traditional developments, impervious surfaces lead to numerous detrimental effects on aquatic ecosystems (see Section 2.0 of this report). Because impervious surfaces have been repeatedly linked to poor water quality, local governments sometimes set limits on the maximum impervious area allowed within a zoning district (Jones *et al.* 2005; USEPA 2005). While the intention of such regulations is to protect aquatic resources, limiting impervious surface areas can result in low-density developments spread over larger land areas and may actually increase water quality problems at the watershed scale (Trauth & Shin 2005). In contrast, the smart growth framework proposes clustered, high-density developments that could dramatically increase impervious surfaces in selected areas of a watershed if these areas were developed using traditional methods (Trauth & Shin 2005). Under the smart growth framework, however, increased stormwater runoff from intensely developed lands is reduced through the application of LID techniques (USEPA 2000a, 2005, 2006a).

Several authors (e.g., Jones *et al.* 2005; USEPA 2004c; 2006b) assert that high development densities hold greater potential to protect water resources when these developments are placed in appropriate locations. This argument is based on the premise that low development densities do not necessarily alleviate the ecological consequences of increasing population growth; they simply determine the spatial patterning of development (USEPA 2006b). For example, low development densities often require more infrastructure such as roads and can increase the amount of impervious surfaces outside of residential parcels (Trauth & Shin 2005; USEPA

2006b). To better understand the relationship between development density and water quality, USEPA scientists modeled the volume of stormwater runoff generated by three different development scenarios at three different scales (USEPA 2006b). Model results indicated that the volume of stormwater runoff generated *per house* would be consistently lower in higher density developments (USEPA 2006b). The volume of stormwater runoff produced by an equivalent number of homes was a function of development pattern, with lower development densities affecting more area within the modeled watershed and collectively generating more stormwater (USEPA 2006b). These findings indicate that high development densities may provide superior protection for aquatic ecosystems and that increasing development density in appropriate areas is one viable strategy for minimizing the negative effects development can impose on aquatic ecosystems (USEPA 2004b, 2006c).

The quantity of water required by developing cities also depends on where and how growth takes place (USEPA 2006a). For example, residents living on larger parcels often use more water than those dwelling in homes situated on smaller lots. A study of residential developments in Seattle (Washington) demonstrated that residents living on 6,500 square foot (0.15 acres) lots used 60% less water than residents living on 16,000 square foot (0.37 acres) lots (USEPA 2006a). Implementing smart growth design strategies (e.g., compact neighborhood layouts) may increase the efficiency with which municipalities use water resources (USEPA 2006a).

Section 9.233: LID and Smart Growth Implementation in the Pacific Northwest

A recent ruling made by the State of Washington's Pollution Control Hearing Board illustrates the role that LID may play in future development in the Pacific Northwest. The August 2008 ruling⁸⁶ represents the first decision in the US to require LID implementation in new developments in order to meet NPDES Phase I stormwater permit requirements. This ruling determined that the use of LID techniques is necessary to meet CWA standards stating that stormwater be managed to the 'maximum extent practicable' using 'all known and reasonable technologies'. Jurisdictions and municipalities affected by the ruling cover a large area in Washington including Clark, King, Pierce, and Snohomish counties and the cities of Seattle and Tacoma (Locklear 2009).

In Oregon, NPDES permits currently in effect do not require the use of LID techniques. Phase I NPDES permits are, however, currently undergoing review and reissuance. Revised permits will likely require the use of LID in new development or redevelopment projects unless a municipality identifies a significant barrier that would make the use of such techniques inappropriate (Benninghoff 2009 pers. comm.⁸⁷). These changes would likely apply to only the largest municipalities in Oregon and to only to new development or redevelopment projects. Phase II NPDES permits that apply to cities with populations under 100,000 also do not currently require the use of LID but will undergo reissuance in 2012.

⁸⁶ Pollution Control Hearings Board. PSA vs. Ecology, Findings of Fact, Conclusions of Law, and Order Phase I PCHB Nos. 07-021, 07-026, 07-027 07-028, 07-029, 0-030, 07-037 August 2008, <http://www.eho.wa.gov/searchdocuments/2008%20archive/pchb%2007-021,07-026,07-027,07-028,07-029,07-030,07-037%20phase%20i%20final.pdf>.

See also <http://www.stormh2o.com/july-august-2009/washington-state-decision.aspx>. Both accessed December 31, 2009.

⁸⁷ Benjamin Benninghoff, Oregon Department of Environmental Quality, Portland, Oregon, personal communication, December 2, 2009.

Many Oregon cities have not yet adopted LID practices for areas undergoing development. As a result, the stormwater generated by ongoing development still has a significant capacity to impair aquatic ecosystems. While changes to the NPDES Phase I permits will reduce the stormwater generated by new development in Oregon's largest and most rapidly growing cities, these changes will not apply to numerous small municipalities throughout the state. The cumulative effects of existing and new developments that are not regulated by the NPDES permitting process could be significant for Oregon's aquatic ecosystems. Rural-residential and urban developments can make substantial contributions to the mission of the Oregon Plan, but it is critical to ensure that continuing development does not perpetuate the damage already inflicted on Oregon's aquatic ecosystems. It is far more effective to invest in preventing such damage rather than attempting to rehabilitate aquatic ecosystems after damage has already occurred (i.e., after a stream has been placed on the 303d list because of impairments caused by stormwater runoff).

Oregon's land use laws already embody many smart growth principles. The urban growth boundary, first implemented in Oregon during the 1970s, protects resource lands by restricting the location of high-density development. Ongoing efforts in the Portland metropolitan region to articulate the 2040 growth concept⁸⁸ and to identify urban and rural reserves outside of the current UGB also integrate many smart growth principles. Such efforts have resulted in the long-standing maintenance of large uninterrupted tracts of forest and agricultural land and have likely provided some protection to Oregon's aquatic resources over the past 35 years. For example, implementation of DLCD's Goal 5⁸⁹ within Oregon's UGBs has resulted in the inventory and protection of riparian and aquatic habitats that might otherwise have been diminished by development.

However, the primary focus of Oregon's land use laws is to protect economically important agricultural and forest resource lands by containing urban sprawl; aquatic habitats are a secondary focus (Wiley 2001). The land use program is implemented within landscapes dominated by human activities that are partitioned according to ownership and government jurisdiction. Also, the language of land use goals (i.e., DLCD Goals 5, 6, 7, 15) that could achieve a significant level of protection for aquatic resources is broad and leaves individual jurisdictions with significant latitude on how to interpret and implement goals. Consequently, the level of protection derived from these land use goals depends on how they are interpreted and implemented within any given jurisdiction (Punton 2009 pers. comm.⁹⁰). This system can result in differing levels of protection of the same resource across individual jurisdictions (Wiley 2001).

The proper functioning of aquatic ecosystems depends on components and processes that overlap and interact within and across different spatial and temporal scales. Natural features and processes important to the conservation of aquatic ecosystems often span jurisdictional boundaries subject to Oregon's land use laws. The focus of Oregon's land use laws on individual resources within human-defined jurisdictions limits the degree to which these laws can be used to address regional conservation priorities (e.g., recovery of ESA-listed salmonids). Increased coordination among jurisdictions and an increased focus on functional landscapes (e.g.,

⁸⁸ <http://www.oregonmetro.gov/index.cfm/go/by.web/id=25104>. Accessed December 28, 2009.

⁸⁹ <http://www.oregon.gov/LCD/docs/goals/goal5.pdf>. Accessed December 31, 2009.

⁹⁰ Amanda Punton, Department of Land Conservation and Development, Portland, Oregon, personal communication, November 2009.

watershed-scale processes) during the implementation of Oregon's land use laws could afford greater protection to aquatic ecosystems. Sufficient protection of aquatic ecosystems may also require augmentation of land use laws with additional tools such as land acquisitions, conservation easements, tax incentives, and land owner education programs. Coordinated implementation of such an array of actions could allow the development of a multi-tiered approach to address the habitat needs of salmonids in developed lands.

Key Findings: Engineering & bioengineering solutions

- New development will result in the continuing impairment of Oregon's aquatic ecosystems and will hinder efforts to rehabilitate urban and rural-residential streams. Rural-residential and urban developments could make significant contributions to the mission of the Oregon Plan by ensuring that new development does not perpetuate the damage already inflicted on Oregon's aquatic ecosystems by existing development.
- Protecting sensitive lands through land acquisitions and designation of freshwater reserves and improving stormwater management on developed lands are strategies that could be used to avoid or minimize the effects of future development.
- Spatially explicit models that integrate information on land use patterns, economic returns from alternate land uses, and the habitat requirements of sensitive species can be used to identify locations where increased conservation benefits can be achieved with minimal economic cost.
- When incorporated into existing or new developments, low impact development (LID) techniques can reduce pollutant loads transferred to surface waters, reduce erosion, and preserve or rehabilitate the pre-development hydrologic regime. Many Oregon cities have not yet adopted LID practices. As a result, the stormwater generated by existing and ongoing development impairs aquatic ecosystems.
- Smart growth is based on a set of land use policies that direct development away from contiguous tracts of land intended to protect the ecological condition of aquatic and riparian ecosystems. Literature reviewed by IMST indicates that constructing high-density developments in appropriate locations is a viable strategy to minimize the negative effects of development.
- Oregon's land use laws embody many smart growth principles and have resulted in the long-term maintenance of large uninterrupted tracts of forest and agricultural land which has afforded some protection to Oregon's aquatic resources. The focus of Oregon's land use laws on individual resources within human-defined jurisdictions limits the degree to which they can be used to address regional or watershed-scale conservation priorities.

Section 9.3: Offsetting Impacts of New Development

Even with the use of smart growth and LID practices, the negative impacts developments have on aquatic ecosystems cannot be completely avoided. Oregon's governments, communities and businesses expend substantial resources on environmental rehabilitation and mitigation projects aimed at offsetting the effects of development (INR 2008). Mitigation or rehabilitation projects implemented 'on-site' may not be effective in regional conservation efforts because individual projects tend to be costly and only protect or rehabilitate small, spatially dispersed areas near developed lands (Sudol & Ambrose 2002; BenDor & Brozović 2007; Primožich & Vickerman 2007; INR 2008). In response to perceived shortcomings of on-site rehabilitation and mitigation actions, various market-based trading strategies have been proposed or developed as economically and ecologically sound alternatives (e.g., Breetz *et al.* 2004; USEPA 2004c; Morgan & Wolverson 2005; Trauth & Shin 2005; BenDor & Brozović 2007; Primožich & Vickerman 2007; Shabman & Stephenson 2007; Willamette Partnership 2007a).

Market-based strategies are used in situations where actions that impair environmental conditions (e.g., release of water pollutants, destruction of habitat) can be treated as tradable commodities and managed in ways that increase environmental gains and reduce overall financial costs of offsetting environmental impacts (Shabman & Stephenson 2007). Trading strategies are based on the premise that individual companies or agencies operating within a defined area (e.g., a watershed) incur different costs to comply with the same environmental regulation. Established trading programs allow entities that incur high financial costs to meet regulatory obligations by purchasing environmental credits from another entity capable of meeting the same regulatory obligation at a lower cost (INR 2008). As a result, environmental regulations are met by all involved parties at a lower overall financial cost. An added benefit is that market-based strategies create incentives for those involved in trading to seek innovations that improve the efficiency and reduce the cost of meeting environmental regulations (Shabman & Stephenson 2007).

For market-based programs to operate effectively, there must be an adequate demand for the environmental commodity to be purchased, a stable supply of marketable credits, and a structure for transactions that make the cost associated with trading affordable (INR 2008). These requirements set up an important interplay between the spatial extent in which a program operates and viability of the program (Farrow *et al.* 2005; Obropta & Rusciano 2006; BenDor *et al.* 2009). Trading programs operating within large spatial areas may result in large distances between sites affected by development and sites where credits are created. Such a situation may allow extensive damage to occur in one location while offsets occur in distant location with little ecological connection to the area disturbed by development. Trading programs operating in small spatial areas may not be able to produce a viable trading market because the land area is not large enough to create a stable supply of credits (e.g., acres of habitat in mitigation banks). These trade-offs should be considered carefully when setting the spatial area for market-based trading programs (BenDor *et al.* 2009).

The implementation framework used for market-based programs depends on the parties involved, the commodity traded, and the location where the program is implemented. Consequently, there is substantial variation in programs currently proposed or operating in the US (Breetz *et al.* 2004; Morgan & Wolverson 2005; Shabman & Stephenson 2007). Several programs are underway or under development by organizations and agencies in Oregon such as the Climate Trust, The Freshwater Trust, Deschutes River Conservancy, and Clean Water

Services (see INR 2008 for a recent overview of programs; Table 9-3). In addition to these organizations, the Willamette Partnership⁹¹ is developing a framework for a market that integrates a number of environmental commodities such as wetlands, water pollutants, water quantity, endangered species habitat, and carbon. The following sections summarize how two general types of market-based strategies operate, provide examples of strategies that have been implemented or are under development in Oregon, and review the benefits and shortcomings identified with the implementation of such strategies.

SECTION 9.31: MARKET-BASED TRADING

Market-based trading involves the establishment of a credit system that is used to regulate actions that impair ecosystem function. The majority of trading programs address water pollution limits set by TMDL requirements and many focus on a single pollutant such as phosphorus, nitrogen, or temperature (Morgan & Wolverton 2005; Obropta & Rusciano 2006). Programs for carbon trading are also under development nationwide (e.g., Western Climate Initiative⁹²). Typically, a watershed-based limit defined by a TMDL or other regulatory structure (e.g., a NPDES permit) stimulates a demand for trading credits by capping the total pollutant discharge allowed within the watershed (Shabman & Stephenson 2007). Supply can be created by allocating the allowable pollutant load among the group of traders that release the pollutant within the watershed. Trading ratios are typically used to address several complexities that arise during the management of water quality trading programs. The collective trading group typically sets rules regarding how pollution loads are allocated among traders and designs a framework for pollutant allocation and trading that maintains total pollutant loads below the level set by the regulatory authority. Market frameworks, transaction costs, trading ratios, and other aspects of the trading schemes vary considerably among programs (Breetz *et al.* 2004; Morgan & Wolverton 2005).

Trading ratios are generally used to standardize pollution credits based on likely environmental effects or to account for uncertainty in trading program effectiveness (Farrow *et al.* 2005; Morgan & Wolverton 2005). For example, both point and non-point pollution releases can be managed under market-based trading systems, but it is often difficult to incorporate non-point pollution sources into trading programs because these sources are dispersed and not easily quantified (Obropta & Rusciano 2006; Shabman & Stephenson 2007). When trades involving both point and non-point pollution sources are made, the point-source trader is typically held responsible if the non-point source trader fails to reduce its pollution discharges by the amount agreed upon (Shabman & Stephenson 2007). A point source trader interested in purchasing credits from a non-point source trader might be required to purchase a credit amount that is double the actual pollution discharge increase (i.e., a 2:1 trading ratio).

The effectiveness of market-based trading in controlling pollution may depend on how environmental regulations shape trading markets (Shabman & Stephenson 2007). In programs where pollutant loads are fully capped at a fixed level by a regulatory agency, any interested entity would have to be assigned a discharge allowance (i.e., trading credits) from the existing fixed supply to legally discharge the pollutant. Trading programs that operate under full (and

⁹¹ <http://www.mwvcog.org/WillamettePartnership/WillamEcoMarket.asp>. Accessed December 31, 2009.

⁹² <http://www.westernclimateinitiative.org/>. Accessed December 31, 2009.

Table 9-3. Existing and emerging markets for environmental credit trading and banking in the Willamette River basin. Adapted from Willamette Partnership (2007b).

Scheme	Mandate	Agencies	Description	Potential
Wetland mitigation banking	Section 404 fill permits from the CWA, and Section 10 of the Rivers and Harbors Act	Federal regulating agencies: USACE; USEPA Oregon regulating agencies: DSL Others involved: USFWS; NOAA; NMFS; ODF; members of the mitigation banking review team.	When land developers fill or otherwise alter a wetland they may buy offsets from a mitigation banker. The mitigation banker restores or creates an area of wetland (or multiple sites under an umbrella agreement) to generate credits.	High: already active with growing demand along I-5 corridor and Washington County. First stream mitigation bank approved in 2006. DSL is exploring building a state clearinghouse or wetland mitigation credits tied to industrial site development.
Endangered species conservation banking	Section 7 (consultations) and Section 10 (incidental take) of the ESA.	Federal regulating agencies: USFWS; NMFS Oregon regulating agencies: None determined Others involved: Future members of the conservation banking review team.	The conservation banking market is a biodiversity offset system that allows for the sale and purchase of endangered species credits to offset negative impacts to endangered species and their habitats. USFWS and NMFS are each responsible for conservation banking for their species.	Medium: USFWS has approved the first conservation banks for Oregon chub for ODOT. NMFS has approved a salmon bank in California. There is no formal process for conservation bank approval. There are no standards for anadromous fish banking.
Water quality trading	NPDES permits; TMDLs; MS4 permits	Federal regulating agencies: USEPA Oregon regulating agencies: ODEQ	Most water quality markets are established to assist industrial and municipal waste water dischargers that must reduce the amount of pollutants they release.	High: already active in the Tualatin River basin with grant monies in place to expand temperature trading in the Willamette. There is a need to authorize other trading for pollutants.
Water supply trading	Water quality goals under the CWA; ESA; other water supply needs.	Oregon regulating agencies: OWRD	Most water quantity trades have involved urban water users leasing water from agricultural water rights holders in the western US. Trading for environmental purposes has increased in the Columbia River basin and California. Flows are also getting attention related to meeting water quality goals and stormwater discharge requirements.	High: Already active throughout the country. Trading for environmental purposes has been facilitated by the Oregon Water Trust which acquires, purchases, and develops agreements to provide water in-stream.
Stormwater trading	Local regulations, MS4 permit, CWA	Federal regulating agencies: USEPA Oregon regulating agencies: ODEQ Others involved: Municipal governments, special districts	The City of Portland is conducting a stormwater trading feasibility study; cannot trade directly within the bounds of their MS4 permit; are using a local ordinance focusing on flows . Trading might occur around impervious pavement, where a green street installation might create credits that could be traded to developers in the same watershed.	Low: Portland may be creating the first stormwater trading program, but it may be unique to Portland. The regulatory drivers are not very clear and much work with ODEQ and USEPA is needed to facilitate trading.

Acronyms used in the table: CWA – Clean Water Act; DSL – Dept. of State Lands (Oregon); ESA – Endangered Species Act; MS4 – municipal separate storm sewer system; NMFS – National Marine Fisheries Service; NOAA – National Oceanic and Atmospheric Administration; ODEQ – Oregon Dept. of Environmental Quality; ODOT – Oregon Dept. of Transportation; OWRD – Oregon Water Resources Dept.; NPDES –National Pollutant Discharge Elimination System; TMDL – total maximum daily load; USACE – US Army Corps of Engineers; USEPA – US Environmental Protection Agency; USFWS- US Fish and Wildlife Service.

fixed) pollution caps are more likely to ensure that water quality will not be continually degraded when new discharge sources arise as economies and human populations grow (Shabman & Stephenson 2007). Programs where pollutant loads are not fully capped (i.e., only a subset of discharge sources are regulated) are less likely to be effective at protecting aquatic resources because only a fraction of the total pollution load is managed by trading (Shabman & Stephenson 2007). Under partially capped programs, water-quality degradation is likely to continue if unregulated discharge sources continued to grow and their pollution loads are not mitigated by reductions in the pollution contributed by the regulated fraction of discharge sources or by other regulatory mechanisms.

SECTION 9.32: MITIGATION BANKING

Environmental mitigation banks also establish a system of credits that can be purchased to offset the adverse effects of development. Credit purchases typically represent acres of habitat that mitigate habitat impaired or destroyed elsewhere. State rules address issues such as where mitigation credits can be used and the compensation that would be required for various types of impacts. Mitigation banks offer the following advantages over on-site mitigation activities (Brown & Lant 1999; USEPA 2001a; BenDor & Brozović 2007; BenDor *et al.* 2009):

- Large areas of wetland and other habitats can be established, conserved, and rehabilitated.
- Mitigation banks may do a better job of protecting ecosystem function compared to the fragmented habitats that can result from on-site rehabilitation efforts.
- Developers can be made aware of the costs associated with mitigation early in the development planning process.
- Mitigation banks create an economy of scale favorable to small development operations that might not be able to afford on-site mitigation costs.
- Mitigation banks potentially create greater assurance of long-term conservation of ecologically important lands.

A key component of effective mitigation banking is that the acres of habitat banked be fully interchangeable with those lost to development. Uncertainty that the banking program will result in 1:1 exchanges of lost to gained habitats is typically addressed by implementing a mitigation ratio where a developer is required to purchase credits representing a habitat area larger than the area actually destroyed (BenDor 2009). Purchases are usually restricted to service areas within the same watershed⁹³. Cross-watershed transfers of habitat (i.e., habitat affected in one watershed is mitigated in another watershed) do occur depending on federal, state, or county-level regulations (see BenDor & Brozović 2007; BenDor *et al.* 2009 for examples from Illinois and North Carolina). As with wetlands and as is the objective of the Clean Water Act, it may be advantageous for Oregon to develop a no-net-loss approach for aquatic ecosystem area, structure and/or function. The following list provides examples of the types of mitigation banks currently in operation (Primožich & Vickerman 2007; Willamette Partnership 2007b):

⁹³For examples of the spatial scales of watersheds serviced by wetland mitigation banks in Oregon visit http://www.oregon.gov/DSL/PERMITS/mitbank_status.shtml. Accessed December 14, 2009.

- Wetland mitigation banks are formed in response to federal, state, or local regulations (e.g., Section 404 of the CWA, and Section 10 of the Rivers and Harbors Act) that require developers to compensate for any actions resulting in loss of wetland acreage or function. Wetland credit banks are derived from landowners restoring wetlands in off-site locations. As of 2002, there were 219 wetland mitigation banks established across the US (Spieles 2005) and more under development (USEPA 2001a).

In Oregon, there are currently 20 wetland mitigation banks in operation with several more under development⁹⁴. All of Oregon's mitigation banks service areas west of the Cascade Mountains. DSL⁹⁵ provides significant guidance on the operation of mitigation banks in Oregon. Wetland mitigation banking is typically conducted within spatial areas encompassed by 4th field hydrologic units⁹⁶ and transfer of wetland habitats beyond areas serviced by mitigation banks is strongly discouraged unless there is an ecologically sound reason (Field 2010 pers. comm.⁹⁷).

- Endangered species/conservation banks exist where landowners that maintain habitat for endangered species are monetarily compensated for the cost of their property and its continued management. Regulatory drivers of such programs include Sections 7 and 10 of the ESA.
- Water supply banks involve water leasing agreements, typically between water right holders and urban municipalities. Agreements aimed at increasing instream flows for environmental purposes have increased in recent years particularly in California, the Columbia River basin, and the Great Lakes region. Regulatory drivers include the CWA and ESA.

SECTION 9.33: EFFECTIVENESS OF WETLAND MITIGATION BANKING

More effort has been expended toward evaluating wetland mitigation banking success than other types of mitigation banks because they have been in use the longest. The literature reviewed by IMST indicates that mitigation banking is a conservation tool with considerable potential if implemented, monitored, and managed properly. However, it is also clear that poor implementation of mitigation banking strategies leads to inadequate replacement of habitats that are degraded or destroyed elsewhere. For example, Kentula *et al.* (2004) found that natural wetlands were traded for ponds with very different ecological function. Also, the information required for landscape-scale analyses of the size and type of mitigation purchases may be lacking (BenDor & Brozović 2007, BenDor 2009). An overriding goal of federal policies that drive wetland mitigation markets is to achieve 'no net loss' of the wetland acreage or function remaining in the US (BenDor 2009). The overall effect of a mitigation banking framework on wetland acreage and function can create complexities that require resolution if the 'no net loss' policy is to be achieved (Brown & Lant 1999). The following bullets list examples of issues and research needs raised in the literature reviewed by IMST:

⁹⁴ http://www.oregon.gov/DSL/PERMITS/mitbank_status.shtml. Accessed December 14, 2009.

⁹⁵ Wetland Mitigation Guidebook for Oregon, http://www.oregon.gov/DSL/PERMITS/mit_guidebook_intro.shtml. Accessed January 7, 2010.

⁹⁶ Hydrologic units are not watersheds or basins, but rather map units used to delineate polygons in the US.

⁹⁷ Dana Field, Department of State Lands, Salem, Oregon, personal communication, January 11, 2010.

- The protection of wetlands provided by mitigation banks may be insufficient when regulatory guidelines are insufficient or are not followed (e.g., Brown & Lant 1999).
- Specific mitigation ratios used to compensate for uncertainty in how well a banking program protects wetlands have not been adequately determined. For example, it is not always clear how much mitigation acreage is required to capture the biological diversity or hydrologic functions that were lost to development. In several locations within the US insufficient mitigation ratios have resulted in net loss of wetland area (Brown & Lant 1999; BenDor 2009; Rubec & Hanson 2009).
- Banking wetland habitats alters the type, position, and distribution of wetlands across the landscape (BenDor & Brozović 2007, BenDor *et al.* 2009). The ecological consequences of such landscape-scale changes have not been adequately researched (Brown & Lant 1999; BenDor *et al.* 2009).
- Certain situations can create a lag between the loss and gain of functional wetlands (BenDor 2009). Restoration or creation of wetland acreage requires extended periods during which vegetation communities, soil structure, and hydrologic function become established (Craft *et al.* 2002; Gutrich & Hitzhusen 2004; BenDor 2009). Wetland mitigation credits are sometimes sold before the wetland acreage on which the credits are based has established full ecological function (Robertson 2006).

Key Findings: Offsetting impacts of development

- Market-based strategies have been proposed as economically and ecologically sound techniques for offsetting aquatic ecosystem impairments caused by development. These strategies manage actions that impair environmental conditions as commodities that can be purchased or traded.
- To begin to achieve positive outcomes, market-based programs at a minimum require an adequate demand for an environmental commodity, a stable supply of marketable credits, and a structure for transactions that make the associated costs affordable. These requirements set up important tradeoffs between the spatial extent in which a program operates and the viability of the program.
- The effectiveness of market-based trading in controlling pollution may depend on how environmental regulations shape trading markets.
- Mitigation banks can allow the establishment and long-term conservation of large areas of habitat and allow developers to determine the costs associated with mitigation early in the development process. Purchases are usually restricted to service areas within the same watershed however mitigation banking can change the type, position, and distribution of habitats across the landscape. The ecological consequences of such landscape-scale changes have not been adequately researched.
- Banks established to mitigate wetland loss have been in use the longest and have received a greater research effort to evaluate their success. The literature reviewed by IMST indicates that mitigation banking is a conservation tool with positive potential if implemented, monitored, and managed properly; however, it is also clear that poor implementation of mitigation banking strategies could lead to a net loss of habitats at the landscape-scale.

Section 9.4: Determining the Effectiveness of Actions Taken to Minimize or Offset the Effects of Development on Aquatic Ecosystems

Achieving the goals of the Oregon Plan requires an understanding of how different land uses and mitigation measures contribute to the recovery or decline of watershed condition. Developing such an understanding requires adequate monitoring of aquatic resources affected by different land uses. Rural-residential and urban lands physically occupy only a small fraction of the total land area in Oregon (see Section 1.4 of this report). If statewide monitoring efforts are allocated according to the area covered by various land uses, rural-residential and urban lands will be inadequately monitored. In addition, the ecological effects of developed areas (i.e., their ecological footprints) extend well beyond their physical boundaries (e.g., Sanderson *et al.* 2002; Rees 2003; Venetoulis *et al.* 2004; Leu *et al.* 2008).

In the western US, the majority of developments have been established and expanded along rivers and estuaries. As a result, lands adjacent to rivers are disproportionately affected by the ecological footprint of developed lands (Leu *et al.* 2008). The ecological footprint includes not only the physical area directly affected by development but also lands that produce goods and services consumed by city residents, lands that assimilate waste generated by city residents, and lands affected by the extended infrastructure (e.g., road networks, shipping channels, power lines, power generation facilities) that support developed areas (Rees 2003; Venetoulis *et al.* 2004; Leu *et al.* 2008). As Oregon's human population grows, the extent and intensity of the ecological footprint will also increase, especially if the per capita consumption of goods and services continues to increase. Considering how the ecological footprint of developed lands affects salmonid habitats and overall watershed condition may yield a more accurate understanding of how well entire watersheds or river basins can support viable salmonid populations (Leu *et al.* 2008; Polasky *et al.* 2005, 2008).

The following sections summarize recovery and monitoring efforts undertaken on Oregon's developed lands and assess how well these efforts address the ecological condition of developed lands and lands affected by the ecological footprint of development. Because it is unique to Oregon, IMST places special emphasis on efforts carried out under the Oregon Plan.

SECTION 9.41: FEDERAL EFFORTS

- The federal Clean Water Act (CWA) has historically focused its regulations on water quality, particularly from point source dischargers. Sections of the CWA relevant to developed areas include the NPDES (402), removal/fill permits (404), identification of 'water quality limited' watercourses (303d), and biennial water quality reports to Congress (305b). The CWA is largely implemented by the USEPA, which invests heavily in stormwater and wastewater treatment infrastructure and treatment in urban areas. Regulation and effectiveness monitoring are delegated to ODEQ which directs site monitoring by dischargers (see Sections 2.0 and 3.0 of this report). Implementation of CWA regulations results in individual dischargers collecting and submitting a considerable amount of monitoring data to ODEQ. However few of those data are available in electronic format. As a result, the usefulness of those data in determining the collective effectiveness of stormwater and wastewater management techniques is limited.

- The federal Endangered Species Act (ESA) constitutes a regulatory framework used to protect threatened and endangered species. Specific protections directed towards listed species include designation and protection of critical habitat, development and implementation of recovery plans, and protection from any harassment, harm, or mortality that constitute 'take' (Taylor *et al.* 2005). Substantial federal funds from ESA permitting agencies (i.e., USFWS, NMFS) and land management agencies (including US Forest Service, Bureau of Land Management, National Park Service, USFWS) are expended for habitat improvement projects. All four land management agencies plus the NMFS have implemented effectiveness monitoring programs to assess the results of their investments⁹⁸. The focus of those monitoring programs is on federal lands, some of which are affected by the ecological footprint of developed areas. IMST could not locate any information on how those agencies monitor the effectiveness of ESA protections within developed areas.
- The USEPA's National Aquatic Resource Survey⁹⁹ was implemented to assess status and trends of aquatic and coastal systems at state, ecoregion (Hughes *et al.* 2004), and national (Paulsen *et al.* 2008) scales. In 2008-2009, USEPA intensified its sampling to insure sufficient monitoring of urban streams (Olsen 2009 pers. comm.¹⁰⁰).
- The USGS's National Water-Quality Assessment Program¹⁰¹ lacks a regulatory or management role, but it has evaluated the effects of urban development in 11 urban centers including Portland (Oregon) (Waite *et al.* 2008; Brown *et al.* 2009) and Seattle (Washington). For each urban center, physical, chemical, and biotic responses to varying levels of development are characterized in 28 to 30 river-reaches.

Although sharing common goals and some common indicators, the efforts described above do not share common sampling protocols, data management, analyses, or reporting units, and only the latter two survey urban waterways. This lack of coordination would make it difficult to determine the sufficiency of efforts to protect salmonids and their habitats on lands affected by rural-residential or urban lands (See IMST 2009 and Roper *et al.* 2010 for further discussion of issues related to the synthesis of disparate data sets).

⁹⁸ Currently, there are two large effectiveness monitoring programs being conducted on federal lands in Oregon: The Aquatic-Riparian Effectiveness Monitoring Program is a joint US Forest Service/Bureau of Land Management program focused on monitoring physical habitat structure of wadeable streams and landscape condition on the federal lands within the range of the Northern spotted owls (*Strix occidentalis caurina*) (Gallo *et al.* 2005).

The PacFish/InFish Biological Opinion, a similar joint Bureau of Land Management/US Forest Service program but with different indicators and sampling methods, is directed at monitoring streams and riparian zone condition in the upper Columbia River basin (Henderson *et al.* 2005).

⁹⁹ <http://www.epa.gov/owow/monitoring/nationalsurveys.html>. Accessed January 14, 2010.

¹⁰⁰ Tony Olsen, USEPA, Corvallis, Oregon, personal communication, 2009.

¹⁰¹ http://water.usgs.gov/nawqa/studies/regional_assessments.html and <http://water.usgs.gov/nawqa/urban/html/studydesign.html>. Accessed January 14, 2010.

SECTION 9.42: OREGON PLAN FOR SALMON AND WATERSHEDS

In Oregon, OWEB funds watershed assessments, rehabilitation and enhancement projects, and monitoring throughout the state. OWEB and the Oregon Plan Monitoring Team manager provided IMST with information pertaining to the proportion of rehabilitation and monitoring efforts occurring on rural-residential and urban lands statewide and how information collected on these projects will be used to determine the effectiveness of the Oregon Plan within these land use categories. IMST also asked OWEB staff to summarize specific information on the number of OWEB-funded projects implemented on rural-residential and urban lands, the total number of projects funded by OWEB, and the number of projects on developed lands that included effectiveness monitoring. Summaries received by IMST covered information submitted to OWEB as of December 2008. OWEB responses to these information requests¹⁰² are summarized below.

At the watershed scale, rehabilitation and monitoring efforts funded by OWEB are determined by various stakeholder groups, often working within the organizational structure of a watershed council. Specific activities are prioritized by a multipart process that includes a watershed assessment to identify rehabilitation and monitoring needs and development of an action plan. Distribution of projects across various land uses are affected by the extent and distribution of different land uses within the watershed, the importance placed on environmental work within different land uses by local watershed councils and stakeholder groups, plus land owner interest and cooperation.

OWEB has tracked information (including land use categories) characterizing fish habitat restoration projects since 1997 through the Oregon Watershed Restoration Inventory¹⁰³ (OWRI). Currently, reporting for the OWRI is mandatory for all projects receiving grant money from OWEB. Reporting information includes completed project location on a 1:24,000 map scale, duration, spatial extent, goals, cost, treatment details, and implementation monitoring (effectiveness monitoring is not required by grants or for reporting). In 2002, OWEB added a section on 'urban' projects to its reporting form with the intent to better characterize projects carried out on urban lands. However, OWEB staff relayed that few urban projects have been reported to date; instead urban projects may be reported under specific project types (e.g., road, passage).

Presently, there is no mechanism to directly obtain an integrated (across all Oregon Plan agency and voluntary efforts) analysis of rehabilitation and monitoring efforts undertaken within particular land uses. With the assistance of OWEB staff, the OWRI database can be used to determine the distribution of OWEB-funded restoration projects on rural-residential and urban lands with high spatial and temporal resolution. However, determining the strategy or distribution (with respect to land use) of rehabilitation or monitoring projects carried out by state agencies or other Oregon Plan partners requires individual information requests directed to specific Oregon Plan partners.

As of December 2008, approximately 138 (4%) of 3,400 OWEB funded rehabilitation projects have been completed within urban growth boundaries. This number does not include projects in rural-residential areas or any information on project size (i.e., spatial extent, duration). OWEB staff reported that, as of December 2008, effectiveness monitoring had not been conducted on

¹⁰² November 15, 2007 letter from IMST to OWEB and the Oregon Plan Monitoring Team.

¹⁰³ <http://willametteexplorer.info/mappingtools/maps.aspx?Res=16660>. Accessed January 14, 2010

any projects within Oregon urban growth boundaries. However, this assessment did not include urban projects reported under other project types. Completed projects are not distributed in all urban areas of the state, and it is unlikely that they adequately address rural-residential or urban effects that extend beyond development boundaries.

The location and nature of monitoring efforts associated with rural-residential and urban rehabilitation projects (or projects on any other land use types) are difficult to determine. OWEB does not track monitoring locations in OWRI or in any other way that would allow determination of an aquatic ecosystem response to rehabilitation projects carried out on rural-residential and urban lands. The Oregon Plan Monitoring Team developed and is currently implementing (in coordination with the Oregon Plan Core Team and the Governor's Natural Resource Office) a monitoring strategy adopted by OWEB (OWEB 2003b). Since 2000, OWEB has required that all funded restoration projects include monitoring of project implementation (typically 1 to 3 years but can extend up to 10 years). Documentation of implementation monitoring activities is stored as hard copy files. Consequently, information pertaining to implementation monitoring or any other type of monitoring (e.g., compliance, effectiveness) is not reported or included in the electronic OWRI database.

The data on rehabilitation projects entered into the OWRI database could be used to design effectiveness monitoring strategies. Exchange of information about rehabilitation and monitoring projects among Oregon Plan agencies and local entities (e.g., watershed councils, soil and water conservation districts, local governments) occurs through the OWRI and specific directives within OWEB grant agreements that pertain to data sharing and storage. OWEB has developed contracts with ODFW's Natural Resource Information Management Program and the Institute for Natural Resource's Oregon Explorer (Oregon State University) to aid in the management and analysis of watershed assessment, rehabilitation project and monitoring project data. While exceptions exist, data collected by municipalities and local government agencies (e.g., cities, counties) are currently under-represented in the OWRI database and in efforts undertaken by others to create an integrated database of assessments, monitoring, and rehabilitation information. As of February 2009 an integrated monitoring database managed by OWEB remains under development.

SECTION 9.43: OTHER STATE-LEVEL MONITORING EFFORTS

Several additional entities such as watershed councils and city governments carry out monitoring projects in Oregon's streams, rivers and estuaries. Some of these entities have adopted common sampling protocols and environmental indicators from the USEPA's Generalized Random Sampling Design or the Environmental Monitoring and Assessment Program. As a result, the data from different monitoring programs can be aggregated and used to characterize the effects of current land uses and outcomes of land management policies. Recently the ODEQ aggregated and summarized monitoring data collected at 450 sites by 12 different monitoring programs implemented in the Willamette River basin, including the Oregon Plan. The resulting report (Mulvey *et al.* 2009) represents significant progress towards characterizing the effects of agricultural, urban and forestry land uses on the chemical, physical, and biological condition of aquatic ecosystems.

Key Findings: Determining effectiveness of efforts

- Achieving the goals of the Oregon Plan requires an understanding of how different land uses and mitigation measures contribute to the recovery or decline of watershed condition. Developing such an understanding requires adequate monitoring of aquatic resources affected by different land uses.
- Considering how the ecological footprint of developed lands affects salmonid habitats and overall watershed condition may yield a more accurate understanding of how well entire watersheds or river basins can support viable salmonid populations.
- Federal and state efforts to monitor the effects of land use on aquatic ecosystems share common goals and some common indicators, but these efforts rarely share common sampling protocols, data management, analyses, or reporting units. This lack of coordination hinders determining the sufficiency of efforts to protect salmonids and their habitats on lands affected by rural-residential or urban lands.

Section 9.5: Spatial Scale and Regional Planning

Actions that avoid or offset (mitigate) the impacts of development on aquatic ecosystems operate across stream reaches, watersheds and river basins. However, there is considerable variation in the scale of influence of such actions, for example:

- Smart growth and associated planning efforts are intended to operate at the watershed scale in ways that impart benefits from stream reach to river basin levels.
- Mitigation strategies are typically regulated at watershed or river basin scales depending on the partners involved in trading strategies. Individual stream reaches may benefit if a mitigation bank is located nearby.
- Market-based trading strategies are also regulated at watershed or river basin scales.
- On-site ordinances, building codes and similar regulations affect stream reaches with potential cumulative benefits at watershed and river basin levels.

Watershed or river basin scale planning involves many interrelated activities (Booth *et al.* 2001; USEPA 2004c; Trauth & Shin 2007) including assessment of existing watershed and water quality conditions, identification of areas containing high-quality habitat, development of futures scenarios, direction of future development toward areas that have the lowest ecological value, and the implementation of LID techniques in areas where future development occurs. This mosaic of activities and spatial effects across the landscape means that managing the effects of development may be more effective if coordinated through an integrated regional or basin planning framework (USEPA 2004c).

Section 9.6: A Role for Education

Advanced planning and mitigation actions alone are unlikely sufficient to minimize the numerous effects development can have on aquatic ecosystems (Booth *et al.* 2001; USEPA 2004c). Achieving Oregon Plan goals on developed lands will also require education of state and county officials, land and business owners, developers, and other local stakeholder groups regarding the effects development can have on aquatic ecosystems. The large number of federal, state, municipal, watershed council and private actions undertaken under the Oregon Plan across land uses means education can also help stakeholders better understand the goals and objectives of the Oregon Plan and coordinate their actions to assist smart growth and environmental mitigation actions.

A recent study by Montgomery & Helvoigt (2006) demonstrated that Oregonians became less supportive of salmon recovery and salmon recovery efforts between 1996 and 2002. Establishing educational opportunities that promote environmentally responsible behaviors can potentially slow or even halt further declines in water quality and salmonid habitat condition (USEPA 2004c). Therefore, educating Oregonians about the importance of various activities aimed at the recovery of salmonid populations appears to be important if recovery goals are to be achieved. Booth *et al.* (2004) recommended implementing landowner stewardship programs that highlight the roles that property owners have in improving aquatic ecosystem condition. The USEPA (2004c) suggests that municipalities and watershed councils organize community events that demonstrate the importance of individual behavior. For example, the non-profit organization Oregon Trout conducts a program called Salmon Watch that integrates salmon viewing into K-12 educational curricula addressing salmonid biology and stream ecology. Salmon Watch students participate in field trips organized by volunteers and fish biologists and view salmon spawning, measure water quality (i.e., temperature, pH, dissolved oxygen), sample aquatic macroinvertebrates, and learn about riparian vegetation. In 2006, the program served 86 schools, 119 teachers, and more than 4,500 students with 152 streamside trips involving 269 volunteers¹⁰⁴. In 2002 evaluations administered by classroom teachers immediately following the program resulted in a 47% gain in perceived knowledge by students (Schmidt 2008 pers. comm.¹⁰⁵).

Dunn *et al.* (2006) suggest that urban populations increasingly experience nature primarily in urban areas. Research on the phenomenon of 'place attachment' demonstrated that exposure to natural settings influences the interest of individuals in environmentally responsible behavior (Vaske & Kobrin 2001). Such findings imply that long-term support for salmonid conservation efforts will be strongly influenced by what people experience and learn about nature in urban areas.

¹⁰⁴ www.healthywatersinstitute.org/salmonWatch.html. Accessed January 14, 2010.

¹⁰⁵ Mary Ann Schmidt, Oregon Trout, Portland, Oregon, personal communication, 2008.

Science Question 3 – What is the current state of knowledge for rehabilitating adverse ecological effects associated with rural-residential and urban development?

Pacific salmonids require access to estuarine and freshwater habitats with clean, cold, well-oxygenated water. Such environmental conditions are created and maintained by physical, chemical, and biological processes that shape hydrology, structural habitat, fish passage, and water quality. Pressures from urban and rural-residential development alter aquatic ecosystems and the processes that form and maintain them. Once altered, several options are available to “fix” the alterations to varying degrees of success. This Science Question evaluates rehabilitation and enhancement techniques in terms of salmonid recovery in urban and rural-residential areas.

Section 10.0: Rehabilitating Aquatic Ecosystems in Developed Areas

In urban and rural-residential areas, efforts to restore ecosystem processes¹⁰⁶ that sustain suitable conditions for salmonids are constrained by municipal infrastructure, such as bridges, dams, roads, buildings, and stormwater and sewage treatment systems (Carpenter *et al.* 2003; Booth 2005; Bernhardt & Palmer 2007). In addition, developed areas have persistent sources of point and nonpoint pollution that could undermine the effectiveness of habitat rehabilitation projects (Paul & Meyer 2001). Consequently, rivers, streams, and estuaries in developed areas cannot be fully restored to unimpaired conditions, but in some cases can be rehabilitated to support salmonid populations (NRC 1996; Booth 2005; Simenstad *et al.* 2005; Roni *et al.* 2008).

In this report, the IMST uses the terms *rehabilitation* and *enhancement* rather than *restoration* when referring to improving environmental conditions for salmonids in developed areas (refer to Text Box on the following page); however, other authors cited herein do not always differentiate between the terms. The general goals of watershed rehabilitation actions are to improve ecosystem processes so that they promote and sustain habitat connectivity, riparian vegetation, water quality, and streamflow regimes (Roni *et al.* 2002; Beechie *et al.* 2008). Enhancement approaches are used as short-term, stream-reach measures that often provide only temporary local benefits to aquatic ecosystems until self-sustaining, habitat-forming processes have been rehabilitated.

In urban and rural-residential areas, rehabilitation actions are frequently planned and implemented at the reach scale and may incorporate one or more techniques. Most rehabilitation and enhancement techniques (e.g., floodplain reconnection, meander construction, fish passage improvement) are implemented throughout the landscape and are not unique to developed areas. However, several water quality improvement approaches (i.e., actions under stormwater management and wastewater treatment) are primarily used in urban and rural-residential areas. Both stormwater management (Section 2.0) and wastewater treatment (Section 3.0) are discussed earlier in this report and are not further reviewed in this Science Question.

¹⁰⁶ Ecosystem processes are basic processes (water and nutrient cycles, energy and material flow, and community dynamics) that work in all landscapes and link organisms to their environment.

Ecological Restoration Terms

In this report, IMST uses the following definitions to distinguish among the terms **restoration**, **rehabilitation**, **mitigation**, and **enhancement** when referring to techniques that are intended to improve environmental conditions for salmonids. The following are definitions commonly used for each of these terms. It is important to note that variations do exist depending on the user, but these definitions embody many of the common principles used with the terms.

RESTORATION

'Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed'. An ecosystem is considered to be restored 'when it contains sufficient biotic and abiotic resources to...sustain itself structurally and functionally...and demonstrates resilience to normal ranges of environmental stress and disturbance' (SER 2004, p 3).

The goal of ecological restoration is to recover:

- **Ecological function by repairing ecosystem processes, which in turn sustain ecological structure** (NRC 1996; SER 2004); and
- **Biotic integrity by re-establishing pre-disturbance species composition and community structure** (NRC 1996; SER 2004).

REHABILITATION

'Rehabilitation emphasizes the [repair] of ecosystem processes, productivity and services' (SER 2004, p 12).

Rehabilitation re-establishes *'self-sustaining conditions that are able to provide some of the ecological requirements'* of the target organisms. In these instances, *'full restoration to pre-disturbance functions and characteristics is unlikely'* (NRC 1996, p 211).

A common goal of ecological rehabilitation is to improve ecological function by repairing ecosystem processes, which in turn sustain ecological structure (NRC 1996; SER 2004)

MITIGATION

Habitat mitigation is a substitution technique *'that is intended to compensate environmental damage'*. In the US, mitigation is often *'a condition for the issuance of permits for private development and public works projects that cause damage to wetlands'* (SER 2004, p 120).

A common goal of habitat mitigation is to artificially create new habitats at one site to legally compensate for the damage and destruction of habitats at another site (NRC 1996; SER 2004).

ENHANCEMENT

Habitat enhancement is a substitution technique that *'selectively alter[s] or modify[ies] habitat features to offset the effects of anthropogenic impacts'*. Enhancement techniques can aid in *'improving fish habitat in some instances, but it has not been very successful in improving conditions that sustain productivity'* (NRC 1996, p 212).

A common goal of instream habitat enhancement is to improve degraded habitats through the introduction of artificial or temporary structures (NRC 1996).

Within the US, numerous aquatic restoration, rehabilitation, and enhancement projects have been implemented across various land uses, particularly in the Chesapeake Bay region, California, and the Pacific Northwest (Bernhardt *et al.* 2005). In Oregon, several hundred aquatic projects have been funded by OWEB since 1997 with more than 50 of these OWEB-funded projects implemented within urban growth boundaries (Gibbs 2009 pers. comm.¹⁰⁷; OWEB 1999, 2008). Other local, state, and federal agencies in Oregon have funded numerous projects within urban and rural-residential areas but these projects are not tracked and information on them is not readily available through comprehensive databases.

Section 10.1: Determining Rehabilitation and Enhancement Success

Monitoring the condition of stream biota and various physical, chemical, and landscape features in reference and target areas allows managers to determine the causes and magnitude of degradation and to track the effectiveness of management programs and actions (Booth *et al.* 2004). Implementation and effectiveness monitoring may be conducted on rehabilitation projects. Implementation monitoring determines whether rehabilitation projects were done according to the project design. Effectiveness monitoring determines whether the objectives of the rehabilitation project are being met. Effectiveness monitoring incorporates information from pre-activity assessments, implementation monitoring, and post-activity assessments, which may include data collected several years after implementation.

How or when an activity or project is determined to be successful is influenced by the physical, biological, and social contexts surrounding it. The context, including natural and anthropogenic constraints and desired future conditions, should be established and clearly articulated when the rehabilitation action is planned but are often not specified (IMST 2006). Ideally, rehabilitation plans and effectiveness monitoring plans should be developed simultaneously, carried out at appropriate spatial and temporal scales, and guided by well-articulated goals that can be evaluated using measurable and quantifiable indicators (IMST 2006). In aquatic ecosystems, desired endpoints could include physical (e.g., channel stabilization, decreased bank erosion, improved fish passage, spawning gravel accumulation, or instream cover for fish), chemical (e.g., decreased nutrient loads and concentrations), biological (e.g., more juvenile salmon, more riparian trees), and social (e.g., increased public awareness, project acceptance, or recreational value) outcomes (Woolsey *et al.* 2007). In general, implementation monitoring is more likely to be incorporated into a rehabilitation project than effectiveness monitoring.

SECTION 10.11: FREQUENCY OF MONITORING

Several investigators have concluded that available research and effectiveness monitoring of commonly used rehabilitation techniques are inadequate to evaluate whether or not the goals have been met (e.g., Roni *et al.* 2002; Bernhardt *et al.* 2005; Alexander & Allan 2006; Palmer & Bernhardt 2006). A review the National River Restoration Science Synthesis database of 37,000 projects demonstrated that only 10% of project records reported any type of monitoring (Bernhardt *et al.* 2005). However, in a follow-up study that involved interviewing 317 managers of large projects, 83% of those projects were found to include some type of monitoring

¹⁰⁷ Courtney Gibbs, Oregon Watershed Enhancement Board, Salem, Oregon, personal communication, 2009.

(Bernhardt *et al.* 2007). Reviewing a regional database containing data on over 23,000 restoration and rehabilitation projects in the Pacific Northwest, Katz *et al.* (2007) found that only 6.7% of project records reported any type of monitoring. From that same database, 47 project managers were interviewed and 70% of interviewees felt that their projects had been successful (Rumps *et al.* 2007). However, specific criteria for determining success were not identified for 43% of these projects by the interviewees, and 34% of the projects did not include monitoring sufficient to determine project effectiveness (Rumps *et al.* 2007). Discrepancies between project managers' assessments of success and the amount of monitoring used to document success also occurred in phone interviews conducted in the Chesapeake Bay area (Hassett *et al.* 2007), southwestern states (Follstad-Shah *et al.* 2007), upper Midwest (Alexander & Allan 2006), and southeastern states (Sudduth *et al.* 2007).

Even projects that include monitoring may not produce information that can be compared to or combined with monitoring results from other projects. The lack of standardized monitoring protocols and indicators¹⁰⁸ hinder broad, integrative rehabilitation assessments. In a call for better coordinated monitoring and analyses, Scholz & Booth (2001) recommended several standardized parameters for projects in urban watersheds that can be used with minimal training and equipment (e.g., riparian canopy cover, large wood density) and those that would need additional expertise (e.g., channel gradient, substrate composition). Alexander & Allan (2006) found that only 11% of projects in the upper Midwest had been monitored for effectiveness, that those studies were of dubious quality, and that standardization of monitoring protocols and documentation were urgently needed. In their global review of rehabilitation and restoration studies, Roni *et al.* (2008) were unable to quantitatively compare or analyze information from published studies because of the lack of similarity between protocols used to collect data. In a meta-analysis to determine whether engineered in-stream structure installations (e.g., weirs, large wood, revetments, boulders) effectively increased salmonid abundance, Stewart *et al.* (2009) were only able to use data from 17 of 179 relevant studies.

Once monitoring data have been collected for individual projects or have been combined from multiple projects, the data still may not be adequate to show rehabilitation benefits to salmonid populations or ecosystem processes. Shields *et al.* (2003) concluded that stream ecosystems are highly complex and heterogeneous so they do not meet the assumptions of rigorous experimental designs, are not scalable, and tend to have very long response times which have led to experiments that are not reproducible. Thompson (2006) found that only 12 of 79 published studies on fish habitat improvement structures installed prior to 1980 contained sufficient data to evaluate the effects of the structures on trout populations, independent of fishing pressure. Of these 12 studies, only two analyses demonstrated benefits to trout populations (Thompson 2006). Stewart *et al.* (2009) found that the heterogeneity of salmonid population size and local habitat preference was significant and the effectiveness of instream structures to increase salmonid abundance was ambiguous. More empirical data were needed to determine effectiveness of the structures.

¹⁰⁸ Indicators are characteristics that are chosen to directly or indirectly quantify ecological or environmental conditions. Single-metric indicators are specific biotic (e.g., number of coho salmon) or abiotic (e.g., water temperature) measures while multi-metric indicators are multiple variables integrated into a single index score (e.g., macroinvertebrate IBI; IMST 2007). Which indicators are chosen depend on rehabilitation objectives, on appropriate temporal and spatial scales over which projects will be completed, and on statistical design needs (ISP 2000).

In some situations insufficient monitoring can be corrected. For example, Tompkins & Kondolf (2007) used systematic post-project appraisals (Kondolf & Micheli 1995; Downs & Kondolf 2002) to supplement existing data with new field data and assess seven complex channel rehabilitation projects in California. They found that two projects achieved geomorphic objectives, three were likely to achieve geomorphic objectives, and two were not likely to achieve geomorphic objectives (Tompkins & Kondolf 2007).

Section 10.2: Current State of Knowledge of Various Rehabilitation Approaches

Because of the diverse effects development can have on aquatic ecosystems and the physical, legal, or landowner constraints on rehabilitation that can be present, rehabilitation in urban and rural-residential areas is difficult and the level of success that can be achieved is uncertain (e.g., Paul & Meyer 2001; Booth 2005; Bernhardt & Palmer 2007). At present, what we know about aquatic rehabilitation in developed areas is based on a few case studies and limited monitoring (e.g., Alexander & Allan 2006; Roni et al. 2008) or is anecdotal (e.g., Booth 2005). This section summarizes what is known about the effectiveness of various rehabilitation and enhancement techniques that are being used within urban and rural-residential areas. Published research and monitoring results from developed areas in the western US are emphasized.

SECTION 10.21: EROSION CONTROL

Erosion control of stream banks is common in urban and rural-residential areas for the protection of property and infrastructure (Bernhardt *et al.* 2005; Alexander & Allan 2006; Bernhardt & Palmer 2007). Stream bank erosion control is also incorporated into aquatic rehabilitation and enhancement projects. Stream bank erosion can be addressed using engineered (armored) or bioengineered (vegetative) methods.

Engineered or Armored Bank Stabilization – Stabilizing banks with large rocks (rip-rap) has been a common practice to prevent river and stream banks from eroding. While rip-rap may protect property and infrastructures (e.g., roads), slow local bank erosion rates, and decrease the amount of sediments entering the channel, it may not benefit salmonids. Schmetterling *et al.* (2001) reviewed an unspecified amount of peer-reviewed and non-peer-reviewed literature on the effects of rip-rap on salmonid populations. They concluded that rip-rap did not provide habitat for multiple salmonid species or age classes, rather it reduced the development of salmonid habitats such as undercut banks that provide cover, river channel gravels, and cover provided by streambank vegetation (Schmetterling *et al.* 2001). Kondolf *et al.* (2006) found that bank armoring can increase downstream bank and/or channel erosion in some rivers.

Bioengineered Streambank Stabilization – Vegetation and geotextile fabrics can be used in place of rip-rap or concrete to stabilize streambanks. This process is referred to as bioengineered streambank stabilization (Sudduth & Meyer 2006). Re-vegetation of banks can increase bank stability and may increase aquatic biodiversity (Bernhardt & Palmer 2007). In an urban study in Atlanta (Georgia), bioengineered stream banks improved the diversity of shredder macroinvertebrates (Sudduth & Meyer 2006), but the direct effects on salmonids in developed areas have not been determined.

SECTION 10.22: FISH PASSAGE IMPROVEMENT

Improving fish passage has a long history in the Pacific Northwest and can involve removing, replacing or retrofitting culverts and dam. Bridges typically allow passage of juvenile and adult salmon, as well as sediments and pieces of large wood and can be used as an alternative to culverts (Roni *et al.* 2005, 2008). Most culvert evaluations have been conducted in steep, forested settings, not low-gradient urban and rural-residential areas or in arid, high desert areas. In general, when properly designed, new and retrofitted culverts have been found to produce fairly rapid, positive responses from fish populations with moderate or high abundances (Beechie *et al.* 2008; Roni *et al.* 2008). However, the seasonal and yearly effectiveness of fish passage structures can be limited by low streamflow levels or high water velocities (Roni *et al.* 2008). Some culvert types that allow passage of adult salmonids may not allow juvenile fish passage or may impede movement of other habitat components such as large wood and sediment (Table 10-1; Roni *et al.* 2005, 2008). Current culvert types have also been shown to constrain channels if the culverts are not sufficiently large enough to allow for large flow events or heavy amounts of sediment and wood transported during those events (Roni *et al.* 2005, 2008).

Table 10-1. Summary of culvert types and how they can affect passage of salmonids, sediment, and large wood during large flow events. Table is based on Roni *et al.* (2005).

Culvert type	Provides for salmonid passage		Allows for transport	
	Juvenile	Adults	Large wood	Sediment
Bottomless pipe arch	Yes	Yes	No	Yes
Round corrugated, baffled	Yes	Yes	No	No
Round corrugated, no baffles	<i>Depends on culvert length and slope</i>	<i>Depends on culvert length and slope</i>	No	No
Smooth, round or box	<i>Depends on culvert length and slope</i>	<i>Depends on culvert length and slope</i>	No	No
Squash pipe or countersunk	Yes	Yes	No	Yes

Modification and/or removal of dams in developed areas can also provide fish passage to upstream reaches (Berhardt & Palmer 2007), but few cases have been documented. One of the earliest actions was the breaching of the Jackson Street irrigation dam in Medford (Oregon) in the late 1990s (Smith *et al.* 2000). It was assumed that breaching the Jackson Street dam improved passage for coho, Chinook salmon, and steelhead; however, fish numbers were not reported. Other dams on the same waterway continued to prevent fish passage further upstream and to negatively affect water quality (Smith *et al.* 2000) making it difficult to draw conclusions about whether the Jackson Street dam project benefited salmonids.

SECTION 10.23: HYDROLOGICAL CONNECTIVITY

Hydrological connectivity within aquatic systems includes longitudinal, lateral, and vertical movement of water, sediments, and organisms. *Longitudinal connectivity* refers to movement through a stream or river network and can be restricted by dams and reduced flows. *Lateral connectivity* refers to the exchange of materials and organisms between aquatic/floodplain ecosystems and terrestrial ecosystems (Woolsey *et al.* 2007) and can be restricted by levees, mainstem channel incision, and reduced flows (Kondolf *et al.* 2006). The channel modifications that lead to losses in lateral connectivity also restrict access to off-channel habitats such as side channels, backwater sloughs, wetlands, and floodplain habitats during high flows. *Vertical connectivity* is the exchange between groundwater and surface water within a river system (Boulton 2007) and can be restricted by reduced streambed permeability and hydraulic gradient, by siltation of streambed gravels and by channel simplification (Kondolf *et al.* 2006)¹⁰⁹.

In their literature review of rehabilitation technique effectiveness, Roni *et al.* (2008) located 84 papers from 16 countries reporting on attempts to improve hydrological connectivity. Included were papers on levee removal or setbacks (7 total), reconnecting off-channel habitats (11), meander creation (20), constructed habitats (17), dam removal (14), and flow modifications (15). The general consensus by Roni *et al.* (2008) was that rehabilitation techniques tended to improve various physical or biological characteristics, but long-term information was lacking. This was especially the case for urban areas, particularly in arid, high desert regions. Most of the published studies were from forested and rural areas. Only one paper cited by Roni *et al.* (2008), the removal of an irrigation dam in Medford, Oregon (Smith *et al.* 2000), was from a western US urban area. The applicability of the North American forested and rural area studies to Oregon urban and rural-residential areas is not clear because so few studies have documented rehabilitation attempts within developed areas. Modeling results indicate that allowing lateral channel migration improves hydrological processes that benefit salmonids (Hall *et al.* 2007). Levee breaching, establishing set-back levees further away from the channel, and removing rip-rap can re-establish lateral connectivity (Beechie *et al.* 2008; Roni *et al.* 2008), but such actions are constrained in developed areas because of existing municipal infrastructure (Bernhardt & Palmer 2007). Since the completion of Roni *et al.*'s (2008) review, a few other studies have been published covering rehabilitation actions implemented in developed areas. These are summarized below.

Levell & Chang (2008) reported the results of a case study on a channel restructuring project carried out on a reach of Kelley Creek (a tributary of Johnson Creek in Portland, Oregon) that had been previously widened, deepened, and armored for flood control. The rehabilitation project reconnected historical meanders, re-graded the channel slope, removed channel fill, created backwater channels, and added instream structures (large wood, cobbles, and gravels) to the channel. The project reach was compared to reaches of Kelley and Richardson Creeks that had been either disturbed by development or that represented pre-development conditions. Comparisons were made one and two years after the project was completed. In that time-frame, the authors reported that residual pool dimension did not substantially change, but particle size

¹⁰⁹Hyporheic rehabilitation of stream channels attempts to improve vertical connectivity. Boulton (2007) speculated that the removal of fine sediments from gravel and cobble or placement of wood and other structures could improve movement of water between the surface and hyporheic zone but available approaches have not been studied in any ecosystem and are not covered in this report.

and cross sectional geometry did change on the project reach. The authors concluded that the change in particle size likely indicates that the channel is aggrading (thereby negatively affecting pool-riffle sequences and spawning gravels) and may be reflecting larger sediment problems in the watershed (Levell & Chang 2008). The authors also concluded that the project reach appeared more stable than the reach affected by development but was less stable than the reach representing pre-development conditions.

In urbanizing areas of the San Francisco Bay region (California), Tompkins & Kondolf (2007) conducted post-project evaluations on seven compound channel rehabilitation projects. The compound channels were designed to maintain low flow channel areas to convey water year around and included adjacent, flat constructed floodplains to convey water during high flows. Tompkins & Kondolf (2007) found that two projects (Green Valley and Miller Creeks) achieved geomorphic objectives and three projects were likely to achieve geomorphic objective with time (Lower Guadalupe River, Lower Silver and Tassajara Creeks). Four projects met in-channel and floodplain habitat objectives (Lower Guadalupe River, Alamo, Green Valley, and Miller Creeks) and one was likely to do so with more time (Lower Silver Creek) and the other two (Wildcat and Tassajara Creeks) likely would require minor interventions to achieve objectives. Four projects also met water conveyance objectives (Lower Guadalupe River, and Alamo, Miller, and Tassajara Creeks) with the other three (Wildcat, Green Valley, and Lower Silver) likely to meet objectives after minor interventions.

A rehabilitation approach that was not addressed in the review by Roni *et al.* (2008) is *stream daylighting*. The technique is unique to urban areas and re-exposes covered stream channels to daylight and allows for seasonal flooding. Converting piped streams to open streams may be very important in urban areas for improving water quality and fish passage to upstream areas (Berhardt & Palmer 2007). Stream daylighting has been accomplished in several places in the US, but no comprehensive studies documenting changes in aquatic ecosystems and fish populations have been conducted. Buchholz & Younos (2007) reviewed 19 stream daylighting case studies across the US and found 8 that had been completed in western states. Of the 19 projects, Buchholz & Younos (2007) found that only five had been done to improve aquatic habitat or water quality. The majority of the projects were done to benefit people and most often were included as part of newly created parks or to alleviate flooding problems associated with piped streams and stormwater. Only 1 of the 5 projects completed to improve aquatic ecosystems had implemented post-treatment monitoring that included vegetation, stream, and fish responses over a three year period. The other 4 included minimal “unofficial” monitoring (i.e., not a post-project requirement) consisting of short-term visual assessments. Because of the lack of available projects and monitoring, Buchholz & Younos (2007) were not able to draw any comprehensive conclusions about water quality improvements, aquatic ecosystem benefits, or fish responses to stream daylighting.

SECTION 10.24: RIPARIAN VEGETATION

Rehabilitation of riparian vegetation in developed areas may focus on providing stream bank stability, channel shading, filtering sediment and nutrients or other compounds from stormwater runoff, or the control of non-native invasive plant species.

Native Riparian Vegetation – Riparian vegetation plantings are one of the most frequently implemented rehabilitation techniques (Bernhardt & Palmer 2007). Riparian tree plantings are frequently conducted in the Pacific Northwest using techniques based on silvicultural practices that emphasize the replacement of hardwoods with conifers along forested streams (reviewed by Roni *et al.* 2002). Despite the frequency of riparian plantings in forested, rural, and urban areas there have only been few a short-term, and no long-term (> 10 years), evaluations of plantings in developed areas. Available information is typically anecdotal (e.g., Booth 2005).

In the evaluations of riparian vegetation plantings in temperate Pacific Northwest forests, herbivory by wildlife was commonly identified as a problem that restricted planting success (reviewed by Roni *et al.* 2002). Wildlife herbivory may not be a primary constraint in developed areas that have experienced soil compaction and changes in water tables and seasonal drainage. In general, authors have suggested riparian vegetation plantings along developed stream channels are more likely to persist if hydrological impacts related to increased impervious surfaces and flow modifications are also addressed (e.g., Groffman *et al.* 2003). Others suggest that replanting aquatic vegetation in native wetlands and estuaries in developed areas can be successful if hydrological connections remain intact (e.g., Roni *et al.* 2008). These conclusions, however, are not currently supported by monitoring or research data because of the lack of long-term monitoring of riparian plantings.

Non-Native, Invasive Plant Species – Riparian plantings are often conducted in concert with the removal of non-native, invasive plant species (Bernhardt & Palmer 2007). Once non-native, invasive plants have been removed, ongoing control and ecosystem improvement are often required to prevent their re-establishment (Bernhardt & Palmer 2007). As with general riparian plantings, no large-scale or long-term evaluations have been conducted on the effectiveness of removing invasive species and replanting with native or non-invasive, non-native species. In a review of the scientific literature on urbanization effects of soils, Pavao-Zuckerman (2008) found that developed land uses can create new soil conditions not found in natural areas by removing organic and topsoil layers or by raising or lowering the water table. These modified soils may not be able to support native vegetation without considerable effort to change the altered physical, chemical, and biological characteristics of the soil. Urbanized soils may also promote invasion and establishment of non-native organisms, including plants and soil invertebrates. For example, Sharp (2002) found Portland (Oregon) riparian area soils had been modified by urbanization. The modified soils contributed to the establishment and perpetuation of non-native plant species including reed canary grass (*Phalaris arundinacea*) and Himalayan blackberry (*Rubus armeniacus*).

SECTION 10.25: INSTREAM HABITAT IMPROVEMENT

Installing habitat structures such as gabions, weirs, large wood, boulders, or gravel substrate in streams, rivers, and estuaries is commonly done to improve salmonid habitat by increasing the size and numbers of pools or accumulations of spawning gravels. Most available research and

published evaluations (e.g., Thompson 2006; Roni *et al.* 2005, 2006, and 2008) are on instream structures placed in forested stream reaches that were altered by logging operations. Roni *et al.* (2008) found in a comprehensive review that results were highly variable, but tended to have positive impacts on physical habitat. Positive fish responses to instream structures have also been reported, but Roni *et al.* (2005) found that most results were inconsistent because of the variability associated with the techniques and the ecosystems treated, and few responses were monitored sufficiently to detect statistically significant changes. In a recent meta-analysis of data from 17 engineered instream structures (e.g., weirs, revetment, deflectors), Stewart *et al.* (2009) found the evidence for structure effectiveness to be ambiguous. While information can be gleaned from these studies, the overall effects instream habitat structures may have in aquatic ecosystems affected by development, particularly low-gradient channels in extensively urbanized areas, may not be similar to those reported in high-gradient, forested streams. Urban watersheds may experience more severe hydrologic conditions than forested streams that could limit the effects that instream structures have on salmonid habitat in urban areas (e.g., Larson *et al.* 2001; Booth 2005).

Water quality impairment in urban and rural-residential areas may also mask biological responses to instream structures. Larson *et al.* (2001) examined the effectiveness of large wood placed at six urban stream reaches in the Puget Sound region (Washington). Wood was installed at five of the sites within 4 years of the study while the wood at the sixth site had been placed 10 years earlier. Half of the projects used anchored wood pieces. Based on physical stream conditions, Larson *et al.* (2001) found that the wood did increase, at least slightly, sediment storage and habitat complexity. Larson *et al.* (2001) also found that benthic macroinvertebrates did not increase with large wood placements in Seattle (Washington), and concluded that the IBI scores were directly related to watershed condition not local habitat structures.

Substrate improvement is used to diversify fine and coarse bed materials and to replace lost spawning gravels for salmonids in streams affected by development. The natural recruitment of spawning gravels is reduced by dams constructed upstream of urban areas that block the downstream movement of fine sediments and gravels during high flows. Projects can include the installation of gabions and weirs to trap gravels as they move downstream or adding gravel directly to the stream bed. Roni *et al.* (2008) reviewed 14 published studies (worldwide) that examined salmonid responses to these types of instream habitat improvement. Of those, 13 reported some type of positive response in terms of salmonid spawning activity or of abundance of adult or fry fish, but none were from developed areas in western North America.

A few gravel augmentation studies in highly degraded stream systems are available for the Pacific Northwest but most are anecdotal (e.g., Madsen Creek in Seattle, Washington reported by Booth (2005)). Merz & Setka (2004) evaluated the effect augmented gravel had on Chinook spawning in the Mokelumne River, a flood-controlled river in central California that is highly disturbed by instream gravel and gold mining plus other activities. Adult Chinook salmon used the site for spawning during the three spawning seasons studied and redds were present but no assessment of egg development or fry production was done (Merz & Setka 2004). In a companion study, Merz *et al.* (2004) found that Chinook salmon embryos planted (in egg-incubation tubes) in enhanced gravel areas had higher rates of survival to the alevin stage than those in non-enhanced areas. Merz & Ochikubo Chan (2005) reported that benthic macroinvertebrates quickly colonized added gravels and macroinvertebrate biomass and densities of the enhanced sites were similar to non-enhanced sites within four weeks. Problems

associated with substrate augmentation include the gravels being covered by fine sediments or moved downstream during high flows requiring additional augmentation over time (Roni *et al.* 2002), or gravels being colonized by aquatic vegetation in dam regulated reaches (Merz *et al.* 2008).

Section 10.3: Common Assumptions about Successful Aquatic Rehabilitation

Authors discussing rehabilitation efforts and apparent short-falls of actions implemented on the ground often conclude that unless reach-scale rehabilitation projects are coordinated with efforts that address watershed-scale constraints governing flow regimes and water quality, the reach-scale efforts will not be successful (e.g., Frissell & Nawa 1992; Muhar 1996; Booth 2005; Wohl 2005; Bernhardt & Palmer 2007; Jansson *et al.* 2007). Based on their conceptual model, Booth *et al.* (2001) argued that the failure to consider all factors limiting stream biota such as flow regime, physical habitat structure, water quality, energy source, and biotic interactions is a common reason for the failure of rehabilitation projects. In general, re-establishing natural flow regimes and improving water quality are of primary importance for success of many rehabilitation actions, but are difficult to accomplish (Carpenter *et al.* 2003; Booth 2005; Simenstad *et al.* 2006; Bernhardt & Palmer 2007). It is also assumed that rehabilitation project success is severely limited if the projects or actions are implemented at the wrong spatial and/or temporal scales, if base causes of impairment are not addressed, and new development continues in the watershed. This is not to say the authors are incorrect; however, the information to support or oppose their assumptions are not currently available. Stewart *et al.* (2009) also came to a similar conclusion on the effectiveness of engineered in-stream structures. Monitoring data are also not available to determine when certain types of rehabilitation actions in developed areas will be most successful at achieving ecological goals under a given set of conditions (Bernhardt & Palmer 2007; Stewart *et al.* 2009).

The following section discusses some of the common assumptions of watershed and aquatic rehabilitation as the basis for determining monitoring and research needs for Oregon.

SECTION 10.31: PRIORITIZING REHABILITATION EFFORTS

Remedying the effects of existing developed areas on water quality, flow regime, and aquatic ecosystem function is challenging. Given the millions of dollars committed to watershed rehabilitation and the uncertainty associated with rehabilitation effectiveness, there is a need to prioritize rehabilitation actions based on their potential for benefiting salmonids and watershed functions (Roni *et al.* 2002; Jenkinson *et al.* 2006; Bernhardt & Palmer 2007; Jansson *et al.* 2007). Rehabilitation of ecosystem processes at the watershed-scale is assumed to have a much greater likelihood of long-term success (as reflected in salmonid recovery) than enhancement of individual habitat characteristics at the reach-scale (Beechie & Bolton 1999).

In recent years the focus of some rehabilitation projects has shifted from localized reach-scale actions to watershed-scale approaches, but most urban rehabilitation projects are still planned at the reach scale (Beechie *et al.* 2008). Ideally, aquatic rehabilitation actions would be planned at the watershed-scale and involve establishing rehabilitation goals and determining a sequence of actions that progress toward those goals (Beechie *et al.* 2008). The following priority of actions

has been suggested for watershed level aquatic restoration and rehabilitation actions (Bradbury *et al.* 1995; Roni *et al.* 2002; Beechie *et al.* 2008):

1. Protect intact habitats.
2. Rehabilitate ecosystem processes in degraded habitats.
3. Enhance instream habitat in degraded habitats.

There is general agreement among scientists and land managers that maintaining ecological processes and existing high-quality habitat is much easier than rehabilitating degraded ecological processes and habitat (NRC 1992; Bradbury *et al.* 1995; NRC 1996; Booth *et al.* 2001, 2004; Roni *et al.* 2002; Bernhardt & Palmer 2007; Beechie *et al.* 2008; Roni *et al.* 2008). Protecting high quality habitat through low impact development techniques (LID), mitigation, and other measures was addressed in Science Question 2.

Roni *et al.* (2008) further developed sub-priorities for rehabilitating ecosystem processes. Under their prioritization, the factors that are most limiting the biological responses to rehabilitation should be addressed first, such as water quality and flow regime (Roni *et al.* 2008). As addressed in Science Question 1, stormwater runoff and wastewater effluent are significant sources of water quality impairment in aquatic ecosystems affected by urban and rural-residential development. Stormwater is also a major contributor to channel erosion, high instream sediment levels, and loss of hydrologic function. Water impoundments, including flood control systems, also alter flow regime in watersheds where large urban and rural-residential developments are present (Carpenter *et al.* 2003; Booth 2005; Simenstad *et al.* 2006; Bernhardt & Palmer 2007). Reach-scale habitat actions may be short-term, small-scale fixes that occasionally benefit aquatic biota, but they should not be expected to rehabilitate aquatic community structure unless the hydrologic regime and water quality are also returned to a more natural state (Blakely & Harding 2005; Bernhardt & Palmer 2007). Therefore, several authors suggest that it is important to begin to address major streamflow and water quality issues early in the process of rehabilitation (e.g., Booth 2005; Bernhardt & Palmer 2007; Roni *et al.* 2008).

SECTION 10.32: TIME DURATIONS ASSOCIATED WITH REHABILITATION EFFORTS

The length of time it takes for a stream reach or watershed to respond to rehabilitation actions or structures and how long those actions or structures may last on the ground have also been considered important issues by several authors (Table 10-2). Since many rehabilitation techniques are fairly new and have not been implemented across a wide variety of regional or climatic conditions or monitored in-depth, these timelines at best can be considered as general guidelines for management and monitoring. This is particularly the case for applying the information to urban and rural-residential areas because most of the information for the Pacific Northwest is based in west-side forests.

Table 10-2. Rehabilitation characteristics. This table gives a summary of general spatial and temporal characteristics of rehabilitation and enhancement categories that have been or could be used in developed areas (based on Bernhardt & Palmer 2007; Beechie *et al.* 2008; Roni *et al.* 2002, 2008).

Approach	Approach Characteristic		
	Spatial Influence	Longevity of Action (years)	Lag-time until Influence (Years)
Erosion Control	channel network/ stream-reach	Variable	-1-5
Fish Passage Improvement	watershed/ stream-reach	10-50+	-1-5
Hydrological Connectivity			
o Flood Plain Reconnection	watershed	10-50+	1-20
o Off-Channel Habitat Creation	watershed/ stream-reach	10-50+	1-10
Riparian Area Vegetation	watershed/ stream-reach	10-50+	1-50
Instream Habitat Improvement			
o Structures	watershed/ stream-reach	-5-20	-1-5
o Substrate	stream-reach	-1-5	-1-5

Section 10.4: Information Needs for Rehabilitation in Developed Areas

Rehabilitation of aquatic ecosystems in urban and rural-residential areas can be expected to have a high level of uncertainty for success (i.e., positive impacts on native salmonids). As has been discussed, the empirical evidence to support which rehabilitation or enhancement techniques are effective under any given situation in developed areas is not generally available. As with aquatic ecosystem restoration and rehabilitation in general, the following major elementary knowledge gaps remain:

- The selection and implementation of techniques for specific regional, site, and watershed conditions;
- The level and timing of specific physical and biological (including salmonid) responses to various rehabilitation and enhancement techniques; and
- How multiple rehabilitation efforts within watersheds affect salmonid populations and their habitats.

While cumulative, global information is being synthesized (e.g., Roni *et al.* 2008) it has not been established if and how these results are applicable to developed lands in Oregon, particularly among the climatic differences between Oregon regions (i.e., coastal, temperate west-side, arid central and eastside). In order to address these information needs and to allow managers to determine rehabilitation goals, proper rehabilitation actions and comprehensive monitoring networks are needed. These would include the establishment of standardized monitoring parameters and protocols that could be integrated into regional analyses by multi-institutional monitoring programs (e.g., Paulsen *et al.* 2008; Mulvey *et al.* 2009).

Key Findings: Rehabilitation effectiveness

- Without the availability of comprehensive, long-term, and integrative monitoring data, it will not be possible to determine how rehabilitation actions are affecting aquatic ecosystems and salmonids in developed areas and how those actions are contributing to salmonid recovery in Oregon.
- Rehabilitation and enhancement techniques are being implemented in urban and rural-residential areas but the effectiveness of these actions is unknown.
- Current levels of monitoring are not adequate to determine the effectiveness of rehabilitation techniques and actions being used, either individually or in concert, in urban and rural-residential areas.
- The current state of knowledge of common rehabilitation techniques implemented in urban and rural-residential areas is based on forested and rural areas which may not be directly applicable to highly altered or degraded stream systems present in many developed areas, or to arid conditions in central and eastern Oregon.

Science Question 4: What are the major research and monitoring needs for urban and rural-residential landscapes?

There are many research and monitoring needs directly related to urban and rural-residential areas, some of which overlap with the research and monitoring needs for other land use types (e.g., Wenger *et al.* 2009). Given the marked effects developed areas can have on surface and ground waters, the continued expansion of development in Oregon, the proportion of the human population residing in these areas, and the limited amount of research and monitoring conducted on them, IMST believes that the following research and monitoring needs warrant greater attention from Oregon Plan partners.

Section 11.0: Research and Monitoring Needs

The needs IMST has identified in this section range in scale from basic research and monitoring needed on statewide variation in urban effects to more focused studies on specific parameters and structures (e.g. low impact development effectiveness, identification and removal of fish passage barriers). ***These needs are not listed in priority order.*** Overall, the effectiveness of policy and management practices needs more research and evaluation. A great challenge lies in the understanding of how toxic chemicals affect the aquatic environment and how effective rehabilitation strategies for salmonid habitat and salmonid populations are in urban and rural-residential watersheds, riparian areas, streams, floodplains, rivers, wetlands, and lakes. A better understanding of how to effectively communicate and engage the public to increase their awareness and knowledge of watershed health and salmonid recovery is crucial to successful implementation of the Oregon Plan in urban and rural-residential areas.

The IMST recognizes that various entities at the federal, state, or local levels may be engaged in addressing some of these needs listed below in ways we were not aware of during the development of this report. This possible lack of knowledge in itself, however, illustrates the communication problem we have in a state as large and varied as Oregon. Given that agencies in various municipalities and counties in Oregon (e.g. City of Portland, Clean Water Services in Washington County) are actively working to address many of these needs, the IMST spells out this list in hopes that it will generate discussion and coordinated responses throughout the State. Ideally individual entities would work together to share experiences, data, and create emergent knowledge regarding the research, monitoring, and management needs listed below as well as a “toolkit” of cost-effective remedies to be shared throughout Oregon.

The IMST further recognizes that this list of research needs is not complete. Other areas needing further research include, but are not limited to, processes of urban impacts that are unique to estuaries, knowledge regarding air quality relationships with water quality, and better knowledge of socio-ecological dynamics (see also Wenger *et al.* 2009 for other urban-related research needs developed for the US). It is the nature of science to raise additional questions in the process of answering others. The potential for unknowns expands significantly given the complexity of dealing concurrently with numerous aspects of biology, human systems, and their interactive effects. The high likelihood that the landscape is also going to change through time because of demographic pressures, economic growth, and climate change further expands the difficulty of anticipating information gaps for the future.

Section 11.1: Needs Related to General Effects of Urban Development

Evaluate the major factors that impair aquatic ecosystems and limit salmonid populations in urban and rural-residential areas. This information could be used to set priorities for addressing the sources of such impairments, whether future, contemporary or historical. In Section 8 we summarized research that reported on the variability in biological indices measured in aquatic ecosystems affected by development. These results suggest that multiple factors associated with development alter the composition of aquatic communities. This research need incorporates three sub-components.

- 1) **Assess how effective impervious area (including its proximity and connectivity to streams), landscape development indices (e.g., Brown & Vivas 2005; McMahon & Cuffney 2000), and measures of traffic or road density affect aquatic ecosystem responses to varying degrees.** By determining the major landscape sources of ecological variability, it may be possible to determine how to minimize the effects of current and future development on aquatic ecosystems.
- 2) **Insure that research on water quality (e.g., toxic chemicals) is integrated into other inter-related landscape-level factors that affect entire aquatic ecosystems (i.e., from headwaters to estuaries and near-shore marine environments) and salmonid recovery.** In general, there has been a recent tendency by aquatic scientists to focus attention on the physical and hydrological stressors of aquatic ecosystems. This is a natural consequence of largely ignoring such physical and hydrological stressors during the 1970s, but such swings in attention ignore the need to consider all the multiple stressors outlined in Figure 2-1. For example, how land use affects toxic chemicals may be just as important as how it affects hydrology, and mitigating one stressor without attending to the others means that aquatic ecosystems will remain impaired.
- 3) **Consider large-scale, long-term changes and anticipate at least 50–100 years of future human population and economic growth in salmonid-supporting watersheds, through the use of futuring and systematic analyses.** Current conditions and short-term, site-scale changes are often considered in risk assessments, but increasingly landscape ecologists are emphasizing temporally and spatially greater perspectives and long-term systematic changes (e.g., Parmesan & Yohe 2003; Baker *et al.* 2004; Steel *et al.* 2010b). Such perspectives often reveal fundamentally different risks than those evident from short-term, site-scale studies. For example, how predicted climate and land use changes will affect future hydrologic regimes and water quantity in basins affected by development needs more research, but cannot be addressed with short-term, reach-scale studies.

Section 11.2: Needs Related to Variation in Effects of Development across Oregon

Assess how the effects of development on aquatic ecosystems vary across Oregon regions (e.g., Coast, Valley, Central, East). The IMST found very few published studies reporting on the effects of urban and rural-residential areas on aquatic biota and their habitats throughout Oregon's varied environments. Most assessments were limited to the Willamette Valley and therefore may be unrepresentative of urbanization effects in other ecoregions (e.g., in more arid

regions or in estuaries). By using a scientifically rigorous sampling design (such as a probability-based design using consistent physical, chemical, and biological indicators and sampling methods, see IMST 2009) with stream sites distributed throughout Oregon's urban and rural residential areas, the State would be able to assess the degree to which those land uses alter aquatic ecosystems. That is, given such a probability-based design, one can assess the proportions and extents of stream length that are meeting desired conditions, and relate those to the stressors associated with those conditions. Such a survey would help establish management and rehabilitation priorities by clarifying the magnitude and effects of stressors. Lacking such a survey, Oregon can only guess about the effects of urban and rural-residential development on stream ecosystems (e.g., Oregon Progress Board 2000). This need incorporates two sub-components.

- 1) **Assess the proportion of urban and rural-residential stream length that is 303(d) listed, the proportions of those with TMDLs, and the proportions of the streams with reduced biological condition that are not listed.** Waterways with 303(d) listings and TMDLs offer insights into the more extreme parts of the water quality picture, but may ignore flow, passage, and habitat structure for salmonids. A more thorough consideration of the effectiveness of water quality standards goes beyond water chemistry and sediment analysis and would include an assessment of biological condition and the role of multiple stressors. However, 303(d) listings depend on sampling (with sometimes either frequency or spatial limitations), and not all urban/rural-residential streams have been rigorously sampled. A state-wide assessment of the proportion of stream lengths that merit 303(d) listing in urban and rural-residential areas would indicate which streams, rivers, or estuaries warrant more water quality monitoring and assessment.
- 2) **Assess the current capacity of Oregon streams and rivers within urban growth boundaries to support salmonids (in terms of parameters such as physical habitat, seasonal flows, storm flows, water temperature, dissolved oxygen, fine sediments, and biota).** A probability-based survey such as that described earlier could be used to assess the proportion of urban and rural-residential streams that support, or that has the potential to support, viable salmonid populations. By sampling in both summer and winter, the State could determine the proportion of stream miles in developed or developing areas that support or could support salmonid spawning, rearing, or both. Recent research in Oregon agricultural streams in the Willamette Valley indicates that intermittent streams may support spawning and rearing of native fish (Colvin *et al.* 2009). Some small urban streams in western Oregon also support small salmonid populations (Friesen & Ward 1996; Hughes *et al.* 1998; Waite *et al.* 2008), but the distributions and sizes of such populations have not been rigorously evaluated.

Section 11.3: Needs Related to Stormwater Runoff

Determine the adequacy of methods currently implemented in Oregon for alleviating or mitigating the adverse effect of stormwater runoff (e.g., by increasing on-site retention) in both urban and rural-residential areas. Impervious surfaces such as roofs, roads, and parking areas rapidly deliver stormwater runoff to streams rather than allowing precipitation to infiltrate into the soil (Section 4.11 of this report). Low impact development methods have the goal of increasing on-site water retention that may better mimic natural hydrologic and vegetation patterns (Section 9.23 of this report). It would be useful for the State of Oregon to determine where and how often low impact development methods are implemented in Oregon's urban and rural-residential areas and their overall effectiveness in protecting Oregon's aquatic ecosystems. This need incorporates two sub-components.

- 1) **Assess the degree to which current technical methods that have been shown to be effective in increasing on-site water retention have been implemented by local development codes.** The implementation frequency of flow retention methods can likely be assessed by surveys of households and of city planning departments. A second tier of assessment could use field studies of paired sites to evaluate the effectiveness of such retention measures on local flow regimes.
- 2) **If methods increasing on-site water retention are not effective, or are not consistently implemented by local governments and residents, determine why.** Assuming that many urban and rural-residential properties lack flow retention measures, city planner and household surveys could indicate possible reasons. The reasons may include current and historical lack of awareness of the importance of storm flow retention for protecting natural stream structure and function, the initial economic costs of such measures, the notion that such features are not attractive, uncertainty concerning the cost-effectiveness of alternative retention methods, or the contrasting values of citizens (e.g., Lakoff 2002; Graham *et al.* 2009; Steel *et al.* 2010a)

Section 11.4: Needs Related to Groundwater

Assess future groundwater hydrologic responses to population pressures and the extent of groundwater contamination in Oregon's urban and rural-residential areas. Better knowledge of both groundwater hydrology and groundwater quality is needed. Further knowledge is needed concerning how groundwater quality, location and supply could be affected as population and economic pressures on groundwater increase. Knowledge needed includes better understanding of the connections between urban surface and groundwater hydrology, the effect of groundwater withdrawals on groundwater supply, and the current and potential effects of groundwater contamination from waste discharges and land use.

Toxic chemical mixtures from urban and rural-residential areas may leach into groundwater and the degree to which this happens and the potential consequences for aquatic ecosystems are unknown (see Section 11.6 for more needs related to toxic chemicals). The use of low impact development techniques to increase stormwater detention and soil infiltration (as well as the potential to inject surface water into dry wells which were not addressed in this report) create the

potential for increased groundwater contamination depending on the sources of the runoff. Further, there is a need to assess the extent to which present and historical landfill, industrial, and commercial facilities leach toxic chemicals into groundwater.

Section 11.5: Needs Related to Fish Passage Barriers

Determine the extent and number of physical fish passage barriers in urban and rural-residential areas, especially concerning prioritization of removal. Removal of fish passage barriers has been found to be an effective stream rehabilitation technique because barrier removal opens up habitat otherwise inaccessible to migratory fishes. Oregon Department of Transportation and the Oregon Department of Fish and Wildlife both have databases with information on fish passage barriers. Better integration of information on all existing barriers is needed in terms of how they are distributed and how they may be prioritized for removal.

Section 11.6: Needs Related to Toxic Chemicals

Determine the effects of, and possible treatment/remediation/elimination methods for, urban toxic substances and mixtures of toxic substances. Our current understanding of the role of the many varied toxic chemicals prevalent in urban and rural-residential areas is poor and needs much work. Generally, much needs to be learned both regarding conveyance systems of toxic chemicals in urban watersheds and regarding the aquatic chemistry and biological response of aquatic organisms to the cumulative and interactive effects of toxic chemicals. The known and potential ways in which toxic mixtures may impair aquatic ecosystems is summarized in Section 7.6 of this report; however, the individual and cumulative effects of toxic chemicals remain an area of major scientific uncertainty. Sewage and stormwater treatment systems already in use in Oregon and elsewhere do not remove many of the toxic chemicals of concern before treated water is discharged into the environment. The Oregon Department of Environmental Quality considers this issue a major concern because deleterious effects on aquatic organisms are often apparent despite sub-toxic concentrations of individual chemicals. Also, little is known how differences in water quality parameters, such as pH, hardness, and temperature, alter the cumulative chemical interactions and their effects on biota. This need incorporates 6 sub-components.

- 1) **Determine how, when, where, and how often to screen for and identify levels of contaminants and mixtures in aquatic ecosystems affected by urban and rural-residential developments.** Chemicals and their breakdown products are released to the environment on a daily basis from urban and rural-residential areas. These releases create a difficult and expensive monitoring challenge.
- 2) **Evaluate the ecologically relevant and chronic toxicities of a wide range of chemicals on salmonids, and compare those toxicities with those that may occur at the concentrations found in the aquatic environment.** If chronic toxicities (i.e., long-term toxicity of a substance in small, repeated doses) are known for pesticides, pharmaceuticals and personal care products, and other commonly used products, they can be compared against concentrations found in urban water bodies. It is likely that toxicities

of many of these chemicals, are unknown, and even more likely that the toxicities of mixtures are unknown. Given the large number of potentially toxic chemicals determining those present in low concentrations but with high frequency would be a priority over those that occur infrequently. Higher priority chemicals could then be evaluated for their endocrinological effects on salmonid physiology and potential consequences at the population level.

- 3) **Assess the degree to which cumulative and synergistic effects of commonly-occurring chemicals prevalent in urban areas alter salmonid behavior, reproduction, and mortality.** A combination of whole effluent chronic toxicity and early developmental tests can be used to evaluate salmonid growth, feeding, predator avoidance, parasite/disease loads, endocrine disrupting potential, and hormones. Acute tests will likely focus on juvenile salmonid mortality rates (USEPA 2002a).
- 4) **Assess the degree to which cumulative and synergistic effects of commonly-occurring urban chemicals alter salmonid-supporting food webs.** Research insights in this area may be best attained through use of experimental streams or model ecosystems (with underlying assumptions clearly identified) because of the complexity of potential interactions among predators, prey, and the food base (e.g., Warren & Davis 1971; Belanger 1997).
- 5) **Conduct research on the relative technical and economic feasibility of removing endocrine disrupting chemicals and other toxic chemicals from the waste stream through sewage and stormwater treatment and/or prohibitions on product sales.** Endocrine disrupters are viewed by some as a fundamental threat to the health and sustainability of salmonids and other aquatic vertebrates because they occur throughout our environment. Endocrine disrupters can affect vertebrate endocrine systems at very low doses. These effects can extend to vertebrate embryological development, juvenile development, general health (including immune system dysfunction and increased vulnerability to cancer) and reproductive fitness (either directly or indirectly) (e.g., Colborn *et al.* 1993, 1996; Hayes *et al.* 2006; Colborn 2009). Assays have been, and continue to be, developed for impairment of physiological systems by endocrine disrupting compounds; given the risks of these chemicals and the extent of their occurrence, however, it would be wise to consider ways of substantially reducing their presence in the environment as well as in salmonids.
- 6) **Determine the best available strategies for keeping toxic chemical from pesticides, herbicides, personal care products, pharmaceuticals, metals, and other anthropogenic-derived products out of surface and ground waters.** Given their widespread occurrence and the potential for toxic substances to impair salmonid and human health at extremely low concentrations, it is advisable that Oregon agencies review methods for eliminating these chemicals from use and waste streams. Research and monitoring resources might best be focused on the effectiveness of cost-effective and

scalable (i.e., from reach to basin-level) strategies to control and mitigate toxic contamination. A more thorough assessment of effectiveness would go beyond chemical analyses to include the perspective of biological condition.

Section 11.7: Needs Related to the Evaluation of Effectiveness of Policies and Regulations

Determine the strengths and areas for improvement of measures currently implemented in Oregon to avoid, remedy or mitigate the impact of urban and rural-residential development in headwaters, wetlands, riparian areas, floodplains, and key salmonid-watersheds. The State of Oregon leads the nation in comprehensive land use planning; however, as described in Section 9.0 of this report, much more can be done, especially regarding sensitive aquatic environments and the watersheds that dominate and buffer the flow regimes of urban streams. A review of current county and municipal land use plans and regulations could indicate the degree to which current laws, regulations and programs adequately remedy or mitigate the adverse impacts of development on watersheds and aquatic ecosystems (e.g., Ozawa & Yeakley 2007). This need incorporates four sub-components.

- 1) **Assess whether or not planning measures for protecting streams, wetlands, riparian areas, floodplains, and other sensitive areas are effective.** If current laws are written such that they could provide adequate protection to aquatic ecosystems, then the implementation consistency of protective measures can be assessed by studying the land use plans of local governments and completed projects to determine how frequently sensitive systems are protected. Assessment of these systems could be evaluated through remote sensing and field surveys.
- 2) **If planning measures are failing to mitigate or remedy the adverse effects of development or are inconsistently implemented, determine why.** If sensitive areas (e.g., water bodies, riparian areas, and unstable lands) within urban growth boundaries are not protected or incompletely protected, a survey of county and urban planners could indicate possible reasons. It also appears prudent to assess the long-term ecological effects and monetary costs associated with the implementation and lack of implementation of these measures. In other words, the effects of a “lack of action” may lead to long-term future costs that greatly outweigh costs associated with implementation of mitigation or remedial actions in the first place (NRC 1992; 2002).
- 3) **Assess the most cost-effective low impact development (LID) practices.** Research is needed to determine the effectiveness of major LID techniques for normalizing hydrological regimes and removing toxic chemicals from runoff. Washington State has eastside and west-side best management practices, reflecting the differing hydrologic regimes east and west of the Cascades. Evaluations would include the degree to which LID increases runoff retention and improves fish physical, chemical and biological habitat and fish species and assemblage condition. It also would be useful to study

whether LID can improve stream physical, chemical, and biological conditions relative to preexisting conditions (Brown *et al.* 2009).

- 4) **Determine how much low impact development (LID) is required in a developed watershed to protect aquatic ecosystems or to improve the condition of already affected streams, rivers and estuaries.** Evaluations are needed concerning whether LID structures in new developments regulated by the NPDES permitting system are sufficient for controlling stormwater and water pollution. Also in need of evaluation are the specific water quality parameters improved by specific forms of LID structures. If sufficient, strategies for integrating LID into existing development need to be determined. It would also be useful to consider assessing LID at site, development, and watershed scales. Here again, a more thorough evaluation of the effectiveness of practices would be evaluated from the perspective of the biological condition of receiving streams.

Section 11.8: Needs Related to Rehabilitation

Assess the effectiveness of efforts to rehabilitate streams in urban and rural-residential areas. A number of projects have been funded to rehabilitate urban streams in Oregon; however to our knowledge, none have been evaluated for their effectiveness in supporting salmonids (Section 10.0 of this report). This need incorporates three sub-components.

- 1) **Assess the effects of urban and rural-residential rehabilitation projects in Oregon on salmonids, aquatic assemblages, and aquatic physical and chemical habitat.** Depending on the number of projects and available funds, project effectiveness could be assessed through a census or survey of sites using a consistent site-scale design and a consistent set of indicators. Incorporating basin coordinators, municipalities and volunteer groups, as well as state and federal agencies, in this monitoring will increase the likelihood of successful salmonid rehabilitation.
- 2) **Evaluate the current technical and implementation processes and estimated costs of removing fish barriers.** Because urban areas are often located downstream of salmonid spawning and rearing streams and because urban areas typically have many barriers (e.g. barriers where roads cross streams), removing these barriers can be an effective way of reducing the effects of developed areas on salmonid production.
- 3) **Assess the ecological and economic costs and benefits that would likely result from rehabilitation efforts directed toward recovering salmonids in developed areas. Evaluate project costs and benefits for households as well as municipalities.** The cost to taxpayers and utility ratepayers is a frequent reason cited for resisting salmonid conservation and water quality improvement. But to IMST's knowledge there has been no rigorous evaluation of those costs, of the costs of incomplete and uncoordinated attempts to comply with state land use and federal ESA and CWA regulations, or of the ancillary benefits to other users and uses if naturally sustainable salmonid populations were attained.

Section 11.9: Needs Related to Communication and Citizen Science

Determine how to communicate science information more widely and effectively to the broadest possible audience via formats that go well beyond technical journal articles.

Citizen science spans a large spectrum, from individual citizens to non-governmental environmental research and management entities (e.g. non-profit organizations and watershed councils). Citizen groups offer the potential to extend the scope of environmental research and to produce a public that is more cognizant of environmental issues. New cross-discipline partnerships (e.g., social scientists, communication scientists, graphic artists, and print and electronic media journalists) are needed to expand the overall effectiveness and social context of citizen science efforts.

Intra- and inter-disciplinary communication on all research gaps is needed. It is critical that government bodies at all levels, including university and agency researchers, work together to ask, evaluate, and answer questions concerning watershed health and the rehabilitation of wild salmonids. While investigator independence and creativity will always be essential to conducting scientific studies, communication and transferability of study outcomes are enhanced by consistency of terminology, methods and indicators. Without consistent and spatially extensive study designs, sampling methods and indicators, the State of Oregon can invest considerable human and fiscal resources and learn little that can be inferred beyond each separate study. If some standardization of experimental designs, methods, and indicators are used by potential investigators and shared through common databases, much more can be learned for the same fiscal and human investments in our common future (e.g. Stranko *et al.* 2005; Paulsen *et al.* 2008; Brown *et al.* 2009; Mulvey *et al.* 2009). In other words, just as spatial and temporal fragmentation limit species richness, fragmented information and management practices limit knowledge and effectiveness.

References

- Abbott C, Howe D, Adler S (eds) (1994) *Introduction in Planning the Oregon Way*. Oregon State University Press, Corvallis, Oregon.
- Abell R, Allan JD, Lehner B (2007) Unlocking the potential of protected areas for freshwater. *Biological Conservation* 134(1): 48–63.
- Achord S, Zabel RW, Sandford BP (2007) Migration timing, growth, and estimated parr-to-smolt survival rates of wild Snake River spring-summer Chinook salmon from the Salmon River basin, Idaho, to the lower Snake River. *Transactions of the American Fisheries Society* 136(1): 142–154.
- Alabaster JS (1988) The dissolved oxygen requirements of upstream migrant Chinook salmon, *Oncorhynchus tshawytscha*, in the lower Willamette River, Oregon. *Journal of Fish Biology* 32(4): 635–636.
- Alberti M, Marzluff JM, Schulenberger E, Bradley G, Ryan C, Zumbrunnen C (2003) Integrating humans into ecology: opportunities and challenges for studying urban ecosystems. *BioScience* 53(122): 1169–1179.
- Alberti M, Booth D, Hill K, Coburn B, Avolio C, Coed S, Spirandelli D (2007) The impact of urban patterns on aquatic ecosystems: An empirical analysis in Puget lowland sub-basins. *Landscape and Urban Planning* 80(4): 345–361.
- Alexander GG, Allan JD (2006) Stream restoration in the upper Midwest, U.S.A. *Restoration Ecology* 14 (4): 595–604.
- Alexander RB, Boyer EW, Smith RA, Schwarz GE, Moore RB (2007) The role of headwater streams in downstream water quality. *Journal of the American Water Resources Association* 43(1): 41–59.
- Alig RJ, Kline JD, Lichtenstein M (2004) Urbanization on the US landscape: Looking ahead in the 21st century. *Landscape and Urban Planning* 69(2-3): 219–234.
- Allan JD (2004) Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology and Systematics* 35(1): 257–284.
- American Forests (1998) *Regional Ecosystem Analysis, Puget Sound Metropolitan Area, Calculating the Value of Nature*. American Forests, Washington, DC.
- American Forests (2001) *Regional Ecosystem Analysis for the Willamette/lower Columbia Region of Northwestern Oregon and Southwestern Washington State, Calculating the Value of Nature*. American Forests, Washington, DC.
- Amlin NM, Rood SB (2002) Comparative tolerances of riparian willows and cottonwoods to water-table decline. *Wetlands* 22(2): 338–346.
- Amoros C, Rostan JC, Pautou G, Bravard JP (1987) The reversible process concept applied to the environmental management of large river systems. *Environmental Management* 11(5): 607–617.
- Anderson TD, Lydy MJ (2002) Increased toxicity to invertebrates associated with a mixture of atrazine and organophosphate insecticides. *Environmental Toxicology and Chemistry* 21(7): 1507–1514.
- Anderson TD, Zhu KY (2004) Synergistic and antagonistic effects of atrazine on the toxicity of organophosphorodithioate and organophosphorothioate insecticides to *Chironomus tentans* (Diptera: Chironomidae). *Pesticide Biochemistry and Physiology* 80(1): 54–64.
- Anderson CW, Rinella FA, Rounds SA (1996) *Occurrence of Selected Trace Elements and Organic Compounds and Their Relation to Land Use in the Willamette River Basin, Oregon, 1992–94*. Water-Resources Investigations Report 96-4234. US Geological Survey, Denver, Colorado.
- Anderson RJ, Bledsoe BP, Hession WC (2004) Width of streams and rivers in response to vegetation, bank material, and other factors. *Journal of the American Water Resources Association* 40(5): 1159–1172.
- Andreasen JK, O'Neill RV, Noss R, Slosser NC (2001) Considerations for the development of a terrestrial index of biological integrity. *Ecological Indicators* 1(1): 21–35.

- Angermeier PL, Karr JR (1984) Relationships between woody debris and fish habitat in a small warmwater stream. *Transactions of the American Fisheries Society* 113(6): 716–726.
- Angilletta MJ, Steel EA, Bartz KK, Kingsolver JG, Scheuerell MD, Beckman BR, Crozier LG (2008) Big dams and salmon evolution: Changes in thermal regimes and their potential evolutionary consequences. *Evolutionary Applications* 1(2): 286–299.
- APA (American Planning Association) (2002) *Planning for Smart Growth: 2002 State of the States*. American Planning Association, Washington, DC.
- Arkoosh MR, Casillas E, Clemons E, Kagley AN (1998a) Effect of pollution on fish diseases: Potential impacts on salmonid populations. *Journal of Aquatic Animal Health* 10(2): 182–190.
- Arkoosh MR, Casillas E, Huffman P, Clemons E, Evered J, Stein JE, Varanasi U (1998b) Increased susceptibility of juvenile Chinook salmon from a contaminated estuary to *Vibrio anguillarum*. *Transactions of the American Fisheries Society* 127(3): 360–374.
- Arkoosh MR, Clemons E, Huffman P, Kagley AN (2001) Increased susceptibility of juvenile Chinook salmon to vibriosis after exposure to chlorinated and aromatic compounds found in contaminated urban estuaries. *Journal of Aquatic Animal Health* 13(3): 257–268.
- Armsworth PR, Daily GC, Kareiva P, Sanchirico JN (2006) Land market feedbacks can undermine biodiversity conservation. *Proceedings of the National Academy of Science* 103(14): 5403–5408.
- Arnfield AJ (2003) Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology* 23(1): 1–26.
- Arnold CL Jr, Gibbons JC (1996) Impervious surface coverage. *Journal of the American Planning Association* 62(2): 243–258.
- Arsenault JTM, Fairchild WL, MacLatchy DL, Burrige L, Haya K, Brown SB (2004) Effects of water-borne 4-nonylphenol and 17 β -estradiol exposures during parr-smolt transformation on growth and plasma IGF-I of Atlantic salmon (*Salmo salar* L). *Aquatic Toxicology* 66(3): 255–265.
- Atasoy M, Palmquist RB, Phaneuf DJ (2006) Estimating the effects of urban residential development on water quality using microdata. *Journal of Environmental Management* 79(4): 399–408.
- Azuma DL, Birch KR, Herstrom AA, Kline JD, Lettman GJ (2002) *Forest, Farms, and People: Land Use Change on Non-federal Land in Western Oregon, 1973-2000*. Oregon Department of Forestry, Salem, Oregon.
- Azuma DL, Birch KR, Herstrom AA, Lettman GJ (2004) *Forest, Farms, and People: Land Use Change on Non-federal Land in Eastern Oregon, 1973-2001*. Oregon Department of Forestry, Salem, Oregon.
- Azuma DL, Herstrom AA, Lettman GJ, McKay N, Robinson TJ (2009) *Forest, Farms and People: Land Use Change on Non-Federal Land in Oregon 1974-2005*. Oregon Department of Forestry, Salem, Oregon.
- Bäckström M, Viklander M, Malmqvist PA (2006) Transport of stormwater pollutants through a roadside grassed swale. *Urban Water Journal* 3(2): 55–67.
- Bailey RC, Kennedy MG, Dervish MZ, Taylor RM (1998) Biological assessment of freshwater ecosystems using a reference condition approach: Comparing predicted and actual benthic invertebrate communities in Yukon streams. *Freshwater Biology* 39(4): 765–774.
- Bailey HC, Deanovic L, Reyes E, Kimball T, Larson K, Cortright K, Connor V, Hinton DE (2000) Diazinon and chlorpyrifos in urban waterways in northern California, USA. *Environmental Toxicology and Chemistry* 19(1): 82–87.
- Baker JP, Hulse DW, Gregory SV, White D, Van Sickle J, Berger PA, Dole D, Schumaker NH (2004) Alternative futures for the Willamette River basin, Oregon. *Ecological Applications* 14(2): 313–324.
- Baldwin DH, Sandahl JF, Labenia JS, Scholz NL (2003) Sublethal effects of copper on coho salmon: Impacts on nonoverlapping receptor pathways in the peripheral olfactory nervous system. *Environmental Toxicology and Chemistry* 22(10): 2266–2274.

- Baltz DM, Moyle PB (1993) Invasion resistance to introduced species by a native assemblage of California stream fishes. *Ecological Applications* 3(2): 246–255.
- Bangsgaard K, Madsen SS, Korsgaard B (2006) Effect of waterborne exposure to 4-*tert*-octylphenol and 17 β -estradiol on smoltification and downstream migration in Atlantic salmon, *Salmo salar*. *Aquatic Toxicology* 80(1): 23–32.
- Barnes DKA, Galgani F, Thompson RC, Barlaz M (2009) Accumulations and fragmentation of plastic debris in global environments. *Philosophical Transactions of the Royal Society B* 364(1526): 1985–1998.
- Barringer TH, Reiser RG, Price CV (1994) Potential effects of development on flow characteristics of two New Jersey streams. *Water Resources Bulletin* 30(2): 283–295.
- Bash J, Berman C, Bolton S (2001) *Effects of Turbidity and Suspended Solids on Salmonids*. Center for Streamside Studies, University of Washington, Seattle, Washington.
- Bastasch R (2006) *The Oregon Water Handbook: A Guide to Water and Water Management*. Oregon State University Press, Corvallis, Oregon.
- Bates K, Barnard B, Heiner B, Klavas P, Powers P (2003) *Fish Passage Design at Road Culverts: A Design Manual for Fish Passage at Road Crossings*. Washington Department of Fish and Wildlife, Habitat and Lands Program, Environmental Engineering Division, Olympia, Washington.
- Battin J, Wiley MW, Ruckelshaus MH, Palmer RN, Korb E, Bartz KK, Imaki H (2007) Projected impacts of climate change on salmon habitat restoration. *Proceedings of the National Academy of Sciences* 104(16): 6720–6725.
- Baxter CV (2002) *Fish Movement and Assemblage Dynamics in a Pacific Northwest Riverscape*. PhD Dissertation. Oregon State University, Corvallis, Oregon.
- Beasley G, Kneale P (2002) Reviewing the impact of metals and PAHs on macroinvertebrates in urban watercourses. *Progress in Physical Geography* 26(2): 236–270.
- Beechie T, Bolton S (1999) An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. *Fisheries* 24(4): 6–15.
- Beechie TJ, Sibley TH (1997) Relationships between channel characteristics, woody debris, and fish habitat in northwestern Washington streams. *Transactions of the American Fisheries Society* 126(12): 217–229.
- Beechie T, Buhle E, Ruckelshaus M, Fullerton A, Holsinger L (2006) Hydrologic regime and the conservation of salmon life history diversity. *Biological Conservation* 130(4): 560–572.
- Beechie T, Pess G, Roni P, Giannico G (2008) Setting river restoration priorities: A review of approaches and a general protocol for identifying and prioritizing actions. *North American Journal of Fisheries Management* 28(3): 891–905.
- Belanger SE (1997) Literature review and analysis of biological complexity in model stream ecosystems: Influence of size and experimental design. *Ecotoxicology and Environmental Safety* 36(1): 1–16.
- Belgiorno V, Rizzo L, Fatta D, Della Rocca C, Lofrano G, Nikolaou A, Naddeo V, Meric S (2007) Review on endocrine disrupting-emerging compounds in urban wastewater: Occurrence and removal by photocatalysis and ultrasonic irradiation for wastewater reuse. *Desalination* 215(1-3): 166–176.
- BenDor T (2009) A dynamic analysis of the wetland mitigation process and its effects on no net loss policy. *Landscape and Urban Planning* 89(1-2): 17–27.
- BenDor T, Brozović N (2007) Determinants of spatial and temporal patterns in compensatory wetland mitigation. *Environmental Management* 40(3): 349–364.
- BenDor T, Sholtes J, Doyle MW (2009) Landscape characteristics of a stream and wetland mitigation banking program. *Ecological Applications* 19(8): 2078–2092.
- Benke AC, Cushing CE (2005) *Rivers of North America*. Elsevier, New York, New York.

- Benner P (1992) Historical reconstruction of the Coquille River and surrounding landscape. Sections 3.2 and 3.3 In *The Action Plan for Oregon Coastal Wetlands, Estuaries and Ocean Waters, 1988-91*. Oregon Department of Environmental Quality, Salem, Oregon.
- Benner P, Sedell JR (1997) Upper Willamette river landscape: A historic perspective. Pages 23–48 In (eds Laenen A, Dunnette DA) *River Quality, Dynamics, and Restoration*. Lewis Publishers, Boca Raton, Florida.
- Benton County (2008) *Phase 1: Benton County Water Analysis and Demand Forecast, Evaluating the Quality and Quantity of Water Resources for all Uses, Needs, and Users of Benton County, OR*. Benton County Water Project, Benton County, Oregon.
- Berg L, Northcote TG (1985) Changes in territorial gill-flaring, and feeding behavior in juvenile coho salmon (*Oncorhynchus kisutch*) following short-term pulses of suspended sediment. *Canadian Journal of Fisheries and Aquatic Sciences* 42(8): 1410–1417.
- Bernert JA, Eilers JM, Eilers BJ, Blok E, Daggett SG, Bierly KF (1999) Recent wetland trends (1981/2–1994) in the Willamette Valley, Oregon, USA. *Wetlands* 19(3): 545–559.
- Bernhardt ES, Palmer MA (2007) Restoring streams in an urbanizing world. *Freshwater Biology* 52(4): 738–751.
- Bernhardt ES, Palmer MA, Allan JD, Alexander G, Barnas K, Brooks S, Carr J, Clayton S, Dahm C, Follstad-Shah J, Galat D, Gloss S, Goodwin P, Hart D, Hassett B, Jenkinson R, Katz S, Kondolf GM, Lake PS, Lave R, Meyer JL, O'Donnell TK, Pagano L, Powell B, Sudduth E (2005) Synthesizing U.S. river restoration efforts. *Science* 308(5722): 636–637.
- Bernhardt ES, Sudduth EB, Palmer MA, Allan JD, Meyer JL, Alexander G, Follstad-Shah J, Hassett B, Jenkinson R, Lave R, Rumps J, Pagano L (2007) Restoring rivers one reach at a time: Results from a survey of U.S. river restoration practitioners. *Restoration Ecology* 15(3): 482–493.
- Bernhardt ES, Band LE, Walsh CJ, Berke PE (2008) Understanding, managing, and minimizing urban impacts on surface water nitrogen loading. *Annals of New York Academy of Science* 1134(1): 61–96.
- Beschta RL (1985) River channel responses to accelerated mass erosion. Pages 155–163 In *Proceedings of Symposium on Effects of Forest Land Use on Erosion and Slope Stability*. East-West Center, Environment and Policy Institute, Honolulu, Hawaii.
- Beschta RL (1997) Restoration of riparian and aquatic systems for improved aquatic habitats in the upper Columbia River basin. Pages 475–492 In (eds Strouder DJ, Bisson PA, Naiman RJ) *Pacific Salmon and Their Ecosystems: Status and Future Options*. Chapman and Hall, New York, New York.
- Beschta RL, Platts WS (1986) Morphological features of small streams: Significance and function. *Water Resources Research* 22(3): 369–379.
- Bilby RE (1984) Removal of woody debris may affect stream channel stability. *Journal of Forestry* 82(10): 609–613.
- Bilby RE, Bisson PA (1998) Function and distribution of large woody debris. Pages 324–346 in: *River Ecology and Management* (eds Naiman RJ, Bilby RE) Springer-Verlag, New York, New York.
- Bilby RE, Mollot LA (2008) Effect of changing land use patterns on the distribution of coho salmon (*Oncorhynchus kisutch*) in the Puget Sound region. *Canadian Journal of Fisheries and Aquatic Sciences* 65(10): 2138–2148.
- Bilby RE, Ward JW (1989) Changes in characteristics and function of woody debris with increasing size of streams in western Washington. *Transactions of the American Fisheries Society* 118(4): 368–378.
- Birch GF, Matthai C, Fazeli MS (2006) Efficiency of a retention/detention basin to remove contaminants from urban stormwater. *Urban Water Journal* 3(2): 69–77.
- Bisson PA, Bilby RE (1982) Avoidance of suspended sediment by juvenile coho salmon. *North American Journal of Fisheries Management* 2(4): 371–374.
- Bisson PA, Bilby RE, Bryant MD, Dolloff CA, Grette GB, House RA, Murphy ML, Koski KV, Sedell JR (1987) Large woody debris in forested streams in the Pacific Northwest: Past, present, and future. Pages 143–190 In

- (eds Salo EO, Cundy TW) *Streamside Management: Forestry and Fisheries Interactions*. Contribution No. 57. University of Washington Forestry Institute, Seattle, Washington.
- Bisson PA, Sullivan K, Nielsen JL (1988) Channel hydraulics, habitat use, and body form of juvenile coho salmon, steelhead, and cutthroat trout in streams. *Transactions of the American Fisheries Society* 117(3): 262–273.
- Bisson PA, Quinn TP, Reeves GH, Gregory SV (1992) Best management practices, cumulative effects, and long-term trends in fish abundance in Pacific Northwest river systems. Pages 189–232 In (ed Naiman RJ) *Watershed Management: Balancing Sustainability and Environmental Change*. Springer-Verlag, New York, New York.
- Bjornn TC, Reiser DW (1991) Habitat requirements of salmonids in streams. Pages 83–138 In (ed Meehan WR) *Influences of Forest and Rangeland Management on salmonid fishes and their habitats*. Special Publication 19. American Fisheries Society, Bethesda, Maryland.
- Black RW, Haggland AL, Voss FD (2000) Predicting the probability of detecting organochlorine pesticides and polychlorinated biphenyls in stream systems on the basis of land use in the Pacific Northwest, USA. *Environmental Toxicology and Chemistry* 19(4): 1044–1054.
- Blakely TJ, Harding JS (2005) Longitudinal patterns in benthic communities in an urban stream under restoration. *New Zealand Journal of Marine and Freshwater Research* 39(1): 17–28.
- Bledsoe BP (2002) Stream erosion potential and stormwater management strategies. *Journal of Water Resources Planning and Management* 128(6): 451–455.
- Bledsoe BP, Watson C (2001a) Effects of urbanization on channel instability. *Journal of the American Water Resources Association* 37(2): 255–270.
- Bledsoe BP, Watson C (2001b) Logistic analysis of channel pattern thresholds: meandering, braiding, and incising. *Geomorphology* 38(3-4): 281–300.
- Boersma PD, Reichard SH, Van Buren AN (eds) (2006) *Invasive Species in the Pacific Northwest*. University of Washington Press, Seattle, Washington.
- Bonar SA, Bolding BD, Divens M, Meyer W (2005) Effects of introduced fishes on wild juvenile coho salmon in three shallow Pacific Northwest lakes. *Transactions of the American Fisheries Society* 134(3): 641–652.
- Booth DB (1990) Stream-channel incision following drainage-basin urbanization. *Water Resources Bulletin* 26(3): 407–417.
- Booth DB (1991) Urbanization and the natural drainage system – impacts, solutions, prognoses. *The Northwest Environmental Journal* 7(1): 93–118.
- Booth DB (2000) *Forest Cover, Impervious-surface Area, and the Mitigation of Urbanization Impacts in King County, Washington*. Center for Urban Water Resources Management, Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington.
- Booth DB (2005) Challenges and prospects for restoring urban streams: A perspective from the Pacific Northwest of North America. *Journal of the North American Benthological Society* 24(3): 724–737.
- Booth DB, Henshaw PC (2001) Rates of channel erosion in small urban streams. Pages 17–38 In *Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas*. American Geophysical Union, Water Science and Application 2. Washington, DC.
- Booth DB, Jackson CR (1997) Urbanization of aquatic systems: Degradation thresholds, stormwater detection, and the limits of mitigation. *Journal American Water Resources Association* 33(5): 1077–1090.
- Booth DB, Reinelt LE (1994) Consequences of urbanization on aquatic systems - measured effects, degradation thresholds, and corrective strategies. Pages 545–550 In *Proceedings: Watershed '93: A National Conference on Watershed Management, March 21-24, Alexandria, Virginia*. United States Bureau of Reclamation and United States Environmental Protection Agency, Washington, DC.
- Booth DB, Karr JR, Schauman S, Konrad CP, Morley SA, Larson MG, Hehshaw PC, Nelson EJ, Burgess SJ (2001) *Urban Stream Rehabilitation in the Pacific Northwest*. University of Washington Final Report, USEPA Grant Number R82-5284-010. Seattle, Washington.

- Booth DB, Hartley D, Jackson R (2002) Forest cover, impervious-surface area, and the mitigation of stormwater impacts. *Journal of the American Water Resources Association* 38(3): 835–845.
- Booth DB, Karr JR, Schauman S, Konrad CP, Morley SA, Larson MG, Burges SJ (2004) Reviving urban streams: Land use, hydrology, biology, and human behavior. *Journal of the American Water Resources Association* 40(5): 1351–1364.
- Borde AB, Thom RM, Rumrill S, Miller LM (2003) Geospatial habitat change analysis in Pacific Northwest coastal estuaries. *Estuaries* 26(4B): 1104–1116.
- Borgström ST, Elmquist T, Angelstam P, Alfsen-Norodom C (2006) Scale mismatches in management of urban landscapes. *Ecology and Society* 11(2): [article 16]
- Bottom DL, Simenstad CA, Burke J, Baptista AM, Jay DA, Jones KK, Casillas E, Schiewe MH (2005) *Salmon at river's end: the role of the estuary in the decline and recovery of Columbia River salmon*. Technical Memorandum NMFS-NWFSC-68. U S Department of Commerce, NOAA, Seattle, Washington.
- Boulton AJ (2007) Hyporheic rehabilitation in rivers: Restoring vertical connectivity. *Freshwater Biology* 52(4): 632–650.
- Boulton AJ, Moss GL, Smithyman D (2003) Short-term effects of aerially-applied fire-suppressant foams on water chemistry and macroinvertebrates in streams after natural wild-fire on Kangaroo Island, South Australia. *Hydrobiologia* 498(1-3): 177–189.
- Bowen JL, Valiela I (2001) The ecological effects of urbanization of coastal watersheds: Historical increases in nitrogen loads and eutrophication of Waquoit Bay estuaries. *Canadian Journal of Fisheries and Aquatic Sciences* 58(8): 1489–1500.
- Bradbury B, Nehlsen W, Nickelson TE, Moore KMS, Hughes RM, Heller D, Nicholas J, Bottom DL, Weaver WE, Beschta RL (1995) *Handbook for Prioritizing Watershed Protection and Restoration to Aid Recovery of Native Salmon*. Pacific Rivers Council, Portland, Oregon.
- Brandes D, Gregory JC, Nilson ML (2005) Base flow trends in urbanizing watersheds of the Delaware river basin. *Journal of the American Water Resources Association* 41(6): 1377–1391.
- Breetz HL, Fisher-Vanden K, Garzon L, Jacobs H, Kroetz K, Terry R (2004) *Water Quality Trading and Offset Initiatives in the US: A Comprehensive Survey*. Dartmouth College, Hanover, New Hampshire.
- Brett JR (1956) Some principles in the thermal requirements of fishes. *Quarterly Review of Biology* 31(2): 75–87.
- Brett JR (1964) The respiratory metabolism and swimming performance of young sockeye salmon. *Journal of the Fisheries Research Board of Canada* 21: 1183–1226.
- Brett MT, Arhonditsis GB, Mueller SE, Hartley DM, Frodge JD, Funke DE (2005a) Non-point source impacts on stream nutrient concentrations along a forest to urban gradient. *Environmental Management* 35(3): 330–342.
- Brett MT, Mueller SE, Arhonditsis GB (2005b) A daily time series analysis of stream water phosphorus concentrations along an urban to forest gradient. *Environmental Management* 35 (1): 56–71.
- Brooks BW, Riley TM, Taylor RD (2006) Water quality of effluent-dominated ecosystems: Ecotoxicological, hydrological, and management considerations. *Hydrobiologia* 556(1): 365–379.
- Brown T, Caraco D (2001) Channel protection. *Water Resources Impact* 3(6): 16–19.
- Brown PH, Lant CL (1999) The effects of wetland mitigation banking on the achievement of no-net-loss. *Environmental Management* 23(3): 333–345.
- Brown MT, Vivas MB (2005) Landscape development intensity index. *Environmental Monitoring and Assessment* 101(1-3): 289–309.
- Brown SB, Evans RE, Vandenbyllardt L, Finsson KW, Palace VP, Kane AS, Yarechewski AY, Muir DCG (2004) Altered thyroid status in lake trout (*Salvelinus namaycush*) exposed to co-planar 3,3',4,4',5-pentachlorobiphenyl. *Aquatic Toxicology* 67(1): 75–85.

- Brown DG, Johnson KM, Loveland TR, Theobald DM (2005a) Rural land-use trends in the conterminous United States, 1950-2000. *Ecological Applications* 15(6): 1851-1863.
- Brown LR, Gray RH, Hughes RM, Meador MR (2005b) Introduction to effects of urbanization on stream ecosystems. Pages 1-6 In (eds Brown LR, Gray RH, Hughes RM, Meador MR) *Effects of Urbanization on Stream Ecosystems*. Symposium 47. American Fisheries Society, Bethesda, Maryland.
- Brown, LR, Cuffney TF, Coles JF, Fitzpatrick F, McMahon G, Steuer J, Bell AH, May JT (2009) Urban streams across the USA: Lessons learned from studies in 9 metropolitan areas. *Journal of the North American Benthological Society* 28(4): 1051-1069.
- Bryce SA (2006) Development of a bird integrity index: Measuring avian response to disturbance in the Blue Mountains of Oregon, USA. *Environmental Management* 38(3): 470-486.
- Bryce SA, Hughes RM (2002) Variable assemblage responses to multiple disturbance gradients: Case studies in Oregon and Appalachia, USA. Pages 539-560 In (ed Simon TP) *Biological Response Signatures: Indicator Patterns Using Aquatic Communities*. CRC Press, Boca Raton, Florida.
- Bryce SA, Hughes RM, Kaufmann PR (2002) Development of a bird integrity index: Using bird assemblages as indicators of riparian condition. *Environmental Management* 30: 294-310.
- Bryce SA, Lomnický GA, Kaufmann PR, McAllister LS, Ernst TL (2008) Development of biologically-based sediment criteria in mountain streams of the western United States. *North American Journal of Fisheries Management* 28(6): 1714-1724.
- Bryce SA, Lomnický GA, Kaufmann PR (2010) Protecting sediment-sensitive aquatic species in mountain streams through the application of biologically based streambed sediment criteria. *Journal of the North American Benthological Society* 29(2): 657-672.
- Buchholz T, Younos T (2007) *Urban Stream Daylighting Case Study Evaluations*. Special Report SR35-2007. Virginia Water Resources Research Center, Virginia Tech, Blacksburg, Virginia.
- Buhl KJ, Hamilton SJ (2000) Acute toxicity of fire-control chemicals, nitrogenous chemicals, and surfactants to rainbow trout. *Transactions of the American Fisheries Society* 129(2): 408-418.
- Burcher CL, Benfield EF (2006) Physical and biological responses of streams to suburbanization of historically agricultural watersheds. *Journal of the North American Benthological Society* 25(2): 356-369.
- Burges SJ, Wigmosta MS, Meena JM (1998) Hydrological effects of land-use change in a zero-order catchment. *Journal of Hydrologic Engineering* 3(2): 86-97.
- Burnett KM, Reeves GH, Miller DJ, Clarke S, Vance-Borland K, Christiansen K (2007) Distribution of salmon-habitat potential relative to landscape characteristics and implications for conservation. *Ecological Applications* 17(1): 66-80.
- Burns D, Vitvar T, McDonnell J, Hassett J, Duncan J, Kendall C (2005) Effects of suburban development on runoff generation in the Croton River basin, New York, USA. *Journal of Hydrology* 311(1-4): 266-281.
- Burton CA, Brown LR, Belitz K (2005) Assessing water source and channel type as factors affecting benthic macroinvertebrate and periphyton assemblages in the highly urbanized Santa Ana River basin, California. Pages 239-262 In (eds Brown LR, Gray RH, Hughes RM, Meador MR) *Effects of Urbanization on Stream Ecosystems*. Symposium 47. American Fisheries Society, Bethesda, Maryland.
- Busby PJ, Wainwright TC, Bryant GJ, Lierheimer LJ, Waples RS, Waknitz FW, Lagomarsino IV (1996) *Status Review of West Coast Steelhead from Washington, Idaho, Oregon, and California*. NOAA Technical Memorandum NMFS-NWFSC 27. US Department of Commerce, National Marine Fisheries Service, Seattle, Washington.
- Bustard DR, Narver DW (1975) Preferences of juvenile coho salmon (*Oncorhynchus kisutch*) and cutthroat trout (*Oncorhynchus clarkii*) relative to simulated alteration of winter habitat. *Journal of the Fisheries Research Board of Canada* 32: 681-687.
- Butler DR, Malanson GP (2005) The geomorphologic influences of beaver dams and failures of beaver dams. *Geomorphology* 71(1-2): 48-60.

- Cadenasso ML, Pickett STA, Groffman PM, Band LE, Brush GS, Galvin MF, Grove JM, Hagar G, Marshall V, McGrath PB, O'Neil-Dunne JPM, Stack WP, Troy AR (2008) Exchanges across land-water-scape boundaries in urban systems: Strategies for reducing nitrate pollution. *Annals of the New York Academy of Science* 1134(1): 213–232.
- Callaway JC, Josselyn MN (1992) The introduction and spread of smooth cordgrass (*Spartina alterniflora*) in south San Francisco Bay. *Estuaries* 15(2): 218–226.
- Carle MV, Halpin PN, Stow CA (2005) Patterns of watershed urbanization and impacts on water quality. *Journal of the American Water Resources Association* 41(3): 693–708.
- Carpenter KD, Waite IR (2000) Relations of habitat-specific algal assemblages to land use and water chemistry in the Willamette basin, Oregon. *Environmental Monitoring and Assessment* 64(1): 247–257.
- Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH (1998) Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8(3): 559–568.
- Carpenter DD, Sinha SK, Brennan K, Slate LO (2003) Urban stream restoration. *Journal of Hydraulic Engineering* 129(7): 491–493.
- Carpenter KD, Sobieszczyk S, Arnsberg AJ, Rinella FA (2008) *Pesticide Occurrence and Distribution in the Lower Clackamas River Basin, Oregon, 2000-2005*. United States Geological Survey Scientific Investigations Report 2008–5027. Reston, Virginia.
- Carrasquero J (2001) *Over-Water Structures: Freshwater Issues*. (Report submitted to Washington Department of Fish and Wildlife, Washington Department of Ecology, and Washington Department of Transportation.) Herrera Environmental Consultants, Seattle, Washington.
- Carter JL, Fend SV (2005) Setting limits: The development and use of factor-ceiling distributions for an urban assessment using macroinvertebrates. Pages 179–191 In (eds Brown LR, Gray RH, Hughes RM, Meador MR): *Effects of Urbanization on Stream Ecosystems*. Symposium 47. American Fisheries Society, Bethesda, Maryland.
- Carter TL, Rasmussen TC (2006) Hydrologic behavior of vegetated roofs. *Journal of the American Water Resources Association* 42(5): 1261–1274.
- Carter J, Owens PN, Walling DE, Leeks GJL (2003) Fingerprinting suspended sediment sources in a large urban river system. *The Science of the Total Environment* 314–316(1): 513–534.
- Casperson JP, Pacala SW, Jenkins JC, Hurtt GC, Moorcroft PR, Birdsey RA (2000) Contributions of land-use history to carbon accumulation in US forests. *Science* 290(5494): 1148–1151.
- Cederholm CJ, Reid LM (1987) Impact of forest management on coho salmon (*Oncorhynchus kisutch*) populations of the Clearwater River, Washington: A project summary. Pages 373–398 In (eds Salo EO, Cundy TW) *Streamside Management: Forestry and Fishery Interactions*. Contribution 57. Institute of Forest Resources, University of Washington, Seattle, Washington.
- Chang H (2007) Comparative streamflow characteristics in urbanizing basins in the Portland Metropolitan area, Oregon, USA. *Hydrological Processes* 21(2): 211–222.
- Chang H, Carlson TN (2005) Water quality during winter storm events in Spring Creek, Pennsylvania USA. *Hydrobiologia* 544(1): 321–332.
- Chapman JW, Miller TW, Coan EV (2003) Live seafood species as recipes for invasion. *Conservation Biology* 17(5): 1386–1395.
- Chin A (2006) Urban transformation of river landscapes in a global context. *Geomorphology* 79(3-4): 460–487.
- Chin A, Gregory KJ (2001) Urbanization and adjustment of ephemeral stream channels. *Annals of the Association of American Geographers* 91(4): 595–608.
- Cho S, Wu J, Alig R (2005) Land development under regulation: Comparison between the east and west sides of the Cascade Range in Oregon, Washington, and California. *Review of Urban and Regional Development Studies* 17(1): 1–17.

- City of Portland (2004) *Willamette River Conditions Report*. Bureau of Planning, City of Portland, Portland, Oregon.
- City of Portland (2005) *Actions for Watershed Health: Portland Watershed Management Plan*. Environmental Services, Portland, Oregon.
- City of Portland (2006) *Stormwater Management Plan: National Pollutant Discharge Elimination System (NPDES) Municipal Separate Storm Sewer (MS4) Discharge Permit; Permit Number: 101314*. City of Portland, Portland, Oregon.
- Claessens L, Hopkinson C, Rastetter E, Vallino J (2006) Effects of historical changes in land use and climate on the water budget of an urbanizing watershed. *Water Resources Research* 42: W03426 [13 p.]. Clara M, Windhofer G, Hartl W, Braun K, Simon M, Gans O, Scheffknecht C, Chovanec A (2010) Occurrence of phthalates in surface runoff, untreated and treated wastewater and fate during wastewater treatment. *Chemosphere* 78(9): 1078–1084.
- Clara M, Windhofer G, Hartl W, Braun K, Simon M, Gans O, Scheffknecht C, Chovanec A (2010) Occurrence of phthalates in surface runoff, untreated and treated wastewater and fate during wastewater treatment. *Chemosphere* 78(9): 1078–1084
- Clark JL (1999) *Effects of Urbanization on Streamflow in Three Basins in the Pacific Northwest*. MS thesis, Portland State University, Portland, Oregon
- Clarkin K, Connor A, Furniss MJ, Gubernick B, Love M, Moynan K, Wilson-Musser S (2005) *National Inventory and Assessment Procedure – for Identifying Barriers to Aquatic Organism Passage at Stream-Road Crossings*. 7700–Transportation Management. National Technology and Development Program, USDA Forest Service, San Dimas, California.
- Climate Impacts Group (2009) *The Washington Climate Change Impacts Assessment* (eds McGuire Elsner M, Littell J, Whitely Binder L). Center for Science in the Earth System. Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington.
- Coats R, Larsen M, Heyvaert A, Thomas J, Luck M, Reuter J (2008) Nutrient and sediment production, watershed characteristics, and land use in the Tahoe basin, California-Nevada. *Journal of the American Water Resources Association*. 44 (3): 754–770.
- Colbert D, McManus J (2003) Nutrient biogeochemistry in an upwelling-influenced estuary of the Pacific Northwest (Tillamook Bay, Oregon, USA). *Estuaries* 26(5): 1205–1219.
- Colborn T (2009) EPA's new pesticide testing is outdated. *Scientific American*. April 27 [online].
- Colborn T, vom Saal FS, Soto AM (1993) Development effects of endocrine-disrupting chemicals in wildlife and humans. *Environmental Health Perspectives* 101(5): 378–384.
- Colborn T, Dumanoski D, Myers JP (1996) *Our Stolen Future*. Dutton, New York.
- Cole ML, Kroeger KD, McClelland JW, Valiela I (2006) Effects of watershed land use on nitrogen concentrations and δ^{15} nitrogen in groundwater. *Biogeochemistry* 77(2): 199–215.
- Collins BD, Montgomery DR, Haas AD (2002) Historical changes in the distribution and functions of large wood in Puget Lowland rivers. *Canadian Journal of Fisheries and Aquatic Sciences* 59(1): 66–76.
- Colt J (1984) *Computation of Dissolved Gas Concentrations in Water as a Function of Temperature, Salinity, and Pressure*. Special Publication 14. American Fisheries Society, Bethesda, Maryland.
- Colvin R, Giannico GR, Li J, Boyer KL, Gerth WJ (2009) Fish use of intermittent watercourses draining agricultural lands in the upper Willamette River valley, Oregon. *Transactions of the American Fisheries Society* 138(6): 1302–1313.
- Comeleo RL, Paul JF, August PV, Copeland J, Baker C, Hale SS, Latimer RW (1996) Relationships between watershed stressors and sediment contamination in Chesapeake Bay estuaries. *Landscape Ecology* 11(5): 307–319.

- Comings KJ, Booth DB, Horner RR (2000) Storm water pollutant removal by two wet ponds in Bellevue, Washington. *Journal of Environmental Engineering* 126 (4): 321–330.
- Conn KE, Barber LB, Brown GK, Siegrist RL (2006) Occurrence and fate of organic contaminants during onsite wastewater treatment. *Environmental Science and Technology* 40(23): 7358–7366.
- Cooke SJ, Hinch SG, Farrell AP, Lapointe MF, Jones SRM, Macdonald JS, Patterson DA, Healey MC, Van Der Kraak G (2004) Abnormal migration timing and high en route mortality of sockeye salmon in the Fraser River, British Columbia. *Fisheries* 29(2): 22–33.
- Cornell JS, Pillard DA, Hernandez MT (2000) Comparative measures of the toxicity of component chemicals in aircraft deicing fluid. *Environmental Toxicology and Chemistry* 19(6): 1465–1472.
- Corsi SR, Harwell GR, Geis SW, Bergman D (2006) Impacts of aircraft deicer and anti-icer runoff on receiving waters from Dallas/Fort Worth International Airport, Texas, USA. *Environmental Toxicology and Chemistry* 25(11): 2890–2900.
- Cortwright R, Weber J, Bailey R (1987) *The Oregon Estuary Plan Book*. Oregon Department of Land Conservation and Development, Salem, Oregon.
- Costello C, Polasky S (2004) Dynamic reserve site selection. *Resource and Energy Economics* 26(2): 157–174.
- Coulter CB, Kolka RK, Thompson JA (2004) Water quality in agricultural, urban, and mixed land use watersheds. *Journal of the American Water Resources Association* 40(6): 1593–1601.
- Coupe RH, Manning MA, Foreman WT, Goolsby DA, Majewski MS (2000) Occurrence of pesticides in rain and air in urban and agricultural areas of Mississippi, April–September 1995. *Science of the Total Environment* 248(2): 227–240.
- Craft C, Broome S, Campbell C (2002) Fifteen years of vegetation and soil development after brackish-water marsh creation. *Restoration Ecology* 10(2): 248–258.
- Cristina CM, Sansalone JJ (2003) ‘First flush’ power law and particle separation diagrams for urban stormwater suspended particulates. *Journal of Environmental Engineering* 129(4): 298–307.
- Crouch RL, Timmenga HJ, Barber TR, Fuchsman PC (2006) Post-fire surface water quality: Comparison of fire retardant versus wildfire-related effects. *Chemosphere* 62(6): 874–889.
- Crouse MR, Callahan CA, Malueg KW, Dominguez SE (1981) Effects of fine sediments on growth of juvenile coho salmon in laboratory streams. *Transactions of the American Fisheries Society* 110(2): 281–286.
- Crozier L, Zabel RW (2006) Climate impacts at multiple scales: Evidence for differential population responses in juvenile Chinook salmon. *Journal of Animal Ecology* 75(5): 1100–1109.
- Cuffney TF, Zappia H, Giddings EMP, Coles JF (2005) Effects of urbanization on benthic macroinvertebrate assemblages in contrasting environmental settings: Boston, Massachusetts; Birmingham, Alabama; and Salt Lake City, Utah. Pages 361–407 In (eds Brown LR, Gray RH, Hughes RM, Meador MR) *Effects of Urbanization on Stream Ecosystems*. Symposium 47. American Fisheries Society, Bethesda, Maryland.
- Cui CW, Ji SL, Ren HY (2006) Determination of steroid estrogens in wastewater treatment plant of a contraceptives producing factory. *Environmental Monitoring and Assessment* 121(1-3): 409–419.
- Cumming G S, Cumming DHM, Redman CL (2006) Scale mismatches in social-ecological systems: Causes, consequences, and solutions. *Ecology and Society* 11(1): [article 14].
- Daggett SG, Boule ME, Bernert JA, Eilers JM, Blok E, Peters D, Morlan J (1998) *Wetland and Land Use Change in the Willamette Valley, Oregon: 1982 to 1994*. Wetlands Program, Oregon Division of State Lands. Salem, Oregon.
- Dahl JA, Maddux BLS, Hutchison JE (2007) Toward greener nanosynthesis. *Chemical Reviews* 107(6): 2228–2269.
- Dale V, Archer S, Chang M, Ojima D (2005) Ecological impacts and mitigation strategies for rural land management. *Ecological Applications* 15(6): 1879–1892.

- Datry T, Malard F, Gibert J (2004) Dynamics of solutes and dissolved oxygen in shallow urban groundwater below a stormwater infiltration basin. *Science of the Total Environment* 329(1-3): 215–229.
- Davis DA (1999) *Pesticides Detected in Urban Streams During Rainstorms and Relations to Retail Sales of Pesticides in King County, Washington*. USGS Fact Sheet 097-99. US Geological Survey, Tacoma, Washington.
- Davies SM, Jackson SK (2006) The biological condition gradient: a descriptive model for interpreting change in aquatic ecosystems. *Ecological Applications* 16(4): 1251–1266.
- Davis AP, Shokouhian M, Ni S (2001) Loading estimates of lead, copper, cadmium, and zinc in urban runoff from specific sources. *Chemosphere* 44(5): 997–1009.
- De Robertis A, Ryer CH, Veloza A, Brodeur RD (2003) Differential effects of turbidity on prey consumption of piscivorous and planktivorous fish. *Canadian Journal of Fisheries and Aquatic Sciences* 60(12): 1517–1526.
- de Wit CA (2002) An overview of brominated flame retardants in the environment. *Chemosphere* 46(5): 583–624.
- Debruyn AMH, Ikonomou MG, Gobas FAPC (2004) Magnification and toxicity of PCBs, PCDDs, and PCDFs in upriver-migrating Pacific salmon. *Environmental Science and Technology* 38(23): 6217–6224.
- Demmer R, Beschta RL (2008) Recent history (1988–2004) of beaver dams along Bridge Creek in central Oregon. *Northwest Science* 82(4): 309–318.
- Dietz ME (2007) Low impact development practices: A review of current research and recommendations for future directions. *Water, Air & Soil Pollution* 186(1-4): 351–363.
- Dietz ME, Clausen JC (2008) Stormwater runoff and export changes with development in a traditional and low impact subdivision. *Journal of Environmental Management* 87(4): 560–566.
- Dole D, Niemi E (2004) Future water allocation and in-stream values in the Willamette River basin: A basin-wide analysis. *Ecological Applications* 14(2): 355–367.
- Dow CL, DeWalle DR (2000) Trends in evaporation and Bowen Ratio on urbanizing watershed in eastern United States. *Water Resources Research* 36(7): 1835–1843.
- Downs PW, Kondolf GM (2002) Post-project appraisals in adaptive management of river channel restoration. *Environmental Management*. 29(4) 477–496.
- Drake MT, Pereira DL (2002) Development of a fish-based index of biotic integrity for small inland lakes in central Minnesota. *North American Journal of Fisheries Management* 22(4): 1105–1123.
- Dunham JB, Young MK, Gresswell RE, Rieman BE (2003) Effects of fire on fish populations: Landscape perspectives on persistence of native fishes and nonnative fish invasions. *Forest Ecology and Management* 178(1-2): 183–196.
- Dunn RR, Gavin MC, Sanchez MC, Solomon JN (2006) The pigeon paradox: Dependence of global conservation on urban nature. *Conservation Biology* 20(6): 1814–1816.
- Dunne T, Leopold LB (1978) *Water in Environmental Planning*. WH Freeman, San Francisco, California.
- Dunning JB, Danielson BJ, Pulliam HR (1992) Ecological processes that affect populations in complex landscapes. *Oikos* 65(1): 169–175.
- Durning AT, Williams-Derry C, de Place E, Chu EW (2002) *This Place on Earth 2002: Measuring What Matters*. Sightline Institute, Seattle, Washington.
- Dykaar BB, Wigington PJ Jr (2000) Floodplain formation and cottonwood colonization patterns on the Willamette River, Oregon, USA. *Environmental Management* 25(1): 87–104.
- Ebbert JC, Embry SS, Black RW, Tesoriero AJ, Hagglund AL (2000) *Water Quality in the Puget Sound Basin, Washington and British Columbia, 1996-98*. USGS Circular 1216. US Geological Survey, Reston, Virginia.
- Ebersole JL, Liss WJ, Frissell CA (2001) Relationship between stream temperature, thermal refugia and rainbow trout *Oncorhynchus mykiss* abundance in arid-land streams in the northwestern United States. *Ecology of Freshwater Fish* 2001(10): 1–10.

- Ebersole JL, Liss WJ, Frissell CA (2003) Thermal heterogeneity, stream channel morphology, and salmonid abundance in northeastern Oregon streams. *Canadian Journal of Fisheries and Aquatic Sciences* 60(10): 1266–1280.
- Ehrenfeld JG (2008) Exotic invasive species in urban wetlands: Environmental correlates and implications for wetland management. *Journal of Applied Ecology* 45(4): 1160–1169.
- Einsweiler RC, Howe DA (1994) Managing 'the land between': A rural development paradigm. Pages 245–274 In (eds Abbott C, Howe D, Adler S) *Planning the Oregon Way*. Oregon State University Press, Corvallis, Oregon.
- Elliott JE, Wilson LK, Wakeford B (2005) Polybrominated diphenyl ether trends in eggs of marine and freshwater birds from British Columbia, Canada, 1979–2002. *Environmental Science and Technology* 39(15): 5584–5591.
- Ellis JB (2006) Pharmaceutical and personal care products (PPCPs) in urban receiving waters. *Environmental Pollution* 144(1): 184–189.
- Ellis PA, Mackay R, Rivett MO (2007) Quantifying urban river–aquifer fluid exchange processes: A multi-scale problem. *Journal of Contaminant Hydrology* 91(1-2): 58–80.
- Ellison ME, Brett MT (2006) Particulate phosphorus bioavailability as a function of stream flow and land cover. *Water Research* 40(6): 1258–1268.
- Even S, Poulin M, Mouchel J-M, Seidl M, Servais P (2004) Modelling oxygen deficits in the Seine River downstream of combined sewer overflows. *Ecological Modelling* 173(2-3): 177–196.
- Everest FH, Reeves GH (2007) *Riparian and Aquatic Habitats of the Pacific Northwest and Southeast Alaska: Ecology, Management History, and Potential Management Strategies*. General Technical Report PNW-GTR-692. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon.
- Farr RA, Ward DL (1993) Fishes of the lower Willamette River, near Portland, Oregon. *Northwest Science* 67(1): 16–22.
- Farrow RS, Schultz MT, Celikkol P, Van Houtven GL (2005) Pollution trading in water quality limited areas: Use of benefits assessment and cost-effective trading ratios. *Land Economics* 81(2): 191–205.
- Faulkner H, Edmonds-Brown V, Green A (2000) Problems of quality designation in diffusely polluted urban streams—the case of Pymme's Brook, north London. *Environmental Pollution* 109(1): 91–107.
- Fausch KD, Young MK (1995) Evolutionary significant units and movement of resident stream fishes: A cautionary tale. Pages 360–370 In (ed Nielsen JL) *Evolution and the Aquatic Ecosystem: Defining Unique Units in Population Conservation*. Symposium 17. American Fisheries Society, Bethesda, Maryland.
- Fausch KD, Karr JR, Yant PR (1984) Regional applications of an index of biotic integrity based on stream-fish communities. *Transactions of the American Fisheries Society* 113(1): 39–55.
- Fausch KD, Torgersen CE, Baxter CV, Li HL (2002) Landscapes to riverscapes: Bridging the gap between research and conservation of stream fishes. *BioSciences* 52(6): 483–498.
- Fausch KD, Rieman BE, Young MK, Dunham JB (2006) *Strategies for Conserving Native Salmonid Populations at Risk from Nonnative Fish Invasions: Tradeoffs in Using Barriers to Upstream Movement*. General Technical Report RMRS-GTR-174. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado.
- Fauth JE, Bernardo J, Camara M, Resetarits WJ Jr, Van Buskirk J, McCollum SA (1996) Simplifying the jargon of community ecology: A conceptual approach. *The American Naturalist* 147(2): 282–286.
- FEMAT (Forest Ecosystem Management Team) (1993) *Forest Ecosystem Management: An Ecological, Economic, and Social Assessment*. US Department of Agriculture and US Department of Interior, Portland, Oregon.
- Fent KA, Weston A, Caminada D (2006) Ecotoxicology of human pharmaceuticals. *Aquatic Toxicology* 76(2): 122–159.
- Ficke AD, Myrick CA, Hansen LJ (2007) Potential impacts of global climate change on freshwater fisheries. *Review of Fish Biology and Fisheries* 17(4): 581–613.

- Fierke MK, Kaufman JB (2005) Structural dynamics of riparian forests along a black cottonwood successional gradient. *Forest Ecology and Management* 215(1-3): 149–162.
- Fierke MK, Kaufman JB (2006) Invasive species influence riparian plant diversity along a successional gradient, Willamette River, Oregon. *Natural Areas Journal* 26(4): 376–382.
- Finkenbine JK, Atwater JW, Mavinic DS (2000) Stream health after urbanization. *Journal of the American Water Resources Association* 36(5): 1149–1160.
- Finn RN (2007) The physiology and toxicology of salmon eggs and larvae in relation to water quality criteria. *Aquatic Toxicology* 81(4): 337–354.
- Fisher DJ, Knott MH, Turley SD, Turley BS, Yonkos LT, Ziegler GP (1995) The acute whole effluent toxicity of storm water from an international airport. *Environmental Toxicology and Chemistry* 14(6): 1103–1111.
- Fisher DS, Steiner JL, Endale DM, Stuedemann JA, Schomberg HH, Franzluebbbers AJ, Wilkinson SR (2000) The relationship of land use practices to surface water quality in the upper Oconee watershed of Georgia. *Forest Ecology and Management* 128(1-2): 39–48.
- Fitzpatrick FA, Diebel MW, Harris MA, Arnold TL, Lutz MA, Richards KD (2005) Effects of urbanization on the geomorphology, habitat, hydrology, and fish index of biotic integrity of streams in the Chicago area, Illinois and Wisconsin. Pages 87–115 In (eds Brown LR, Gray RH, Hughes RM, Meador MR) *Effects of Urbanization on Stream Ecosystems*. Symposium 47. American Fisheries Society, Bethesda, Maryland.
- Flint KR, Davis AP (2007) Pollutant mass flushing characterization of highway stormwater runoff from an ultra-urban area. *Journal of Environmental Engineering* 133(6): 616–626.
- Folke C, Jansson A, Larsson J, Costanza R (1997) Ecosystem appropriation by cities. *Ambio* 26(3): 167–172.
- Follstad-Shah JJ, Dahm CN, Gloss SP, Bernhardt ES (2007) River and riparian restoration in the Southwest: Results of the National River Restoration Science synthesis project. *Restoration Ecology*. 15(3): 550–562.
- Fore LS (2003) Response of diatom assemblages to human disturbance: Development and testing of a multi-metric index for the mid-Atlantic region (USA) Pages 445–480 In (ed Simon TP) *Biological Response Signatures: Indicator Patterns using Aquatic Communities* CRC Press, Boca Raton, Florida.
- Fore LS, Grafe C (2002) Using diatoms to assess the biological condition of large rivers in Idaho (USA). *Freshwater Biology* 47(10): 2015–2037.
- Foster D, Swanson F, Aber J, Burke I, Brokaw N, Tilman D, Knapp A (2003) The importance of land-use legacies to ecology and conservation. *Bioscience* 53(1): 77–88.
- Freeman MC, Pringle CM, Jackson CR (2007) Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. *Journal of the American Water Resources Association* 43(1): 5–14.
- Friesen TA, Ward DL (1996) Status and condition of fish assemblages in streams of the Tualatin River basin, Oregon. *Northwest Science* 70(2): 120–131.
- Fresh KL, Casillas E, Johnson LL, Bottom DL (2005) *Role of the Estuary in the Recovery of Columbia River Basin Salmon and Steelhead: An Evaluation of the Effects of Selected Factors on Salmonid Population Viability*. NOAA Technical Memorandum NMFS-NWFSC-69. Northwest Fisheries Science Center, National Marine Fisheries Service, Seattle, Washington.
- Frey DG (1975) Biological integrity of water - An historical approach. Pages 127–140 In (eds Ballentine RK, Guarraia LJ) *The Integrity of Water: Proceedings of a Symposium, March 10-12, 1975 in: Washington, DC*. Report-335. US Environmental Protection Agency, Washington, DC.
- Friesen TA (2005) *Biology, Behavior, and Resources of Resident and Anadromous Fish in the Lower Willamette River*. Final report 2000-2004 to the City of Portland. Oregon Department of Fish and Wildlife, Clackamas, Oregon.
- Frissell CA, Nawa RK (1992) Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. *North American Journal of Fisheries Management* 12(1): 182–197.

- Fritts AL, Pearsons TN (2005) The role of predator and prey size in evaluating predation risk by smallmouth bass in the Yakima River, Washington. Pages 88–106 In (eds Pearsons T, Temple G, Fritts A, Johnson C, Webster T, Pitts N) *Yakima River Species Interactions Studies: Yakima/Klickitat Fisheries Project Monitoring and Evaluation*. Annual Report 2004 - 2005, Project No. 199506325, BPA Report DOE/BP-00017478-3. Bonneville Power Administration, Portland, Oregon.
- Fuhrer GJ, Tanner DQ, Morace JL, McKenzie SW, Skach KA (1996) *Water Quality of the Lower Columbia River Basin: Analysis of Current and Historical Water-Quality Data through 1994*. Investigations Report 95–4294. US Geological Survey Water-Resources, Denver, Colorado.
- Fullerton AH, Beechie TJ, Baker SE, Hall JE, Barnas KA (2006) Regional patterns of riparian characteristics in the interior Columbia River basin, northwestern USA: Applications for restoration planning. *Landscape Ecology* 21(8): 1347–1360.
- Gaddis EJB, Vladich H, Voinov A (2006) Participatory modeling and the dilemma of diffuse nitrogen management in a residential watershed. *Environmental Modelling & Software* 22(5): 619–629.
- Gaikowski MP, Hamilton SJ, Buhl KJ (1996) Acute toxicity of three retardant and two fire-suppressant foam formulations to the early life stages of rainbow trout (*Oncorhynchus mykiss*). *Environmental Toxicology and Chemistry* 15(8): 1365–1374.
- Galbraith RV, MacIsaac EA, Macdonald JS, Farrell AP (2006) The effect of suspended sediment on fertilization success in sockeye (*Oncorhynchus nerka*) and coho (*Oncorhynchus kisutch*) salmon. *Canadian Journal of Fisheries and Aquatic Sciences* 63(11): 2487–2494.
- Galli J (1990) *Thermal Impacts Associated with Urbanization and Stormwater Management Best Management Practices*. Metropolitan Washington Council of Governments, Publication Number 91701. Washington, DC.
- Gallo K, Lanigan SH, Eldred P, Gordon SN, Moyer C (2005) *Northwest Forest Plan – The First 10 Years (1994-2003): Preliminary Assessment of the Condition of Watersheds*. General Technical Report PNW-GTR-647. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon.
- Gammon JR (2005) Wabash River fishes from 1800 to 2000. Pages 365–381 In (eds Rinne JN, Hughes RM, Calamusso B) *Historical Changes in Large River Fish Assemblages of the Americas*. Symposium 45. American Fisheries Society, Bethesda, Maryland.
- GAO (US General Accounting Office) (1998) *Oregon Watersheds: Many Activities Contribute to Increased Turbidity during Large Storms*. GAO/RCED-98-220. US General Accounting Office, Washington, DC.
- GAO (US General Accounting Office) (2000) *Aviation and the Environment: Airport Operations and Future Growth Present Environmental Challenges*. GAO/RCED-00-153. US General Accounting Office, Washington, DC.
- GAO (US General Accounting Office) (2001) *Restoring Fish Passage Through Culverts on Forest Service and BLM Lands in Oregon and Washington Could Take Decades*. GAO-02-136. US General Accounting Office, Washington, DC.
- GAO (US General Accounting Office) (2004) *Watershed Management: Better Coordination of Data Collection Efforts Needed to Support Key Decisions*. GAO-04-382. US General Accounting Office, Washington, DC.
- Gerrard, AJ (1981) *Soils and Landforms*. George Allen & Unwin, London, United Kingdom.
- Gertzen E, Familiar O, Leung B (2008) Quantifying invasion pathways: Fish introductions from the aquarium trade. *Canadian Journal of Fisheries and Aquatic Sciences* 65(7): 1265–1273.
- Gibson CA, Meyer JL (2007) Nutrient uptake in a large urban river. *Journal of the American Water Resources Association* 43(3): 576–587.
- Gibson CA, Meyer JL, Poff NL, Hay LE, Georgakakos A (2005) Flow regime alterations under changing climate in two river basins: Implications for freshwater ecosystems. *River Research and Applications* 21(8): 849–864.
- Gilliom RJ, Barbash JE, Crawford CG, Hamilton PA, Martin JD, Nakagaki N, Nowell LH, Scott JC, Stackelberg PE, Thelin GP, Wolock DM (2006) *The Quality of Our Nation's Waters: Pesticides in the Nation's Streams and Ground Water, 1999–2001*. USGS Circular 1291. US Geological Survey, Reston, Virginia.

- Giménez A, Pastor E, Zárata L, Planas E, Arnaldos J (2004) Long-term forest fire retardants: A review of quality, effectiveness, application and environmental considerations. *International Journal of Wildland Fire* 13(1): 1–15.
- Glasby TM (1999) Effects of shading on subtidal epibiotic assemblages. *Journal of Experimental Marine Biology and Ecology* 234(2): 275–290.
- Godwin D, Parry B, Burris F, Chan S, Punton A (2008) *Barriers and Opportunities for Low Impact Development: Case Studies from Three Oregon Communities*. Oregon Sea Grant, Oregon State University, Corvallis, Oregon.
- Gonia TM, Keefer ML, Bjornn TC, Peery CA, Bennett DH, Stuehrenberg LC (2006) Behavioral thermoregulation and slowed migration by adult fall Chinook salmon in response to high Columbia River water temperatures. *Transactions of the American Fisheries Society* 135(2): 408–419.
- Good JW (1999) Estuarine science, management, and restoration. Pages 33–44 in (OSU Extension Service) *Watershed Stewardship: A Learning Guide*. Oregon State University Extension Service, Corvallis, Oregon.
- Good JW (2000) Summary and current status of Oregon's estuarine ecosystems. Pages 33–44 In (ed Risser PG): *Oregon State of the Environment Report*. Oregon Progress Board, Salem, Oregon.
- Good TP, Waples RS, Adams P (2005) *Updated Status of Federally Listed ESUs of West Coast Salmon and Steelhead*. Technical Memorandum, NMFS-NWFSC-66. US Department of Commerce, National Oceanic and Atmospheric Administration, Seattle, Washington.
- Goodale CL, Aber JD (2001) The long-term effects of land-use history on nitrogen cycling in northern hardwood forests. *Ecological Applications* 11(1): 253–267.
- Gosnell H, Kline JD, Chrostek G, Duncan (2010) Is Oregon's land use planning program conserving forest and farm land? A review of the evidence. *Land Use Policy* 28(1): 185–192.
- Gordon JD, Schild DE, Capesius JP, Slaughter CB (2005) *Surface Water-Quality and Water-Quantity Data from Selected Urban Runoff-Monitoring Sites at the Rocky Mountain Arsenal, Commerce City, Colorado, Water Years 1988-2004*. Investigations Report 2005-5214. US Geological Survey, Reston, Virginia.
- Gormley KL, Teather KL (2003) Developmental, behavioral, and reproductive effects experienced by Japanese medaka (*Oryzias latipes*) in response to short-term exposure to endosulfan. *Ecotoxicology and Environmental Safety* 54(3): 330–338.
- Gowan C, Young MK, Fausch KD, Riley SC (1994) Restricted movement in resident stream salmonids: A paradigm lost? *Canadian Journal of Fisheries and Aquatic Sciences* 51(11): 2626–2637.
- Graves GA, Wan Y, Fike DL (2004) Water quality characteristics of storm water from major land uses in south Florida. *Journal of the American Water Resources Association* 40(6): 1405–1419.
- Graham J, Haidt J, Nosek BA (2009) Liberals and conservatives rely on different sets of moral foundations. *Journal of Personality and Social Psychology* 96(5): 1029–1046.
- Gray L (2004a) Changes in water quality and macroinvertebrate communities resulting from urban stormflows in the Provo River, Utah, USA. *Hydrobiologia* 518(1-3): 33–46.
- Gray M (2004b) *Introduced Fishes Impacts: Coastal Coho Assessment (Policy for Evaluation and Conservation Format)*. Oregon Department of Fish and Wildlife and Oregon Plan for Salmon and Watersheds, Salem, Oregon.
- Gregory RS (1993) Effect of turbidity on the predator avoidance behavior of juvenile Chinook salmon (*Oncorhynchus tshawytscha*). *Canadian Journal of Fisheries and Aquatic Sciences* 50(2): 241–246.
- Gregory SV, Bisson PA (1997) Degradation and loss of anadromous salmonid habitat in the Pacific Northwest. Pages 277–314 In (eds Stouder DJ, Bisson PA, Naiman RJ) *Pacific Salmon & their Ecosystems: Status and Future Options*. Chapman & Hall, New York, New York.
- Gregory RS, Levings CD (1998) Turbidity reduces predation on migrating juvenile Pacific salmon. *Transactions of the American Fisheries Society* 127(2): 275–285.

- Gregory SV, Swanson FJ, McKee WA, Cummins KW (1991) An ecosystem perspective of riparian zones: Focus on links between land and water. *BioScience* 41(8): 540–551.
- Gregory KJ, Davis RJ, Downs PW (1992) Identification of river channel change due to urbanization. *Applied Geography* 12(4): 299–318.
- Gregory S, Ashkenas L, Oetter D, Minear P, Wildman KCJ, Kolar S, Alverson E (2002a) Presettlement vegetation ca. 1851. Page 38–39 In (eds Hulse D, Gregory S, Baker J) *Willamette River Basin: Trajectories of Environmental and Ecological Change, A Planning Atlas*. Oregon State University Press, Corvallis, Oregon.
- Gregory S, Ashkenas L, Oetter D, Wildman R, Minear P, Jett S, Wildman K (2002b) Revetments. Pages 32–33 In (eds Hulse D, Gregory S, Baker J) *Willamette River Basin: Trajectories of Environmental and Ecological Change, A Planning Atlas*. Oregon State University Press, Corvallis, Oregon.
- Gregory S, Ashkenas L, Nygaard C (2007) *Summary Report to Assist Development of Ecosystem Flow Recommendations for the Coast Fork and Middle Fork of the Willamette River, Oregon*. Institute for Water and Watersheds, Oregon State University, Corvallis, Oregon.
- Greig SM, Sear DA, Carling PA (2005) The impact of fine sediment accumulation on the survival of incubating salmon progeny: Implications for sediment management. *Science of the Total Environment* 344(1-3): 241–258.
- Gresens SE, Belt KT, Tang JA, Gwinn DC, Banks PA (2007) Temporal and spatial responses of Chironomidae (Diptera) and other benthic invertebrates to urban stormwater runoff. *Hydrobiologia* 575(1): 173–190.
- Gresh T, Lichatowich J, Schoonmaker P (2000) An estimation of historic and current levels of salmon production in the northeast Pacific ecosystem: Evidence of a nutrient deficit in the freshwater systems of the Pacific Northwest. *Fisheries* 25(1): 15–21.
- Grimm NB, Sheibley RW, Crenshaw CL, Dahm CN, Roach WJ, Zeglin LH (2005) N retention and transformation in urban streams. *Journal of the North American Benthological Society* 24(3): 626–642.
- Grimm NB, Foster D, Groffman P, Grove JM, Hopkinson CS, Nadelhoffer KJ, Pataki DE, Peters DPC (2008) The changing landscape: Ecosystem responses to urbanization and pollution across climatic and societal gradients. *Frontiers in Ecology and the Environment* 6(5): 264–272.
- Grimmond CSB, Oke TR (1986) Urban water balance 2. Results from a suburb of Vancouver, British Columbia. *Water Resources Research* 22(10): 1404–1412.
- Groffman PM, Bain DJ, Band LE, Belt KT, Brush GS, Grove JM, Pouyat RV, Yesilonis IC, Zipperer WC (2003) Down by the riverside: Urban riparian ecology. *Frontiers in Ecology and the Environment* 1(6): 315–321.
- Groot C, Margolis L (1991) *Pacific Salmon Life Histories*. University of British Columbia Press, Vancouver, BC, Canada.
- GSRO (Governor's Salmon Recovery Office) (1999) *Statewide Strategy to Recover Salmon: Extinction is not an Option*. Governor's Salmon Recovery Office, Olympia, Washington.
- Gude PH, Hansen AJ, Jones DA (2007) Biodiversity consequences of alternative future land use scenarios in greater Yellowstone. *Ecological Applications* 17(4): 1004–1018.
- Gustafson GC, Daniels TL, Shirack RP (1982) The Oregon Land Use Act: Implications for farmland and open space protection. *Journal of the American Planning Association* 48(3): 365–373.
- Gutrich JJ, Hitzhusen FJ (2004) Assessing the substitutability of mitigation wetlands for natural sites: Estimating restoration lag costs of wetland mitigation. *Ecological Economics* 48(4): 409–424.
- Guzmán KAD, Taylor MR, Banfield JF (2006) Environmental risks of nanotechnology: National nanotechnology initiative funding, 2000–2004. *Environmental Science & Technology* 40(5): 1401–1407.
- Haas ME, Simenstad CA, Cordell JR, Beauchamp DA, Miller BS (2002) *Effects of Large Overwater Structures on Epibenthic Juvenile Aalmon Prey Assemblages in Puget Sound, Washington*. Washington State Department of Transportation, Seattle, Washington.
- Hall JE, Holzer DM, Beechie TJ (2007) Predicting river floodplain and lateral channel migration for salmon habitat conservation. *Journal of the American Water Resources Association* 43(3): 786–797.

- Hamilton PA, Miller TL, Myers DN (2004) *Water Quality in the Nation's Streams and Aquifers – Overview of Selected Findings, 1991-2001*. USGS Circular 1265, US Geological Survey, Reston, Virginia.
- Hamlet AF, Lettenmaier DP (1999) Effects of climate change on hydrology and water resources in the Columbia River basin. *Journal of the American Water Resources Association* 35(6): 1597–1623.
- Hammer TR (1972) Stream channel enlargement due to urbanization. *Water Resources Research* 8(6): 1530–1540.
- Hancock PJ (2002) Human impacts on the stream-groundwater exchange zone. *Environmental Management* 29(6): 763–781.
- Hanna SS (2008) Institutions for managing resilient salmon (*Oncorhynchus* spp.) ecosystems: The role of incentives and transaction costs. *Ecology and Society* 13(2): [article 35].
- Hansen JA, Marr CA, Lipton J, Cacela D, Bergman HL (1999a) Differences in neurobehavioral responses of Chinook salmon (*Oncorhynchus tshawytscha*) and rainbow trout (*Oncorhynchus mykiss*) exposed to copper and cobalt: Behavioral avoidance. *Environmental Toxicology and Chemistry* 18(9): 1972–1978.
- Hansen JA, Rose JD, Jenkins RA, Gerow KG, Bergman HL (1999b) Chinook salmon (*Oncorhynchus mykiss*) exposed to copper: Neurophysiological and histological effects on the olfactory system. *Environmental Toxicology and Chemistry* 18(9): 1979–1991.
- Hansen AJ, Rasker R, Maxwell B, Rotella JJ, Johnson JD, Parmenter AW, Langner U, Cohen WB, Lawrence RL, Kraska PV (2002) Ecological causes and consequences of demographic change in the new west. *Bioscience* 52(2): 151–162.
- Hansen AJ, Knight RL, Marzluff JM, Powell S, Brown K, Gude PH, Jones K (2005) Effects of exurban development on biodiversity: Patterns, mechanisms, and research needs. *Ecological Applications* 15(6): 1893–1905.
- Hanski IA (1996) Metapopulation dynamics: from concepts and observations to predictive models. Pages 69–91 In (eds Hanski IA, Gilpin ME) *Metapopulation Biology: Ecology, Genetics, and Evolution*. Academic Press, New York, New York.
- Hanski IA (1999) *Metapopulation Ecology*. Oxford University Press, New York, New York.
- Hanski IA, Gilpin M (1991) Metapopulation dynamics: Brief history and conceptual domain. *Biological Journal of the Linnean Society* 42(1-2): 3–16.
- Harbor JM (1994) A practical method for estimating the impact of land-use change on surface runoff, groundwater recharge and wetland hydrology. *Journal of the American Planning Association* 60(1): 95–108.
- Harbor J (1999) Engineering geomorphology at the cutting edge of land disturbance: Erosion and sediment control on construction sites. *Geomorphology* 31(1-4): 247–263.
- Harding JS, Benfield EF, Bolstad PV, Helfman GS, Jones EBD (1998) Stream biodiversity: The ghost of land use past. *Proceedings of the National Academy of Science USA* 95(25): 14843–14847.
- Harper SL, Dahl JA, Maddux BLS, Tanguay RL, Hutchison JE (2008) Proactively designing nanomaterials to enhance performance and minimize hazard. *International Journal of Nanotechnology* 5(1): 124–142.
- Harris CA, Santos EM, Janbakhsh A, Pottinger TG, Tyler CR, Sumpter JP (2001) Nonylphenol affects gonadotropin levels in the pituitary gland and plasma of female rainbow trout. *Environmental Science and Technology* 35(14): 2909–2916.
- Harrison S (1991) Local extinction in a metapopulation context: An empirical evaluation. *Biological Journal of the Linnean Society* 42(1-2): 73–88.
- Hartwell SI, Jordahl DM, Evans JE, May EB (1995) Toxicity of aircraft de-icer and anti-icer solutions to aquatic organisms. *Environmental Toxicology and Chemistry* 14(8): 1375–1386.
- Hassett BA, Palmer MA, Bernhardt ES (2007) Evaluating stream restoration in the Chesapeake Bay watershed through practitioner interviews. *Restoration Ecology* 15(3): 563–572.

- Hatt BE, Fletcher TD, Walsh CJ, Taylor SL (2004) The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants from streams. *Environmental Management* 34(1): 112–124.
- Hawkins CP, Norris RH, Hogue JN, Feminella JW (2000) Development and evaluation of predictive models for measuring the biological integrity of streams. *Ecological Applications* 10(5): 1456–1477.
- Hayes TB, Case P, Chui S, Chung D, Haeffele C, Haston K, Lee L, Mai VP, Marjuoa Y, Parker J, Tsui M (2006) Pesticide mixtures, endocrine disruption, and amphibian declines: Are we underestimating the impact? *Environmental Health Perspectives* 114(S-1): 40–50.
- Hayslip G, Edmond L, Partridge V, Nelson W, Lee H, Cole F, Lamberson J, Caton L (2006) *Ecological Condition of the Estuaries of Oregon and Washington*. EPA 910-R-06-001. US Environmental Protection Agency, Office of Environmental Assessment, Seattle, Washington.
- Heaney JP, Huber WC, Lehman ME (1980) *Nationwide Assessment of Receiving Water Impacts from Urban Storm Water Pollution*. US Environmental Protection Agency, Cincinnati, Ohio.
- Heller D, Sanchez J (2005) *An Assessment of Fish Passage at Road-Stream Crossings on the National Forests of Oregon and Washington*. R6-NR-WFW-TP-02-5. USDA Forest Service, Portland, Oregon.
- Henderson RC, Archer EK, Bouwes BA, Coles-Ritchie MS, Kershner JL (2005) *PACFISH/INFISH Biological Opinion (PIBO): Effectiveness Monitoring Program Seven-Year Status Report 1998-2004*. General Technical Report RMRS-GTR-162. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado.
- Henley WF, Patterson MA, Neves RJ, Lemly AD (2000) Effects of sedimentation and turbidity on lotic food webs: A concise review for natural resource managers. *Reviews in Fisheries Science* 8(2): 125–139.
- Henshaw PC, Booth DB (2000) Natural restabilization of stream channels in urban watersheds. *Journal of the American Water Resources Association* 36(6): 1219–1236.
- Hessburg PF, Agee JK (2003) An environmental narrative of inland northwest United States forests, 1800-2000. *Forest Ecology and Management* 178(1): 23–59.
- Heywood MJT, Walling DE (2007) The sedimentation of salmonid spawning gravels in the Hampshire Avon catchment, UK: Implications for the dissolved oxygen content of intragravel water and embryo survival. *Hydrological Processes* 21(6): 770–788.
- Hicks BJ, Hall JD, Bisson PA, Sedell JR (1991) Responses of salmonids to habitat changes. Pages 483–518 In (ed Meehan WR) *Influences of Forest and Rangeland on Salmonid Fishes and Their Habitat*. Special Publication 19. American Fisheries Society, Bethesda, Maryland.
- Hill BH, Herlihy AT, Kaufmann PR, Stevenson RJ, McCormick FH, Johnson CB (2000) Use of periphyton assemblage data as an index of biotic integrity. *Journal of the North American Benthological Society* 19(1): 50–67.
- Hill BH, Herlihy AT, Kaufmann PR, DeCelles SJ, Vanter Borgh MA (2003) Assessment of streams of the eastern United States using a periphyton index of biological integrity. *Ecological Indicators* 2(4): 325–338.
- Hillel, D (1980) *Fundamentals of Soil Physics*. Academic Press, San Diego, California.
- Hillman TW, Griffith JS, Platts WS (1987) Summer and winter habitat selection by juvenile Chinook salmon in a highly sedimented Idaho stream. *Transactions of the American Fisheries Society* 116(2): 185–195.
- Hilsenhoff WL (1982) *Using a Biotic Index to Evaluate Water Quality in Streams*. Technical Bulletin 132. Wisconsin Department of Natural Resources, Madison, Wisconsin.
- Hinkle SR, Weick RJ, Johnson JM, Cahill JD, Smith SG, Rich BJ (2005) *Organic Wastewater Compounds, Pharmaceuticals, and Coliphage in Ground Water Receiving Discharge from Onsite Wastewater Treatment Systems near La Pine, Oregon: Occurrence and Implications for Transport*. Scientific Investigations Report 2005–5055. US Geological Survey, Reston, Virginia.
- Hinkle SR, Böhlke JK, Duff JH, Morgan DS, Weick RJ (2007) Aquifer-scale controls on the distribution of nitrate and ammonium in ground water near La Pine, Oregon, USA. *Journal of Hydrology* 333(2-4): 486–503.

- Hinkle SR, Weick RJ, Johnson JM, Cahill JD, Smith SG, Rich BJ (2009) *Organic Wastewater Compounds, Pharmaceuticals, and Coliphage in Ground Water Receiving Discharge from Onsite Wastewater Treatment Systems Near La Pine, Oregon: Occurrence and Implications for Transport*. Scientific Investigations Report 2005-5055, Version 1.1. US Geological Survey, Reston, Virginia.
- Hinman C (2005) *Low Impact Development: Technical Guidance Manual for Puget Sound*. Publication No. PSAT05-03. Puget Sound Action Team, Office of the Governor, Olympia, Washington.
- Hoffman RS, Capel PD, Larson SJ (2000) Comparison of pesticides in eight US urban streams. *Environmental Toxicology and Chemistry* 19(9): 2249–2258.
- Hoffnagle J, Olson R (1974) *The Salt Marshes of the Coos Bay Estuaries*. Oregon Institute of Marine Biology, University of Oregon, Charleston, Oregon.
- Holland CC, Honea J, Gwin SE, Kentula ME (1995) Wetland degradation and loss in the rapidly urbanizing area of Portland, Oregon. *Wetlands* 15(4): 336–345.
- Hollis GE (1975) The effect of urbanization on floods of different recurrence interval. *Water Resources Research* 11(3): 431–435.
- Hood WG (2007) Large woody debris influences vegetation zonation in an oligohaline tidal marsh. *Estuaries and Coasts* 30(3): 441–450.
- Hook AM, Yeakley JA (2005) Stormflow dynamics of dissolved organic carbon and total dissolved nitrogen in a small urban watershed. *Biogeochemistry* 75(3): 409–431.
- Hope D, Naegeli MW, Chan A, Grimm NB (2004) Nutrients on asphalt parking surfaces in an arid urban ecosystem. *Water, Air and Soil Pollution: Focus* 4(2-3): 371–390.
- Horner RR, Booth DB, Azous A, May CW (1997) Watershed determinants of ecosystem functioning. Pages 251–274 In (ed Roesner LA) *Effects of Watershed Development and Management on Aquatic Ecosystems*. American Society of Civil Engineers, New York, New York.
- Hosack GR, Dumbauld BR, Ruesink JL, Armstrong DA (2006) Habitat associations of estuarine species: Comparisons of intertidal mudflat, seagrass (*Zostera marina*), and oyster (*Crassostrea gigas*) habitats. *Estuaries and Coasts* 29(6): 1150–1160.
- Hossain MA, Alam M, Yonge DR, Dutta P (2005) Efficiency and flow regime of a highway stormwater detention pond in Washington, USA. *Water, Air, and Soil Pollution* 164(1-4): 79–89.
- Houston LL, Watanabe M, Kline JD, Alig RJ (2003) *Past and Future Water Use in Pacific Coast States*. General Technical Report PNW-GTR-588. USDA Forest Service, Pacific Northwest Research Station, Corvallis, Oregon.
- Hughes RM (1995) Defining acceptable biological status by comparing with reference conditions. Pages 31–48 In (eds Davis WS, Simon TP): *Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making*. Lewis Publishing, Boca Raton, Florida.
- Hughes RM, Davis GE (1986) Production of coexisting juvenile coho salmon and steelhead trout in heated model stream communities. Pages 322–337 In (ed Cairns J Jr.): *Community Toxicity Testing*. American Society for Testing and Materials, Philadelphia, Pennsylvania.
- Hughes RM, Gammon JR (1987) Longitudinal changes in fish assemblages and water quality in the Willamette River, Oregon. *Transactions of the American Fisheries Society* 116(2): 196–209.
- Hughes RM, Oberdorff T (1999) Applications of IBI concepts and metrics to waters outside the United States and Canada. Pages 79–96 In (ed Simon TP) *Assessing the Sustainability and Biological Integrity of Water Resources Using Fish Communities*. CRC Press, Boca Raton, Florida.
- Hughes RM, Larsen DP, Omernik JM (1986) Regional reference sites: A method for assessing stream potentials. *Environmental Management* 10(5): 629–635.

- Hughes RM, Kaufmann PR, Herlihy AT, Kincaid TM, Reynolds L, Larsen DP (1998) A process for developing and evaluating indices of fish assemblage integrity. *Canadian Journal of Fisheries and Aquatic Sciences* 55(7): 1618–1631.
- Hughes RM, Howlin S, Kaufmann PR (2004) A biointegrity index (IBI) for coldwater streams of western Oregon and Washington. *Transactions of the American Fisheries Society* 133(6): 1497–1515.
- Hughes RM, Rinne JN, Calamusso B (2005a) Introduction to historical changes in large river fish assemblages of the Americas. Pages 1–12 In (eds Rinne JN, Hughes RM, Calamusso B) *Historical Changes in Large River Fish Assemblages of the Americas*. Symposium 45. American Fisheries Society, Bethesda, Maryland.
- Hughes RM, Rinne JN, Calamusso B (2005b) Historical changes in large river fish assemblages of the Americas: A synthesis. Pages 603–612 In (eds Rinne JN, Hughes RM, Calamusso B) *Historical Changes in Large River Fish Assemblages of the Americas*. Symposium 45. American Fisheries Society, Bethesda, Maryland.
- Hughes RM, Wildman RC, Gregory SV (2005c) Changes in fish assemblage structure in the mainstem Willamette River, Oregon. Pages 61–74 In (eds Rinne JN, Hughes RM, Calamusso B) *Historical Changes in Large River Fish Assemblages of the Americas*. Symposium 45. American Fisheries Society, Bethesda, Maryland.
- Hulse D, Gregory S, Baker J (2002) *Willamette River Basin Planning Atlas: Trajectories of Environmental and Ecological Change*. Pacific Northwest Ecosystem Research Consortium. Oregon State University Press, Corvallis, Oregon.
- Hulse DW, Branscomb A, Payne SG (2004) Envisioning alternatives: Using citizen guidance to map future land and water use. *Ecological Applications* 14(2): 325–341.
- Huo C, Hickey P (2007) EDC Demonstration Programme in the UK—Anglian Water's approach. *Environmental Technology* 28(7): 731–741.
- Huston MA (2005) The three phases of land-use change: Implications for biodiversity. *Ecological Applications* 15(6): 1864–1878.
- IMST (Independent Multidisciplinary Science Team) (1999) *Recovery of Wild Salmonids in Western Oregon Forests: Oregon Forest Practices Act Rules and the Measures in the Oregon Plan for Salmon and Watersheds*. Technical Report 1999-1. Governor's Natural Resources Office, Salem, Oregon.
- IMST (Independent Multidisciplinary Science Team) (2002a) *IMST Review of Instream Aggregate Mining Regulations in Oregon in Relation to Salmonid Habitat*. Governor's Natural Resources Office, Salem, Oregon.
- IMST (Independent Multidisciplinary Science Team) (2002b) *Recovery of Wild Salmonids in Western Oregon Lowlands*. Technical Report 2002-1. Governor's Natural Resources Office, Salem, Oregon.
- IMST (Independent Multidisciplinary Science Team) (2004) *Oregon's Water Temperature Standard and its Application: Causes, Consequences, and Controversies Associated with Stream Temperature*. Technical Report 2004-1. Oregon Watershed Enhancement Board, Salem, Oregon.
- IMST (Independent Multidisciplinary Science Team) (2006) *Watershed and Aquatic Habitat Effectiveness Monitoring: A Synthesis of the Technical Workshop*. IMST Technical Report 2006-1. Oregon Watershed Enhancement Board, Salem, Oregon.
- IMST (Independent Multidisciplinary Science Team) (2007) *Considerations for the use of Ecological Indicators in Restoration Effectiveness Evaluation*. IMST Technical Report 2007-1. Oregon Watershed Enhancement Board, Salem, Oregon.
- IMST (Independent Multidisciplinary Science Team) (2009) *Issues in the Aggregation of Data to Assess Environmental Conditions*. IMST Technical Report 2009-1. Oregon Watershed Enhancement Board, Salem, Oregon.
- Inkpen EL, Embrey SS (1998) *Nutrient Transport in the Major Rivers and Streams of the Puget Sound Basin, Washington*. USGS Fact Sheet FS-009-98. US Geological Survey, National Water-Quality Assessment Program, Reston, Virginia.
- INR (Institute for Natural Resources) (2008) *Policy Cornerstones and Action Strategies for an Integrated Ecosystem Marketplace in Oregon*. Institute for Natural Resources, Oregon State University, Corvallis, Oregon.

- Isaak DJ, Thurow RF, Rieman BE, Dunham JB (2007) Relative roles of habitat quality, size, and connectivity in Chinook salmon use of spawning patches. *Ecological Applications* 17(2): 352–364.
- ISAB (Independent Scientific Advisory Board) (2005) *Report on harvest management of Columbia Basin Salmon and Steelhead*. ISAB 2005-4. Northwest Power and Conservation Council, Portland, Oregon.
- ISAB (Independent Scientific Advisory Board) (2007a) *Climate Change Impacts on Columbia River Basin Fish and Wildlife*. ISAB 2007-2. Northwest Power and Conservation Council, Portland, Oregon.
- ISAB (Independent Scientific Advisory Board) (2007b) *Human Population Impacts on Columbia River Basin Fish and Wildlife*. ISAB 2007-3. Northwest Power and Conservation Council, Portland, Oregon.
- ISP (Independent Science Panel) (2000) *Recommendations for Monitoring Salmonid Recovery in Washington State*. Report 2000-2, Independent Science Panel, Olympia, Washington.
- ISP (Independent Science Panel) (2003) *Review of 'Stormwater Management Manual for Western Washington (August 2001)*. Report 2003-1. Independent Science Panel, Olympia, Washington.
- Jacobson RB, Femmer SR, McKenney RA (2001) *Land-use Changes and the Physical Habitat of Streams – A Review with Emphasis on Studies within the US Geological Survey Federal-State Cooperative Program*. Circular 1175. US Geological Survey, Reston, Virginia.
- Jaensson A, Scott AP, Moore A, Kylin H, Olsén KH (2007) Effects of a pyrethroid pesticide on endocrine responses to female odours and reproductive behaviour in male parr of brown trout (*Salmo trutta* L.). *Aquatic Toxicology* 81(1): 1–9.
- Jansson R, Nilsson C, Malmqvist B (2007) Restoring freshwater ecosystems in riverine landscapes: The roles of connectivity and recovery processes. *Freshwater Biology* 52(4): 589–596.
- Jarrard HE, Delaney KR, Kennedy CJ (2004) Impacts of carbamate pesticides on olfactory neurophysiology and cholinesterase activity in coho salmon (*Oncorhynchus kisutch*). *Aquatic Toxicology* 69(2): 133–148.
- Jay DA, Simenstad CA (1996) Downstream effects of water withdrawal in a small, high-gradient basin: Erosion and deposition on the Skokomish River delta. *Estuaries* 19(3): 501–517.
- Jelks HL, Walsh SJ, Burkhead NM, Contreras-Balderas S, Diaz-Pardo E, Hendrickson DA, Lyons J, Mandrak NE, McCormick F, Nelson JS, Platania SP, Porter BA, Renaud CB, Schmitter-Soto JJ, Taylor EB, Warren ML Jr (2008) Conservation status of imperiled North American freshwater and diadromous fishes. *Fisheries* 33(8): 372–407.
- Jenerette GD, Larsen L (2006) A global perspective on changing sustainable urban water supplies. *Global and Planetary Change* 50(3-4): 202–211.
- Jenkinson RG, Barnas KA, Braatne JH, Bernhardt ES, Palmer MA, Allan JD, The National River Restoration Science Synthesis (2006) Stream restoration databases and case studies: A guide to information resources and their utility in advancing the science and practice of restoration. *Restoration Ecology*. 14(2): 177–186.
- Jennings MJ, Bozek MA, Hatzenbeler GR, Emmons EE, Staggs MD (1999) Cumulative effects of incremental shoreline habitat modification on fish assemblages in north temperate lakes. *North American Journal of Fisheries Management* 19(1): 18–27.
- Jin-Clark Y, Lydy MJ, Zhu KY (2002) Effects of atrazine and cyanazine on chlorophyrfifos toxicity in *Chironomus tentans* (Diptera: Chironomidae). *Environmental Toxicology and Chemistry* 21(3): 598–603.
- Jobling S, Sheahan D, Osborne JA, Matthiessen P, Sumpter JP (1996) Inhibition of testicular growth in rainbow trout (*Oncorhynchus mykiss*) exposed to estrogenic alkylphenolic chemicals. *Environmental Toxicology and Chemistry* 15(15): 194–202.
- Johannessen CL, Davenport WA, Miller A, McWilliams S (1971) The vegetation of the Willamette Valley. *Annals of the Association of American Geographers* 61(2): 286–302.
- Johnson Creek Watershed Council (2003) *Johnson Creek Watershed Action Plan. An Adaptive Approach*. Johnson Creek Watershed Council. Portland, Oregon.

- Johnson OW, Grant WS, Kope RG, Neely K, Waknitz FW, Waples RS (1997) *Status Review of Chum Salmon from Washington, Oregon and California*. Technical Memorandum NMFS-NWFSC-32. US Department of Commerce, National Oceanic and Atmospheric Administration, Seattle, Washington.
- Johnson LL, Ylitalo GM, Arkoosh MR, Kagley AN, Stafford C, Bolton JL, Buzitis J, Anulacion BF, Collier TK (2007a) Contaminant exposure in outmigrant juvenile salmon from Pacific Northwest estuaries of the United States. *Environmental Monitoring and Assessment* 124(1-3): 167–194.
- Johnson LL, Ylitalo GM, Sloan CA, Anulacion BF, Kagley AN, Arkoosh MR, Lundrigan TA, Larson K, Siipola M, Collier TK (2007b) Persistent organic pollutants in outmigrant juvenile Chinook salmon from the lower Columbia estuary, USA. *Science of the Total Environment* 374(2-3): 342–366.
- Jones JB, Mulholland PJ (2000) *Streams and Ground waters*. Academic Press, San Diego, California.
- Jones OAH, Voulvoulis N, Lester JN (2001) Human pharmaceuticals in the aquatic environment: A review. *Environmental toxicology* 22(12): 1383–1394.
- Jones JE, Earles TA, Fassman EA, Herricks EE, Urbonas B, Clary JK (2005) Urban storm-water regulations – Are impervious area limits a good idea? *Journal of Environmental Engineering* 131(2): 176–179.
- Jørgensen SE, Halling-Sørensen B (2000) Drugs in the environment. *Chemosphere* 40(7): 691–699.
- Julien HP, Bergeron NE (2006) Effect of fine sediment infiltration during the incubation period on Atlantic salmon (*Salmo salar*) embryo survival. *Hydrobiologia* 563(1): 61–71.
- Junk WJ, Bayley PB, Sparks RE (1989) The flood pulse concept in river-floodplain systems. Pages 110–127 In (ed Dodge DP) *Proceedings of the International Large River Symposium (LARS)*. Canadian Special Publication of Fisheries and Aquatic Sciences 106. Department of Fisheries and Oceans, Ottawa, Canada.
- Kalbus E, Reinstorf F, Schirmer M (2006) Measuring methods for groundwater – surface water interactions: A review. *Hydrology and Earth System Sciences* 10(6): 873–887.
- Kang J-H, Li Y, Lau S-L, Kayhanian M, Stenstrom MK (2007) Particle destabilization in highway runoff to optimize pollutant removal. *Journal of Environmental Engineering* 133(4): 426–434.
- Karr JR (1991) Biological integrity: A long-neglected aspect of water resource management. *Ecological Applications* 1(1): 66–84.
- Karr JR, Chu EW (1999) *Restoring Life in Running Waters: Better Biological Monitoring*. Island Press, Covelo, California.
- Karr JR, Chu EW (2000) Sustaining living rivers. *Hydrobiologia* 422/423: 1–14.
- Karr JR, Dudley DR (1981) Ecological perspective on water quality goals. *Environmental Management* 5(1): 55–68.
- Karr JR, Yoder CO (2004) Biological assessment and criteria improve total maximum daily load decision making. *Journal of Environmental Engineering* 130(6): 594–604.
- Karr JR, Fausch KD, Angermeier PL, Yant PR, Schlosser IJ (1986) *Assessing Biological Integrity in Running Waters: A Method and its Rationale*. Special Publication 5. Illinois Natural History Survey, Champaign, Illinois.
- Karrenberg SP, Edwards PJ, Kollmann J (2002) The life history of Salicaceae living in the active zone of floodplains. *Freshwater Biology* 47(4): 733–748.
- Katz SL, Barnas K, Hicks R, Cowen J, Jenkinson R (2007) Freshwater habitat restoration action in the Pacific Northwest: A decade's investment in habitat improvement. *Restoration Ecology* 15(3): 494–505.
- Kaye JP, Groffman PM, Grimm NB, Baker LA, Pouyat RV (2006) A distinct urban biogeochemistry? *Trends in Ecology & Evolution* 21(4): 192–199.
- Keefer TN, Simons RK, McQuivey RS (1979) *Dissolved Oxygen Impact from Urban Storm Runoff*. EPA-60N2-79-150. US Environmental Protection Agency, Cincinnati, Ohio.
- Keery J, Binley A, Crook N, Smith JWN (2007) Temporal and spatial variability of groundwater–surface water fluxes: Development and application of an analytical method using temperature time series. *Journal of Hydrology* 336(1-2): 1–16.

- Keller EA (1999) *Environmental Geology*, 8th edition. Prentice Hall, Inc., New Jersey.
- Keller EA, Swanson FJ (1979) Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes and Landforms* 4(4): 361–380.
- Kelsey KA, West SD (1998) Riparian wildlife. Pages 235–260 In (eds Naiman R, Bilby R) *River Ecology and Management: Lessons from the Pacific Coastal Ecosystem*. Springer, New York, New York.
- Kemp PS, Gessel MH, Williams JG (2005) Seward migrating subyearling Chinook salmon avoid overhead cover. *Journal of Fish Biology* 67(5): 1381–1391.
- Kennen JG, Ayers MA (2002) *Relations of Environmental Characteristics to the Composition of Aquatic Assemblages Along a Gradient of Urban Land Use in New Jersey, 1996-98. Water-Resources Investigations Report 02-4069. US Geological Survey, National Water-Quality Assessment Program, West Trenton, New Jersey.*
- Kennish MJ (2002) Environmental threats and environmental future of estuaries. *Environmental Conservation* 29(1): 78–107.
- Kentula ME, DeWitt TH (2003) Abundance of seagrass (*Zostera marina* L.) and macroalgae in relation to the salinity-temperature gradient in Yaquina Bay, Oregon, USA. *Estuaries* 26 (4): 1130–1141.
- Kentula ME, Gwin SE, Pierson SM (2004) Tracking changes in wetlands with urbanization: Sixteen years of experience in Portland, Oregon, USA. *Wetlands* 24(4): 734–743.
- Kerans BL, Karr JR (1994) A benthic index of biotic integrity (B-IBI) for rivers of the Tennessee Valley. *Ecological Applications* 4(4): 768–785.
- Kidd KA, Blanchfield PJ, Mills KH, Palace VP, Evans RE, Lazorchak JM, Flick RW (2007) Collapse of a fish population after exposure to a synthetic estrogen. *Proceedings of the National Academy of Science* 104(21): 8897–8901.
- Kime DE (1998) *Endocrine Disruption in Fish*. Kluwer Academic Publishers, Dordrecht, Netherlands.
- King RS, Beaman JR, Whigham DF, Hines AH, Baker ME, Weller DE (2004) Watershed land use is strongly linked to PCBs in white perch in Chesapeake Bay subestuaries. *Environmental Science and Technology* 38(24): 6546–6552.
- King RS, Baker ME, Whigham DF, Weller DE, Jordan TE, Kazyak PF, Hurd MK (2005) Spatial considerations for linking watershed land cover to ecological indicators in streams. *Ecological Applications* 15(1): 137–153.
- Kinouchi T (2007) Impact of long-term water and energy consumption in Tokyo on wastewater effluent: Implications for the thermal degradation of urban streams. *Hydrological Processes* 21(9): 1207–1216.
- Kinouchi T, Yagi H, Miyamoto M (2007) Increase in stream temperature related to anthropogenic heat input from urban wastewater. *Journal of Hydrology* 335(1-2): 78–88.
- Klein RD (1979) Urbanization and stream quality impairment. *Water Resources Bulletin* 15(4): 948–963.
- Klemm DJ, Blocksom KA, Fulk FA, Herlihy AT, Hughes RM, Kaufmann PR, Peck DV, Stoddard JL, Thoeny WT, Griffith MB, Davis WS (2003) Development and evaluation of a macroinvertebrate biotic integrity index (MBII) for regionally assessing mid-Atlantic highlands streams. *Environmental Management* 31(5): 656–69.
- Kline JD (2005a) Forests and farmland conservation effects of Oregon's (USA) land-use planning program. *Environmental Management* 35(4): 368–380.
- Kline JD (2005b) *Forest and Farmland Development in Western Oregon with and without Land Use Zoning in Effect*. Research Note PNW-RN-548. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon.
- Kline JD, Moses A, Alig RJ (2001) Integrating urbanization into landscape-level ecological assessments. *Ecosystems* 4(1): 3–18.
- Kline JD, Azuma DL, Moses A (2003) Modeling the spatially dynamic distribution of humans in the Oregon (USA) Coast Range. *Landscape Ecology* 18(4): 347–361.

- Kline JD, Moses A, Lettman GJ, Azuma DL (2007) Modeling forest and range land development in rural locations, with examples from eastern Oregon. *Landscape and Urban Planning* 80(3): 320–332.
- Kohler CC, Courtenay WR Jr (2002) *American Fisheries Society Position on Introductions of Aquatic Species*. Policy Statement #15. American Fisheries Society, Bethesda, Maryland.
- Kolpin DW, Furlong ET, Meyer MT, Thurman EM, Zaugg SD, Barber LB, Buxton HT (2002) Pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams, 1999-2000: A national reconnaissance. *Environmental Science and Technology* 36(6): 1202–1211.
- Kondolf GM (1994) Geomorphic and environmental effects of instream gravel mining. *Landscape and Urban Planning* 28(2-3): 225–243.
- Kondolf GM (2000) Assessing salmonid spawning gravel quality. *Transactions of the American Fisheries Society* 129(1): 262–281.
- Kondolf GM (2006) River restoration and meanders. *Ecology and Society* 11(2): [Article 42].
- Kondolf GM, Micheli ER (1995) Evaluating stream restoration projects. *Environmental Management* 19(1): 1–5.
- Kondolf GM, Boulton AJ, O'Daniel S, Poole GC, Rahel FJ, Stanley EH, Wohl E, Bång A, Carlstrom J, Cristoni C, Huber H, Koljonen S, Louhi P, Nakamura K (2006) Process-based ecological river restoration: Visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. *Ecology and Society* 11(2): [Article 5].
- Konrad CP (2003) *Effects of Urban Development on Floods*. Fact Sheet FS-076-03. US Geological Survey, Tacoma, Washington.
- Konrad CP, Booth DB (2002) *Hydrologic Trends Associated with Urban Development in Western Washington Streams*. Water-Resources Investigations Report 02-4040. US Geological Survey, Tacoma, Washington.
- Konrad CP, Booth DB (2005) Hydrologic changes in urban streams and their ecological significance. Pages 157–177 In (eds Brown LR, Gray RH, Hughes RM, Meador MR) *Effects of Urbanization on Stream Ecosystems*. Symposium 47. American Fisheries Society, Bethesda, Maryland.
- Konrad CP, Booth DB, Burges SJ (2005) Effects of urban development in the Puget Lowland, Washington, on interannual streamflow patterns: Consequences for channel form and streambed disturbance. *Water Resources Research* 41(7): W07009 [15 p.].
- Korstrom JS, Birtwell IK (2006) Effects of suspended sediment on the escape behavior and cover-seeking response of juvenile Chinook salmon in freshwater. *Transactions of the American Fisheries Society* 135(4): 1006–1016.
- Kostow K (1995) *Biennial Report on the Status of Wild Fish in Oregon*. Oregon Department of Fish and Wildlife, Portland, Oregon.
- Krause CW, Lockard B, Newcomb TJ, Kibler D, Lohani V, Orth DJ (2004) Predicting influences of urban development on thermal habitat in a warm water stream. *Journal of the American Water Resources Association* 40(6): 1645–1658.
- Krümmel EM, Macdonald RW, Kimpe LE, Gregory-Eaves I, Demers MJ, Smol JP, Finney B, Blais JM (2003) Delivery of pollutants by spawning salmon. *Nature* 425(6955): 255–256.
- Krümmel EM, Gregory-Eaves I, Macdonald RW, Kimpe LE, Demers MJ, Smol JP, Finney B, Blais JM (2005) Concentrations and fluxes of salmon-derived polychlorinated biphenyls (PCBs) in lake sediments. *Environmental Science & Technology* 39(18): 7020–7026.
- Ku HFH, Hagelin NW, Buxton HT (1992) Effects of urban storm-runoff control on ground-water recharge in Nassau County, New York. *Ground Water* 30(4): 507–514.
- Kummerer K (2001) Drugs in the environment: Emission of drugs, diagnostic aids and disinfectants into wastewater by hospitals in relation to other sources—A review. *Chemosphere* 45(6-7): 957–969.
- Lackey RT, Lach DH, Duncan SL (2006) Wild salmon in western North America: The historical and policy context. Pages 13–55 In (eds Lackey RT, Lach DH, Duncan SL) *Salmon 2100: The Future of Wild Pacific Salmon*. American Fisheries Society, Bethesda, Maryland.

- Laetz CA, Baldwin DH, Collier TK, Hebert V, Stark JD, Scholz NL (2009) The synergistic toxicity of pesticide mixtures: Implications for risk assessment and the conservation of endangered Pacific salmon. *Environmental Health Perspectives* 117(3): 348–353.
- Lahnsteiner F, Berger B, Kletzl M, Weismann T (2006) Effect of 17 β -estradiol on gamete quality and maturation in two salmonid species. *Aquatic Toxicology* 79(2): 124–131.
- Lake RG, Hinch SG (1999) Acute effects of suspended sediment angularity on juvenile coho salmon (*Oncorhynchus kisutch*). *Canadian Journal of Fisheries and Aquatic Sciences* 56(5): 862–867.
- Lakoff G (2002) *Moral Politics: How Liberals and Conservatives Think*. University of Chicago Press. Chicago, Illinois.
- Lane Council of Governments (2003) *Rivers to Ridges: Metropolitan Regional Parks and Open Space Study, Visions and Strategies*. Lane Council of Governments, Eugene, Oregon.
- Larsen DP, Kaufmann PR, Kincaid TM, Urquhart NS (2004) Detecting persistent change in the habitat of salmon-bearing streams in the Pacific Northwest. *Canadian Journal of Fisheries and Aquatic Sciences* 61(1): 283–291.
- Larson MG, Booth DB, Morley SA (2001) Effectiveness of large woody debris in stream rehabilitation projects in urban basins. *Ecological Engineering* 18(2): 211–226.
- LaVigne HR, Hughes RM, Wildman RC, Gregory SV, Herlihy AT (2008) Summer distribution and species richness of non-native fishes in the mainstem Willamette River, Oregon, 1944-2006. *Northwest Science* 82(2): 83–93.
- Lawler DM, Petts GE, Foster IDL, Harper S (2006) Turbidity dynamics during spring storm events in an urban headwater river system: The upper Tame, West Midlands, UK. *Science of the Total Environment* 360(1-3): 109–126.
- LCDC (Land Conservation and Development Commission) (1996a) *Exclusive Farm Use Report, 1994-1995*. Oregon Department of Land Conservation and Development, Salem, Oregon.
- LCDC (Land Conservation and Development Commission) (1996b) *Forest Use Report, 1994-1995*. Oregon Department of Land Conservation and Development, Salem, Oregon.
- LCREP (Lower Columbia River Estuary Partnership) (2007) *Lower Columbia River and Estuary Ecosystem Monitoring: Water Quality and Salmon Sampling Report*. Lower Columbia River Estuary Partnership, Portland, Oregon.
- LeBlanc RT, Brown RD, FitzGibbon JE (1997) Modeling the effects of land use change on the water temperature in unregulated urban streams. *Journal of Environmental Management* 49(4): 445–469.
- Lee HE II, Chapman JW (2001) *Nonindigenous Species – An Emerging Issue for the EPA Volume 2: A landscape in Transition: Effects of Invasive Species on Ecosystems, Human Health, and EPA Goals*. US Environmental Protection Agency, Western Ecology Division, Newport, Oregon.
- Lee JG, Heaney JP (2003) Estimation of urban imperviousness and its impacts on storm water systems. *Journal of Water Resources Planning and Management* 129(5): 419–426.
- Lee JH, Bang KW, Ketchum LH, Choe JS, Yu MJ (2002) First flush analysis of urban storm runoff. *Science of the Total Environment* 293(1-3): 163–175.
- Lee SY, Dunn RJK, Young RA, Connolly RM, Dale PER, DeHayr R, Lemckert CJ, McKinnon S, Powell B, Teasdale PR, Welsh DT (2006) Impact of urbanization on coastal wetland structure and function. *Austral Ecology* 31(2): 149–163.
- Lehrter JC (2006) Effects of land use and land cover, stream discharge, and interannual climate on the magnitude and timing of nitrogen, phosphorus, and organic carbon concentrations in three coastal plain watersheds. *Water Environment Research* 78(12): 2356–2368.
- Lenat DR, Penrose DL (1996) History of the EPT taxa richness metric. *Journal of the North American Benthological Society* 13(2): 305–307.
- Leonard PM, Orth DJ (1986) Application and testing of an index of biotic integrity in small, coolwater streams. *Transactions of the American Fisheries Society* 115(3): 401–415.

- Leopold LB (1968) *Hydrology for Urban Planning – A Guidebook on the Hydrologic Effects of Urban Land Use*. Circular 554. US Geological Survey, Washington, DC
- Leprieur F, Beauchard O, Blanchet S, Oberdorff T, Brosse S (2008) Fish invasions in the world's river systems: When natural processes are blurred by human activities. *Public Library of Science-Biology* 6(2): [e28].
- Lerner DN (1986) Leaking pipes recharge groundwater. *Groundwater* 24(5): 654–662.
- Lerner DN (1990) Groundwater recharge in urban areas. *Atmospheric Environment. Part B. Urban Atmosphere* 24(1): 29–33.
- Lerner DN (2002) Identifying and quantifying urban recharge: A review. *Hydrology Journal* 10(1): 143–152.
- Leu M, Hanser SE, Knick ST (2008) The human footprint in the west: A large-scale analysis of anthropogenic impacts. *Ecological Applications* 18(5): 1119–1139.
- Leung LR, Wigmosta MS (1999) Potential climate change impacts on mountain watersheds in the Pacific Northwest. *Journal of the American Water Resources Association* 35(6): 1463–1472.
- Levasseur M, Bergeron NE, Lapointe MF, Bérubé F (2006) Effects of silt and very fine sand dynamics in Atlantic salmon (*Salmo salar*) redds on embryo hatching success. *Canadian Journal of Fisheries and Aquatic Sciences* 63(7): 1450–1459.
- Levell AP, Chang H (2008) Monitoring the channel process of a stream restoration project in an urbanizing watershed: A case study of Kelley Creek, Oregon, USA. *River Research and Applications* 24(2): 169–182.
- Li HW, Schreck CB, Bond CE, Rexstad E (1987) Factors influencing changes in fish assemblages of Pacific streams. Pages 103–202 In (eds Matthews WJ, Heins DC) *Community and Evolutionary Ecology in North American Stream Fishes*. University of Oklahoma Press, Norman, Oklahoma.
- Li HW, Lamberti GA, Pearsons TN, Tait CK, Li JL, Buckhouse JC (1994) Cumulative effects of riparian disturbances along high desert trout streams of the John Day basin, Oregon. *Transactions of the American Fisheries Society* 123(4): 627–640.
- Li Y, Lau S-L, Kayhanian M, Stenstrom MK (2006) Dynamic characteristics of particle size distribution in highway runoff: Implications for settling tank design. *Journal of Environmental Engineering* 132(8): 852–861.
- Lichatowich J (1999) *Salmon Without Rivers*. Island Press, Covelo, California.
- Light T, Marchetti MP (2007) Distinguishing between invasions and habitat changes as drivers of diversity loss among California's freshwater fishes. *Conservation Biology* 21(2): 434–446.
- Limburg KE, Schmidt RE (1990) Patterns of fish spawning in Hudson River tributaries: Response to an urban gradient? *Ecology* 71(4): 1238–1245.
- Limburg KE, Stainbrook KM, Erickson JD, Gowdy JM (2005) Urbanization consequences: case studies in the Hudson River watershed. Pages 23–37 In (eds Brown LR, Gray RH, Hughes RM, Meador MR) *Effects of Urbanization on Stream Ecosystems*. Symposium 47. American Fisheries Society, Bethesda, Maryland.
- Line DE, Osmond DL, Coffey SW, McLaughlin RA, Jennings GD, Gale JA, Spooner J (1997) Nonpoint sources. *Water Environment Research* 69(Literature Review): 844–860.
- Liney KE, Hagger, JA, Tyler CR, Depledge MH, Galloway TS, Jobling S (2006) Health effects in fish of long-term exposure to effluents from wastewater treatment works. *Environmental Health Perspectives* 114(S-1): 81–89.
- Linke S, Norris RH, Pressey RL (2008) Irreplaceability of river networks: Towards catchment-based conservation planning. *Journal of Applied Ecology* 45(5): 1486–1495.
- Liu J, Daily GC, Ehrlich PR, Luck GW (2003) Effects of household dynamics on resource consumption and biodiversity. *Nature* 421(6922): 530–533.
- Lloyd DS (1987) Turbidity as a water quality standard for salmonid habitats in Alaska. *North American Journal of Fisheries Management* 7(1): 34–45.
- Lloyd DS, Koenings JP, LaPerriere JD (1987) Effects of turbidity in fresh waters of Alaska. *North American Journal of Fisheries Management* 7(1): 18–33.

- Locklear HHP (2009) Washington state decision makes LID mandatory. *Stormwater* 10(5): 14–15.
- Lodge DM, Shrader-Frechette K (2003) Nonindigenous species: ecological explanation, environmental ethics, and public policy. *Conservation Biology* 17(1): 31–37.
- Löffler D, Römbke J, Meller M, Ternes TA (2005) Environmental fate of pharmaceuticals in water/sediment systems. *Environmental Science and Technology* 39(14): 5209–5218.
- Loge FJ, Arkoosh MR, Ginn TR, Johnson LL, Collier TK (2005) Impact of environmental stressors on the dynamics of disease transmission. *Environmental Science and Technology* 39(18): 7329–7336.
- Lohse KA, Newburn DA, Opperman JJ, Merenlender AM (2008) Forecasting relative impacts of land use on anadromous fish habitat to guide conservation planning. *Ecological Applications* 18(2): 467–482.
- Luck MA, Jenerette GD, Wu J, Grimm NB (2001) The urban funnel model and the spatially heterogeneous ecological footprint. *Ecosystems* 4(8): 782–796.
- Luo Q, Ban M, Ando H, Kitahashi T, Bandari RK, McCormick SD, Urano A (2005) Distinct effects of 4-nonylphenol and estrogen-17 β on expression of estrogen receptor α gene in smolting sockeye salmon. *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology* 140(1): 123–130.
- Lutzenhiser M, Netusil NR (2001) The effect of open spaces on a home's sale price. *Contemporary Economic Policy* 19(3): 291–298.
- Lyons J, Wang L, Simonson TD (1996) Development and validation of an index of biotic integrity for coldwater streams in Wisconsin. *North American Journal of Fisheries Management* 16(2): 241–256.
- MacCoy D, Blew D (2005) Impacts of land-use changes and hydrologic modification on the lower Boise River, Idaho, USA. Pages 133–156 In (eds Brown LR, Gray RH, Hughes RM, Meador MR) *Effects of Urbanization on Stream Ecosystems*. Symposium 47. American Fisheries Society, Bethesda, Maryland.
- Macdonald JS, Foreman MGG, Farrell T, Williams IV, Grout J, Cass A, Woodey JC, Enzenhofer H, Clarke WC, Houtman R, Donaldson EM, Barnes D (2000) The influence of extreme water temperatures on migrating Fraser River sockeye salmon (*Oncorhynchus nerka*) during the 1998 spawning season. Number 2326. *Canadian Technical Report of Fisheries and Aquatic Sciences* Vancouver, British Columbia.
- Madsen SS, Skovbølling S, Nielsen C, Korsgaard B (2004) 17- β estradiol and 4-nonylphenol delay smolt development and downstream migration in Atlantic salmon, *Salmo salar*. *Aquatic Toxicology* 68(2): 109–120.
- Mahan BL, Polasky S, Adams RM (2000) Valuing urban wetlands: A property price approach. *Land Economics* 76(1): 100–113.
- Marchetti MP, Light T, Moyle PB, Viers JH (2004) Fish invasions in California watersheds: Testing hypotheses using landscape patterns. *Ecological Applications* 14(5): 1507–1525.
- Marchetti MP, Lockwood JL, Light T (2006) Effects of urbanization on California's fish diversity: Differentiation, homogenization and the influence of spatial scale. *Biological Conservation* 127(3): 310–318.
- Markoff MS, Cullen AC (2008) Impact of climate change on Pacific Northwest hydropower. *Climatic Change* 87(3–4): 451–469.
- Maser C, Tarrant RF, Trappe JM, Franklin JF (1988) *From the Forest to the Sea: A Story of Fallen Trees*. General Technical Report PNW-GTR-229. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon.
- Matzen DA, Berge HB (2008) Assessing small-stream biotic integrity using fish assemblages across an urban landscape in the Puget Sound lowlands of western Washington. *Transactions of the American Fisheries Society*. 137(3): 677–689.
- Matthews KR, Berg NH (1997) Rainbow trout responses to water temperature and dissolved oxygen stress in two southern California stream pools. *Journal of Fisheries Biology* 50(1): 50–67.
- Matthiessen P (1998) Effects on fish of estrogenic substances in English rivers. Pages 239–247 In (eds Kendall R, Dickerson R, Geisy J, Suk W) *Principles and Processes for Evaluating Endocrine Disruption in Wildlife*. SETAC Press, Pensicola, Florida.

- Matthiessen P, Sumpter JP (1998) Effects of estrogenic substances in the aquatic environment. Pages 310–335 In: (eds Braunbeck T, Hinton DE, Streit B) *Fish Ecotoxicology*. Birkhäuser Verlag, Basel, Switzerland.
- Maule AG, Jørgensen EH, Vijayan MM, Killie J-EA (2005) Arochlor 1254 reduces disease resistance and innate immune responses in fasted Arctic char. *Environmental Toxicology and Chemistry* 24(1): 117–124.
- May CW, Horner RR (2000) The cumulative impacts of watershed urbanization on stream-riparian ecosystems. Pages 281–286 In (eds Wiginton PJ, Beschta RL) Proceedings of the International Conference on Riparian Ecology and Management in Multi-land Use Watersheds. American Water Resources Association, Portland, Oregon.
- May CW, Horner RR, Karr JR, Mar BW, Welch EB (1997) Effects of urbanization on small streams in the Puget Sound Lowland ecoregion. *Watershed Protection Techniques* 2(4): 483–494.
- McAllister LS (2008) Reconstructing historical riparian conditions of two river basins in eastern Oregon, USA. *Environmental Management* 42(3): 412–425.
- McBride M, Booth DB (2005) Urban impacts on physical stream condition: Effects of spatial scale, connectivity, and longitudinal trends. *Journal of the American Water Resources Association* 41(3): 565–580.
- McCain BB, Malins DC, Krahn MM, Brown DW, Gronlund WD, Moore LK, Chan SL (1990) Uptake of aromatic and chlorinated hydrocarbons by juvenile Chinook salmon (*Oncorhynchus tshawytscha*) in an urban estuary. *Archives of Environmental Contamination and Toxicology* 19(1): 10–16.
- McCormick FH, Hughes RM, Kaufmann PR, Peck DV, Stoddard JL, Herlihy AT (2001) Development of an index of biotic integrity for the Mid-Atlantic Highlands region. *Transactions of the American Fisheries Society* 130(5): 857–877.
- McCuen, RH (1998) *Hydrologic Analysis and Design*. Prentice-Hall, Inc., Upper Saddle River, New Jersey.
- McCuen RH (2003) Smart growth: hydrologic perspective. *Journal of Professional Issues in Engineering, Education, and Practice* 129(3): 151–154.
- McCullough DA (1999) *A Review and Synthesis of Effects of Alterations to the Water Temperature Regime on Freshwater Life Stages of Salmonids, With Special Reference to Chinook Salmon*. EPA 910-R-99-010. US Environmental Protection Agency, Seattle, Washington.
- McCullough D, Spalding S, Sturdevant D, Hicks M (2001) *Issue Paper 5: Summary of Technical Literature Examining the Physiological Effects of Temperature*. EPA-910-D01-005. US Environmental Protection Agency, Seattle, Washington.
- McDade MH, Swanson FJ, McKee WA, Franklin JF, Van Sickle J (1990) Source distances for coarse woody debris entering small streams in western Oregon and Washington. *Canadian Journal of Forest Research* 20(3): 326–330.
- McGarvey DJ, Hughes RM (2008) Longitudinal zonation of Pacific Northwest (USA) fish assemblages and the species-discharge relationship. *Copeia* 2008(2): 311–321.
- McGreer DJ, Andrus C (1992) Woody debris in streams and riparian zone management research. Pages 47–67 In (ed Skaugset A) *Forest Soils and Riparian Zone Management: The Contribution of Dr. Henry Froehlich to Forestry*. Oregon State University, Corvallis, Oregon.
- McIntosh BA, Sedell JR, Thurow RF, Clarke SE, Chandler GL (2000) Historical changes in pool habitats in the Columbia River basin. *Ecological Applications* 10(5): 1478–1498.
- McIntyre JK, Baldwin DH, Meador JP, Scholz NL (2008) Chemosensory deprivation in juvenile coho salmon exposed to dissolved copper under varying water chemistry conditions. *Environmental Science and Technology* 42(4): 1352–1358.
- McIntyre NE, Knowles-Yáñez K, Hope D (2000) Urban ecology as an interdisciplinary field: differences in the use of ‘urban’ between the social and natural sciences. *Urban Ecosystems* 4(1): 5–24.
- McMahon G, Cuffney TF (2000) Quantifying urban intensity in drainage basins for assessing stream ecological conditions. *Journal of the American Water Resources Association* 36(6): 1247–1261.

- McNabb A, Schreck C, Tyler C, Thomas P, Kramer V, Specker J, Mayes M, Selcer K (1999) *Basic Physiology*. Pages 113–223 In (eds DiGiulio RT, Tillitt DE) *Reproductive and Developmental Effects of Contaminants in Oviparous Vertebrates*. Society of Toxicology and Chemistry, Pensacola, Florida.
- McPherson EG (1994) Cooling urban heat islands with sustainable landscapes. Pages 151–171 In (eds Platt RH, Rowntree RA, Muick PC) *The Ecological City, Preserving and Restoring Urban Biodiversity*. University of Massachusetts Press, Boston, Massachusetts.
- Meador JP, Stein JE, Reichert WL, Varanasi U (1995) A review of bioaccumulation of polycyclic aromatic hydrocarbons by marine organisms. *Reviews of Environmental Contamination and Toxicology* 143: 79–165.
- Meador JP, Collier TK, Stein JE (2002) Use of tissue and sediment-based threshold concentrations of polychlorinated biphenyls (PCBs) to protect juvenile salmonids listed under the US Endangered Species Act. *Aquatic Conservation: Marine and Freshwater Ecosystems* 12(5): 493–516.
- Meador MR, Brown LR, Short T (2003) Relations between introduced fish and environmental conditions at large geographic scales. *Ecological Indicators* 3(2): 81–92.
- Meador JP, Sommers FC, Ylitalo GM, Sloan CA (2006) Altered growth and related physiological responses in juvenile Chinook salmon (*Oncorhynchus tshawytscha*) from dietary exposure to polycyclic aromatic hydrocarbons (PAHs). *Canadian Journal of Fisheries and Aquatic Sciences* 63(10): 2364–2376.
- Meador MR, Whittier TR, Goldstein RM, Hughes RM, Peck DV (2008) Evaluation of an index of biotic integrity approach to assess fish assemblage condition in western USA streams and rivers at varying spatial scales. *Transactions of the American Fisheries Society* 137(1): 13–22.
- Mebane CA, Maret TR, Hughes RM (2003) An index of biological integrity (IBI) for Pacific Northwest rivers. *Transactions of the American Fisheries Society* 132(2): 239–261.
- Meehan WR, Swanson FJ, Sedell JR (1977) Influences of riparian vegetation on aquatic ecosystems with particular references to salmonid fishes and their food supply. Pages 137–145 in: *Importance, Preservation and Management of Riparian Habitat* (eds Johnson RR, Jones DA) General Technical Report RM-43. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.
- Merz JE, Setka JD (2004) Evaluation of a spawning habitat enhancement site for Chinook salmon in a regulated California river. *North American Journal of Fisheries Management* 24(2): 397–407.
- Merz JE, Ochikubo Chan LK (2005) Effects of gravel augmentation on macroinvertebrate assemblages in a regulated California River. *River Research and Applications*. 21(1): 61–74.
- Merz JE, Setka, JD, Pasternack GB, Wheaton JM (2004) Predicting benefits of spawning-habitat rehabilitation to salmonid (*Oncorhynchus* spp.) fry production in a regulated California River. *Canadian Journal of Fisheries and Aquatic Sciences*. 61(8): 1433–1446.
- Merz JE, Smith JR, Workman ML, Setka JD, Mulchaey B (2008) Aquatic macrophyte encroachment in Chinook salmon spawning beds: Lessons learned from gravel enhancement monitoring in the lower Mokelumne River, California. *North American Journal of Fisheries Management*. 28(5): 1568–1577.
- Metro (1999) *Streamside CPR: Development of Measures to Conserve, Protect and Restore Riparian Corridors in the Metro region*. Metro Growth Management Services Department, Portland, Oregon.
- Metro (2000) *The Nature of 2040: The Region's 50-year Plan for Managing Growth*. Metro, Portland, Oregon.
- Metro (2002) *Metro's Technical Report for Goal 5*. July 2002 revised draft. Metro, Portland, Oregon.
- Metro, USFWS (US Fish and Wildlife Service) (2005) *Metropolitan Greenspaces Program: Summary of Accomplishments 1991-2005*. Metro Regional Parks and Greenspaces and US Fish and Wildlife Service, Portland, Oregon
- Meyer CB (2003) The importance of measuring biotic and abiotic factors in the lower egg pocket to predict coho salmon egg survival. *Journal of Fish Biology* 62(3): 534–548.
- Meyer WB, Turner BL II (1992) Human population growth and global land use/cover change. *Annual Review of Ecology and Systematics* 23: 39–61.

- Meyer JL, Sale MJ, Mulholland PJ, Poff NL (1999) Impacts of climate change on aquatic ecosystem functioning and health. *Journal of the American Water Resources Association* 35(6): 1373–1386.
- Meyer JL, Paul MJ, Taulbee WK (2005) Stream ecosystem function in urbanizing landscapes. *Journal of the North American Benthological Society* 24(3): 602–612.
- Meyer JL, Strayer DL, Wallace JB, Eggert SL, Helfman GS, Leonard NE (2007) The contribution of headwater streams to biodiversity in river networks. *Journal of the American Water Resources Association* 43(1): 86–103.
- Mielke HW, Gonzales CR, Smith MK, Mielke PW (2000) Quantities and associations of lead, zinc, cadmium, manganese, chromium, nickel, vanadium, and copper in fresh Mississippi delta alluvium and New Orleans alluvial soils. *Science of the Total Environment* 246(2-3): 249–259.
- Miles EL, Snover AK, Hamlet AF, Callahan B, Fluharty D (2000) Pacific Northwest Regional Assessment: The impacts of climate variability and climate change on the water resources of the Columbia River basin. *Journal of the American Water Resources Association* 36(2): 399–420.
- Miller RJ, Brannon EL (1982) The origin and development of life history patterns in Pacific salmonids. Pages 296–309 In (eds EL Brannon, Salo EO) *Salmon and Trout Migratory Behavior Symposium*. School of Fisheries, University of Washington, Seattle, Washington.
- Miller BA, Sadro S (2003) Residence time and seasonal movements of juvenile coho salmon in the ecotone and lower estuary of Winchester Creek, South Slough, Oregon. *Transactions of the American Fisheries Society* 132(3): 546–559.
- Miller MP, Vincent ER (2008) Rapid natural selection for resistance to an introduced parasite of rainbow trout. *Evolutionary Applications* 1(2): 336–341.
- Miller DL, Leonard PM, Hughes RM, Karr JR, Moyle PB, Schrader LH, Thompson BA, Daniels RA, Fausch KD, Fitzhugh GA, Gammon JR, Halliwell DB, Angermeier PL, Orth DJ (1988) Regional applications of an index of biotic integrity for use in water resource management. *Fisheries* 13(5): 12–20.
- Milston RH, Fitzpatrick MS, Vella AT, Clements S, Gunderson D, Feist G, Crippen TL, Leong J, Schreck CB (2003) Short-term exposure of Chinook salmon (*Oncorhynchus tshawytscha*) to o,p'-DDE or DMSO during early life-history stages causes long-term humoral immunosuppression. *Environmental Health Perspectives* 111(13): 1601–1607.
- Minshall GW (1988) Stream ecosystem theory: A global perspective. *Journal of the North American Benthological Society* 7(4): 263–288.
- Mirati AH, Jr. (1999) *Assessment of Road Culverts for Fish Passage Problems on State- and County-owned Roads: Statewide Summary Report*. Oregon Department of Fish and Wildlife, Portland, Oregon.
- Missildine BR, Peters RJ, Chin-Leo G, Houck D (2005) Polychlorinated biphenyl concentrations in adult Chinook salmon (*Oncorhynchus tshawytscha*) returning to coastal and Puget Sound hatcheries of Washington state. *Environmental Science and Technology* 39(18): 6944–6951.
- Misumi I, Vella AT, Leong J-AC, Nakanishi T, Schreck CB (2005) p,p'-DDE depresses the immune competence of Chinook salmon (*Oncorhynchus tshawytscha*) leukocytes. *Fish and Shellfish Immunology* 19(2): 97–114.
- Mitchell TJ, Harding AK (1996) Who is drinking nitrate in their well water? *Journal of Environmental Health* 59(3): 14–19.
- Moerke AH, Lamberti GA (2006a) Relationships between land use and stream ecosystems: A multistream assessment in southwestern Michigan. Pages 323–338 In (eds Hughes RM, Wang L, Seelbach PW) *Landscape Influences on Stream Habitats and Biological Assemblages*. Symposium 48. American Fisheries Society, Bethesda, Maryland.
- Moerke AH, Lamberti GA (2006b) Scale-dependent influences on water quality, habitat, and fish communities in streams of the Kalamazoo River basin, Michigan (USA). *Aquatic Sciences* 68(2): 193–205.
- Montgomery DR (1999) Process domains and the river continuum. *Journal of the American Water Resources Association* 35(2): 397–410.

- Montgomery DR, Buffington JM (1997) Channel reach morphology in mountain drainage basins. *Geological Society of America Bulletin* 109(5): 596–611.
- Montgomery DR, Buffington JM (1998) Channel processes, classification, and response. Pages 13–42 In (eds Naiman RJ, Bilby RE) *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion*. Springer-Verlag, New York, New York.
- Montgomery CA, Helvoigt TL (2006) Changes in attitudes about importance of and willingness to pay for salmon recovery in Oregon. *Journal of Environmental Management* 78(4): 330–340.
- Montgomery DR, Buffington JM, Smith RD, Schmidt KM, Pess G (1995) Pool spacing in forest channels. *Water Resources Research* 31(4): 1097–1105.
- Montgomery DR, Abbe TB, Peterson NP, Buffington JM, Schmidt KM, Stock JD (1996) Distribution of bedrock and alluvial channels in forested mountain drainage basins. *Nature* 381(6583): 587–589.
- Montgomery DR, Beamer EM, Pess GR, Quinn TP (1999) Channel type and salmonid spawning distribution and abundance. *Canadian Journal of Fisheries and Aquatic Sciences* 56(3): 377–387.
- Moore A, Waring CP (1996) Sublethal effects of the pesticide diazinon on olfactory function in mature male Atlantic salmon parr. *Journal of Fish Biology* 48(4): 758–775.
- Morace JL (2006) *Water-Quality Data, Columbia River Estuary, 2004-2005*. Data Series 213. US Geological Survey, Reston, Virginia.
- Moran MJ, Zogorski JS, Squillace PJ (2005) MTBE and gasoline hydrocarbons in ground water of the United States. *Ground Water* 43(4): 615–627.
- Morgan C, Wolverton A (2005) *Water Quality Trading in the United States*. Working Paper 05-07. US Environmental Protection Agency, National Center for Environmental Economics Washington, DC.
- Morley SA, Karr JR (2002) Assessing and restoring the health of urban streams in the Puget Sound basin. *Conservation Biology* 16(6): 1498–1509.
- Morse CC, Huryn AD, Cronan C (2003) Impervious surface area as a predictor of the effects of urbanization on stream insect communities in Maine, USA. *Environmental Monitoring and Assessment* 89(1): 95–127.
- Moscrip AL, Montgomery DR (1997) Urbanization, flood frequency, and salmon abundance in Puget lowland streams. *Journal of the American Water Resources Association* 33(6): 1289–1297.
- Moss D, Furse MT, Wright JF, Armitage PD (1987) The prediction of the macro-invertebrate fauna of unpolluted running-water sites in Great Britain using environmental data. *Freshwater Biology* 17(1): 41–52.
- Mote PW, Parson EA, Hamlet AF, Keeton WS, Lettenmaier D, Mantua N, Miles EL, Peterson DW, Peterson DL, Slaughter R, Snover AK (2003) Preparing for climatic change: The water, salmon, and forests of the Pacific Northwest. *Climatic Change* 61(1-2): 45–88.
- Moya N, Tomanova S, Oberdorff T (2007) Initial development of a multi-metric index based on aquatic macroinvertebrates to assess streams condition in the Upper Isiboro-Secure Basin, Bolivian Amazon. *Hydrobiologia* 589(1): 107–116.
- Moyle PB, Light T (1996a) Biological invasions of fresh water: Empirical rules and assembly theory. *Biological Conservation* 78(1-2): 149–161.
- Moyle PB, Light T (1996b) Fish invasion in California: Do abiotic factors determine success? *Ecology* 77(6): 1666–1670.
- Moyle PB, Marchetti MP (2006) Predicting Invasion Success: Freshwater Fishes in California as a Model. *Bioscience* 56(6): 515–524.
- Moyle PB, Randle PJ (1998) Evaluating the biotic integrity of watersheds in the Sierra Nevada, California. *Conservation Biology* 12(6): 1318–1326.

- Moyle PB, Li HW, Barton BA (1986) The Frankenstein effect: impact of introduced fishes on native fishes in North America. Pages 415–426 In (ed Stroud RH) *Fish Culture in Fisheries Management*. American Fisheries Society, Bethesda, Maryland.
- Mrazik S (2006) *Oregon Water Quality Index Summary Report: Water Years 1996-2005*. Oregon Department of Environmental Quality, Laboratory Division, Portland, Oregon.
- Mueller DK, Spahr NE (2006) *Nutrients in Streams and Rivers across the Nation: 1992–2001*. Scientific Investigations Report 2006–5107. US Geological Survey Reston, Virginia.
- Muhar S (1996) Habitat improvement of Austrian rivers with regard to different scales. *Regulated Rivers: Research and Management* 12(4-5): 471–482.
- Mulvey M, Leferink R, Borisenko A (2009) *Willamette Basin Rivers and Streams Assessment*. DEQ 09-LAB-016. Oregon Department of Environmental Quality, Portland, Oregon.
- Mundahl ND, Simon TP (1999) Development and application of an index of biotic integrity for coldwater streams of the upper midwestern United States. Pages 384–415 In (ed Simon TP) *Assessing the Sustainability and Biological Integrity of Water Resources Using Fish Communities*. CRC Press, Boca Raton, Florida.
- Murray CB, McPhail JD (1988) Effect of incubation temperature on the development of five species of Pacific salmon (*Oncorhynchus*) embryos and alevins. *Canadian Journal of Zoology* 66(1): 266–273.
- Myers JM, Kope RG, Bryant GJ, Teel D, Lierheimer LJ, Wainwright TC, Grant WS, Waknitz FW, Neely K, Lindley ST, Waples RS (1998) *Status Review of Chinook Salmon from Washington, Idaho, Oregon, and California*. Technical Memorandum NMFS-NWFSC-35. US Department of Commerce, National Oceanic and Atmospheric Administration, Seattle, Washington.
- Myers J, Busack C, Rawding D, Marshall A, Teel D, Van Doornik DM, Maher MT (2006) *Historical Population Structure of Pacific Salmonids in the Willamette River and Lower Columbia River Basins*. Technical Memorandum NMFS-NWFSC-73. US Department of Commerce, National Oceanic and Atmospheric Administration, Seattle, Washington.
- Neal C, Robson AJ (2000) A summary of river water quality data collected within the Land-Ocean Interaction Study: Core data for eastern UK rivers draining to the North Sea. *Science of the Total Environment* 251/252: 585–665.
- Nehlsen W, Williams JE, Lichatowich JA (1991) Pacific salmon at the crossroads: Stocks at risk from California, Oregon, Idaho, and Washington. *Fisheries* 16(2): 4–21.
- Neilsen JL, Lisle TE, Ozaki V (1994) Thermally stratified pools and their use by steelhead in northern California streams. *Transactions of the American Fisheries Society* 123(4): 613–626.
- Nelitz MA, MacIsaac EA, Peterman RM (2007) A science-based approach for identifying temperature-sensitive streams for rainbow trout. *North American Journal of Fisheries Management* 27(2): 405–424.
- Neller RJ (1988) A comparison of channel erosion in small urban and rural catchments, Armidale, New South Wales. *Earth Surface Processes* 13(1): 1–7.
- Nelson EJ, Booth DB (2002) Sediment sources in an urbanizing, mixed land-use watershed. *Journal of Hydrology* 264(1-4): 51–68.
- Nelson KC, Palmer MA (2007) Stream temperature surges under urbanization and climate change: Data, models, and responses. *Journal of the American Water Resources Association* 43(2): 440–452.
- Nelson JA, Gotwalt PS, Snodgrass JW (2003) Swimming performance of blacknose dace (*Rhinichthys atratulus*) mirrors home-stream current velocity. *Canadian Journal of Fisheries and Aquatic Sciences* 60(3): 301–308.
- Nelson JA, Gotwalt PS, Simonetti CA, Snodgrass JW (2008) Environmental correlates, plasticity, and repeatability of differences in performance among blacknose dace (*Rhinichthys atratulus*) populations across a gradient of urbanization. *Physiological and Biochemical Zoology* 81(1): 25–42.
- Neraas LP, Spruell P (2001) Fragmentation of riverine systems: the genetic effects of dams on bull trout (*Salvelinus confluentus*) in the Clark Fork River system. *Molecular Ecology* 10(5): 1153–1164.

- Neville H, Dunham J, Peacock M (2006a) Assessing connectivity in salmonid fishes with DNA microsatellite markers. Pages 318–342 In (eds Crooks K, Sanjayan MA) *Connectivity Conservation*. Cambridge University Press, Cambridge, England.
- Neville H, Rosenberger A, Dunham J (2006b) *Wildlife, Stream Channel Disturbance, and Genetic Variation within Aquatic Vertebrate Populations. Final Report*. Joint Venture Agreement between the USDA Forest Service, Rocky Mountain Research Station, Research Work Unit Number 4353 and the University of Nevada-Reno. RJVA 04-JV-11222014-184, 1320-114-2399. Reno, Nevada.
- Newall P, Walsh CJ (2005) Response of epilithic diatom assemblages to urbanization influences. *Hydrobiologia* 532(1): 53–67.
- Newburn DA, Berck P, Merenlender AM (2006) Habitat and open space at risk of land-use conversion: Targeting strategies for land conservation. *American Journal of Agricultural Economics* 88(1): 28–42.
- Newcombe CP (2003) Impact assessment model for clear water fishes exposed to excessively cloudy water. *Journal of the American Water Resources Association* 39(3): 529–544.
- Newcombe CP, Flagg TA (1983) Some effects of Mt. St. Helens volcanic ash on juvenile salmon smolts. *Marine Fisheries Review* 45(2): 8–12.
- Newcombe CP, Jensen JOT (1996) Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact. *North American Journal of Fisheries Management* 16(4): 693–727.
- Newcombe CP, MacDonald DD (1991) Effects of suspended sediments on aquatic ecosystems. *North American Journal of Fisheries Management* 11(1): 72–82.
- Newell JC, Fresh KL, Quinn TP (2007) Arrival patterns and movements of adult sockeye salmon in Lake Washington: Implications for management of an urban fishery. *North American Journal of Fisheries Management* 27(3): 908–917.
- Nickerson C (2001) Smart Growth: Implications for agriculture in urban fringe areas. *Agricultural Outlook*. AGO-280: 24–27.
- Nielson L, Smith CL (2005) Influences on residential yard care and water quality: Tualatin watershed, Oregon. *Journal of the American Water Resources Association* 41(1): 93–106.
- Nilsson C, Pizzuto JE, Moglen GE, Palmer MA, Stanley EH, Bockstael NE, Thompson LC (2003) Ecological forecasting and the urbanization of stream ecosystems: Challenges for economists, hydrologists, geomorphologists, and ecologists. *Ecosystems* 6(7): 659–674.
- NMFS (National Marine Fisheries Service) (2000) Final Rule; Endangered and threatened species; final rule governing take of 14 threatened salmon and steelhead evolutionary significant units (ESUs). July 10. *Federal Register* 65(132): 42422–42481.
- NMFS (National Marine Fisheries Service) (2005a) Designation of critical habitat for 12 evolutionarily significant units of west coast salmon and steelhead in Washington, Oregon, and Idaho. September 2. *Federal Register* 70(170): 52630–52858.
- NMFS (National Marine Fisheries Service) (2005b) Final listing determinations for 16 ESUs of west coast salmon and final 4(d) protective regulations for threatened salmonid ESUs. June 28. *Federal Register* 70 (123): 37160–37204.
- NMFS (National Marine Fisheries Service) (2006a) Endangered and threatened species; final protective regulation for threatened upper Columbia river steelhead. August 18. *Federal Register* 71(21): 5178–5180.
- NMFS (National Marine Fisheries Service) (2006b) Notice of intent to prepare an environmental impact statement for the proposed issuance of an incidental take permit. March 27. *Federal Register* 71(58): 15168–15171.
- NMFS (National Marine Fisheries Service) (2007) *Columbia River estuary ESA recovery plan module for salmon and steelhead*. Proposed Plan, November 5, 2007. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Portland, Oregon.

- NOAA (National Oceanic and Atmospheric Administration) (2000) *A Citizen's Guide to the 4(d) Rule for Threatened Salmon and Steelhead on the West Coast*. Seattle, Washington.
- NOAA (National Oceanic and Atmospheric Administration) (2009) *Smart Growth for Coastal and Waterfront Communities*. Seattle, Washington.
- Norris DO (2000) Endocrine disruptors of the stress axis in natural populations: How can we tell? *American Zoologist* 40(3): 393–401.
- Norton KK (2008) *Within-pond Dynamics of Sediment Resuspension from Urban Storm Water Detention Ponds*. MS Thesis, Portland State University, Portland, OR.
- Novotny, V. (Ed.) 1995. *Nonpoint Pollution and Urban Stormwater Management*. Water Quality Management Library – Volume 9. Technomic Publishing Company.
- NRC (National Research Council) (1992) *Restoration of Aquatic Ecosystems: Science, Technology, and Public Policy*. National Academy Press, Washington, DC.
- NRC (National Research Council) (1996) *Upstream: Salmon and Society in the Pacific Northwest*. National Academy Press, Washington, DC.
- NRC (National Research Council) (2002) *Riparian Areas: Functions and Strategies for Management*. National Academy Press, Washington, DC.
- Nugent M, Alexanian K, Chan S, Cudd S, Demasi R, Guntermann C, Henry R, Hilburn D, Reynolds B, Schwamberger E, Systma M, Tu M (2005) *Oregon Invasive Species Action Plan*. Oregon Invasive Species Council, Oregon Department of Agriculture Plant Division, Salem, Oregon.
- Oberdorff T, Pont D, Huguency B, Porcher J-P (2002) Development and validation of a fish-based index for the assessment of 'river health' in France. *Freshwater Biology* 47(9): 1720–1734.
- Obropta CC, Rusciano GM (2006) Addressing total phosphorus impairments with water quality trading. *Journal of the American Water Resources Association* 42(5): 1297–1306.
- ODEQ (Oregon Department of Environmental Quality) (2001a) *Fact Sheet: Combined Sewer Overflows*. Oregon Department of Environmental Quality, Portland, Oregon.
- ODEQ (Oregon Department of Environmental Quality) (2001b) *Tualatin Subbasin: Total Maximum Daily Load (TMDL)*. Oregon Department of Environmental Quality, Portland, Oregon.
- ODEQ (Oregon Department of Environmental Quality) (2004) *Oregon's Water Quality Assessment: Section 305(b) Report*. Oregon Department of Environmental Quality, Portland, Oregon.
- ODEQ (Oregon Department of Environmental Quality) (2005) *Sandy River Basin Total Maximum Daily Load (TMDL)*. Oregon Department of Environmental Quality, Portland, Oregon.
- ODEQ (Oregon Department of Environmental Quality) (2006) *Best Management Practices for Storm Water Discharges Associated with Construction Activities*. Oregon Department of Environmental Quality, Portland, Oregon.
- ODEQ (Oregon Department of Environmental Quality) (2007) *Oregon 2006 Nonpoint Source Pollution Program Annual Report*. Oregon Department of Environmental Quality, Portland, Oregon.
- ODFW (Oregon Department of Fish and Wildlife) (2006) *The Oregon Conservation Strategy*. Oregon Department of Fish and Wildlife, Salem, Oregon.
- Oehlmann J, Schulte-Oehlmann U, Kloas W, Jagnytsch O, Lutz I, Kusk KO, Wollenberger L, Santos EM, Paull GC, Van Look KJW, Tyler CR (2009) A critical analysis of the biological impacts of plasticizers on wildlife. *Philosophical Transactions of the Royal Society B* 364(1526): 2047–2062.
- Olden JD, Poff NL, McKinney ML (2006) Forecasting faunal and floral homogenization associated with human population geography in North America. *Biological Conservation* 127(3): 261–271.

- Olding DD, Steele TS, Nemeth JC (2004) Operational monitoring of urban stormwater management facilities and receiving subwatersheds in Richmond Hill, Ontario. *Water Quality Research Journal of Canada* 39(4): 392–405.
- Opperman JJ, Lohse KA, Brooks C, Maggi Kelly N, Merenlender AM (2005) Influence of land use on fine sediment in salmonid spawning gravels within the Russian River basin, California. *Canadian Journal of Fisheries and Aquatic Sciences* 62(12): 2740–2751.
- OEC (2007) *Stormwater Solutions: Turning Oregon's Rain Back into a Resource*. Oregon Environmental Council. Portland, OR.
- Oregon Invasive Species Council (2007) *100 Most Dangerous Invaders to Keep out of Oregon in 2007*. Oregon Invasive Species Council, Salem, Oregon.
- Oregon Office of the Secretary of State (2005) *The Oregon Blue Book*. Office of the Secretary of State, Salem, Oregon.
- Oregon Plan (1997) *Oregon Plan for Salmon and Watersheds* (consisting of the Oregon Coastal Salmon Restoration Initiative, March 10, 1997 and as amended with the Steelhead Supplement, December 1997). Governor's Natural Resources Office, State of Oregon, Salem, Oregon.
- Oregon Progress Board (2000) *Oregon State of the Environment Report*. Oregon Progress Board, Salem, Oregon.
- Osgood DT, Yozzo DJ, Chambers RM, Jacobson D, Hoffman T, Wnek J (2003) Tidal hydrology and habitat utilization by resident nekton in *Phragmites* and non-*Phragmites* marshes. *Estuaries* 26(2B): 522–533.
- O'Toole S, Metcalfe C, Craine I, Gross M (2006) Release of persistent organic contaminants from carcasses of Lake Ontario Chinook salmon (*Oncorhynchus tshawytscha*). *Environmental Pollution* 140(1): 102–113.
- Ourso RT, Frenzel SA (2003) Identification of linear and threshold responses in streams along a gradient of urbanization in Anchorage, Alaska. *Hydrobiologia* 501(1-3): 117–131.
- OWEB (Oregon Watershed Enhancement Board) (1999) *Oregon Aquatic Habitat Restoration and Enhancement*. Oregon Watershed Enhancement Board, Salem, Oregon.
- OWEB (Oregon Watershed Enhancement Board) (2003a) *2001-2003 Oregon Plan Biennial Report*. Oregon Watershed Enhancement Board, Salem, Oregon.
- OWEB (Oregon Watershed Enhancement Board) (2003b) *Monitoring Strategy – Oregon Plan for Salmon and Watersheds*. Salem, Oregon.
- OWEB (Oregon Watershed Enhancement Board) (2005) *2003-2005 Oregon Plan Biennial Report, Volume 1*. Oregon Watershed Enhancement Board, Salem, Oregon.
- OWEB (Oregon Watershed Enhancement Board) (2008) *2008-2009 Oregon Plan Biennial Report*. Oregon Watershed Enhancement Board, Salem, Oregon.
- OWRRI (Oregon Water Resources Research Institute) (1995) *Gravel Disturbance Impacts on Salmon Habitat and Stream Health*. Volumes 1 & 2. Oregon Water Resources Research Institute, Oregon State University, Corvallis, Oregon.
- Ozawa CP, Yeakley JA (2004) Keeping the green edge: stream corridor protection in the Portland metropolitan region. Pages 257–279 In (ed Ozawa CP) *The Portland Edge: Challenges and Successes in Growing Communities*. Island Press, Washington, DC.
- Ozawa CP, Yeakley JA (2007) Performance of management strategies in the protection of riparian vegetation in three Oregon cities. *Journal of Environmental Planning and Management* 50(6): 803–822.
- Palmer M, Bernhardt ES (2006) Hydroecology and river restoration: ripe for research and synthesis. *Water Resources Research* 42: W03S07 [4 p.].
- Palmer MA, Moglen GE, Bockstael NE, Brooks S, Pizzuto JE, Wiegand C, VanNess K (2002) The ecological consequences of changing land use for running waters, with a case study of urbanizing watersheds in Maryland. Pages 85–113 In (ed Krchnak KM) *Human Population and Freshwater Resources*. Yale University Press, New Haven, Connecticut.

- Pan Y, Herlihy A, Kaufmann P, Wigington J, Van Sickle J, Moser T (2004) Linkages among land-use, water quality, physical habitat conditions and lotic diatom assemblages: A multi-spatial scale assessment. *Hydrobiologia* 515(1-3): 59–73.
- Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421(6918): 37–42.
- Parrott JL, Blunt BR (2005) Life-cycle exposure of fathead minnows (*Pimephales promelas*) to an ethinylestradiol concentration below 1 ng/L reduces egg fertilization success and demasculinizes males. *Environmental Toxicology* 20(2): 131–141.
- Paul MJ, Meyer JL (2001) Streams in the urban landscape. *Annual Review of Ecology and Systematics* 32: 333–365.
- Paulsen SG, Mayo A, Peck DV, Stoddard JL, Tarquinio E, Holdsworth SM, Van Sickle J, Yuan LL, Hawkins CP, Herlihy A, Kaufmann PR, Barbour MT, Larsen DP, Olsen AR (2008) Condition of stream ecosystems in the US: An overview of the first national assessment. *Journal of the North American Benthological Society* 27(4): 812–821.
- Pavao-Zuckerman MA (2008) The nature of urban soils and their role in ecological restoration in cities. *Restoration Ecology* 16(4): 642–649.
- Payne S (2002) Urban Land Use. Pages 106–107 In (eds Hulse D, Gregory S, Baker J) *Willamette River Basin: Trajectories of Environmental and Ecological Change, A Planning Atlas*. Oregon State University Press, Corvallis, Oregon.
- Payne JT, Wood AW, Hamlet AF, Palmer RN, Lettenmaier DP (2004) Mitigating the effects of climate change on the water resources of the Columbia River basin. *Climatic Change* 62(1-3): 233–256.
- Perkins MA, Sloane J, Pederson R, Stober QJ, Steward CR, Scott J (1980) *Ecological Impacts of Stormwater Runoff in Urban Streams*. FRI-UW-8013. Fisheries Research Institute, University of Washington, Seattle, Washington.
- Pess GR, Montgomery DR, Steel EA, Bilby RE, Feist BE, Greenburg HM (2002) Landscape characteristics, land use, and coho salmon (*Oncorhynchus kisutch*) abundance, Snohomish River, Wash., USA. *Canadian Journal of Fisheries and Aquatic Sciences* 59(4): 613–623.
- Peterson SA, Van Sickle J, Herlihy AT, Hughes RM (2007) Mercury concentration in fish from streams and rivers throughout the western United States. *Environmental Science and Technology* 41(1): 58–65.
- Pickett STA, Cadenasso ML, Grove JM, Groffman PM, Band LE, Boone CG, Burch Jr WR, Grimmond CSB, Hom J, Jenkins JC, Law NL, Nilon CH, Pouyat RV, Szlavecz K, Warren PS, Wilson MA (2008) Beyond urban legends: An emerging framework of urban ecology, as illustrated by the Baltimore Ecosystem Study. *BioScience* 58(2): 139–150.
- Pijanowski B, Ray DK, Kendall AD, Duckles JM, Hyndman DW (2007) Using backcast land-use change and groundwater travel-time models to generate land-use legacy maps for watershed management. *Ecology and Society* 12(2): [article 25].
- Pillard DA (1995) Comparative toxicity of formulated glycol deicers and pure ethylene and propylene glycol to *Ceriodaphnia dubia* and *Pimephales promelas*. *Environmental Toxicology and Chemistry* 14(2): 311–315.
- Pitt RE (1979) *Demonstration of Non-point Pollution Abatement through Improved Street Cleaning Properties*. EPA-600/2-79-161. US Environmental Protection Agency, Cincinnati, Ohio.
- Pitt RE (1995) Biological effects of urban runoff discharges. Pages 127–162 In (ed Herricks EE) *Stormwater Runoff and Receiving Systems - Impact Monitoring and Assessment*. CRC Lewis, New York, New York.
- Plafkin JL, Barbour MT, Porter KD, Gross SK, Hughes RM (1989) *Rapid Bioassessment Protocols for use in Streams and Rivers: Benthic Macroinvertebrates and Fish*. EPA/444/4-89/001. US Environmental Protection Agency, Washington, DC.
- Poff NL (1996) A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. *Freshwater Biology* 36(1): 71–91.

- Poff NL, Ward JV (1989) Implications of streamflow variability and predictability for lotic community structure: A regional analysis of streamflow patterns. *Canadian Journal of Fisheries and Aquatic Sciences* 46(10): 1805–1818.
- Poff NL, Allan JD, Bain MB, Karr JR, Prestegard KL, Richter BD, Sparks RE, Stromberg JC (1997) The natural flow regime: A paradigm for river conservation and restoration. *Bioscience* 47(11): 769–784.
- Poff NL, Bledsoe BP, Cuhaciyan CO (2006a) Hydrologic variation with land use across the contiguous United States: Geomorphic and ecological consequences for stream ecosystems. *Geomorphology* 79(3-4): 264–285.
- Poff NL, Olden JD, Pepin DM, Bledsoe BP (2006b) Placing global streamflow variability in geographic and geomorphic contexts. *River Research and Applications* 22(2): 149–166.
- Polasky S, Nelson E, Lonsdorf E, Fackler P, Starfield A (2005) Conserving species in a working landscape: Land use with biological and economic objectives. *Ecological Applications* 15(4): 1387–1401.
- Polasky S, Nelson E, Camm J, Csuti B, Fackler P, Lonsdorf E, Montgomery C, White D, Arthur J, Garber-Yonts B, Haight R, Kagan J, Starfield A, Tobalske C (2008) Where to put things? Spatial land management to sustain biodiversity and economic returns. *Biological Conservation* 141(6): 1505–1524.
- Pont D, Hugueny B, Beier U, Goffaux D, Melcher A, Noble R, Rogers C, Roset N, Schmutz S (2006) Assessing river biotic condition at a continental scale: A European approach using functional metrics and fish assemblages. *Journal of Applied Ecology* 43(1): 70–80.
- Pont D, Hughes RM, Whittier TR, Schmutz S (2009) A predictive Index of Biotic Integrity model for Aquatic-Vertebrate Assemblages of Western US streams. *Transactions of the American Fisheries Society* 138(2): 292–305.
- Poole GC, Berman CH (2001) An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human-caused thermal degradation. *Environmental Management* 27(6): 787–802.
- Poole G, Dunham J, Hicks M, Keenan D, Lockwood J, Materna E, McCullough D, Mebane C, Risley J, Sauter S, Spalding S, Sturdevant D (2001) *Scientific Issues Relating to Temperature Criteria for Salmon, Trout, and Char Native to the Pacific Northwest: A Summary Report Submitted to the Policy Workgroup of the EPA Region 10 Water Temperature Criteria Guidance Project*. Technical Synthesis EPA910-R-01-007. US Environmental Protection Agency, Washington, DC.
- Poole GC, Dunham JB, Keenan DM, Sauter ST, McCullough DA, Mebane C, Lockwood JC, Essig DA, Hicks MP, Sturdevant DJ, Materna EJ, Spalding SA, Risley J, Deppman M. (2004) The case for regime-based water quality standards. *Bioscience* 54(2): 155–161.
- Potapova M, Coles JF, Gidings EMP, Zappia H (2005) A Comparison of the influences of urbanization in contrasting environmental settings on stream benthic algal assemblages. Pages 333–359 In (eds Brown LR, Gray RH, Hughes RM, Meador MR) *Effects of Urbanization on Stream Ecosystems*. Symposium 47. American Fisheries Society, Bethesda, Maryland.
- Pratt JR, Tolman D, Sutton L, Doppelt B (2000) Summary of current status and health of Oregon's urban ecosystems. Pages 107–110 in *The Oregon State of the Environment Report 2000*. Oregon Progress Board, Salem, Oregon.
- Preston BL (2006) Risk-based reanalysis of the effects of climate change on U.S. cold-water habitat. *Climatic Change* 76(1-2): 91–119.
- Primozich D, Vickerman S (2007) *Willamette Ecosystem Marketplace*. Willamette Partnership, Salem, Oregon.
- Purdum CE, Hardiman PA, Bye VJ, Eno NC, Tyler CR, Sumpter JP (1994) Estrogenic effects of effluents from sewage treatment works. *Chemistry and Ecology* 8(4): 275–285.
- Pyke CR, Andelman SJ (2007) Land use and land cover tools for climate adaptation. *Climatic Change* 80(3-4): 239–251.
- Quinn TP (2005) *The Behavior and Ecology of Pacific Salmon and Trout*. University of Washington Press, Seattle, Washington.

- Quinn TP, Adams DJ (1996) Environmental changes affecting the migratory timing of American shad and sockeye salmon. *Ecology* 77(4): 1151–1162.
- Quinn TP, Myers KW (2004) Anadromy and the marine migrations of Pacific salmon and trout: Rounsefell revisited. *Reviews in Fish Biology and Fisheries* 14(4): 421–442.
- Quinn TP, Hodgson S, Peven C (1997) Temperature, flow, and the migration of adult sockeye salmon (*Oncorhynchus kisutch*) in the Columbia River. *Canadian Journal of Fisheries and Aquatic Sciences* 54(6): 1349–1360.
- Ragsdale D (2007) *Advanced Wastewater Treatment to Achieve Low Concentration of Phosphorus*. EPA 910-R-07-002. US Environmental Protection Agency, Washington, DC.
- Rahel FJ (2000) Homogenization of fish faunas across the United States. *Science* 288(5467): 854–856.
- Rahel FJ (2007) Biogeographic barriers, connectivity and homogenization of freshwater faunas: it's a small world after all. *Freshwater Biology* 52(4): 696–710.
- Ramankutty N, Foley JA, Olejniczak NJ (2002) People on the land: Changes in global population and croplands during the 20th century. *Ambio* 31(3): 251–257.
- Rand PS, Hinch SG, Morrison J, Foreman MGG, MacNutt MJ, Macdonald JS, Healey MC, Farrell AP, Higgs DA (2006) Effects of river discharge, temperature, and future climates on energetics and mortality of adult migrating Fraser River sockeye salmon. *Transactions of the American Fisheries Society* 135(3): 655–667.
- Rayne S, Ikononou MG, Antcliffe B (2003) Rapidly increasing polybrominated diphenyl ether concentrations in the Columbia River system from 1992 to 2000. *Environmental Science and Technology* 37(13): 2847–2854.
- Redmond KT, Koch RW (1991) Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. *Water Resources Research* 27(9): 2381–2399.
- Reed KM, Czech B (2005) Causes of fish endangerment in the United States, or the structure of the American economy. *Fisheries* 30(7): 36–38.
- Rees WE (2000) Eco-footprint analysis: Merits and brickbats. *Ecological Economics* 32(3): 371–374.
- Rees WE (2003) A blot on the land. *Nature* 421(6926): 898.
- Rees WE, Wackernagel M (1996) Urban ecological footprints: Why cities cannot be sustainable—And why they are a key to sustainability. *Environmental Impact Assessment Review* 16(4-6): 223–248.
- Reeves GH, Everest FH, Hall JD (1987) Interactions between the redbreasted shiner (*Richardsonius balteatus*) and the steelhead trout (*Salmon gairdneri*) in western Oregon: The influence of water temperature. *Canadian Journal of Fisheries and Aquatic Sciences* 44(9): 1603–1613.
- Reeves GH, Everest FH, Sedell JR (1993) Diversity of juvenile anadromous salmonid assemblages in coastal Oregon basins with different levels of timber harvest. *Transactions of the American Fisheries Society* 122(3): 309–317.
- Reeves GH, Bisson PA, Dambacher JM (1998) Fish communities. Pages 200–234 in (eds Naiman RJ, Bilby RE) *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion*. Springer-Verlag, New York, New York.
- Reeves GH, Burnett KM, Gregory SV (2002) Fish and aquatic ecosystems of the Oregon Coast Range. Pages 68–98 In(eds Hobbs SD, Hayes JP, Johnson RL, Reeves GH, Spies TA, Tappeiner JC II, Wells GE) *Forest and Stream Management in the Oregon Coast Range*. Oregon State University Press, Corvallis, Oregon.
- Regetz J (2003) Landscape-level constraints on recruitment of Chinook salmon (*Oncorhynchus tshawytscha*) in the Columbia River basin, USA. *Aquatic Conservation: Marine and Freshwater Ecosystems* 13(1): 35–49.
- Reinelt L, Horner R, Azous A (1998) Impacts of urbanization on palustrine (depressional freshwater) wetlands—Research and management in the Puget Sound region. *Urban Ecosystems* 2(4): 219–236.
- Reynaud S, Deschaux P (2006) The effects of polycyclic aromatic hydrocarbons on the immune system of fish: A review. *Aquatic Toxicology* 77(2): 229–238.

- Rice CA (2006) Effects of shoreline modification on a northern Puget Sound beach: Microclimate and embryo mortality in surf smelt (*Hypomesus pretiosus*). *Estuaries and Coasts* 29(1): 63–71.
- Richards C, Host G (1994) Examining land use influences on stream habitats and macroinvertebrates: A GIS approach. *Water Resources Bulletin* 30(4): 729–738.
- Richardson DM, Pysek P, Rejmanek M, Barbour MG, Panetta FD, West CJ (2000) Naturalization and invasion of alien plants: Concepts and definitions. *Diversity and Distributions* 6(2): 93–107.
- Rieman BE, Dunham JB (2000) Metapopulations and salmonids: A synthesis of life history patterns and empirical observations. *Ecology of Freshwater Fish* 9(1-2): 51–64.
- Rieman BE, Isaak D, Adams S, Horan D, Nagel D, Luce C, Myers D (2007) Anticipating climate warming effects on bull trout habitats and populations across the interior Columbia River basin. *Transactions of the American Fisheries Society* 136(6): 1552–1565.
- Riley AL (1998) *Restoring Streams in Cities. A Guide for Planners, Policymakers, and Citizens*. Island Press, Washington, DC.
- Riley SPD, Busteed GT, Kats LB, Vandergon TL, Lee LFS, Dagit RG, Kerby JL, Fisher RN, Sauvajot RM (2005) Effects of urbanization on the distribution and abundance of amphibians and invasive species in southern California streams. *Conservation Biology* 19(6): 1894–1907.
- Ritter DF, Kochel RC, Miller JR (1995) *Process Geomorphology, 3rd edition*. Wm. C. Brown Publishers, Dubuque, Iowa.
- Ritter L, Solomon K, Sibley P, Hall K, Keen P, Mattu G, Linton B (2002) Sources, pathways, and relative risks of contaminants in surface water and groundwater: A perspective prepared for the Walkerton Inquiry. *Journal of Toxicology and Environmental Health, Part A* 65(1): 1–142.
- Robertson MM (2006) Emerging ecosystem service markets: Trends in a decade of entrepreneurial wetland banking. *Frontiers in Ecology and the Environment* 4(6): 297–302.
- Robertson MJ, Scruton DA, Gregory RS, Clarke KD (2006) Effect of suspended sediment on freshwater fish and fish habitat. No. 2644. *Canadian Technical Report of Fisheries and Aquatic Sciences*. Fisheries and Oceans Canada, St. John's NL Canada
- Robertson MJ, Scruton DA, Clarke KD (2007) Seasonal effects of suspended sediment on the behavior of juvenile Atlantic salmon. *Transactions of the American Fisheries Society* 136(3): 822–828.
- Rodriguez MA (2002) Restricted movement in stream fish: The paradigm is incomplete, not lost. *Ecology* 8(1)3: 1–13.
- Rodriguez W, August PV, Wang Y, Paul JF, Gold A, Rubinstein N (2007) Empirical relationships between land use/cover and estuarine condition in the northeastern United States. *Landscape Ecology* 22(3): 403–417.
- Roni P, Beechie TJ, Bilby RE, Leonetti FE, Pollock MM, Pess GR (2002) A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds. *North American Journal of Fisheries Management* 22: 1–20.
- Roni P, Hanson K, Beechie TJ, Pess GR, Pollock MM, Barley DM. 2005. *Habitat rehabilitation for inland fisheries. Global review of effectiveness and guidance for rehabilitation of freshwater ecosystems*. Fisheries Technical Paper 484. Food and Agriculture Organization of the United Nations, Rome, Italy.
- Roni P, Bennett T, Morley S, Pess GR, Hanson K, van Slyke D, Olmstead P (2006) Rehabilitation of bedrock stream channels: The effects of boulder weir placement on aquatic habitat and biota. *River Research and Applications*. 22(9): 967–980.
- Roni P, Hanson K, Beechie T (2008) Global review of the physical and biological effectiveness of stream habitat rehabilitation techniques. *North American Journal of Fisheries Management* 28(3): 856–890.
- Roper BB, Scarnecchia DL (1999) Emigration of age-0 Chinook salmon (*Oncorhynchus tshawytscha*) smelts from the upper South Umpqua River basin, Oregon, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 56(6): 939–946.

- Roper BB, Buffington JM, Bennett S, Lanigan SH, Archer E, Dowine ST, Faustini J, Hillman TW, Hubler S, Jones K, Jordan C, Kauffman PR, Merritt G, Moyer C, Pleus A (2010) A comparison of the performance and compatibility of protocols used by seven monitoring groups to measure stream habitat in the Pacific Northwest. *North American Journal of Fisheries Management* 30(2): 565–587.
- Rose S, Peters NE (2001) Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. *Hydrological Processes* 15(8): 1441–1457.
- Rosenfeld JS, MacDonald S, Foster D, Amrhein S, Bales B, Williams T, Race F, Livingstone T (2002) Importance of small streams as rearing habitat for coastal cutthroat trout. *North American Journal of Fisheries Management* 22(1): 177–187.
- Rosenthal H, Alderdice DF (1976) Sublethal effects of environmental stressors, natural and pollutional, on marine fish eggs and larvae. *Journal of Fish Research Board Canada* 33: 2047–2065.
- Roset N, Grenouillet G, Goffaux D, Pont D, Kestemont P (2007) A review of existing fish assemblage indicators and methodologies. *Fisheries Management and Ecology* 14(6): 393–405.
- Ross ST (1991) Mechanisms structuring stream fish assemblages: Are there lessons from introduced species? *Environmental Biology of Fishes* 30(4): 359–368.
- Roy AM, Faust CL, Freeman MC, Meyer JL (2005) Reach-scale effects of riparian forest cover on urban stream ecosystems. *Canadian Journal of Fisheries and Aquatic Sciences* 62(1): 2312–2329.
- Roy AH, Freeman MC, Freeman BJ, Wenger SJ, Meyer JL, Ensign WE (2006) Importance of riparian forests in urban catchments contingent on sediment and hydrologic regimes. *Environmental Management* 37(4): 523–539.
- Rubec CDA, Hanson AR (2009) Wetland mitigation and compensation: Canadian experience. *Wetlands Ecology and Management* 17(1): 3–14.
- Ruckelshaus MH, Levin P, Johnson JB, Kareiva PM (2002) The Pacific salmon wars: What science brings to the challenge of recovering species. *Annual Review of Ecology and Systematics* 33: 665–706.
- Rumps JM, Katz SL, Barnas K, Morehead MD, Jenkinson R, Clayton SR, Goodwin P (2007) Stream restoration in the Pacific Northwest: Analysis of interviews with project managers. *Restoration Ecology* 15(3): 506–515.
- Sanborn SC, Bledsoe BP (2006) Predicting streamflow regime metrics for ungauged streams in Colorado, Washington, and Oregon. *Journal of Hydrology* 325(1–4): 241–261.
- Sandahl JF, Baldwin DH, Jenkins JJ, Scholz NL (2004) Odor-evoked field potentials as indicators of sublethal neurotoxicity in juvenile coho salmon (*Oncorhynchus kisutch*) exposed to copper, chlorpyrifos, or esfenvalerate. *Canadian Journal of Fisheries and Aquatic Sciences* 61(3): 404–413.
- Sandahl JF, Baldwin DH, Jenkins JJ, Scholz NL (2005) Comparative thresholds for acetylcholinesterase inhibition and behavioral impairment in coho salmon exposed to chlorpyrifos. *Environmental Toxicology and Chemistry* 24(1): 136–145.
- Sandahl JF, Miyasaka G, Koide N, Ueda H (2006) Olfactory inhibition and recovery in chum salmon (*Oncorhynchus keta*) following copper exposure. *Canadian Journal of Fisheries and Aquatic Sciences* 63(8): 1840–1847.
- Sandahl JF, Baldwin DH, Jenkins JJ, Scholz NL (2007) A sensory system at the interface between urban stormwater runoff and salmon survival. *Environmental Science and Technology* 41(8): 2998–3004.
- Sanders RA (1986) Urban vegetation impacts on the hydrology of Dayton, Ohio. *Urban Ecology* 9(3–4): 361–376.
- Sanderson EW, Jaiteh M, Levy MA, Redford KH, Wannebo AV, Woolmer G (2002) The human footprint and the last of the wild. *Bioscience* 52(10): 891–904.
- Sanderson BL, Barnas KA, Wargo Rub M (2009) Nonindigenous species of the Pacific Northwest: An overlooked risk to endangered salmon. *BioScience* 59(3): 245–256.
- Sansalone JJ, Cristina CM (2004) First flush concepts for suspended and dissolved solids in small impervious watersheds. *Journal of Environmental Engineering* 130(11): 1301–1314.

- Santos LHMLM, Araújo AN, Fachini A, Pena A, Delerue-Matos C, Montenegro MCBSM (2010) Ecotoxicological aspects related to the presence of pharmaceuticals in the aquatic environment. *Journal of Hazardous Materials* 175(1-3): 45–95.
- Saunders JW, Smith MW (1965) Changes in a stream population of trout associated with increased silt. *Journal of the Fisheries Research Board of Canada* 22: 395–404.
- Sauter ST, McMillan J, Dunham J (2001) *Salmonid behavior and water temperature*. EPA-910-D-01-001. US Environmental Protection Agency, Washington, DC.
- Schade CB, Bonar SA (2005) Distribution and abundance of nonnative fishes in streams of the western United States. *North American Journal of Fisheries Management* 25(4): 1386–1394.
- Schiff R, Benoit G (2007) Effects of impervious cover at multiple spatial scales on coastal watershed streams. *Journal of the American Water Resources Association* 43(3): 712–730.
- Schlösser IJ (1995) Critical landscape attributes that influence fish population dynamics in headwater streams. *Hydrobiologia* 303(1-3): 71–81.
- Schmetterling DA, Clancy CG, Brandt TM (2001) Effects of riprap bank reinforcement on stream salmonids in the western United States. *Fisheries*. 26(7): 6–13.
- Schoettler RJ (1953) *Helping Nature. 62nd Annual Report*. Washington Department of Fisheries, Olympia, Washington.
- Scholz JG, Booth DB (2001) Monitoring urban streams: Strategies and protocols for humid-region lowland streams. *Environmental Monitoring and Assessment* 71(2): 143–164.
- Scholz NL, Truelove NK, French BL, Berejikian BA, Quinn TP, Casillas E, Collier TK (2000) Diazinon disrupts antipredator and homing behavior in Chinook salmon (*Oncorhynchus tshawytscha*). *Canadian Journal of Fisheries and Aquatic Sciences* 57(9): 1911–1918.
- Scholz NL, Truelove NK, Labenia JS, Baldwin DH, Collier TK (2006) Dose-additive inhibition of Chinook salmon acetylcholinesterase activity by mixtures of organophosphate and carbamate insecticides. *Environmental Toxicology and Chemistry* 25(5): 1200–1207.
- Schowaneck D, Webb S (2002) Exposure simulation for pharmaceuticals in European surface waters with GREAT-ER. *Toxicology Letters* 131(1-2): 39–50.
- Schueler TR (1994) The importance of imperviousness. *Watershed Protection Techniques* 1(3): 100–111.
- Schultz IR, Skillman A, Nicolas J-M, Cyr DG, Nagler JJ (2003) Short-term exposure to 17 α -ethynylestradiol decreases the fertility of sexually maturing male rainbow trout (*Oncorhynchus mykiss*). *Environmental Toxicology and Chemistry* 22: 1272–1280.
- Schumm SA (1971) Fluvial geomorphology: Channel adjustment and river metamorphosis. Pages 5-1 & 5-22 in (ed Shen HW) *River Mechanics*. Colorado State University Press, Ft. Collins, Colorado.
- Schuster S, Grismer ME (2004) Evaluation of water quality projects in the Lake Tahoe basin. *Environmental Monitoring and Assessment* 90(1-3): 225–242.
- Scott MC (2006) Winners and losers among stream fishes in relation to land use legacies and urban development in the southeastern US. *Biological Conservation* 127(3): 301–309.
- Scott MC, Helfmann GS (2001) Native invasions, homogenization, and the mismeasure of integrity of fish assemblages. *Fisheries* 26(11): 6–15.
- Scott JB, Steward CR, Stober QJ (1986) Effects of urbanization on fish population dynamics in Kelsey Creek, Washington. *Transactions of the American Fisheries Society* 115(4): 555–567.
- Scott MC, Helfman GS, McTammany ME, Benfield EF, Bolstad PV (2002) Multiscale influences on physical and chemical stream conditions across blue ridge landscapes. *Journal of the American Water Resources Association* 38(5): 1379–1392.

- Sedell JR, Froggatt JL (1984) Importance of streamside forests to large rivers: The isolation of the Willamette River, Oregon, USA from its floodplain by snagging and streamside forest removal. *Verhandlung Internationale Vereinigung Limnologie* 22(3): 1828–1834.
- Sedell JR, Luchessa KJ (1981) Using the historical record as an aid to salmonid habitat enhancement. Pages 210–223 In (ed Armantrout NB) *Acquisition and Utilization of Aquatic Habitat Inventory Information: Proceedings of Symposium held on October 28–30, 1981*. American Fisheries Society, Portland, Oregon.
- Sedell JR, Reeves GH, Hauer FR, Stanford JA, Hawkins CP (1990) Role of refugia in recovery from disturbances: Modern fragmented and disconnected river systems. *Environmental Management* 14(5): 711–724.
- Sedell JR, Leone FN, Duval WS (1991) Water transportation and storage of logs. Pages 325–367 in (ed Meehan WR) *Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats*. Special Publication 19. American Fisheries Society, Bethesda, Maryland.
- Sedell JR, Bisson PA, Swanson FJ, Gregory SV (1988) What we know about large trees that fall into streams and rivers. Pages 47–82 in (eds Maser C, Tarrant RF, Trappe JM, Franklin JF) *From the Forest to the Sea: A Story of Fallen Trees*. General Technical Report PNW-GTR-229. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon.
- SER (Society for Ecological Restoration International Science & Policy Working Group) (2004) *The SER International Primer on Ecological Restoration*. Society for Ecological Restoration International, Tucson, Arizona.
- Servizi JA, Martens DW (1992) Sublethal responses of coho salmon (*Oncorhynchus kisutch*) to suspended sediments. *Canadian Journal of Fisheries and Aquatic Sciences* 49(7): 1389–1395.
- Shabman L, Stephenson K (2007) Achieving nutrient water quality goals: Bringing market-like principles to water quality management. *Journal of the American Water Resources Association* 43(4): 1076–1089.
- Shafer DJ (1999) The effects of dock shading on the seagrass *Halodule wrightii* in Perdido Bay, Alabama. *Estuaries* 22(4): 936–943.
- Sharp MM (2002) *Effects of Physical Soil Properties on the Coverage of Native and Non-Native Plants in Urban Riparian Areas*. MS Thesis. Environmental Science, Portland State University, Portland, Oregon.
- Sheehan DM, Willingham E, Gaylor D, Bergeron JM, Crews D (1999) No threshold dose for estradiol-induced sex reversal of turtle embryos: How little is too much? *Environmental Health Perspectives* 107(2): 155–159.
- Sheer MB, Steel EA (2006) Lost watersheds: Barriers, aquatic habitat connectivity, and salmon persistence in the Willamette and lower Columbia River basins. *Transactions of the American Fisheries Society* 135(6): 1654–1669.
- Shields FD, Cooper Jr CM, Knight SS, Moore MT (2003) Stream corridor restoration research: A long and winding road. *Ecological Engineering* 20(5): 441–454.
- Shuster WD, Bonta J, Thurston H, Warnemuende E, Smith DR (2005) Impacts of impervious surface on watershed hydrology: A review. *Urban Water Journal* 2(4): 263–275.
- Sigler JW, Bjornn TC, Everest FH (1984) Effects of chronic turbidity on density and growth of steelheads and coho salmon. *Transactions of the American Fisheries Society* 113(2): 142–150.
- Simenstad CA, Nightingale BJ, Thom RM, Shreffler DK (1999) *Impacts of Ferry Terminals on Juvenile Salmon Migrating Along Puget Sound Shorelines, Phase I: Synthesis of State of Knowledge*. Washington State Transportation Center, Seattle, Washington.
- Simenstad C, Tanneriji C, Crandelli C, White J, Corde J (2005) Challenges of habitat restoration in a heavily urbanized estuary: Evaluating the investment. *Journal of Coastal Research* 40(Special Issue): 6–23.
- Simenstad C, Reed D, Ford M (2006) When is restoration not? Incorporating landscape-scale processes to restore self-sustaining ecosystems in coastal wetland restoration. *Ecological Engineering* 26(1): 27–39.
- Simmons DL, Reynolds RJ (1982) Effects of urbanization on base flow of selected south-shore streams, Long Island, New York. *Water Resources Bulletin* 18(5): 797–805.

- Simon TP, Lyons J (1995) Application of the index of biotic integrity to evaluate water resource integrity in freshwater ecosystems. Pages 243–260 in (eds Davis WS, Simon TP) *Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making*. Lewis Publishers, Boca Raton, Florida.
- Simon A, Rinaldi M (2006) Disturbance, stream incision, and channel evolution: The roles of excess transport capacity and boundary materials in controlling channel response. *Geomorphology* 79(3-4): 361–383.
- Slatkin M (1985) Rare alleles as indicators of gene flow. *Evolution* 39(1): 53–65.
- Sloan CA, Anulacion BF, Bolton JL, Boyd D, Olson OP, Sol SY, Ylitalo GM, Johnson LL (2010) Polybrominated diphenyl ethers in outmigrant juvenile Chinook salmon from the lower Columbia River and estuary and Puget Sound, Washington. *Archives of Environmental Contamination and Toxicology* 58(2): 403–414.
- Smith RA, Alexander RB, Lanfear KJ (1993) Stream water quality in the conterminous United States – Status and trends of selected indicators during the 1980's. Pages 111–140 In (eds Paulson RW, Chase EB, Williams JS, Moody DW) *National Water Summary 1990-91 – Stream Water Quality*. Water-Supply Paper 2400. US Geological Survey, Reston, Virginia.
- Smith LW, Dittmer E, Prevost M, Burt DR (2000) Breaching a small irrigation dam in Oregon: A case history. *North American Journal of Fisheries Management*. 20(1): 205–219.
- Smith JA, Baeck ML, Meierdiercks KL, Nelson PA, Miller AJ, Holland EJ (2005) Field studies of the storm event hydrologic response in an urbanizing watershed. *Water Resources Research* 41(10): W10413.
- Smokorowski KE, Pratt TC (2007) Effect of a change in physical structure and cover on fish and fish habitat in freshwater ecosystems – a review and meta-analysis. *Environmental Review* 15(1): 15–41.
- Snell A, Colbert D (2007) Oregon water supply: Assessing future water supply needs. *Oregon Insider* 406/407: 1–3.
- Snyder CD, Young JA, Vilella R, Lemarié DP (2003) Influences of upland and riparian land use patterns on stream biotic integrity. *Landscape Ecology* 18(7): 647–664.
- Sommer TR, Nobriga ML, Harrell WC, Batham W, Kimmerer WJ (2001) Floodplain rearing of juvenile Chinook salmon: Evidence of enhanced growth and survival. *Canadian Journal of Fisheries and Aquatic Sciences* 58(2): 325–333.
- Song J, Mann DA, Cott PA, Hanna BW, Popper AN (2008) The inner ears of northern Canadian freshwater fishes following exposure to seismic air gun sounds. *Journal of the Acoustical Society of America* 124(2): 1360–1366.
- Sonneman JA, Walsh CJ, Breen PF, Sharpe AK (2001) Effects of urbanization on streams of the Melbourne region, Victoria, Australia. II. Benthic diatom communities. *Freshwater Biology* 46(4): 553–565.
- Sonoda K, Yeakley JA, Walker CE (2001) Near-stream landuse effects on streamwater nutrient distribution in an urbanizing watershed. *Journal of the American Water Resources Association* 37(6): 1517–1532.
- Souch C, Grimmond S (2006) Applied climatology: Urban climate. *Progress in Physical Geography* 30 (2): 270–279.
- Southard SL, Thom RM, Williams GD, Toft JD, May CW, McMichael GA, Vucelick JA, Newell JT, Southard JA (2006) *Impacts of ferry terminals on juvenile salmon movement along Puget Sound shorelines*. Report Number WA-RD 648.1, Washington State Department of Transportation, Olympia, Washington.
- Sparling DW, Fellers G (2007) Comparative toxicity of chlorpyrifos, diazinon, malathion, and their oxon derivatives to larval *Rana boylei*. *Environmental Pollution* 147(3): 535–539.
- Spence BC, Lomnický GA, Hughes RM, Novitzki RP (1996) *An Ecosystem Approach to Salmonid Conservation*. TR-4501-96-6057. ManTech Environmental Research Services Corp., Corvallis, Oregon.
- Spieles DJ (2005) Vegetation development in created, restored, and enhanced mitigation wetland banks of the United States. *Wetlands* 25(1): 51–63.
- Spromberg JA, Meador JP (2006) Relating chronic toxicity responses to population-level effects: A comparison of population-level parameters for three salmon species as a function of low-level toxicity. *Ecological Modelling* 199(3): 240–252.

- Squillace PJ, Moran MJ (2007) Factors associated with sources, transport, and fate of volatile organic compounds and their mixtures in aquifers of the United States. *Environmental Science and Technology* 41(7): 2123–2130.
- Stanfield LW, Kilgour BW (2006) Effects of percent impervious cover on fish and benthos assemblages and instream habitats in Lake Ontario tributaries. Pages 577–599 In (eds Hughes RM, Wang L, Seelbach PW) *Landscape Influences on Stream Habitats and Biological Assemblages*. Symposium 48. American Fisheries Society, Bethesda, Maryland.
- Stanfield LW, Gibson SF, Borwick JA (2006) Using a landscape approach to identify the distribution and density patterns of salmonids in Lake Ontario tributaries. Pages 601–621 In (eds Hughes RM, Wang L, Seelbach PW) *Landscape Influences on Stream Habitats and Biological Assemblages*. Symposium 48. American Fisheries Society, Bethesda, Maryland.
- Stanford JA, Ward JV, Liss WJ, Frissell CA, Williams RN, Lichatowich JA, Coutant CC (1996) A general protocol for restoration of regulated rivers. *Regulated Rivers: Research and Management* 12(4-5): 391–413.
- Stark JD, Maxted JR (2004) *Macroinvertebrate Community Indices for Auckland's Soft Bottomed Streams and Applications to SOE Reporting*. Auckland Regional Council, Auckland, New Zealand.
- Steel BS, Hubbard M, Wolters EA (2010a) *Oregon Water Policy Survey*. Master of Public Policy Program, Oregon State University, Corvallis, Oregon.
http://www1.wrd.state.or.us/files/Publications/staff_reports/2010%20November/Item%20A%20-%20IWR%20Update/Attachment%201.pdf (accessed December 9, 2010).
- Steel EA, Hughes RM, Fullerton AH, Schmutz S, Young JA, Fukushima M, Muhar S, Poppe M, Feist B, Trautwein C (2010b) Are we meeting the challenges of landscape scale riverine research: A review. *Living Reviews in Landscape Research* 4, 1 [online article] (60 p.).
- Stefansson SO, Björnsson BT, Sundell K, Nyhammer G, McCormick SD (2003) Physiological characteristics of wild Atlantic salmon post-smolts during estuarine and coastal migration. *Journal of Fish Biology* 63(4): 942–955.
- Steffy LY, Kilham SS (2004) Elevated $\delta^{15}\text{N}$ in stream biota in areas with septic tank systems in an urban watershed. *Ecological Applications* 14(3): 637–641.
- Stehr CM, Brown DW, Hom T, Anulacion BF, Reichert WL, Collier TK (2000) Exposure of juvenile Chinook and chum salmon to chemical contaminants in the Hylebos Waterway of Commencement Bay, Tacoma, Washington. *Journal of Aquatic Ecosystem Stress and Recovery* 7(3): 215–227.
- Stein JE, Hom T, Collier TK, Brown DW, Varanasi U (1995) Contaminant exposure and biochemical effects in outmigrant juvenile Chinook salmon from urban and non-urban estuaries of Puget Sound, Washington. *Environmental Toxicology and Chemistry* 14(6): 1019–1029.
- Stein SM, McRoberts RE, Alig RJ, Nelson MD, Theobald DM, Eley M, Dechter M, Carr M (2005) *Forests on the Edge: Housing Development on America's Private Forests*. General Technical Report PNW-GTR-636. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon.
- Stewart GB, Bayliss HR, Showler DA, Sutherland WJ, Pullin AS (2009) Effectiveness of engineered in-stream structure mitigation measures to increase salmonid abundance: A systematic review. *Ecological Applications* 19(4): 931–941.
- Stoddard JL, Peck DV, Paulsen SG, Van Sickle J, Hawkins CP, Herlihy AT, Hughes RM, Kaufmann PR, Larsen DP, Lomnický G, Olsen AR, Peterson SA, Ringold PL, Whittier TR (2005) *An Ecological Assessment of Western Streams and Rivers*. EPA 620/R-05/005. US Environmental Protection Agency, Washington, DC.
- Stoddard JL, Larsen DP, Hawkins CP, Johnson RK, Norris RH (2006) Setting expectations for the ecological condition of running waters: The concept of reference condition. *Ecological Applications* 16(4): 1267–1276.
- Stoddard JL, Herlihy AT, Peck DV, Hughes RM, Whittier TR, Tarquinio E (2008) A process for creating multi-metric indices for large-scale aquatic surveys. *Journal of the North American Benthological Society* 27(4): 878–891.
- Stone B Jr (2004) Paving over paradise: How land use regulations promote residential imperviousness. *Landscape and Urban Planning* 69(1): 101–113.

- Stone B, Bullen JL (2006) Urban form and watershed management: How zoning influences residential stormwater volumes. *Environment and Planning B: Planning and Design* 33(1): 21–37.
- Stranko SA, Hurd MK, Klauda RJ (2005) Applying a large, statewide database to the assessment, stressor diagnosis, and restoration of stream fish communities. *Environmental Monitoring and Assessment* 108(1-3): 99–121.
- Stranko SA, Hilderbrand RH, Morgan RP II, Staley MW, Becker AJ, Roseberry-Lincoln A, Perry ES, Jacobson PT (2008) Brook trout declines with land cover and temperature changes in Maryland. *North American Journal of Fisheries Management* 28(4): 1223–1232.
- Strayer DL, Beighley RE, Thompson LC, Brooks S, Nilsson C, Pinay G, Naiman RJ (2003) Effects of land cover on stream ecosystems: Roles of empirical models and scaling issues. *Ecosystems* 6(5): 407–423.
- Sturtevant BR, Cleland DT (2007) Human and biophysical factors influencing modern fire disturbance in northern Wisconsin. *International Journal of Wildland Fire* 16(4): 398–413.
- Sudduth EB, Meyer JL (2006) Effects of bioengineered streambank stabilization on bank habitat and macroinvertebrates in urban streams. *Environmental Management* 38(2): 218–226.
- Sudduth EB, Meyer JL, Bernhardt ES (2007) Stream restoration practices in the southeastern United States. *Restoration Ecology*. 15(3): 573–583.
- Sudol MF, Ambrose RF (2002) The US Clean Water Act and habitat replacement: Evaluation of mitigation sites in Orange County, California, USA. *Environmental Management* 30(5): 727–734.
- Suttle KB, Power ME, Levine JM, McNeely C (2004) How fine sediment in riverbeds impairs growth and survival of juvenile salmonids. *Ecological Applications* 14(4): 969–974.
- Svendsen TC, Vorkamp K, Frederiksen M, Rønsholdt B, Frier J-O (2007) Body burdens of persistent halogenated compounds during different development stages of anadromous brown trout (*Salmo trutta*). *Environmental Science and Technology* 41(17): 5980–5985.
- Swartz CH, Reddy S, Benotti MJ, Yin H, Barber LB, Brownawell BJ, Rudel RA (2006) Steroid estrogens, nonylphenol ethoxylate metabolites, and other wastewater contaminants in groundwater affected by a residential septic system on Cape Cod, MA. *Environmental Science and Technology* 40(16): 4894–4902.
- Swetnam TW, Allen CD, Betancourt JL (1999) Applied historical ecology: Using the past to manage for the future. *Ecological Applications* 9(4): 1189–1206.
- Syphard AD, Radeloff VC, Keeley JE, Hawbaker TJ, Clayton MK, Stewart SI, Hammer RB (2007) Human influence on California fire regimes. *Ecological Applications* 17(5): 1388–1402.
- Tabor RA; Brown GS, Luiting VT (2004) The effect of light intensity on sockeye salmon fry migratory behavior and predation by cottids in the Cedar River, Washington. *North American Journal of Fisheries Management* 24(1): 128–145.
- Tague C, Grant GE (2004) A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River basin, Oregon. *Water Resources Research* 40(4): W04303.
- Tanner DQ (2002) *Selected Elements and Organic Chemicals in Streambed Sediment in the Salem Area, Oregon, 1999*. Water-Resources Investigations Report 02–4194. US Geological Survey, Portland, Oregon.
- Tate CM, Cuffney TF, McMahon G, Giddings EMP, Coles JF, Zappia H (2005) Use of an urban intensity index to assess urban effects on streams in three contrasting environmental settings. Pages 291–315 In (eds Brown LR, Gray RH, Hughes RM, Meador MR) *Effects of Urbanization on Stream Ecosystems*. Symposium 47. American Fisheries Society, Bethesda, Maryland.
- Taylor B (1998) *Salmon and Steelhead Runs and Related Events of the Sandy River Basin – A Historical Perspective*. IPS2-17180, Bull Run Project, FERC No. 477. Portland General Electric, Hydro Licensing Department, Portland, Oregon.
- Taylor SL, Roberts SC, Walsh CJ, Hatt BE (2004) Catchment urbanization and increased benthic algal biomass in streams: linking mechanisms to management. *Freshwater Biology* 49(6): 835–851.

- Taylor MFJ, Suckling KF, Rachlinski JJ (2005) The effectiveness of the Endangered Species Act: A quantitative analysis. *Bioscience* 55(4): 360–367.
- Teuten EL, Saquing JM, Knappe DRU, Barlaz MA, Jonsson S, Björn A, Rowland SJ, Thompson RC, Galloway TS, Yamashita R, Ochi D, Watanuki Y, Moore C, Viet PH, Tana TS, Prudente M, Boonyatumanond R, Zakaria MP, Akkhavong K, Ogata Y, Hirari H, Iwasa S, Mizukawa K, Hagino Y, Imamura A, Saha M, Takada H (2009) Transport and release of chemicals from plastics to the environment and to wildlife. *Philosophical Transactions of the Royal Society B: Biological Sciences* 364(1526): 2027-2045.
- Theobald DM (2005) Landscape patterns of exurban growth in the USA from 1980 to 2020. *Ecology and Society* 10(1): [article 32].
- Thom RM, Borde AB, Richter KO, Hibler LF (2001) Influence of urbanization on ecological processes in wetlands. Pages 5–16 In (eds Wigmosta MS, Lewis J, Dunne T, Montgomery DR, Sidle RC) *Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas*. Water Science and Application 2, American Geophysical Union, Washington, DC.
- Thompson DM (2006) Did the pre-1980 use of instream structures improve streams? A reanalysis of historical data. *Ecological Applications* 16(2): 784–796.
- Thorpe JE (1994) Salmonid fishes and the estuarine environment. *Estuaries* 17(1A): 76–93.
- Thorpe KL, Cummings RI, Hutchinson TH, Scholze M, Brighty G, Sumpter JP, Tyler CR (2003) Relative potencies and combination effects of steroidal estrogens in fish. *Environmental Science and Technology* 37(6): 1142–1149.
- Tickner DP, Angold PG, Gurnell AM, Mountford JO (2001) Riparian plant invasions: hydrogeomorphical control and ecological impacts. *Progress in Physical Geography* 25(1): 22–52.
- Tierney KB, Ross PS, Jarrard HE, Delaney KR, Kennedy CJ (2006a) Changes in juvenile coho salmon electro-olfactogram during and after short-term exposure to current-use pesticides. *Environmental Toxicology and Chemistry* 25(10): 2809–2817.
- Tierney KB, Taylor AL, Ross PS, Kennedy CJ (2006b) The alarm reaction of coho salmon parr is impaired by the carbamate fungicide IPBC. *Aquatic Toxicology* 79(2): 149–157.
- Tierney KB, Singh CR, Ross PS, Kennedy CJ (2007) Relating olfactory neurotoxicity to altered olfactory-mediated behaviors in rainbow trout exposed to three currently-used pesticides. *Aquatic Toxicology* 81(1): 55–64.
- Tierney KB, Sampson JL, Ross PS, Sekela MA, Kennedy CJ (2008) Salmon olfaction is impaired by an environmentally realistic pesticide mixture. *Environmental Science and Technology* 42(13): 4996–5001.
- Tiffan KF, Clark LO, Garland RD, Rondorf DW (2006) Variables influencing the presence of subyearling fall Chinook salmon in shoreline habitats of the Hanford Reach, Columbia River. *North American Journal of Fisheries Management* 26(2): 351–360.
- Tinus ES, Koloszar JA, Ward DL (2003) *Abundance and Distribution of Fish in City of Portland Streams: Final report 2001-03*. Oregon Department of Fish and Wildlife, Clackamas, Oregon.
- Toft JD, Cordell JR, Simenstad CA, Stamatidou LA (2007) Fish distribution, abundance, and behavior along city shoreline types in Puget Sound. *North American Journal of Fisheries Management* 27(2): 465–480.
- Tompkins MR, Kondolf GM (2007) Systematic postproject appraisals to maximize lessons learned from river restoration projects: Case study of compound channel restoration projects in northern California. *Restoration Ecology*. 15(3): 524–537.
- Torgersen CE, Price DM, Li HW, McIntosh BA (1999) Multiscale thermal refugia and stream habitat associations of Chinook salmon in northeastern Oregon. *Ecological Applications* 9(1): 301–319.
- Trauth KM, Shin Y-S (2005) Implementation of the EPA's water quality trading policy for storm water management and smart growth. *Journal of Urban Planning and Development* 131(4): 258–269.
- Trimble SJ (1997) Contribution of stream channel erosion to sediment yield from an urbanizing watershed. *Science* 278(5342): 1442–1444.

- Tyler CR, Jobling S (2008) Roach, sex, and gender-bending chemicals: the feminization of wild fish in English rivers. *Bioscience* 58(11): 1051–1059.
- UNH (University of New Hampshire) Stormwater Center (2010) *University of New Hampshire Stormwater Center: 2009 Biannual Report*. Durham, New Hampshire
- Urban MC, Skelly DK, Burchsted D, Price W, Lowry S (2006) Stream communities across a rural-urban landscape gradient. *Diversity and Distributions* 12(4): 337–350.
- US Census Bureau (2003) *Census of Population and Housing*. Population and Housing Counts, PHC-3-39. US Census Bureau, Washington, DC.
- US Census Bureau (2005) *Table A1: Interim Projections of the Total Population for the United States and States: April 1, 2000 to July 1, 2030*. United States Census Bureau, Population Division, Interim State Population Projections. Washington, DC.
- USEPA (US Environmental Protection Agency) (1993) *Guidance Specifying Management Measures for Sources of Nonpoint Source Pollution in Coastal Waters*. EPA-840-B-92-002. US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (1995) *The Quality of Our Nation's Water: 1994*. EPA-841-S-95-004. Office of Water, US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (1996) *Environmental Indicators of the Water Quality in the United States*. EPA-841-R-96-002. US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (1998) *Advanced Wastewater Treatment to Achieve Low Concentration of Phosphorus*. EPA 910-R-07-002, US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (2000a) *Low Impact Development (LID): A Literature Review*. EPA-841-B-00-005. US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (2000b) *Mid-Atlantic Highlands Streams Assessment*. EPA-903-R-00-015. US Environmental Protection Agency, Philadelphia, Pennsylvania.
- USEPA (US Environmental Protection Agency) (2000c) *Preliminary Data Summary: Airport Deicing Operations (Revised)*. EPA-821-R-00-016. US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (2001a) *The United States Experience with Economic Incentives for Protecting the Environment*. EPA-240-R-01-001. US Environmental Protection Agency, Office of Policy, Economics, and Innovation, Washington, DC.
- USEPA (US Environmental Protection Agency) (2001b) *What is Smart Growth?* EPA 231-F-01-001A. US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (2002a) *Methods for Measuring the Acute Toxicity of Effluents and Receiving Waters to Freshwater and Marine Organisms*. Fifth edition. EPA-821-R-02-012. US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (2002b) *National Water Quality Inventory: 2000 Report*. EPA-841-R-02-001. US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (2004a) *National Coastal Condition Report II*. EPA-620/R-03/002. US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (2004b) *Primer for Municipal Wastewater Treatment Systems*. EPA-832-R-04-001. US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (2004c) *Protecting Water Resources with Smart Growth*. EPA 231-R-04-002. US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (2005) *Using Smart Growth Techniques as Stormwater Best Management Practices*. EPA 231-B-05-002. US Environmental Protection Agency, Washington, DC.

- USEPA (US Environmental Protection Agency) (2006a) *Growing Towards More Efficient Water Use: Linking Development, Infrastructure, and Drinking Water Policies*. EPA 230-R-06-001. US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (2006b) *Protecting Water Resources with Higher-Density Development*. EPA 231-R-06-001. US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (2006c) *The Wadeable Streams Assessment: A Collaborative Survey of the Nation's Streams*. EPA 841-B-06-002. US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency) (2007) *Reducing Stormwater Costs through Low Impact Development (LID) Strategies and Practices*. EPA 841-F-07-006. US Environmental Protection Agency, Washington, DC.
- USEPA (US Environmental Protection Agency), USFWS (US Fish and Wildlife Service), NMFS (National Marine Fisheries Service) (2001) Memorandum of agreement between the Environmental Protection Agency, Fish and Wildlife Service, and National Marine Fisheries Service regarding enhanced coordination under the Clean Water Act and Endangered Species Act. February 22. *Federal Register* 66(36): 11202–11217.
- USFWS (US Fish and Wildlife Service) (1995) *Lahontan Cutthroat Trout (Oncorhynchus clarkii henshawi) Recovery Plan*. US Fish and Wildlife Service, Portland, Oregon.
- USFWS (US Fish and Wildlife Service) (1998) Determination of threatened status for the Klamath River and Columbia River distinct population segments of bull trout. *Federal Register* 63 (111): 31647–31674.
- USFWS (2006) *Sediment Removal from Active Stream Channels in Oregon: Considerations for Federal Agencies for the Evaluation of Sediment Removal Actions from Oregon Streams*. US Fish and Wildlife Service. Portland, Oregon
- USGS (US Geological Survey) (1999) *The Quality of Our Nation's Waters: Nutrients and Pesticides*. Circular No. 1225. US Geological Survey, Reston, Virginia.
- USGS (US Geological Survey) (2001) *Selected Findings and Current Perspectives on Urban and Agricultural Water Quality by the National Water-Quality Assessment Program*. FS-047-01. US Geological Survey, Reston, Virginia.
- Uveges JL, Corbett AL, Mal TK (2002) Effects of lead contamination on the growth of *Lythrum salicaria* (purple loosestrife). *Environmental Pollution* 120(2): 319–323.
- Van Metre PC, Mahler BJ, Furlong ET (2000) Urban sprawl leaves its PAH signature. *Environmental Science and Technology* 34(19): 4064–4070.
- Van Sickle J, Baker J, Herlihy A, Bayley P, Gregory S, Haggerty P, Ashkenas L, Li J (2004) Projecting the biological condition of streams under alternative scenarios of human land use. *Ecological Applications* 14(2): 368–380.
- Vaske JJ, Kobrin KC (2001) Place attachment and environmentally responsible behavior. *The Journal of Environmental Education* 32(4): 16–21.
- Venetoulis J, Chazan D, Gaudet C (2004) *Ecological Footprint of Nations*. Sustainability Indicators Program, Redefining Progress, Oakland, California.
- Vesterby M, Krupa KS (2002) Rural residential land use: Tracking its growth. *Agricultural Outlook 2002* AGO-293: 14–17.
- Vidra RL, Shear TH (2008) Thinking locally for urban forest restoration: a simple method links exotic species invasion to local landscape structure. *Restoration Ecology* 16(2): 217–220.
- Voelz NJ, Zuellig RE, Shieh S-H, Ward JV (2005) The effects of urban areas on benthic macroinvertebrates in two Colorado plains rivers. *Environmental Monitoring and Assessment* 101(1-3): 175–202.
- Voogt JA, Oke TR (2003) Thermal remote sensing of urban climates. *Remote Sensing of Environment* 86(3): 370–384.

- Wackernagel M, Deumling D, Monfreda C, Linares AC, Falfan ISL, Sanchez MAV (2001) *Ecological Footprint of Nations: December 2001 Update*. Redefining Progress, Oakland, California
- Wackernagel M, Monfreda C, Deumling D (2002) *Ecological Footprint of Nations: November 2002 Update*. Redefining Progress, Oakland, California.
- Wahl MH, McKeller HN, Williams TM (1997) Patterns of nutrient loading in forested urbanized coastal streams. *Journal of Experimental Marine Biology and Ecology* 213(1): 111–131.
- Waite IR, Sobieszczyk S, Carpenter KD, Arnsberg AJ, Johnson HM, Hughes CA, Sarantou MJ, Rinella FA (2008) *Effects of Urbanization on Stream Ecosystems in the Willamette River Basin and Surrounding Area, Oregon and Washington*. Scientific Investigations Report 2006-5101-D. National Water-Quality Assessment Program, US Geological Survey, Washington, DC.
- Walker CE, Pan Y (2006) Using diatom assemblages to assess urban stream conditions. *Hydrobiologia* 561(1): 179–189.
- Wallick JR, Anderson SW, Cannon C, O'Connor JE (2009) *Channel change and bed-material transport in the lower Chetco River, Oregon*. Open-File Report 2009–1163. US Geological Survey, Portland, Oregon.
- Walsh CJ (2000) Urban impacts on the ecology of receiving waters: A framework for assessment, conservation and restoration. *Hydrobiologia* 431(2-3): 107–114.
- Walsh CJ (2004) Protection of in-stream biota from urban impacts: Minimize catchment imperviousness or improve drainage design? *Marine and Freshwater Research* 55(3): 317–326.
- Walsh CJ, Fletcher TD, Ladson AR (2005a) Stream restoration in urban catchments through redesigning stormwater systems: Looking to the catchment to save the stream. *Journal of the North American Benthological Society* 24(3): 690–705.
- Walsh CJ, Roy AH, Feminella JW, Cottingham PD, Groffman PM, Morgan RP II (2005b) The urban stream syndrome: Current knowledge and the search for a cure. *Journal of the North American Benthological Society* 24(3): 706–723.
- Walton BM, Salling M, Wyles J, Wolin J (2007) Biological integrity in urban streams: Towards resolving multiple dimensions of urbanization. *Landscape and Urban Planning* 79(1): 110–123.
- Wan MT, Kuo J-N, Buday C, Schroeder G, van Aggelen G, Pasternak J (2007) Toxicity of α -, β -, ($\alpha+\beta$)-endosulfan and their formulated and degradation products to *Daphnia magna*, *Hyalella azteca*, *Oncorhynchus mykiss*, *Oncorhynchus kisutch*, and biological implications in streams. *Environmental Contamination and Toxicology* 24(5): 1146–1154.
- Wang L, Kanehl P (2003) Influences of watershed urbanization and instream habitat on macroinvertebrates in cold water streams. *Journal of the American Water Resources Association* 39(5): 1181–1196.
- Wang L, Lyons J, Kanehl P, Bannerman R, Emmons E (2000) Watershed urbanization and changes in fish communities in southeastern Wisconsin streams. *Journal of the American Water Resources Association* 36(5): 1173–1189.
- Wang L, Lyons J, Kanehl P, Bannerman R (2001) Impacts of urbanization on stream habitat and fish across multiple spatial scales. *Environmental Management* 28(2): 255–266.
- Wang H, Hondzo M, Xu C, Poole V, Spacie A (2003a) Dissolved oxygen dynamics of streams draining an urbanized and an agricultural catchment. *Ecological Modelling* 160(1-2): 145–161.
- Wang L, Lyons J, Kanehl P (2003b) Impacts of urban land cover on trout streams in Wisconsin and Minnesota. *Transactions of the American Fisheries Society* 132(5): 825–839.
- Wang L, Lyons J, Rasmussen P, Seelbach P, Simon T, Wiley M, Kanehl P, Baker E, Niemela S, Stewart PM (2003c) Watershed, reach, and riparian influences on stream fish assemblages in the Northern Lakes and Forest Ecoregion, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 60(5): 491–505.
- Wang L, Seelbach PW, Lyons J (2006) Effects of levels of human disturbance on the influence of catchment, riparian, and reach-scale factors on fish assemblages. Pages 1–23 In (eds Hughes RM, Wang L, Seelbach PW)

- Landscape Influences on Stream Habitats and Biological Assemblages*. Symposium 48. American Fisheries Society, Bethesda, Maryland.
- Waring CP, Moore AP (1997) Sublethal effects of a carbamate pesticide on pheromonal mediated endocrine function in mature male Atlantic salmon (*Salmo salar* L.) parr. *Fish Physiology and Biochemistry* 17(1-6): 203–211.
- Waring RH, Running SW (1998) *Forest Ecosystems: Analysis at Multiple Scales, 2nd Edition*. Academic Press, San Diego, California.
- Warren CE (1971) *Biology and Water Pollution Control*. Saunders, Philadelphia, Pennsylvania.
- Warren CE, Davis GE (1971) Laboratory stream research: Objectives, possibilities, and constraints. *Annual Review of Ecology and Systematics* 2: 111–142.
- Waters TF (1995) *Sediment in Streams: Sources, Biological Effects, and Control*. Monograph 7. American Fisheries Society, Bethesda, Maryland.
- Weaver LA, Garman GC (1994) Urbanization of a watershed and historical changes in a stream fish assemblage. *Transactions of the American Fisheries Society* 123(2): 162–172.
- Weilhoefer CL, Pan Y (2006) Relationships between diatoms and environmental variables in wetlands in the Willamette Valley, Oregon, USA. *Wetlands* 27(3): 668–682.
- Weilhoefer CL, Pan Y (2007) Diatom assemblages and their associations with environmental variables in Oregon Coast Range streams, USA. *Hydrobiologia* 561(1): 207–219.
- Weitkamp LA, Wainwright TC, Bryant GJ, Milner GB, Teel DJ, Kope RG, Waples RS (1995) *Status Review of Coho Salmon from Washington, Oregon, and California*. Technical Memorandum NMFS-NWFSC-24. US Department of Commerce, National Oceanic and Atmospheric Administration, Seattle, Washington.
- Welcomme RL (1979) *Fisheries Ecology of Floodplain Rivers*. Longman, London, United Kingdom.
- Wenger SJ, Roy AH, Jackson CR, Bernhardt ES, Carter TL, Filoso S, Gibson CA, Hession WC, Kaushal SS, Marti E, Meyer JL, Palmer MA, Paul MJ, Purcell AH, Ramirez A, Rosemond AD, Schofield KA, Sudduth EB, Walsh CJ (2009) Twenty-six key research questions in urban stream ecology: An assessment of the state of the science. *Journal of the North American Benthological Society* 28(4): 1080–1098.
- Wentz DA, Bonn BA, Carpenter KD, Hinkle SR, Janet ML, Rinella FA, Uhrich MA, Waite IR, Laenen A, Bencala KE (1998) *Water Quality in the Willamette Basin, Oregon, 1991–95*. Circular 1161. US Geological Survey, Reston, Virginia.
- Weston RF (1998) *Portland Harbor Sediment Investigation Report*. Multnomah County, Oregon. EPA 910/R-98-006. US Environmental Protection Agency Report, Seattle, Washington.
- White EM, Morzillo AT, Alig RJ (2009) Past and projected rural land conversion in the US at state, regional, and national levels. *Landscape and Urban Planning* 89(1-2): 37–48.
- Whitely Binder LC (2006) Climate change and watershed planning in Washington state. *Journal of the American Water Resources Association* 42(4): 915–926.
- Whittier TR, Hughes RM, Lomnický GA, Peck DV (2007a) Fish and amphibian tolerance values and an assemblage tolerance index for streams in the western USA. *Transactions of the American Fisheries Society* 136(1): 254–271.
- Whittier TR, Hughes RM, Stoddard JL, Lomnický GA, Peck DV, Herlihy AT (2007b) A structured approach for developing indices of biotic integrity: Three examples from streams and rivers in the western USA. *Transactions of the American Fisheries Society* 136(3): 718–735.
- Wiley P (2001) *No Place for Nature: The limits of Oregon's land use program in protecting fish and wildlife habitat in the Willamette Valley*. Defenders of Wildlife, Portland, Oregon.
- Willamette Partnership (2007a) *A Primer on Existing and Emerging Markets for Environmental Off-set Credits in the Willamette River Basin*. Willamette Partnership, Salem Oregon.

- Willamette Partnership (2007b) *Beyond Compliance: Transforming The Way We Manage, Regulate, Restore And Sustain Ecosystems By Building The Willamette Ecosystem Marketplace*. Willamette Partnership, Salem Oregon.
- Williams JE, Johnson JE, Hendrickson DA, Contreras-Balderas S, Williams JD, Navarro-Mendoza M, McAllister DE, Deacon JE (1989) Fishes of North America endangered, threatened, or of concern: 1989. *Fisheries* 14(6): 2–20.
- Williams JS, Morgan DS, Hinkle SR (2007) *Questions and Answers about the Effects of Septic Systems on Water Quality in the La Pine Area, Oregon*. Fact Sheet 2007-3103. US Geological Survey, Portland, Oregon.
- Wilson A, Boehland J (2005) Small is beautiful: US house size, resource use, and the environment. *Journal of Industrial Ecology* 9(1-2): 277–287.
- Wing MG, Skaugset A (2002) Relationships of channel characteristics, land ownership, and land use patterns to large woody debris in western Oregon streams. *Canadian Journal of Fisheries and Aquatic Sciences* 59(5): 796–807.
- Wipfli MS, Richardson JS, Naiman RJ (2007) Ecological linkages between headwaters and downstream ecosystems: Transport of organic matter, invertebrates, and wood down headwater channels. *Journal of the American Water Resources Association* 43(1): 72–85.
- Wissmar RC, Smith JE, McIntosh BA, Li HW, Reeves GH, Sedell JR (1994) A history of resource use and disturbance in riverine basins of eastern Oregon and Washington (early 1800s-1990s). *Northwest Science* 68(Special Issue): 1–35.
- Witmer GW, Lewis JC (2001) Introduced wildlife of Oregon and Washington. Pages 423–443 In (eds Johnson DH, O'Neil TA) *Wildlife-Habitat Relationships in Oregon and Washington*. Oregon State University Press, Corvallis, Oregon.
- Wofford JEB, Gresswell RE, Banks MA (2005) Influence of barriers to movement on within-watershed genetic variation of coastal cutthroat trout. *Ecological Applications* 15(2): 628–637.
- Wohl E (2005) Compromised rivers: Understanding historical human impacts on rivers in the context of restoration. *Ecology and Society* 10(2): [article 2].
- Wolman MG, Schick AP (1967) Effects of construction on fluvial sediment, urban and suburban areas of Maryland. *Water Resources Research* 3(2): 451–464.
- Woltemade, CT (1994) Form and process: Fluvial geomorphology and flood-flow interaction, Grant River, Wisconsin. *Annals of the Association of American Geographers* 84(3): 462–479.
- Wolter C, Minow J, Vilcinskis A, Grosch UA (2000) Long-term effects of human influence on fish community structure and fisheries in Berlin waters: An urban water system. *Fisheries Management and Ecology* 7(1-2): 97–104.
- Woolsey S, Capelli F, Gonser T, Hoehn E, Hostmann M, Junker B, Paetzold A, Roulier C, Schweizer S, Tiegs S, Tockner K, Weber C, Peter A (2007) A strategy to assess river restoration success. *Freshwater Biology* 52(4): 752–769.
- Wright JF (1995) Development and use of a system for predicting macroinvertebrates in flowing waters. *Australian Journal of Ecology* 20(1): 181–197.
- Xiao Q, McPherson EG (2002) Rainfall interception by Santa Monica's municipal urban forest. *Urban Ecosystems* 6(4): 291–302.
- Yoder CO, Rankin ET (1995) Biological criteria program development and implementation in Ohio. Pages 109–144 In (eds Davis WS, Simon TP) *Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making*. Lewis Publishers, Boca Raton, Florida.
- Zaroban DW, Mulvey MP, Maret TR, Hughes RM, Merritt GD (1999) Classification of species attributes for Pacific Northwest fishes. *Northwest Science* 73(2): 81–93.

- Zedler JB, Kercher S (2004) Causes and consequences of invasive plants in wetlands: Opportunities, opportunists, and outcomes. *Critical Reviews in Plant Sciences* 23(5): 431–452.
- Zheng J, Nanbakhsh H, Scholz M (2006) Case study: Design and operation of sustainable urban infiltration ponds treating storm runoff. *Journal of Urban Planning and Development* 132(1): 36–41.
- Zhu W, Dillard ND, Grimm NB (2004) Urban nitrogen biogeochemistry: Status and processes in green retention basins. *Biogeochemistry* 71(2): 177–196.
- Zimmer CA, Heathcote IW, Whiteley HR, Schroeter H (2007) Low-impact-development practices for stormwater: Implications for urban hydrology. *Canadian Water Resources Journal* 32(3): 193–212.

Appendix A. Indices of Biological Integrity

Biological integrity is defined as “the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a composition and diversity comparable to that of the natural habitats of the region” (Frey 1975). In other words, assemblages have integrity if they resemble those at natural or minimally disturbed reference sites (Hughes *et al.* 1986; Hughes 1995; Stoddard *et al.* 2006, 2008). The simplest index is based on the percent of individuals in a collection represented by Ephemeroptera, Plecoptera, and Trichoptera (EPT; Lenat & Penrose 1996), which are aquatic insect orders generally considered sensitive to pollution. Another commonly used index, the Hilsenhoff Biotic Index (HBI; Hilsenhoff 1982) represents the relative tolerances to organic pollution by all individuals sampled. Increasingly, an index of biotic integrity is used (IBI; Plafkin *et al.* 1989; Kerans & Karr 1994; Karr & Chu 1999; USEPA 2006c). Various IBIs and predictive models have been developed and tested to assess the condition of major aquatic assemblages (macroinvertebrates, algae, and fish). Predictive models of taxonomic richness are commonly used in the United Kingdom (Moss *et al.* 1987; Wright 1995; Bailey *et al.* 1998) and increasingly in the US (Hawkins *et al.* 2000; Paulsen *et al.* 2008). Recently, predictive IBI multi-metric models have been developed for fish (Oberdorff *et al.* 2002; Pont *et al.* 2006; 2009) and macroinvertebrates (Moya *et al.* 2007).

The IBI has been widely used and modified since 1981, including applications to fish (Karr *et al.* 1986; Simon & Lyons 1995; Miller *et al.* 1988; Hughes & Oberdorff 1999; Roset *et al.* 2007), macroinvertebrates (Kerans & Karr 1994; Klemm *et al.* 2003), algae (Hill *et al.* 2000, 2003; Fore 2003), and riparian birds (Bryce *et al.* 2002; Bryce 2006). Others have proposed using the IBI format to create a terrestrial index of ecological integrity (Andreasen *et al.* 2001). IBIs integrate multiple key aspects of assemblage ecology into a single number, and the metrics respond not only to water quality degradation but also to changes in physical habitat, flow regime, migration barriers, and energy source (Karr & Chu 1999). The USEPA and several states (e.g., Ohio, Utah, California, Maryland, Texas, Iowa, Florida, Kentucky) use IBIs to assess status and trends of surface waters at local and regional or statewide scales. The European Union and the USEPA use them for continental scale assessments (Pont *et al.* 2006; Paulsen *et al.* 2008).

Macroinvertebrate and fish IBIs vary regionally and by user. Macroinvertebrate IBIs typically combine measurements of total taxa richness, richness of major taxonomic groups, dominance by one to three taxa, and percent of individuals in various tolerance and trophic or feeding guilds (Plafkin *et al.* 1989; Kerans & Karr 1994; Karr & Chu 1999; USEPA 2006c; Stoddard *et al.* 2008). Fish IBIs typically include metrics for total taxa richness, richness of major taxonomic groups, abundance, anomalies, non-native species, and various tolerance, habitat, trophic, reproductive, and life history guilds (Simon & Lyons 1995; Hughes & Oberdorff 1999; Roset *et al.* 2007; Whittier *et al.* 2007b). IBIs are widely used for assessing fish assemblage condition in cool and coldwater streams and rivers (Leonard & Orth 1986; Hughes & Gammon 1987; Lyons *et al.* 1996; Moyle & Randle 1998; Mundahl & Simon 1999; McCormick *et al.* 2001; Mebane *et al.* 2003; Hughes *et al.* 2004; Whittier *et al.* 2007b; Meador *et al.* 2008; Matzen & Berge 2008; Pont *et al.* 2009). Salmonids are key indicators of the condition of coldwater fish assemblages because they are sensitive to a number of stressors. Salmon tend to be more sensitive to most stressors than all resident salmonids with the exception of bull trout, which require very cold water and complex, connected, habitat structure (Zaroban *et al.* 1999; Whittier *et al.* 2007a). However, salmonid populations can exhibit high spatial and temporal variability in abundance,

even in minimally disturbed sites. As a result, entire fish assemblages are often assessed in addition to salmonid populations.