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The State of the Salish Sea

Kathryn L. Sobocinski
Western Washington University

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state of the SALISH SEA

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KATHRYN L. SOBOCINSKI

STATE OF THE SALISH SEA

EXECUTIVE SUMMARY

The Salish Sea is a biologically diverse inland international sea that is surrounded by mountainous watersheds of spectacular beauty. For more than 10,000 years, Indigenous peoples have lived along the shores of and cared for the Salish Sea. Today, the region is home to almost nine million people, and that number is rapidly growing.

Our expanding human footprint brings with it urbanization and ensuing impacts on the seascape as ports become busier, underwater habitats become noisier, natural shorelines give way to hardened infrastructure, and watersheds are converted from native forests to housing developments, industrial parks, and other impervious surfaces. At the same time, global climate change is producing profound impacts on the Salish Sea, as sea level rise threatens low lying areas and as ocean acidification and other changes threaten the intricacies of marine life.

In short, the Salish Sea is under relentless pressure from an accelerating convergence of global and local environmental stressors and the cumulative impacts of 150 years of development and alteration of our watersheds and seascape. Some of these impacts are well understood but many remain unknown or are difficult to predict.

In the years and generations ahead, restoring the Salish Sea and supporting its resilience are both possible—and urgently necessary. As detailed in this report, many stakeholders and programs offer hope in how to lead the way, but an integrated, transboundary ecosystem approach is needed, supported by collaboration across borders, governments, disciplines, and sectors.

> **The Salish Sea is compromised by the cumulative impacts of global climate change, regional urbanization and a growing population, and intensive human use and abuse across the ecosystem over the last two centuries.**
>
> Dr. Kathryn Sobocinski,
> *State of the Salish Sea Report*

The Salish Sea is a dynamic and productive estuary ecosystem.

The Salish Sea is a complex waterbody defined by freshwater and marine water that mix in two primary basins (Puget Sound and Strait of Georgia) and numerous subbasins carved by glacial history. These basins are strongly influenced by their surrounding watersheds, especially the Fraser River. The Salish Sea is also tightly connected to the biophysical dynamics of the Pacific Ocean. Freshwater input gives the Salish Sea its status as an estuary and the immense volume of freshwater from the Fraser River is what drives the physical oceanography of the Salish Sea. Briefly stated, as the relatively warmer, less dense freshwater flows out from the Fraser River onto the surface layers of the Salish Sea, the colder and relatively dense saltwater from the Pacific Ocean is drawn in, creating an oceanographic process known as exchange flow. This large-scale exchange flow in turn drives the fundamental circulation in the Salish Sea.

Similar in function to the circulatory system within our own human bodies, understanding how water within the Salish Sea circulates is important because it distributes the nutrients, oxygen, and other essentials that fuel primary productivity and a very diverse food web. That natural fuel and productivity sustain numerous inter-connected habitats, like eelgrass beds, kelp forests, and sponge and oyster reefs, each of which are described in this report. Those biogenic habitats in turn provide structure and shelter for multitudes of other organisms, including many of importance to humans. Meanwhile, circulation mitigates local impacts of some human harms, such as contaminants, eutrophication, and low dissolved oxygen by continually moving water throughout the system. As climate change disrupts this strong, longstanding, and predictable circulation by altering, for example, the timing and volume of freshwater inputs, the ramifications to the Salish Sea estuarine ecosystem are potentially significant.

"Here in our waters in Puget Sound and into the Salish Sea, we're caught a bit in a vice grip. One arm is rapid climate change—our waters are warming and they're becoming more acidified. At the same time, we're piling on human population. Those two factors act synergistically, and both put a lot of stress on our marine ecosystem."

Dr. Drew Harvell,
Professor of Marine Ecology
at Cornell University and affiliate faculty
at the University of Washington
School of Aquatic and Fishery Sciences

English Bay, Vancouver BC, with Mount Baker
Photo: Kimon Berlin

Local urbanization and global climate change are converging on the Salish Sea with profound impact.

Human impacts are multifaceted and extensive within the Salish Sea. Population growth drives urbanization and development, which in turn triggers structural changes to the landscape and seascape like habitat fragmentation, shoreline armoring, conversion of vegetated areas to impervious surfaces, and profound changes in watershed and wetland hydrology. These gradual but damaging trends also increase nutrient and contaminant loading to the estuarine waters and limit the scope and scale of local fisheries.

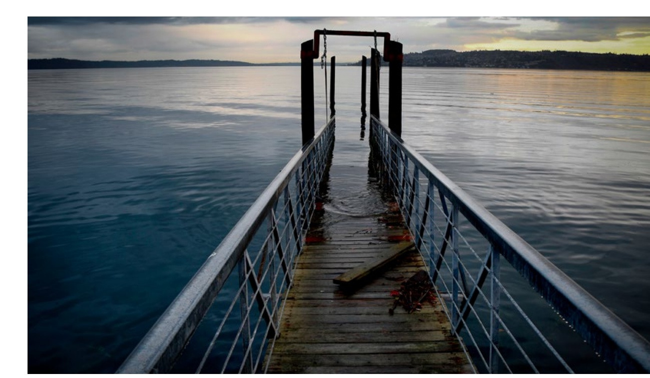
While the causes of climate change are global and primarily from greenhouse gas emissions, impacts of climate change manifest locally and are already becoming physically and biologically evident in the Salish Sea. As described in this report, that evidence includes documented, measurable warming of the atmosphere and oceans, changes in global and regional precipitation patterns, and rising mean sea level—all effects contributing to known changes within the Salish Sea ecosystem. Increased seawater temperatures and ocean acidification are currently stressing biota, and accelerating rates of both point to potentially significant ecosystem changes ahead.

Fortunately, scientists and managers continue to compile data and analyze trends that collectively help us better understand some of the predicted near-term effects of global climate change, aided by global- and regional-scale models. Regional accuracy of such models and their predictions is improving, but our understanding of how Salish Sea organisms, ecosystem processes, and interactions are affected by global climate change is less certain, especially looking ahead into the future. When the effects of global change in our oceans are combined with the increasing disruption from local urbanization, the Salish Sea estuarine ecosystem will continue to degrade. Forecasting and planning related to these changes is a challenge for the coming decades.

Cumulative effects impair systems and species.

Salmon and orcas are emblematic of the beauty of the Salish Sea and, along with numerous lesser-known species, signal to us that cumulative troubles are mounting in our ecosystem over time and space. Theory and observation suggest an eventual tipping point, and scientists and managers are rushing to understand if and how the Salish Sea has the capacity to recover from short-term disruptions alongside ongoing chronic stress. Much more work is needed to unravel the repercussions of cumulative and relentless stress on the Salish Sea ecosystem, including its resident salmon, orcas, and hundreds of other aquatic species.

Orcas provide a case study for how one species is faring under the cumulative effects of human activities. The Southern Resident population—salmon eating orcas found in the Salish Sea in the summer months—are challenged by at least three main threats: scarce food, contaminants, and marine noise. Chinook salmon are their primary food source and also the species most in decline throughout the region. Contaminants in the fish they eat are taken up and stored in their bodies impeding their ability to reproduce and fight disease. Orcas are also increasingly forced to hunt in a fog of noise, which can affect their ability to capture the food they need to successfully reproduce. As a top predator, orcas rely on a functional ecosystem—at all levels—for survival, but face an increasingly inhospitable habitat.



Water level above a dock during Tacoma King Tide
Photo: Ryan Dicks via MyCoast

OPPORTUNITIES FOR IMPROVING ASSESSMENT AND UNDERSTANDING OF THE SALISH SEA: OVERVIEW

BUILD HABITS AND SUPPORT FOR COLLABORATING ACROSS DISCIPLINES AND BORDER

Establish a Salish Sea Science Panel

Convene scientists from Indigenous Nations, Washington, and British Columbia to re-prioritize formal collaboration and develop large-scale actionable science needs, priorities, and methods. Maintaining the strength and priority of science in the Salish Sea is essential for identifying emerging concerns and creating actionable solutions.

Advance Data Collection and Monitoring Using Novel Tools

Leverage creative partnerships and new technologies to collect data over long time periods and larger spatial scales to better understand changes from climate change and local human impacts.

Use Models as Integrative Tools

Ongoing modeling work throughout the Salish Sea is bringing together data, computing power, and technical expertise to better understand oceanographic and ecosystem processes. Modeling tools should incorporate the multiple simultaneous and cumulative impacts on the Salish Sea from climate change, urbanization, and more. To become truly powerful and integrative, models must incorporate the transboundary, social-ecological system at multiple levels of spatial and temporal complexity.

Create a Transboundary Salish Sea Data and Information Repository

Develop strategies for integrated data management, including efforts to harmonize data across the border and across disciplines, jurisdictions, and agencies. Long-term collection and curation of Salish Sea-wide data, information, and stories will support shared efforts toward transboundary science, policy, and education.

EMBRACE MULTIPLE WAYS OF KNOWING AND CONNECTING TO THE SALISH SEA

Apply Social-Ecological Systems Science

Invest in initiatives that address human well-being and cultivate a strong sense-of-place within Salish Sea communities. Understanding the complex relationships between people and their environment can stimulate wise management decisions and development actions for ecosystem restoration and protection, as well as economic sustainability.

Recognize Indigenous Knowledge Systems

Recognize traditional ecological knowledge in assessing, managing, and restoring the state of the Salish Sea and its ecosystem functions. Through co-management, creating ethical space for collaboration, and working together as equal partners, we can better ensure the future health and wellness of the Salish Sea.

Build Knowledge, Relationships, and Connection through Place-Based Learning

Invest in more intentional Salish Sea-wide place-based education, including support for Indigenous communities to build capacity for ecological and cultural restoration. Education initiatives can increase appreciation of the Salish Sea, creating stronger ties with the lands and waters around us.

STRENGTHEN THE SCIENCE-TO-MANAGEMENT BRIDGE

Enable Practitioners to Bridge Science and Community Investment

The Salish Sea benefits from many local- and regional-scale organizations that operate at the interface of science and practice, bringing additional participants into actionable science. Foster community science initiatives by promoting local involvement in data collection, restoration, and priority-setting to elevate calls to action within the Salish Sea.

Use Adaptive Management Tools to Strengthen Planning

Use adaptive management strategies to address cumulative impacts associated with climate change and human development in the Salish Sea. The iterative nature of adaptive management allows for simultaneously confronting complexity and uncertainty while also being proactive and responsive at local and regional scales.

Build Sustained and Regenerative Ecosystem Functions to Improve Resilience

Build resilience, especially at the land-sea ecotone where human infrastructure will exacerbate problems associated with rising sea level. Positive, protective, restorative, and regenerative actions are increasingly necessary as the population grows and threats from climate change alter ecosystem processes.

Ecosystem decline has outpaced restoration and protection. Structural changes are needed to be truly effective in supporting a thriving ecosystem.

Over time, government agencies and others around the Salish Sea have implemented numerous management programs, policies, and regulations to protect the ecosystem. Transboundary governance agreements have been signed and initiatives launched. Yet, as the 2010 Coast Salish Gathering Treatise asks, "Would the Salish Sea be in the state [it's] in if, in fact, these agreements were doing what they intended to do?" Indeed, layers of laws, treaties, regulations, and jurisdictions make for a complicated and even fragmented approach to Salish Sea governance, exacerbating challenges from global climate change to local lack of enforcement and funding. The cost of business as usual is high, especially as we anticipate further declines and unknown repercussions for the region.

Righting the course to a more functional and sustainable Salish Sea requires a strong scientific foundation. It also requires a renewed and clear commitment to strategic planning, systemic changes in governance, large-scale investment, and significant shifts in our economic systems, collective values, and changing relationships to our lands and waters. Now is the time to shift thought and policy paradigms from treating the environment as a resource to instead build systems of relationships and responsiveness that are based in science and incorporate the interconnected system of humans and environments. As illustrated by several encouraging examples in this report from all around the region, we know that much can be achieved through well-coordinated restoration, mitigation, and protection measures.

Looking ahead, there is hope through more action and ecosystem-scale collaboration.

Not since The Shared Waters Report in 1994 has there been a holistic assessment of the Salish Sea as an integrated ecosystem. More than 25 years later, a fresh snapshot is timely—and necessary. The regional population has grown by over two million people since the publication of The Shared Waters Report, and new threats are recognized in the form of climate change, warming waters, sea level rise, ocean acidification, microplastics, and more. Perhaps of greatest concern is the cumulative impacts of these persisting, continuing, and emerging threats intersecting within the seascape during more than 150 years of anthropogenic change.

The State of the Salish Sea Report

With the help of dozens of contributors from around the region, this report is an effort to synthesize and characterize the most pervasive problems and state of the ecosystem. For the benefit of all readers, irrespective of current role or interest in the Salish Sea, we end the report with a spectrum of specific needs and associated opportunities for how governments, organizations, and individuals can work together to meet the needs of science and science-driven management for the Salish Sea — as well as questions to open substantive dialogue and prompt collective action across the seascape.

The science presented herein is intended to inform, illuminate, and ultimately ignite deep discussion and meaningful action, from grassroots efforts to large-scale collective and governmental investments. Addressing centuries of degradation, swelling human population, and global climate change requires vision and solutions for the future that are innovative, adapt easily to local needs, and spark change in our collective values and relationships with the Salish Sea.

Regeneration of the Salish Sea will require multi-faceted and collaborative approaches that support greater understanding through education and science, plus sufficient political will, public support, and systemic changes. Fundamental alteration of human–environment relationships, coupled with new and ambitious goals, are needed to change the arc of anthropogenic impacts.

We ask readers to consider your roles, responsibilities, and opportunities for caring for our shared waters in the days, years, and generations ahead. Will we choose to work together to make these commitments and investments toward a future of resilience and connection across the Salish Sea?

An aerial look at the Nooksack River delta looking out to the Strait of Juan de Fuca. Photo: Frank James, M.D.

PREFACE

Western Washington University created the Salish Sea Institute to raise awareness and protection for the Salish Sea. We are situated on the lands and waters of the Lummi Nation and Nooksack Tribe, and near the US-Canada border that cuts across Indigenous territories. At the Institute, we work to share knowledge across the border and across the disciplines to care for the future of the Salish Sea. This report is one of many ways we are expressing this mission. We are committed to learning from 10,000 years of knowing as we look ahead to the future.

People and Contributors

Salish Sea Institute

Ginny Broadhurst, Director
Natalie J.K. Baloy, Associate Director

Lead Author

Kathryn L. Sobocinski is an Assistant Professor in the Department of Environmental Sciences and the Marine and Coastal Science program at Western Washington University. She is an applied marine ecologist focusing on fishes, fish habitats, and impacts of human disturbance and climate change in coastal ecosystems. She holds a BA in Environmental Studies from Connecticut College, MS in Aquatic and Fishery Sciences from the University of Washington, and PhD in Marine Science from the Virginia Institute of Marine Science/College of William & Mary. She completed post-doctoral work at Oregon State University and NOAA-NWFSC prior to joining the WWU faculty. She resides in Bellingham, WA.

Contributors

- Jeff Adams, Washington Sea Grant
- Jude Apple, Padilla Bay National Estuarine Research Reserve
- Will Atlas, Wild Salmon Center
- Ashley Bagley, Long Live the Kings
- Natalie Ban, University of Victoria
- Jennifer Boldt, Fisheries and Oceans Canada
- Nicholas Bond, Cooperative Institute for Climate, Ocean and Ecosystem Studies, University of Washington
- Rob Butler, Pacific Wildlife Foundation
- Katherine Butts, Lax Kw'alaams Fisheries
- Jackson W.F. Chu, University of Victoria
- Jaclyn Cleary, Fisheries and Oceans Canada
- Katrina Connors, Pacific Salmon Foundation
- Sarah Dal Santo, Tsleil-Waututh Nation's Treaty Lands and Resources Department
- Morgan Eisenlord, Department of Ecology and Evolutionary Biology, Cornell University
- Roger Fuller, Padilla Bay National Estuarine Research Reserve
- Olivia Graham, Department of Ecology and Evolutionary Biology, Cornell University
- Emily Grason, Washington Sea Grant
- Larry Greba, Kitasoo/Xai'xais First Nations
- Correigh Greene, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration
- Spencer Greening, Simon Fraser University and Gitga'at First Nation
- Lucas Hart, Northwest Straits Commission
- Drew Harvell, Department of Ecology and Evolutionary Biology, Cornell University
- Jess Housty, QQs Projects Society
- William Housty, Heiltsuk Integrated Resource Management Department
- Emily Howe, The Nature Conservancy
- Laura Kehoe, Oxford University and The Nature Conservancy
- Iris Kemp, Long Live the Kings
- Tarang Khangaonkar, Salish Sea Modeling Center, University of Washington, Tacoma, and Pacific Northwest Laboratory
- Olivia Klein, Salish Sea Institute 2020-2021 Intern
- Donna Macintyre, Lake Babine Nation Fisheries
- Lynda Mapes, Seattle Times
- Tara Martin, University of British Columbia
- P. Sean McDonald, University of Washington
- Johnathan Moore, Simon Fraser University
- Jason Morgan, Northwest Straits Foundation
- Nicole Morven, Nisga'a Nation
- Stuart H. Munsch, Ocean Associates, Inc., under contract to National Oceanic and Atmospheric Administration Northwest Fisheries Science Center
- Lindsey Ogston, Tsleil-Waututh Nation's Treaty Lands and Resources Department
- Betsy Peabody, Puget Sound Restoration Fund
- Isobel Pearsall, The Pacific Salmon Foundation
- Ian Perry, Emeritus, Pacific Biological Station, Fisheries and Oceans Canada
- Allen Pleus, Washington Department of Fish and Wildlife
- Anuradha Rao, Tsleil-Waututh Nation's Treaty Lands and Resources Department
- Andrea Reid, University of British Columbia & Nisga'a Nation
- Brian Riddell, The Pacific Salmon Foundation
- Todd Sandell, Washington Department of Fish and Wildlife
- Michael Schmidt, Long Live the Kings
- Christina Service, Kitasoo/Xai'xais First Nations
- Alexandra Simpson, Northwest Straits Commission
- Matthew Sloat, Wild Salmon Center
- Elissa Sweeney-Bergen, Lake Babine Nation Fisheries
- Spencer Taft, Tsleil-Waututh Nation's Treaty Lands and Resources Department
- Ronald Thom, Staff Scientist Emeritus, Marine and Coastal Research Laboratory, Pacific Northwest National Laboratory
- Carleen Thomas, Tsleil-Waututh Nation's Treaty Lands and Resources Department
- Jason Toft, University of Washington
- Jodie Toft, Puget Sound Restoration Fund
- David J. Trimbach, Oregon State University
- Adrian Tuohy, Wild Fish Conservancy
- Bert Webber, Senior Fellow, Salish Sea Institute
- Elroy White, Central Coast Archaeology
- Northwest Indian Fisheries Commission

State of the Salish Sea Report Advisory Committee
- Jenny Ferone, Environment and Climate Change Canada
- Joe Gaydos, SeaDoc Society
- Ian Perry, Emeritus Scientist, Fisheries and Oceans Canada
- Scott Redman, Puget Sound Partnership
- Brian Riddell, Emeritus, Pacific Salmon Foundation
- Michael Rylko, US Environmental Protection Agency
- Ronald Thom, Staff Scientist Emeritus, Marine and Coastal Research Laboratory, Pacific Northwest National Laboratory
- Bert Webber, Senior Fellow, Salish Sea Institute

Section Reviewers: Jackson Chu, Lisa Crozier, Cristiana Figueroa-Kaminski, Tom Good, Correigh Greene, Isaac Kaplan, Terrie Klinger, Michele Koehler, Brooke Love, Parker MacCready, Ian Miller, Teizeen Mohamedali, Hem Morzaria-Luna, Ian Perry, Emily Roland, Michael Schmidt, Gus Seixas, Ruth Sofield, Fran Wilshusen

Other Contributors: Sarah Bartnik, Environment and Climate Change Canada; BC Information Sharing Workshop attendees: Nadine Parker, Elly Chmelnitsky, Jenifer Boldt, Anya Dunham, and Ian Perry (Fisheries and Oceans Canada), Carrie Baron (City of Surrey), Jenny Ferone (Environment and Climate Change Canada); Eliza Ghitis and members of the Northwest Indian Fisheries Commission Climate Change Workgroup; and Kat Middleton (Fisheries and Oceans Canada).

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Cartographer and Spatial Analyst: Aquila Flower, Western Washington University

Technical Editors: Steven Perry and MacKenna Perry, Clarity Scientific

Layout and Design: Nick Pinkham and Fabrice Tchékou, Western Washington University

Peer Reviewers: Megan Dethier (University of Washington, Friday Harbor Laboratory), Sylvia Yang (Padilla Bay National Estuary Research Reserve), Peter Arcese (University of British Columbia), Cheyenne Arnold-Cunningham (Union of BC Indian Chiefs), Cecilia Wong (Environment and Climate Change Canada), and Patricia Rojas (British Columbia Assembly of First Nations).

Western Washington University Student Assistants: Lileigh Thomas (References and Bibliography), Taylor Bayly, Caitlyn Blair, and Olivia Klein

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We are extremely grateful.

About the State of the Salish Sea Report

The focus of this report is the Salish Sea estuarine ecosystem and the past, current, and emerging stressors within. While the Salish Sea watershed includes the estuarine waters and connected watersheds landward to mountain ridges, we focus this current effort on the estuarine waters and adjacent shorelines, tidal wetlands, and deltas, recognizing that freshwater input from surrounding landscapes influences estuarine ecosystem function. The lead author and contributors examine the most pervasive and damaging impacts affecting the transboundary ecosystem, recognizing that some are generated locally while others are the locally realized impacts from global-scale changes in climate, oceans, land use, and biodiversity.

The intended report audience is defined broadly as the typical participants in the Salish Sea Ecosystem Conference, a regional, biennial exchange of information related to the Salish Sea. The participants include educators, managers, scientists, practitioners, students, and interested community members. The report contains ample citations so interested parties can embark on further exploration of a topic, but it is written in a tone less technical than a scientific paper to be accessible to non-specialists. The value of a regional conference with a broad audience like the Salish Sea Ecosystem Conference is that presentations and discussions are shared by participants from multiple sectors, all of whom value the Salish Sea ecosystem. We intend for this report to attract a similar readership.

The scope of the report is purposefully focused on two pervasive drivers of ecosystem change–urbanization and climate change. This report aims to provide an overall biophysical assessment of the Salish Sea at this point in time (circa 2020/2021). Recent data (2010-2021) were incorporated where possible, especially for newer and rapidly changing topics like climate change. Chronic impacts are supported with primary literature stemming from earlier time periods (1990s-2000s or prior). This report does not attempt to provide an exhaustive compilation of all ecosystem components and threats, nor does it present new data. It is instead a synthesis of existing works.

The Institute staff, lead author, and Advisory Committee acknowledge that a degraded ecosystem has significant impacts to human well-being and economic growth (WHO 2015), and anthropogenic development and economic growth have significant impacts on the Salish Sea ecosystem. Suggestions provided in the final section are intended to continue a discourse about ecosystem science and the science-management interface that has flagged in recent years, but is deeply needed to prevent further decline and restore function to impaired areas.

Process

The initial stages of the State of the Salish Sea report development involved scoping meetings with the report Advisory Committee at Western Washington University beginning in the Spring of 2019. Through a series of five meetings, the lead author (K. Sobocinski) and Salish Sea Institute Director (G. Broadhurst) and Associate Director (N. Baloy) provided vision for the report and facilitated discussions related to history, scope, topic areas, audience, and approach. Advisory Committee members provided input on draft outlines, identified topics of pressing concern, and drafted report objectives to guide the development and scope.

The objectives agreed upon by the report Advisory Committee with regard to scope and content are:

- Provide a credible assessment of the ecosystem structure and processes of the estuarine waters of the Salish Sea for the populations that rely upon it for aesthetic, subsistence, and recreational value.
- Highlight two key and overarching threats to ecosystem function—population growth/urbanization and climate change—and identify the key socio-ecological variables impacted by these threats.
- Identify information gaps and emerging concerns.
- Highlight the types of actions that can be taken to change the course toward restoration and recovery where ecosystem processes are negatively impacted by current and future threats.

The lead author was responsible for content creation and report vision and scope. Contributions from vignette authors were solicited to add perspective, diversity of voice, and expertise to certain topical areas. The vignette authors were provided guidance related to the scope of the report and the focal impacts to the Salish Sea, but tone and content were at their discretion. Technical experts volunteered reviews of sections with which they had expertise. Salish Sea Institute staff and the Advisory Committee reviewed drafts and provided further guidance based upon understanding, professional networks, and expertise in the region. Peer reviewers provided substantive comments on content and scope. The technical editors brought a unified structure that improved overall flow and construction. The Western Washington University student team was dedicated to, among other contributions, referencing and building a considerable bibliography to accompany the report, plus visual design to build a report that was accessible and arranged to be understandable and aesthetically pleasing. This report was developed as a result of a private and anonymous philanthropic gift.

Throughout the report, primary literature is cited in support of ideas and concepts to provide references for further reading. Where agency or program reports are available, we have cited these as appropriate. In recognition that not all topics are best covered in peer-reviewed literature or formal reports, we have cited websites related to projects or organizations about relevant topics.

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INTRODUCTION

Curious Steller sea lions off of Denman Island, BC
Photo: Yuri Choufour

The Salish Sea is a biologically diverse inland sea that spans the international border, is surrounded by mountainous watersheds of spectacular beauty, and features a rich cultural history (Benedict & Gaydos 2015). For over 10,000 years, Indigenous peoples have lived on their traditional territories on the Pacific Northwest Coast (Lindo et al. 2017), including the shores and rivers of the Salish Sea (Ritchie et al. 2016). Today, the region is home to almost nine million people, and that number is rapidly growing.

This human footprint brings with it stressors that threaten the health and resilience of the Salish Sea ecosystem and surrounding bioregion through a complex array of legacy, continuing, and emerging impacts associated with industrialization and urbanization. Compounding those local impacts is the rapid pace of global-scale change in climate. This global threat is already having local impacts on watershed hydrology and marine biophysical processes, impacts that collectively manifest as cumulative effects in the Salish Sea.

In short, the Salish Sea is under relentless stress from an accelerating convergence of global and local environmental stressors, some of which are well understood, and many that remain unknown and/or difficult to predict. Therein lies a core purpose of this report: assemble a compendium of information and lines of evidence that describe the dominant stressors and current state of the Salish Sea. Not since **The Shared Waters Report** (Copping et al. 1994) has there been a holistic assessment of the Salish Sea as an integrated international ecosystem. More than 25 years later, a fresh snapshot is timely—and necessary—because the local population has grown by over two million people since then and new threats are recognized in the form of climate change, sea level rise, ocean acidification, microplastics, and more.

Current efforts to study, monitor, and protect the Salish Sea are encouraging, but with continued impacts, additional efforts are needed to understand a changing ecosystem, to restore lost function, and to strengthen the long-term resilience of the ecosystem. To that end, a list of opportunities for collaboration and decisive action in the coming years is provided (see Sections 6 and 7) as an invitation for residents, researchers, organizations, and governments to take action so that a similar report written in another 25 years will look back favorably on actions taken to sustain the Salish Sea.

The Salish Sea

Stretching from the Pacific Ocean to the Strait of Georgia and Puget Sound, the combined marine and estuarine waters of the Salish Sea span an impressive 17,803 km^2 (6,874 mi^2; Flower 2020). Feeding those waters is an extensive network of rivers and contributing watersheds reaching up thousands of meters to prominent peaks in the Coast, Cascade, and Olympic ranges. Cartographers have designated the Salish Sea's primary features and boundaries, describing it as an international estuarine ecosystem composed of an intricate network of inland marine waterways (Flower 2020). When combined into one cross-border biogeographic unit, the international waters of the Salish Sea and its surrounding watersheds are considered a distinct and contiguous bioregion (Figure 1.1; Spalding et al. 2007) that encompasses 102,727 km^2 (39,663 mi^2) and over 320,000 km^2 (124,000 mi^2) when the upper Fraser River basin is included (Flower 2020; A. Flower, Western Washington University, personal communication).

The western boundary of the Salish Sea is defined as the entrance to the Strait of Juan de Fuca (along a line between Cape Flattery and Carmanah Point), the southern boundary extends to the southern ends of Puget Sound and Hood Canal, and the northern boundary is just beyond the Strait of Georgia and includes channels and waterways such as Discovery Passage, Sutil Channel, and Desolation Sound (BC Geographical Names Office n.d.).

The dominant characteristics that distinguish the inland estuarine waters of the Salish Sea from the adjoining Pacific Ocean are differences in freshwater inputs, sediment composition, upwelling, currents, and bathymetric and coastal complexity. Another distinction, as made clear in this report, is that human impacts are multifaceted and extensive within the Salish Sea. The biophysical interactions within the Salish Sea defy geopolitical boundaries as marine water, nutrients, and organisms circulate in the estuary with inflows of freshwater and sediments from the uplands. These biophysical features interact with human impacts, like shoreline armoring and contaminants. Many past and ongoing studies within Washington and British Columbia subbasins are unlocking the complexity of these interactions, but more work is needed—both science and regulatory action—at the cross-

The Shared Waters

In 1992, British Columbia Premier Mike Harcourt and Washington State Governor Booth Gardner established the first Environmental Cooperation Agreement between British Columbia and Washington. This agreement created an important platform for years of collaborative work including the establishment of the British Columbia-Washington Environmental Cooperation Council and an international Marine Science Panel. The Science Panel issued a report in 1994, called *The Shared Waters of British Columbia and Washington: A Scientific Assessment of Current Status and Future Trends in Resource Abundance and Environmental Quality in the Strait of Juan de Fuca, Strait of Georgia and Puget Sound* (Copping et al. 1994; referenced hereafter as *The Shared Waters Report*). There is an excellent summary of the history of the agreement and associated work in that report.

The Shared Waters Report was geographically comprehensive, looking at what we now call the Salish Sea, and considered scientific questions posed by the international Science Panel. Those questions included an analysis of threats and recommendations of indicators for state-of-the-environment reporting for the transboundary marine ecosystem. Ecosystem conditions were on the decline, and it was timely that British Columbia and Washington shared information about common threats and shared strategies for common solutions.

Since *The Shared Waters Report* was published, numerous programs and initiatives have sprung up aimed at gauging aspects of the Salish Sea ecosystem, from watersheds to salmon. In fact, there are a multitude of reports available that are pertinent to the ecological health of specific waterbodies, such as Howe Sound, Puget Sound, or the Strait of Georgia, and smaller units, such as individual watersheds or inlets. However, no single resource addresses the ecoregion as a whole and the ecosystem attributes and stressors to those attributes that threaten sustainability. This report serves as an update to *The Shared Waters Report*, providing a status assessment highlighting progress, uncertainties, continued problems, and identifying opportunities.

border ecosystem scale to more fully understand and protect the Salish Sea.

The toponym "Salish Sea" emerged within research organizations and through political efforts across the region to recognize and cultivate a bioregional scale connection in ways that decenter the United States-Canada border and reorient residents, scientists, and policymakers to our shared waters and shared responsibility for stewardship. The name is officially recognized by the Coast Salish Gathering, an annual convening of Tribal and First Nations leaders and non-Indigenous governing officials on environmental issues in the Salish Sea ecosystem. The geographic naming boards in Washington State and British Columbia, and both the United States and Canadian federal governments also recognize the name.

The name recognizes the Coast and Straits Salish peoples who have continuously inhabited the region **since time immemorial**, including more than 65 sovereign Tribes and First Nations throughout the region today. Tribes and First Nations across the Salish Sea hold inherent title and rights—and in some parts of the Salish Sea treaty rights—including the right to traditional governance of their lands, waters, and resources. The recognition of these rights is emphasized in international law (United Nations' Declaration on the Rights Indigenous Peoples, see for example, Article 25, 26, and 32). In Canada, title and rights are recognized and protected (Section 35 of Canada's *Constitution Act*, 1982) and have been affirmed by the Supreme Court of Canada (for example, *R. v. Sparrow, R. v. Gladstone, and Delgamuukw v. British Columbia*). British Columbia's *Declaration on the Rights of Indigenous Peoples Act* recognizes the need to respect and promote inherent rights of Indigenous peoples while emphasizing the importance of facilitating Indigenous self-determination and self-governance in varying contexts. In the US, rights have been affirmed and recognized through historic treaties, Supreme Court rulings like *US v. Washington* ("the Boldt Decision"), and government-to-government relationships formalized through agreements like the Centennial Accord.

Indigenous communities cultivated and continue to maintain relationships of reciprocity with the Salish Sea and formally maintain active programs to protect their title and rights, including treaty rights, to create cultural and environmental resilience, and to build strategies to adapt to environmental change (Norman 2017). The Coast and Straits Salish peoples are distinct nations with distinct languages, place names, legal orders, traditional knowledge systems, and associated values, protocols and teachings that describe human-environment relationships and responsibilities across the Salish Sea seascape.

While we know that Indigenous peoples have inhabited the Salish Sea region for more than 10,000 years, exact settlement

Since Time Immemorial

Since Time Immemorial is a phrase in acknowledgement of Indigenous peoples' existence on the landscape and histories conveyed through origin stories and oral histories, without specifying dates of occupation. Since Time Immemorial acknowledges Indigenous peoples' existence and connection to their traditional territories and ancestral lands prior to settler arrival. Origin stories and oral histories record Coast and Straits Salish peoples' connection to the Salish Sea. Their inherent sovereignty has existed since time immemorial and continues to exist today.

Left : Figure 1.1. Map of the Salish Sea, major waterways, and surrounding watersheds, which when combined form a distinct transboundary bioregion. Source: Flower (2020) dates are unknown and likely varied by location. In contrast, European settlers first arrived relatively recently in the Salish Sea: in the 1770s on Spanish and British ships. Subsequent waves of crews and captains arrived in search of the Northwest Passage, otter pelts, gold, timber, and salmon. Between the 1840s to 1870s, settlers established what is currently called British Columbia in Canada and Washington in the United States, displacing Indigenous peoples and dispossessing them of their lands in the process. In this same era, settlers drew the land and marine borders between the United States and Canada and established the major cities of the region: Vancouver, Victoria, Seattle, Tacoma, and Olympia (Figure 1.3).

To put in perspective the numerous anthropogenic impacts described in this report, humans have been living in the region for thousands of years, yet the political borders and industrial-scale human settlements emerged in only the last 150 years. Likewise, on a larger scale, human migration and population growth have accelerated alongside a technology and fossil-fueled era of globalization, urbanization, and industrial growth, launching the planet into a new geologic epoch known as the Anthropocene (Zalasiewicz et al. 2011).

Physical evidence of the human footprint in the region includes the highway (I-5/Hwy 99) corridor between Vancouver, BC, and Olympia, WA, which features highly urbanized landscapes, hardened and industrialized shorelines, and geographically concentrated economic activity on land and sea. When combined with other major cities like Victoria, BC, Seattle, WA, and major ports in Tsawwassen, BC, and Tacoma, WA, the Salish Sea and its environs are urbanized from its central core to its southern extremities. The Sea's naturally deep waters and network of designated shipping channels have helped the region become a globally significant and highly trafficked hub for international transport of freight and fossil fuels, especially between the large ports of Vancouver and Seattle. While these economic centers are significant in their own right for driving local economies, population density and modern ways of life have meant growing dissociation from the environment globally (Turner et al. 2004) and results in less connection to the Salish Sea ecosystem locally.

Human well-being is an important aspect of any socio-ecological system, and emerging initiatives related to human-environment health (Galvani et al. 2016) are more explicitly drawing these connections. The Salish Sea has a rich social and cultural fabric rooted in the landscape, seascape, and Coast and Straits Salish traditions. Association with the ecosystem contributes to human well-being by fostering and maintaining connections to place, identity, and values, or by directly enabling cultural practices (Poe et al. 2016). In turn, these aspects affect how people interact with the ecosystem. The Salish Sea, like any ecosystem, can therefore hold different importance for different people based upon economic or ecological perspective and cultural or family traditions (Poe et al. 2016). The Salish Sea is a source of well-being for contemporary inhabitants of the region (Biedenwig 2017) through tourism, recreation, and its intrinsic value. Although economically important to the growing human population, the physical transformation and intensive use of the landscape and seascape are compromising social-ecological health today and weaken future resilience in the Salish Sea.

Figure 1.2. Salishan Languages in the Salish Sea region. Source: Brotherton (2008)

Figure 1.3. US Counties, Canadian Regional Districts, and major cities in the Salish Sea Bioregion.

Map by Aquila Flower, 2021

State of: Defining, Describing, and Measuring Ecosystem Health

Governments, interest groups, and environmental managers set "ecosystem health" as a priority in many ecosystems, yet there is little consensus over the definition of the term or how to assess properties of health (O'Brien et al. 2016). Generally, ecosystem health is thought of as an integrative concept combining aspects of the physical and biological properties of an ecosystem, and its persistence, sustainability, resilience, and human well-being (Rapport et al. 1998; Karr 1999; O'Brien et al. 2016; and table on page 11 for definitions of a healthy ecosystem). While this is a powerful concept, measuring the health of an ecosystem is problematic in its lack of specificity and accepted diagnostic measures. Furthermore, Indigenous climate science and legal systems may have different definitions and experiences of "ecosystem health."

Here we define the concept of *ecosystem health*, sometimes called ecosystem integrity, as the state or condition of an ecosystem that displays the characteristics of the historical ecosystem, such as species composition, community structure, and/or physical and chemical processes, and that is fully capable of sustaining normal ecosystem functioning. However, we also acknowledge that we have little functional understanding of the historical ecosystem prior to human perturbations or how early alterations may have skewed contemporary perceptions of "historical condition." In fact, ecosystems have always changed, more so with human use, and collective memory is typically short, resulting in "shifting baselines" (Pauly 1995; Lotze et al. 2006; Duarte et al. 2015; Little et al. 2017). Understanding the fundamental structures (e.g., biogenic habitats) and processes (e.g., estuarine circulation) of the ecosystem, and in turn, identifying indicators that provide evidence of change to these structures and processes vis-a-vis some baseline is key to describing the health of the Salish Sea.

Ecosystem health, or integrity, condition, or status, may be measured by indicators, such as those used for the Puget Sound Vital Signs (Puget Sound Partnership 2021) or the transboundary Health of the Salish Sea Report (US Environmental Protection Agency & Environment and Climate Change Canada 2021), much in the way a doctor would assess the health of a patient through measures of body temperature, blood pressure, and blood chemistry. However, the mechanistic understanding of ecosystem indicators lags behind those used in human medicine in many cases. And as with indicators of human health, ecosystem indicators may provide insight into general health but won't diagnose an illness or imbalance and may not be responsive to all conditions.

There are a number of existing programs designed to measure aspects of the Salish Sea ecosystem with the objective of detecting trends over time (Figure 1.4 for examples). However, no one program is extensive enough to adequately capture trends throughout the ecoregion due to spatial limitations, focus on selective, tractable metrics, or limited time-series (i.e., a collection of observations obtained through repeated measurements over time). Without time-series long enough to capture natural variability and observe emerging trends, the ability to detect change is limited.

When we consider the *State of the Salish Sea*, it is critical to evaluate the metrics we use to describe a state (i.e., a snapshot in time) or assess a *trend* (i.e., a general direction in which the ecosystem or a component of the ecosystem is changing over time). The integration of status and trends can provide a more complete assessment, but may still be limited by specific indicators failing to address the complexities of interactions or cumulative effects. Here, we do not provide a catalog of specific status and trends, but instead we provide a synthesis of current information on the dominant stressors that are contributing to ecosystem decline and illustrate numerous examples of ecosystem response to those impacts.

Many targeted studies addressing specific questions of research interest exist and are ongoing. These programs are an important component of Salish Sea ecosystem assessment and provide the mechanistic underpinnings connecting various aspects of Salish Sea oceanography and ecology, leading to greater understanding of ecosystem function. These studies, along with systematic monitoring, contribute to an understanding of function and aid in identifying causes of decline. There exists a tension between a perfectly designed monitoring program that can detect changes early and provide adequate information to scientists and decision-makers and the funding and human and data resources needed to support such a program. Developing the ability to detect—and more importantly, respond to—ecosystem change is a primary challenge for the region into the future.

Figure 1.4. Indicators of ecosystem status, health, and trends.
Three examples from programs with ecosystem assessment objectives.

US Environmental Protection Agency and Environment and Climate Change Canada

In 2000, the US Environmental Protection Agency and Environment and Climate Change Canada signed a Joint Statement of Cooperation to facilitate cross-border understanding, science dialogue, and collaboration on Salish Sea issues. From this partnership the Salish Sea Ecosystem Indicators project emerged, aiming to track progress in managing the Salish Sea ecosystem, and identifying priorities for action. The transboundary indicators range from air quality to Chinook salmon population abundance to swimming beach water quality—crossing a wide array of ecosystem components and mechanisms.

Puget Sound Partnership

Vital Signs gauge the health of Puget Sound and guide assessment of the progress made toward ecosystem recovery goals. Each Vital Sign represents a component of the ecosystem; each component is represented by one or more indicators. Vital Sign indicators are used to measure and report important, specific aspects of the Puget Sound ecology and human wellbeing, while targets associated with indicators are policy statements that define desired future outcomes. Indicator themes: Abundant Water, Healthy Water Quality, Healthy Human Population, Vibrant Human Quality of Life, Thriving Species and Food Web, Protected and Restored Habitat.

Ocean Wise Research Institute

The **Ocean Watch health ratings** (Critical, Caution, Healthy, and Limited Data/ Not Rated) provide a clear interpretative assessment. A trend indicator reflects on progress made (or not) since 2017. An upward arrow alongside the rating indicates positive actions have been taken, but the overall trend does not yet warrant an upward shift in rating. A downward arrow indicates a lack of actions although the overall trend does not warrant a downward shift in rating. A committee of researchers and community members was formed to assign the ratings.

What is a Healthy Ecosystem?

First Nations people have long recognized that the health of the environment and the health of the individual are intimately connected. From a First Nations holistic perspective, health includes the physical, mental, emotional, social and spiritual aspects. The environment plays a vital role with respect to all aspects of health. Understanding the linkages between the environment and the health of First Nations' peoples is crucial in order to enhance the protection of their health from exposure to future environmental hazards.

Assembly of First Nations (2021)

The causal links between environmental change and human health are complex because they are often indirect, displaced in space and time, and dependent on a number of modifying forces. Human health ultimately depends upon ecosystem products and services (e.g., availability of fresh water, food, and fuel sources) which are requisite for good human health and productive livelihoods. Ecosystem services are the benefits that people obtain from ecosystems. Ecosystem services are indispensable to the well-being of all people, everywhere in the world. They include provisioning, regulating, and cultural services that directly affect people, and supporting services needed to maintain the other services.

World Health Organization (2005)

An ecological system is healthy and free from "distress syndrome" if it is stable and sustainable—that is, if it is active and maintains its organization and autonomy over time and is resilient to stress.

Toward an Operational Definition of Ecosystem Health (Costanza 1992)

A healthy ecosystem is one that is intact in its physical, chemical, and biological components and their interrelationships, such that it is resilient to withstand change and stressors. It is a system that is not experiencing the abnormal growth or decline of native species, the concentration of persistent contaminants, or drastic anthropogenic changes to its landscape or ecological processes. If healthy ecosystems foster economic prosperity, unhealthy ones represent lost opportunity and income.

SeaDoc Society (2021)

Health is the physical, social, mental and cultural realms on individual, familial and community scales, including reciprocal relations between people, their natural environment, and nonhuman beings… The Indigenous Health Indicators (IHI) are a set of community-scale, non-physical aspects of health that are integral to Coast Salish health and wellbeing. The IHI reflect deep connections between humans, the local environment, and spirituality.

- talx̌cut: self determination: healing and restoration, development, trust
- x̌əčusadad: education: the teachings, elders, youth
- qʷiq̓cut: resilience: self-esteem, identity, sustainability
- yayusbid: cultural use: respect and stewardship, sense of place, practice
- sʔutix̌dxʷ ti swatixʷtəd: resource security: quality, access, safety
- ʔəshigʷd tə adʔiišəd: community connection, work, sharing, relations

Swinomish Climate Change Initiative (2021)

Roadmap to the Report

In the sections that follow, we illustrate the watershed and oceanographic processes that make the Salish Sea a unique ecosystem while highlighting impacts to ecosystem function that threaten ecosystem integrity and sustainability (i.e., ecosystem "health"). Overall, we focus on two persistent and continuing threats—urbanization and climate change—and demonstrate the associated impacts to select ecosystem structures and processes. For example, we refer to specific declines in abundance or reduction in area for species, sub-lethal impacts to biota, changes to ecosystem physical processes, and impacts to ecosystem services, which are those direct and indirect contributions of ecosystems to human well-being such as water filtration, carbon storage, and wave energy reduction that support human survival and quality of life (World Health Organization 2005).

Much of the science in the region is limited to a basin (e.g., Strait of Georgia) or subbasin (e.g., Hood Canal), driven by federal or municipal priorities and limitations on spending government funds at all levels within jurisdictions. Given strong science-to-management linkages in Puget Sound over a period of decades, a disproportionate amount of research and reporting has occurred there due to both the increased urbanization in that basin as well as the management structures and programs that have been geographically focused there (e.g., Puget Sound Partnership, the US Environmental Protection Agency's National Estuary Program, and the Puget Sound Nearshore Ecosystem Restoration Project in the past). However, more recently Environment and Climate Change Canada has focused efforts in the Strait of Georgia on understanding cumulative effects and specific impacts from marine shipping.

While most regional reports focus on specific waterbodies, such as Howe Sound, Puget Sound, or the Strait of Georgia, or contributing habitat types or organisms (see the Northwest Indian Fish Commission's State of Our Watersheds reports (2020); Puget Sound Partnership's State of the Sound reports (2019); the Ocean Watch Átl'ḵa7tsem/Txwnéwu7ts/Howe Sound Edition report (Miller et al. 2020); Fisheries and Oceans Canada's State of the Pacific Ocean reports (Boldt et al. 2019); and others), only the Health of the Salish Sea Ecosystem Report (US Environmental Protection Agency & Environment and Climate Change Canada 2021) addresses the cross-border bioregion. In contrast to most reports about the region, the goal of this *State of the Salish Sea* report is to address the Salish Sea ecosystem as a whole, synthesizing the biophysical attributes and human-induced stressors impacting estuarine health.

Ecosystem impacts occur across a variety of spatial and temporal scales, and we use a continuum of legacy, continuing, and emerging concerns to describe these impacts. In reality, the Salish Sea is experiencing simultaneous and temporally cumulative impacts, the ecosystem responses to which scientists are still disentangling.

- **Section 2** sets a foundation for understanding the Salish Sea ecosystem by describing its fundamental biophysical processes and structure, including estuarine circulation, ecological productivity, and an overview of several important biogenic habitats.
- **Section 3** turns to an in-depth discussion of stressors and impacts to the ecosystem from population growth and urbanization, such as increases in impervious surfaces, hardening of shorelines, and the problems caused by a myriad of marine contaminants.
- **Section 4** shifts from the local impacts of urbanization to the locally realized impacts of global climate change, including ocean acidification and sea level rise, followed by evidence of climate change in the ecosystem, ranging from phytoplankton and kelp, to wetlands, salmon, and marine birds.
- **Section 5** introduces cumulative effects and brings in brief case discussions focused on herring, salmon, and orcas. Understanding the layers of stressors the ecosystem faces is integral to gaining a full picture of declines in ecosystem function.
- **Section 6** offers a list of science-based needs and opportunities brought to light by the report and various existing efforts within the Salish Sea science community, representing opportunities for greater collaboration across geographic and jurisdictional boundaries.
- **Section 7** provides perspective from the Salish Sea Institute, acknowledging that science alone will not resolve continuing problems or emerging issues. Stronger policies along with education, leadership, and collaboration are needed.
- **Vignettes** are placed throughout the report to offer diverse perspectives on several of the key topics. Written by specialists and other invited contributors, the vignettes are brief and intended to spur curiosity, conversation, and optimism about the many research and management efforts underway by people and organizations that care about the Salish Sea and its future.
- **References** cited in this report are in and of themselves an impressive resource, with scores of studies and sources listed in support of this report and to help fulfill the objective of providing an up-to-date compendium of information that readers can use to further explore specific topics of interest.

SECTION 2

CONTEXT

Larrabee State Park, Bellingham, Washington
Photo: Nick Pinkham

SECTION 2

SALISH SEA BIOPHYSICAL PROCESSES

Geology and Hydrology
Terrestrial Ecology
Primary Basins and Subbasins
Circulation and Mixing
Productivity and Marine Ecology

ESTUARINE BIOGENIC HABITATS

Eelgrass
Kelp
Glass Sponges
Oysters

BIOPHYSICAL CONNECTIVITY ACROSS THE ECOSYSTEM

VIGNETTES

1: The Salish Sea Estuary
2: Lower Trophic Levels in the Salish Sea
3: Birds of the Salish Sea
4: Olympia Oysters

Exploring geology of Sucia Island, San Juans
Photo: Taylor Bayly

SALISH SEA BIOPHYSICAL PROCESSES

The Salish Sea is a complex waterbody defined by freshwater and marine water that mix in two primary basins and numerous subbasins carved by glacial history. While we think of this waterbody as the estuary that is the Salish Sea, these basins are strongly influenced by their surrounding watersheds. The watersheds and the subbasins they flow into have unique physical characteristics that shape the complex geography, oceanography, and biota within them and contribute to differences in response to urbanization and climate change. Many of those characteristics and ecological interdependencies that define the Salish Sea and drive its biophysical processes are described in this subsection.

Geology and Hydrology

Today, the Salish Sea is framed by more than 9,400 km (5,850 mi) of shoreline, including mainland and island shores (Flower 2020; see Figure 1.1). The landscape that surrounds and underlies the Salish Sea has been influenced on geologic timescales by the tectonics associated with the Pacific and North America plate boundary along the outer coast of Oregon, Washington, and British Columbia where the Cascadia Subduction Zone accommodates convergent plate motions. Associated with this, folding, uplift, and faulting contributed to the Georgia Depression and Puget Lowlands regions since at least the Cretaceous period (~150 million years ago; Dash et al. 2007). During the Pleistocene, multiple glaciations carved hills and valleys and created the surface geology that characterizes the Salish Sea.

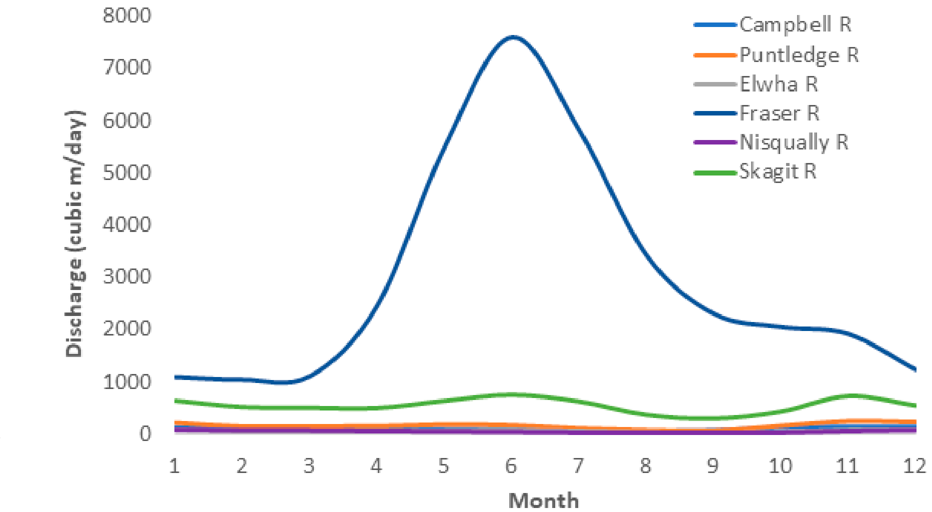
About 14,000 years ago, slow moving glaciers receded north across the existing Georgia Depression, forming the basins of Puget Sound, Strait of Georgia, and the Strait of Juan de Fuca. Meltwater flowing beneath the glaciers is believed to have scoured the major troughs that define the Salish Sea today (Booth 1994), and most of the sediment exposed on the edges of river valleys and along the coastal bluffs is glacially derived. The current geophysical configuration of the Salish Sea is a function of the complex shape of the waterbody and the geology of the coastline, combined with the glacial deposits that have been redistributed by waves, tides, and rivers over time (Shipman 2008). The resulting landscape features along the shoreline include coastal bluffs, estuaries, rocky shores, barrier beaches, and river deltas. The watersheds surrounding the Salish Sea are also complex and are a defining aspect of

the ecoregion, from the crests of the Cascade, Olympic, and Coast Mountains and Vancouver Island Ranges to the saltwater shorelines of the Salish Sea. The 17,803 km^2 (6,874 mi^2; Flower 2020) of the estuarine waters of the Salish Sea are freshened by several major rivers and the additional freshwater runoff from approximately 45 watersheds. In total, these watersheds comprise almost 320,000 km^2 (124,000 mi^2) of land area (Flower 2020). Streams and rivers within the watersheds serve as ecological corridors that transport freshwater, sediment, organic matter, organisms, and nutrients downstream where they influence the estuarine ecosystem; in turn, species like Pacific salmon, smelt, and seabirds deliver ocean-derived nutrients to the uplands.

The Fraser River is the dominant source of freshwater and sedimentary particles to the Salish Sea (Figure 2.1). It contributes approximately 50% of the freshwater entering the Salish Sea system (Khangaonkar et al. 2018) and more than

Left: Figure 2.1. The Fraser River plume, southern Strait of Georgia, Admiralty Inlet, Whidbey Basin, and the San Juan and Gulf Islands, as seen by the European Space Agency's Copernicus satellite. Source: European Space Agency 2021

Right: Figure 2.2. Average discharge from a subset of rivers flowing into the Salish Sea. Mean values aggregated by month and averaged from 1999-2016 show how much greater the freshwater input is from the Fraser River compared to other rivers. Data from Washington Department of Ecology.



70% of the freshwater in the Strait of Georgia (Johannessen et al. 2003). Though much smaller than the Columbia River in both watershed size and annual discharge—the Columbia averages 7,500 m^3/s (265,000 ft^3/s), while the Fraser averages 3,475 m^3/s (122,700 ft^3/s)—the Fraser is a dominant feature within the Salish Sea, contributing freshwater and driving circulation throughout the system (Figure 2.2). Of the 240,000 km^2 (92,660 mi^2) in the watershed (Déry et al. 2012), only the Lower Fraser River basin is within the Salish Sea bioregion. Much of the Fraser River watershed is east of the bioregion boundary, but salmon migrating upstream into the British Columbia interior and the massive spring freshet (averaging about 7,000 m^3/s/d; Curry & Zwiers 2018) flowing to the sea are a reminder of the connectivity between the upper basins and the Salish Sea (Déry et al. 2012).

The Fraser River may be the dominant source of freshwater in the Salish Sea as a whole, but other freshwater sources are important locally for bringing sediment and freshwater to their deltas and estuarine wetlands (Figure 2.3). Other major freshwater inputs include the Campbell, Puntledge, Big Qualicum, Englishman, Cowichan, Powell, Squamish, Cedar, Duwamish/Green, Elwha, Nisqually, Nooksack, Puyallup, Skagit, Skokomish, Snohomish, and Stillaguamish Rivers. Seasonal influxes of freshwater vary considerably.

For all river systems, lower volume base flows occur in late summer. Peak flows occur in mid-winter in rain-dominated systems and in early summer in snow-dominated systems, where melting winter snow generates a spring freshet (e.g., Fraser, Nooksack, and Skagit Rivers among others; Morrison et al. 2012). The variation in freshwater inflow across the year has implications for estuarine circulation, but also for changing sediment delivery, salinities, and temperatures in lower portions of rivers and the **nearshore**, impacting organisms living there (Figure 2.4).

Nearshore

The area that extends from the head of tide (the uppermost reach of tidal influence) in water and the upper edge of coastal bluffs on land seaward to the offshore limit of the photic zone is referred to as the nearshore.

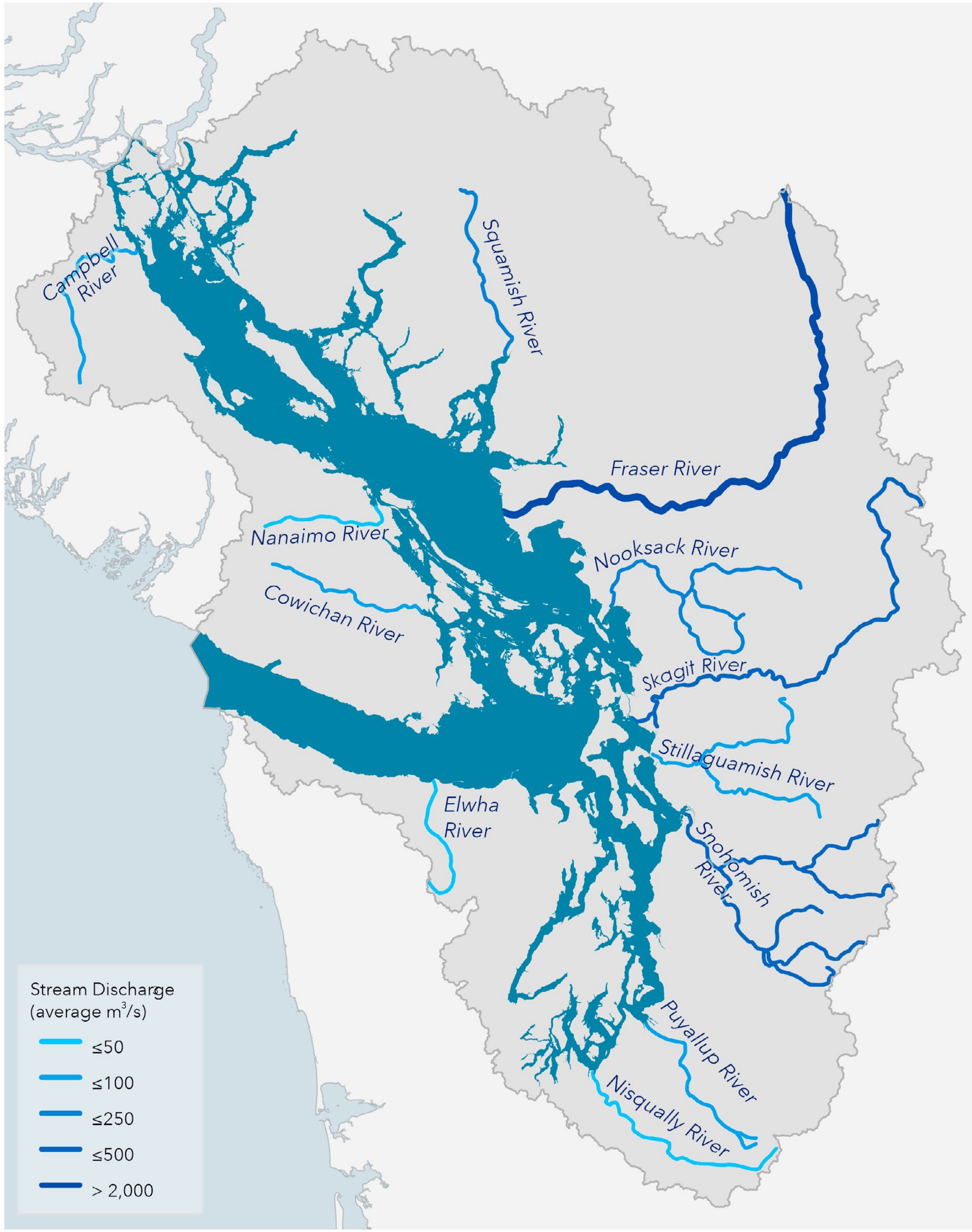


Figure 2.3. Major rivers of the Salish Sea and average stream discharge (cubic meters per second). Data are based on annual averages from 1981 to 2010.

Map by Aquila Flower, 2021.

Terrestrial Ecology

The terrestrial landscapes within the watersheds that drain into the Salish Sea are largely dominated by highly productive coniferous forests, where many of the conifer species reach their maximum growth potential for height and diameter (Franklin & Dryness 1998). The lowland forests in the Salish Sea were once mostly dominated by dense coniferous forests, commonly made up of western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), and Douglas fir (*Pseudotsuga menziesii*) interspersed with hardwoods, such as bigleaf maple (*Acer macrophyllum*) and red alder (*Alnus rubra*). This dominant flora remains in some areas. On drier sites, Garry oak (*Quercus garrayana*), Pacific dogwood (*Cornus nuttallii*), and arbutus (*Arbutus menziesii*, also called madrone) are common. Open areas resulting from soil conditions and human practices occurred throughout the forests (Charnley et al. 2008). Early Indigenous peoples used a variety of practices to maintain forests for production of food and products, including burning, pruning, tilling, and transplanting (Turner et al. 2013). Today, many of the lowland forests have been converted to urban or agricultural land, although stands of forest remain in some areas.

Vegetation within riparian corridors along rivers and streams plays an especially important role in regulating freshwater input and quality to the Salish Sea (Naiman et al. 2000). For example, during high stream flows, riparian vegetation slows and dissipates floodwaters, which helps reduce erosion and sediment load that continues downstream. In many other ways, riparian zones are important in maintaining watershed hydrology, stream flows, water quality, stream nutrients, and habitat characteristics needed to maintain native aquatic species (Naiman et al. 1992).

Vegetation along shorelines, river deltas, sloughs, and tidal floodplains is important in regulating freshwater and nutrient exchange, as well as temperature and organic matter flux, serving as an important ecotone between terrestrial and estuarine ecosystems. Shoreline vegetation, also known as marine riparian vegetation (Brennan 2007), includes the common conifers of upland forests, as well as Sitka spruce (*Picea sitchensis*), shore pine (*Pinus contorta*), and hardwoods like red alder, bigleaf maple, and madrone (arbutus), along with numerous shrubs, such as oceanspray (*Holodiscus discolor*) and salal (*Gaultheria shallon*). Local variations in soils, temperature, exposure to sun and wind, precipitation, topography, soil stability, tidal inundation, and microclimate cause small-scale variations in vegetation community types throughout the watersheds but along the estuarine shorelines, salt exposure is also a defining factor (Levings & Jamieson 2001). Buffered shorelines along both fresh and marine waters protect ecological processes and critical habitats for organisms in this important region of exchange.

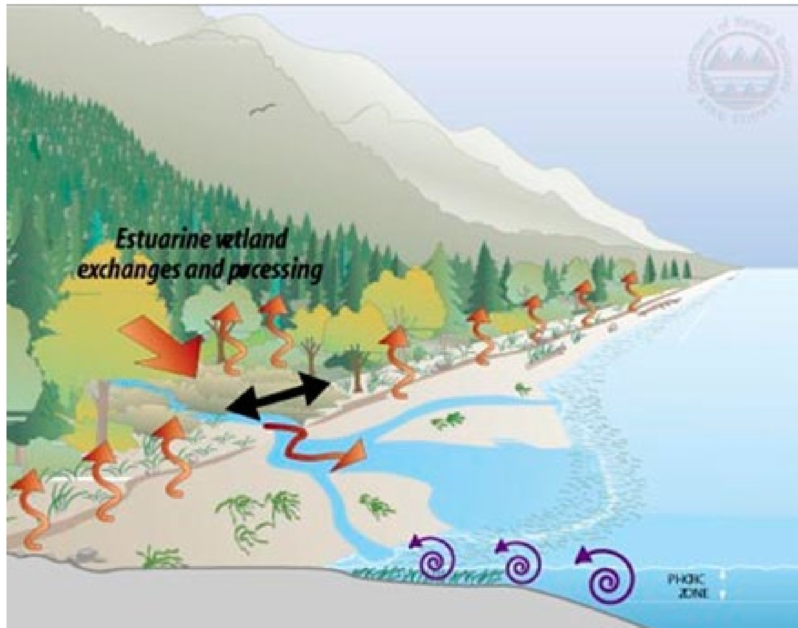


Figure 2.4. Schematic of the nearshore ecotone in the Salish Sea. Source: King County (2016)

Primary Basins and Subbasins

The combination of freshwater input from the watersheds and Pacific Ocean-derived marine waters gives the Salish Sea its unique oceanography and ecology. The main connection of the Salish Sea to the Pacific Ocean is through the Strait of Juan de Fuca, with a smaller connection at the north end of the Strait of Georgia through Johnstone Strait. The two primary basins are the Strait of Georgia and Puget Sound, but the Salish Sea is further divided into subbasins by a series of sills (Figure 2.5). These submarine ridges are important bathymetric features and geospatial reference points because they influence the circulation of water and bathymetrically define subbasins within the Salish Sea.

The Strait of Juan de Fuca forms the channel between Vancouver Island and Washington State, with the international boundary running down the middle of the Strait. Its depth decreases eastward, from about 250 m (820 ft) at its western end where it meets the Pacific Ocean to 55 m (180 ft) in the sill region at its eastern extent (Thomson 1981). At its eastern end, the Strait of Juan de Fuca bifurcates to form the channels of the San Juan/Gulf Islands archipelago, including Haro and Rosario Straits connecting the Strait of Juan de Fuca to the Strait of Georgia to the north, with Admiralty Inlet leading southward to Puget Sound.

The Strait of Georgia is large (surface area of about 9,000 km^2 or 3,500 mi^2) and deep, with an average depth of 155 m (509 ft) (Thomson 1981). The Strait has two deep basins: a south-central basin with maximum depths of about 445 m (1,460 ft) and a northern basin with maximum depths of about 760 m (2,493 ft). Texada Island, the largest of the Gulf Islands, separates the south-central and northern parts of the Strait, with a 170 m (558 ft) sill on the southwestern side. Malaspina Strait, an area of high current, runs along the east side of the island bordering the British Columbia mainland.

The northern exit of the Strait of Georgia consists of narrow and relatively shallow passages through numerous islands in the Desolation Sound region, eventually passing through Johnstone Strait, a constricted passage with strong current (Beamish & McFarlane 2014). The northern passage comprises only 7% of the cross-sectional area of all exits from the Strait of Georgia but has been estimated to carry about 17% of the outflow (Pawlowicz et al. 2007). These waters eventually empty into Queen Charlotte Sound on the central coast of British Columbia. The Strait of Georgia also has several large fjords on the mainland side of the Strait, with a variety of striking oceanographic and biological characteristics (e.g., Sechelt Inlet and its Skookumchuck Narrows).

Puget Sound has a surface area of about 2,600 km^2 (1,004 mi^2) and is divided into several subbasins. These subbasins are bathymetrically defined by the presence of sills that constrict the flow of water from one subdivision of the Puget Sound Basin to the next (Cannon 1983). The subbasins of Puget Sound include Admiralty Inlet, Main Basin (sometimes called Central Basin or Central Puget Sound), Whidbey Basin, South Puget Sound, and Hood Canal (Williams et al. 2001). Main Basin is the largest and has the greatest volume of water of any subbasin in Puget Sound, with depths ranging from 65 m (213 ft) at Admiralty Inlet to 270 m (886 ft) deep farther south. Whidbey Basin, which sits to the east of Whidbey Island, is unique in that there is

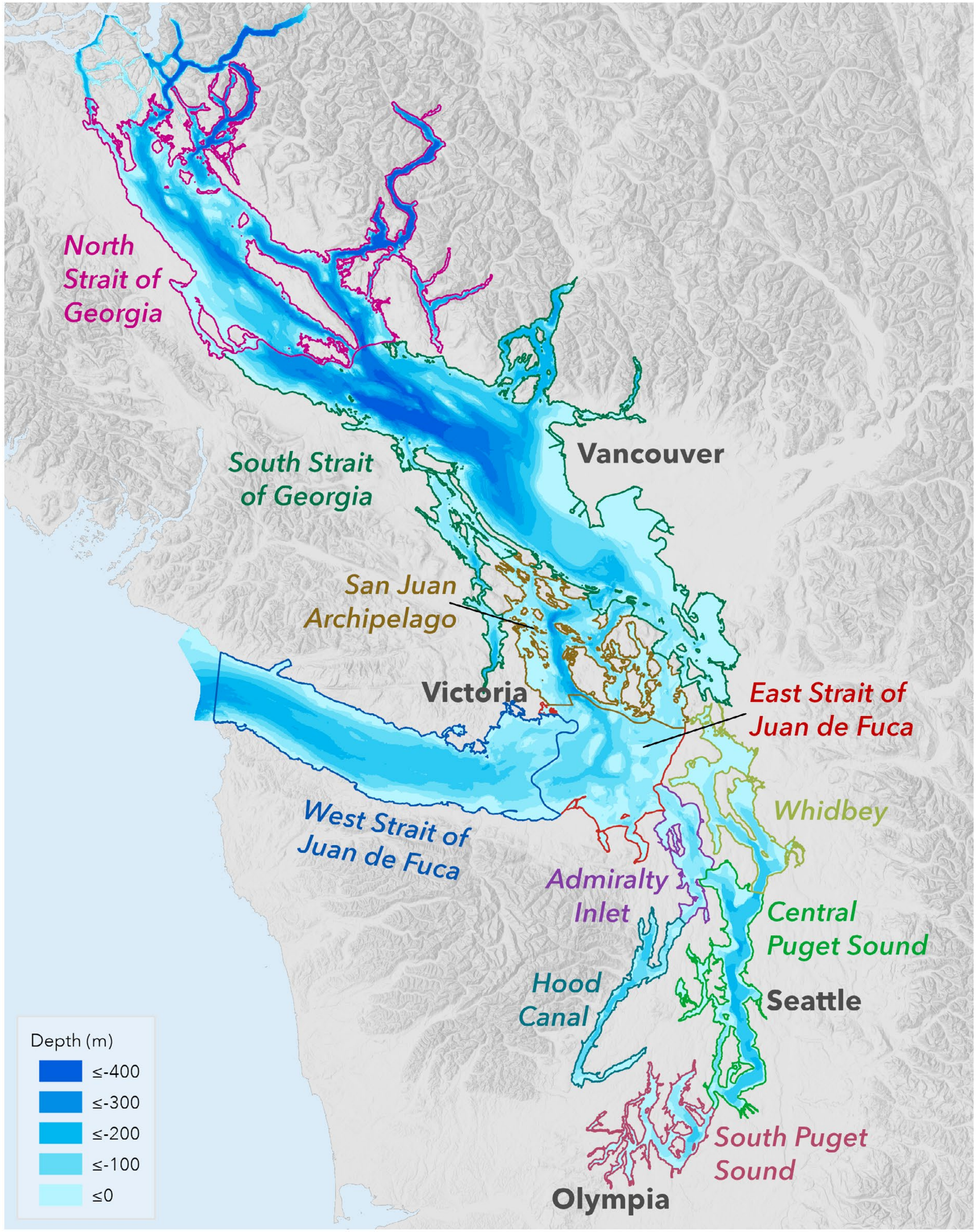


Figure 2.5. Subbasins and bathymetry of the Salish Sea. Basins are delineated based on water depth and circulation. Shallower areas associated with underwater sills separate many of the basins, creating distinct oceanography.

Map by Aquila Flower, 2021.

no sill across the entrance; therefore, it is defined more by geography than bathymetry. It is a much shallower basin, with a much higher percentage of tidelands than any of the other basins. In addition, Whidbey Basin has three major freshwater sources in the Stillaguamish, Snohomish, and Skagit Rivers, the latter of which delivers about half of the freshwater flow to Puget Sound. South Puget Sound is defined by a sill at the Tacoma Narrows. The sill is 45 m (148 ft) deep but the maximum depth of the South Puget Sound basin (167 m or 548 ft) occurs just on its south side. The mean depth in South Puget Sound is only 32 m (105 ft) and, like Whidbey Basin, the relatively shallow depth yields large areas of tidelands. South Puget Sound is also defined by numerous islands and complex shorelines around many inlets.

The distinct geological and oceanographic characteristics of the subbasins means circulation, residence time, water chemistry, physical properties and biota are variable on small spatial scales across the ecosystem. Most previous studies have treated Puget Sound and the Strait of Georgia basins as separate entities given regional differences in oceanography and the international border and distinct research enterprises on either side. However, increasing numbers of researchers are studying the oceanography of the Salish Sea in its entirety (Sutherland et al. 2011; Khangaonkar et al. 2018, 2019; Barth et al. 2019; MacCready et al. 2020). The resulting models and research approaches are becoming more integrated across the border and will further unify understanding of biological and physical oceanography within the Salish Sea.

Seastar at Larabee State Park, Washington
Photo: Faith Owens

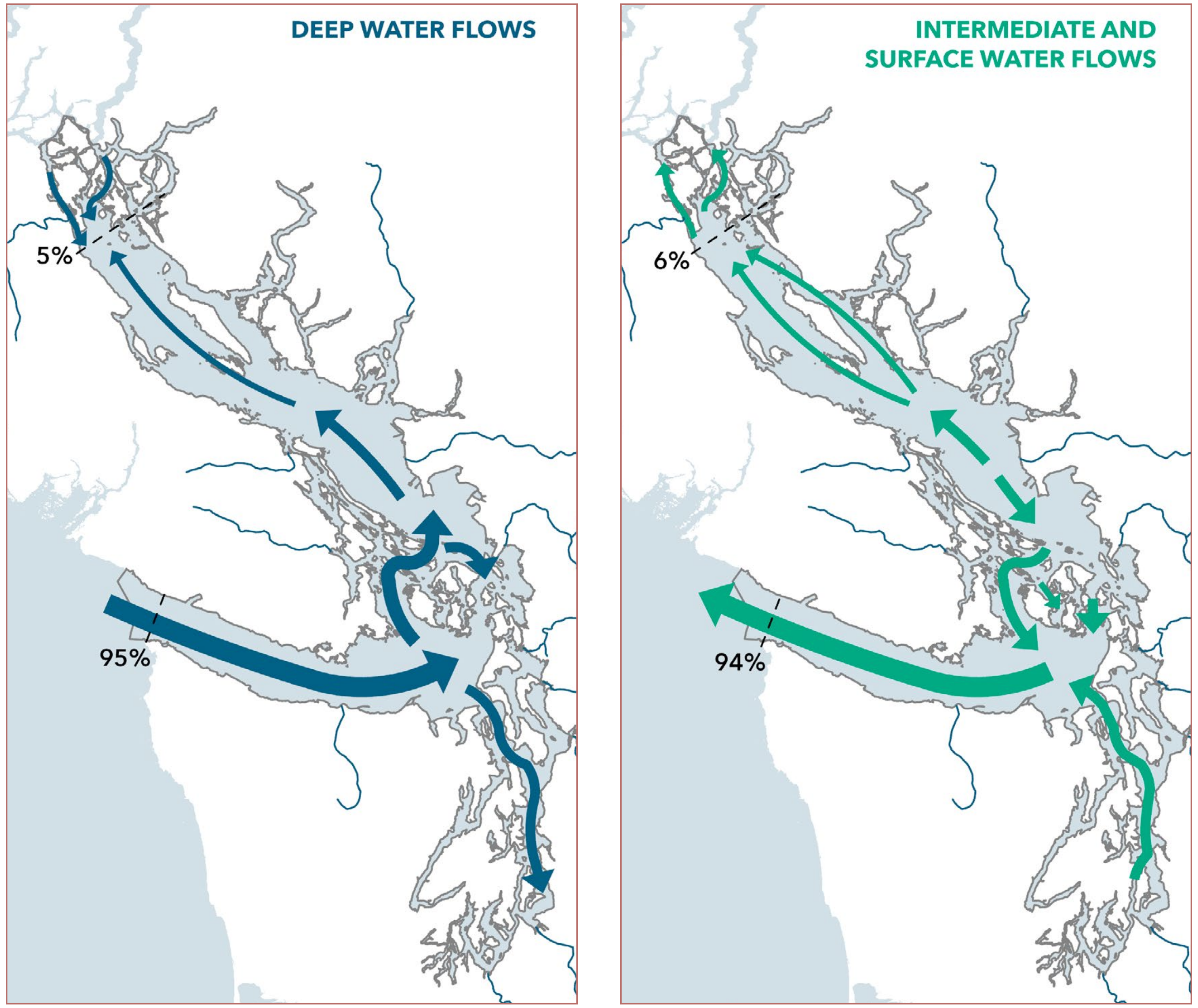


Figure 2.6. Direction and relative magnitude (line width) of net water flow in the Salish Sea. Deep water flows represent primarily marine waters entering the Salish Sea from the Pacific Ocean. Intermediate depth and surface flows represent a mix of marine waters and freshwater from rivers in the Salish Sea. Actual circulation patterns are highly complex and seasonally variable, this diagram shows a simplified model of net exchanges. Labels indicate percent of the total water exchange that moves in and out of the Salish Sea through the Strait of Juan de Fuca in the south and through the northern boundary of the Strait of Georgia.

Aquila Flower, 2021. CC BY-NC-SA 4.0 License. Data from the Salish Sea Atlas.

Circulation and Mixing

The circulation patterns in the sill-basin system of the Salish Sea are estuary-like. The large amount of freshwater entering at the surface through rivers in Puget Sound and the Strait of Georgia—especially the Fraser River—drives a multi-layer flow, with fresher water flowing west toward the Pacific Ocean and the denser Pacific Ocean waters flowing east into the Salish Sea at depth through the Strait of Juan de Fuca (Geyer & Cannon 1982; Figure 2.6). This is known as estuarine exchange flow (Figure 2.7). The deep saline inflow from the Pacific Ocean travels through the Strait of Juan de Fuca and over a series of shallow sills where it mixes with the overlying fresh (and less dense) surface waters travelling seaward (Soontiens & Allan 2017). Mixing is modulated by tidal currents creating turbulent mixing in a mid-layer and results from the spring and neap tidal cycle on short time scales (Figure 2.7, middle panel), with higher mixing rates during the spring tides when tidal currents are stronger (Soontiens & Allan 2017). Wind also drives mixing and water movement and patterns change seasonally. Seasonal cycles in freshwater outflow mediate mixing and circulation on annual timescales. Water exiting the Salish Sea through Johnstone Strait and the Strait of Juan de Fuca is relatively salty (30-32 ppt, seasonally variable) due to tides and currents and the turbulence induced at the shallower sills throughout the Salish Sea system (Martin & MacCready 2011). It is not uncommon for the movement of water at the immediate surface to be counter to that in the mid-layer and/or at depth (Stevens et al. 2021; S. Allen, University of British Columbia, personal communication), creating complex circulation patterns.

The low-density fresh or brackish waters can sit atop deeper layers of saltwater and be relatively resistant to vertical mixing. When there is a strong density difference between the layers (known as a pycnocline), stratification between layers may occur. Stratification is more common in the basins of the Strait of Georgia and Puget Sound than in the Strait of Juan de Fuca, but mixing and stratification of water types is patchy in time and space throughout the Salish Sea (Sutherland et al. 2011).

The transport of ocean water into and freshwater out of the Salish Sea decreases the residence time of waters within this inland body of water. In Puget Sound, it is estimated that the freshwater filling time based on river flow alone is approximately 5 years; however, after accounting for the exchange flow generated by the surface movement of freshwater out of the region and deep ocean water into the region, the estimated residence time is dramatically reduced to 90–180 days (Babson et al. 2006). The steep reduction in residence time is an expression of the relative size of the exchange flow, which is roughly 20 times greater than the sum of all the rivers (Sutherland et al. 2011). In the Strait of Georgia, the residence time is highly variable by season, with longer surface residence times in the winter, when Fraser River discharge is lower (Pawlowicz et al. 2019). Circulation and an understanding of the processes that control the exchange and mixing of oceanic and freshwater are critical and play a central role as environmental issues, such as hypoxia (i.e., low concentrations of dissolved oxygen), pollution, ocean acidification, and climate change continue to be of concern in the Salish Sea (Sutherland et al. 2011; Khangaonkar et al. 2018).

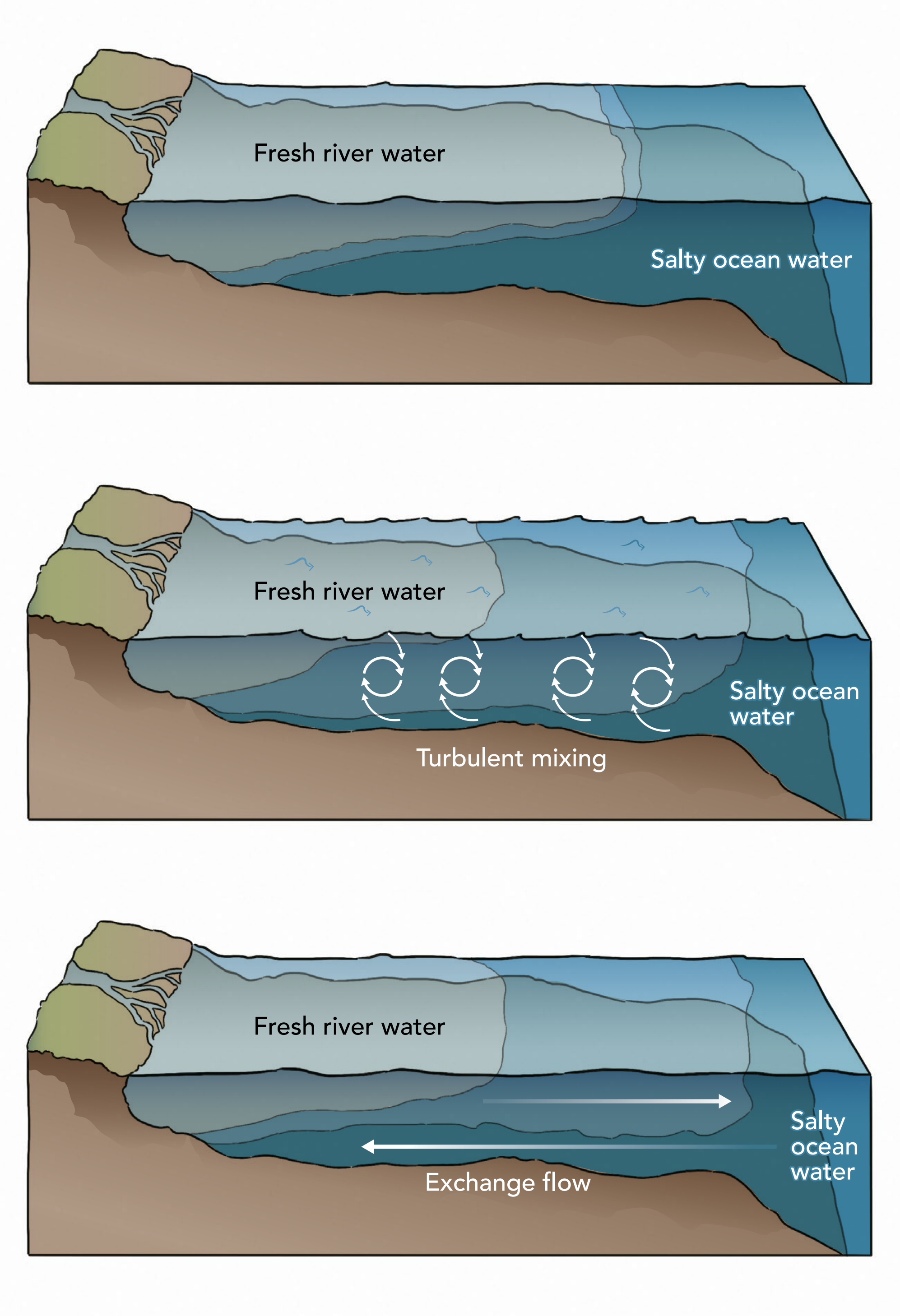


Figure 2.7. Schematic diagram of exchange flow in the Salish Sea. Freshwater from the Fraser River flows at the surface out into the Strait of Georgia and Strait of Juan de Fuca while salt water from the Pacific Ocean enters the Strait of Juan de Fuca at depth (top panel). Turbulent mixing caused by tides, currents, and estuarine circulation mixes the water masses (middle panel). Mixed salinity water exits back to the Pacific Ocean near the surface creating the exchange flow (bottom panel), which drives estuarine circulation in the Salish Sea. Illustration by Emily Eng for the Salish Sea Institute, adapted from P. MacCready, University of Washington.

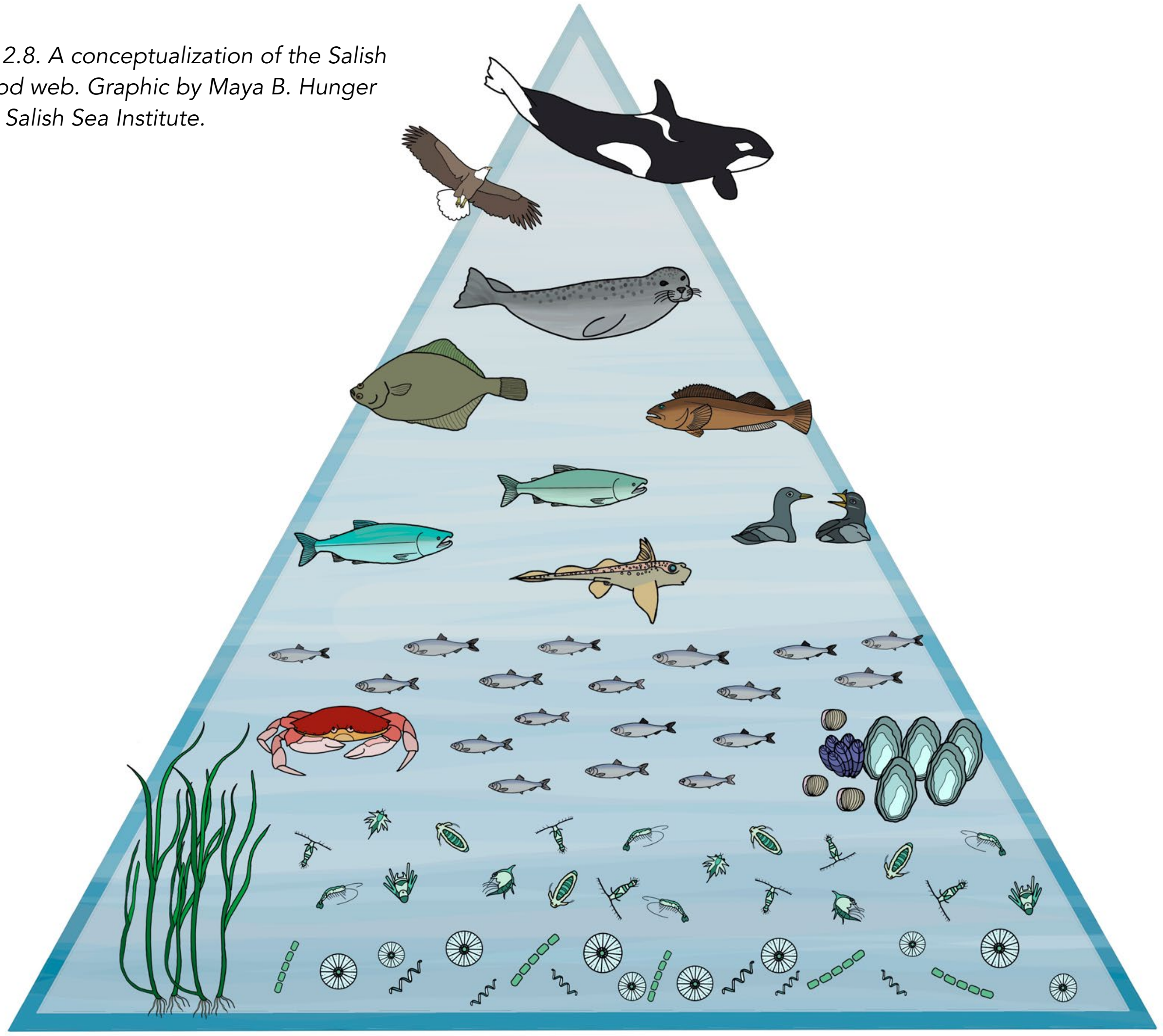
Productivity and Marine Ecology

The geology, bathymetry, and physical features of the Salish Sea can strengthen or weaken biological productivity by affecting nutrient delivery via the mixing process. However, biological productivity within the system is largely driven by marine sources (Conway-Cranos et al. 2015). This marine-driven productivity is an important feature of the Salish Sea estuary. Vertical mixing benefits primary production in that it brings ocean-derived nutrients up from deeper water layers towards the surface, where light is abundant but nutrients are less plentiful. For photosynthesis to occur, a balance between mixing and stratification is necessary because mixing can drive plankton deeper and out of the photic zone (the upper-most layer where light is available for photosynthesis). As precipitation and snowmelt peaks in the spring, an influx of freshwater to the surface layers combines with lengthening days and greater solar input and phytoplankton growth surges. During this time, stratification is maintained by relatively calm weather, creating a strong pycnocline and ample sunlight to facilitate photosynthesis.

The high productivity of biota in the Salish Sea is driven by abundant nutrients, specifically nitrogen, entering the Sea from Pacific Ocean water (Mackas & Harrison 1997; Davis et al. 2014). This nitrogen-rich water mixes with surface waters as it circulates from the entry in the Strait of Juan de Fuca throughout the Strait of Georgia and Puget Sound basins (see Vignette 1, The Salish Sea Estuary System). A lesser amount of nutrients, some of which, like silica, are critically important to the base of the food web, comes from freshwater inputs. Weathering from the mountain ranges and rocks brings essential macronutrients like phosphate and silica into the Salish Sea. These nutrients, delivered to the estuary by both ocean water and freshwater, are the raw material with which microplankton and phytoplankton build their cell walls, forming the base of the food web.

Phytoplankton form the base of marine food webs as the dominant photosynthetic producers. They influence water chemistry and nutrient dynamics in space and time, and their distributions are driven by the availability of light and nutrients. Major groups of phytoplankton in Salish Sea waters include diatoms, dinoflagellates, and nanoflagellates. The phytoplankton community in the Salish Sea is dominated by centric, chain-forming diatoms (Esenkulova & Pearsall 2016; Nemcek et al. 2020). Diatoms are a major food source for a wide variety of zooplankton, including larger species that are important prey for fish. In contrast, dinoflagellates and nanoflagellates generally flourish under lower nutrient conditions, as in winter in the Salish Sea. There is a seasonal progression from diatom-dominated communities in the spring when light and nutrients are abundant to more diverse communities of smaller, motile (flagellated) types of phytoplankton in the summer as grazing occurs and stratification makes nutrients less available (see Vignette 2, Lower Trophic Levels in the Salish Sea).

Figure 2.8. A conceptualization of the Salish Sea food web. Graphic by Maya B. Hunger for the Salish Sea Institute.



The Salish Sea zooplankton community is composed chiefly of copepods, which graze on diatoms, especially at the surface where phytoplankton prey are readily available. Recent studies from the Strait of Georgia found that copepods (calanoid copepods in particular) dominated zooplankton by abundance, while larger crustaceans (euphausiids, amphipods, and decapods) and cnidarians (hydromedusae, ctenophores, and siphonophores) dominated by biomass (Young et al. 2017; Perry et al. 2021). Zooplankton distribution is determined by their physical dimensions and the characteristics of the environment. Mid- and deeper-water communities may consist of euphausiids, chaetognaths, and some deep-living copepods that are able to overwinter at depth (Harrison et al. 1983). Distribution of zooplankton tends to be patchy in both space and time, as zooplankton respond to changing ocean currents and available prey. Horizontal patches of zooplankton may be important feeding sites for some fish species. The Salish Sea supports numerous other fauna critical in providing food for both humans and animal inhabitants. Macroinvertebrates, such as bivalve mollusks and crabs, are of subsistence, recreational, and commercial importance. Over 250 fish species swim in these waters, ranging from sharks to small gobies (Pietsch & Orr 2015), and include all five species of Pacific salmon, steelhead, and cutthroat trout. In addition, over 170 bird species rely on the habitats and

species found within the Salish Sea (Gaydos & Pearson 2011), with both resident and migratory species in high abundance (see Vignette 3, Birds of the Salish Sea).
Among all the fauna that rely on the marine-derived food web of the Salish Sea, the orca (*Orcinus orca*) is perhaps the most iconic species in the region. Although the orca may garner the greatest public attention, over 30 other marine mammals occur in the Salish Sea, including Dall's and harbor porpoise (*Phocoenoides dalli* and *Phocoena phocoena*, respectively), California sea lion (*Zalophus californianus*), and the harbor seal (*Phoca vitulina*). All of these species rely on an interconnected and highly productive food web.

The Salish Sea food web is like many other trophic webs that move energy and nutrients from one trophic level to another: from primary producers (e.g., phytoplankton) to higher trophic levels of secondary and tertiary consumers (e.g., zooplankton and fishes), and through decomposers (Figure 2.8). With each increasing trophic level, biomass declines. Trends in how the overall food web has changed over time are not well resolved, but there is some evidence that a trophic shift occurred over the last 30 years. Studies are ongoing to understand the connections between primary production and upper trophic levels, like herring, Pacific salmon, and orcas. Recently, researchers in British Columbia began using trophic biomarkers (e.g., stable isotopes and fatty acids) to explore connections between phytoplankton and the availability of high-quality prey for juvenile Pacific salmon and Pacific herring in the Strait of Georgia (Costalago et al. 2020). They demonstrated that the plankton food web in the region is largely supported by both diatom and flagellate production, depending upon the season, and showed that spatial differences in energy transfer exist. The variation in community composition and energy transfer that the biomarkers showed provides evidence for differential productivity and growth within the Salish Sea.

While the Salish Sea is a single ecoregion, the series of sills, basins, and unique physical and chemical oceanography can all be strong mediating forces on biological production, particularly over short time scales and small spatial scales. Understanding variation in the Salish Sea is as important as understanding the characteristics that make this a contiguous estuarine ecosystem.

ESTUARINE BIOGENIC HABITATS

The pelagic (open water) marine environment makes up the largest proportion of habitat in the Salish Sea ecosystem. Across the **seascape**, there are also multiple biogenic structured habitats that provide refuge for organisms and myriad other ecosystem services. These estuarine biogenic habitats are connected with the pelagic realm via tides, currents, and circulation that drive fluxes of energy (biomass), sediments, and nutrients.

Highlighted in this subsection are four biogenic habitats: eelgrass beds, oyster reefs, kelp forests, and sponge reefs. While all four are sentinels of ecosystem change, two of these (eelgrass and kelp) receive much attention and are the subject of monitoring programs on both sides of the border. The other two (oysters and glass sponge reefs) are not as well understood and are thus featured here to highlight their historical and potential roles in maintaining resilience in the Salish Sea.

When species are considered together with the habitats they use, from the pelagic environment to biogenic habitats that are important for rearing and refuge, a more complete picture of ecological complexity and function becomes evident (Culhane et al. 2018). For example, native oysters were once an important natural occurrence within the Salish Sea and contributed structural habitat for other organisms. Restoration efforts highlight their habitat value, even though contemporarily, most people think of oysters in the context of commercial production (which is dominated by the introduced Pacific oyster, *Crassostrea gigas*). In another example, sponge reefs are being studied in Canada and are gaining attention for their high rates of carbon sequestration and complex habitat. Protecting these kinds of habitats and the ecosystem services they provide is a promising way to mitigate the effects of global climate change.

Although not discussed in detail below, there are many additional and important benthic (bottom) habitats in the Salish Sea ecosystem, including intertidal mudflats, subtidal rocky reefs, mixed-substrate beaches, and rocky shorelines. Additionally, deltaic estuaries with complex channels and emergent, forested, and mixed-vegetation marshes along the freshwater to saltwater gradient were once common features at river mouths but have been much reduced due to development. Where they remain, they are important habitats for many invertebrate, fish, and bird species (Sutherland et al. 2013). Each of these biotopes provides habitat for a multitude of species, many of which move from across a mosaic of features, facilitating cross-habitat connectivity by moving nutrients and biomass throughout the ecosystem (Howe & Simenstad 2015; Chalifour et al. 2019).

Seascape

The term seascape (*sensu* Pittman et al. 2011) is used throughout this report to refer to the geographic and physical characteristics, including chemical properties, of the Salish Sea estuarine ecosystem. The complex spatial and geographic heterogeneity that exists on land (i.e., the landscape) does not end at the estuary's edge. Fundamentally landscape-like patterns associated with the geology and physical, chemical, and biological oceanography occur in estuarine and marine systems as well. These patterns drive variation in biodiversity of species, life history, and ecology within the seascape. Connectivity with the terrestrial and ocean ecosystems and their contributions to the Salish Sea estuarine seascape further defines this ecosystem.

Eelgrass

Eelgrass (*Zostera marina*) is a flowering plant that grows in shallow coastal waters throughout the northern hemisphere. Like most seagrasses, it prefers shallow soft substrate of sand and silt, where light is plentiful. Multiple factors determine eelgrass distribution, including substrate availability, water clarity, wave energy, light attenuation, water temperature, tidal amplitude, and desiccation stress (Hemminga & Duarte 2000; Thom et al. 2018). Eelgrass is patchy in distribution throughout the Salish Sea around the shorelines and islands (Wright et al. 2014), but is absent from the inlets of South Puget Sound (Christiaen et al. 2019). In the Salish Sea, eelgrass tends to occur as a linear band of fringing habitat along shorelines, from the intertidal zone to deepest edge of the photic zone, approximately 10 m (33 ft) in depth. The deepest beds are found where water clarity is greatest, such as in the Strait of Juan de Fuca and the San Juan Islands (Gaeckle et al. 2009). In addition to occurring as fringing habitat along beaches, eelgrass also is found in extensive beds at river deltas and in large flats, such as Padilla Bay, WA. Eelgrass is the most abundant of six seagrass species in the Salish Sea. The other five are: *Zostera japonica* (an introduced species), *Phyllospadix serrulatus, Phyllospadix scouleri, Phyllospadix torreyi,* and *Ruppia maritima*.

Eelgrass provides a multitude of ecosystem services. Through photosynthesis, eelgrass contributes to the global carbon cycle and carbon fixation that support local biota (Poppe & Rybczyk 2018; Prentice et al. 2020). It creates important biogenic habitat, and dense stands can help attenuate waves (Lacy & Wyllie-Echeverria 2011). Eelgrass also has been shown to contribute to waste treatment through the breakdown of contaminants, such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) (Huesemann et al. 2009). It offers numerous cultural services through bird watching, recreational fishing, and educational opportunities (Plummer et al. 2013), and eelgrass beds are valued harvesting grounds for Indigenous peoples (Cullis-Suzuki 2007; Wyllie-Echeverria & Ackerman 2003).

The biogenic habitat created by eelgrass makes up a small proportion of the Salish Sea seascape, yet it provides an outsized contribution to the nearshore ecosystem, is sensitive to change, and is relatively easy to monitor (Wright et al. 2014; Christiaen et al. 2019). Perhaps most notably, eelgrass supports a rich biota and provides important habitat for many fishes and invertebrates. For example, eelgrass provides structure for Dungeness crab (*Metacarcinus magister*) (Armstrong et al. 1988), offers spawning grounds for Pacific herring (*Clupea pallasi*) that use eelgrass blades as substrate for their eggs, and creates rearing opportunities for juvenile salmon (*Oncorhynchus spp.*) (Simenstad 1994; Kennedy et al. 2018). It also provides important feeding and foraging habitats for crustaceans, fishes, and waterbirds, such as black brant (*Branta bernicla*) (Wilson & Atkinson 1995).

Eelgrass supports multiple species of epiphytic algae that serve as a food source for numerous marine crustaceans, such as amphipods, isopods, and harpacticoid copepods, that are then consumed by higher trophic level species (Hayduk et al. 2019). Recent work using stable isotopes has shown evidence of epiphyte signatures in the tissues of fishes and invertebrates (Chittaro et al. 2020) in the Salish Sea, and eelgrass provides a substrate for these important algal primary producers. The importance of eelgrass epiphytes to the marine food web is well documented in other regions (Valentine & Duffy 2006) including in the Pacific Northwest (Williams & Ruckelshaus 1993; Hayduk et al. 2019). Most eelgrass biomass enters the food web through detritus, as the blades senesce (deteriorate with age) and slough off seasonally with fall storms (McConnaughey & McRoy 1979; Howe et al. 2017). Some eelgrass detritus likely sinks into deeper water, but the fate and importance of this carbon source is unknown.

Eelgrass is one of the "Vital Signs" used by the Puget Sound Partnership (McManus et al. 2020) and the subject of numerous monitoring efforts in both Washington and British Columbia because of the extensive ecosystem services it provides and the fact that eelgrass responds rapidly to stressors (Thom et al. 2011; Yang et al. 2013; Wright et al. 2014). Monitoring in Puget Sound and the Strait of Georgia has largely been site specific, but larger-scale efforts are currently underway. The Washington State Department of Natural Resources maintains a considerable monitoring effort and has systematically assessed eelgrass coverage for the last 20 years (Washington State Department of Natural Resources 2021). The total amount of eelgrass in Puget Sound has remained largely stable over this period, although localized losses and gains have occurred (Shelton et al. 2017). Recent research on eelgrass wasting disease highlights that while eelgrass losses are not considerable overall, threats to its health and persistence exist and may be exacerbated by warming seawater (see vignette on Eelgrass Wasting Disease in Section 4). In British Columbia, mapping and monitoring is undertaken by numerous groups associated with the Seagrass Conservation Working Group and its affiliates (Seagrass Conservation Working Group 2021). Although eelgrass losses in British Columbia are documented from shoreline development at specific sites (Nahirnick et al. 2020), identifying long-term trends in coverage is not possible without a transboundary monitoring program.

Deeper subtidal eelgrass shoots shimmering in False Bay, San Juan Island. Photo: Olivia Graham.

Kelp

Kelp forests are receiving increased attention as important biogenic habitats within the Salish Sea (Costa et al. 2020; Schroeder et al. 2020). Kelps are large brown seaweeds in the taxonomic order Laminariales. They are prominent members of the Salish Sea ecosystem and prefer shallow rocky bottoms where they can attach their holdfasts to suitable sized cobbles or bedrock and receive ample light for photosynthesis. More than 20 species of kelp are found in the Salish Sea (Mumford & Thomas 2007), among which are two primary species of floating canopy-forming kelp: the annual bull kelp (*Nereocystis luetkeana*) and the perennial giant kelp (*Macrocystis pyrifera*). *N. luetkeana* is the more common and abundant species within the Salish Sea and the focus of many ongoing monitoring efforts. *M. pyrifera* is less common and is mostly restricted to exposed shores along the Strait of Juan de Fuca (Pfister et al. 2018). These species occur throughout the California Current Large Marine Ecosystem and are found on the outer coasts of Washington and British Columbia, as well as in the inland waters of the Salish Sea. Kelps are found in high current areas, like the Tacoma Narrows, throughout Admiralty Inlet, and along the Strait of Juan de Fuca. In addition to the canopy-forming kelps, numerous understory kelp species are abundant in subtidal areas of the Salish Sea.

Kelps serve several ecological functions and provide habitat and nutrients to numerous species. For example, they affect their physical environment by modifying current and wave energy, contribute to carbon cycling and storage via large algal fronds, and they facilitate nutrient exchange (Hurd et al. 2014). Kelps also contribute to local biodiversity and feed herbivores with their high rates of primary production (Teagle et al. 2017). Kelps support a wide array of flora and fauna, from epiphytes that attach to the kelp's stipes and blades, to fishes that use surface and subtidal canopies of kelp as refuge. The kelp crab (*Pugettia producta*) is an especially common associate that eats kelp and other animals associated with kelp, such as mussels, barnacles, and crustaceans. It is likely that these crabs also provide food for fishes and mammals that utilize the kelp canopy, but few studies have been done in this region (see Zuercher & Galloway 2019 for a general discussion). Multiple species of fish use kelp forests as habitat, including rockfish, juvenile salmon, and herring which spawn on the kelp blades (Schweigert et al. 2018) and provide a food source for Indigenous peoples (Gauvreau et al. 2017).

Trends in kelp cover in the Salish Sea are variable, but no transboundary monitoring effort exists across the seascape. In the Strait of Juan de Fuca and more exposed areas, kelp canopy cover had remained stable or increased (Berry et al. 2005) until recently when reductions in cover were observed (Shelton et al. 2018). In the South Puget Sound, recent monitoring showed a decline in *Nereocystis* in many areas, but stable cover persisted around the Tacoma Narrows, which is an area of high current and tidal exchange (Berry et al. 2019; Berry et al. 2021). In British Columbia, most work focuses on the west coast of Vancouver Island, but recent research using remote sensing shows a decline in kelp abundance in the Salish Sea around Cowichan Bay and Sansum Narrows in recent years (Schroeder et al. 2020). Studies aimed at identifying mechanisms related to these declines are ongoing in both Washington and British Columbia, but time-series with broad spatial coverage are needed to adequately assess long-term trends and separate them from annual or shorter-term variability in kelp canopy cover and species diversity.

Large bull kelp bed in Puget Sound
Photo: Rich Yukubousky

Glass Sponges

Glass sponges form unique reef ecosystems found along the Pacific coast of Canada and the United States. Similar glass sponge reefs went extinct during the age of the dinosaurs, but modern versions were discovered in Hecate Strait in central British Columbia in the mid-1980s and have become the subject of more recent research in the Strait of Georgia and the ocean waters off of Washington, British Columbia, and north to Alaska. Sponge reefs in the Salish Sea have been found in Howe Sound, around the Gulf Islands, and in the Strait of Georgia. Perhaps surprisingly, no records of glass sponge reefs exist for Puget Sound. Most reefs are found in very deep waters, greater than 150 m (492 ft), which is beyond the range of SCUBA. As remotely operated vehicle (ROV) and autonomous underwater vehicle (AUV) technology has become more available, exploration and study of these habitats has become possible. Recent work in the Strait of Georgia has identified their role in the northern Salish Sea (Kahn et al. 2015), and management actions like designating reefs as marine protected areas have ensured protection of these habitats.

Glass sponges form reefs similar to tropical corals, where successive generations build upon existing sponge structures. The oldest parts of the reef are cemented together and buried by sediments, forming bioherms. Using scaffolding made of silica, the bioherms formed can be extensive, spanning hundreds of square kilometers and reaching heights of 20 meters or more (66 feet or more). In the Strait of Georgia, the reefs are smaller than in Queen Charlotte Sound and along the northwest coast. The reefs are generally very old, with estimates dating to over 9,000 years in some places (Krautter et al. 2001) and over 200 years in the Strait of Georgia. There are two main species that form the glass sponge reefs of the Salish Sea: the vase sponge (*Heterochone calyx*, sometimes called goblet sponge) and the cloud sponge (*Aphrocallistes vastus*). A third species (*Farrea occa*) is found in northern coastal reefs.

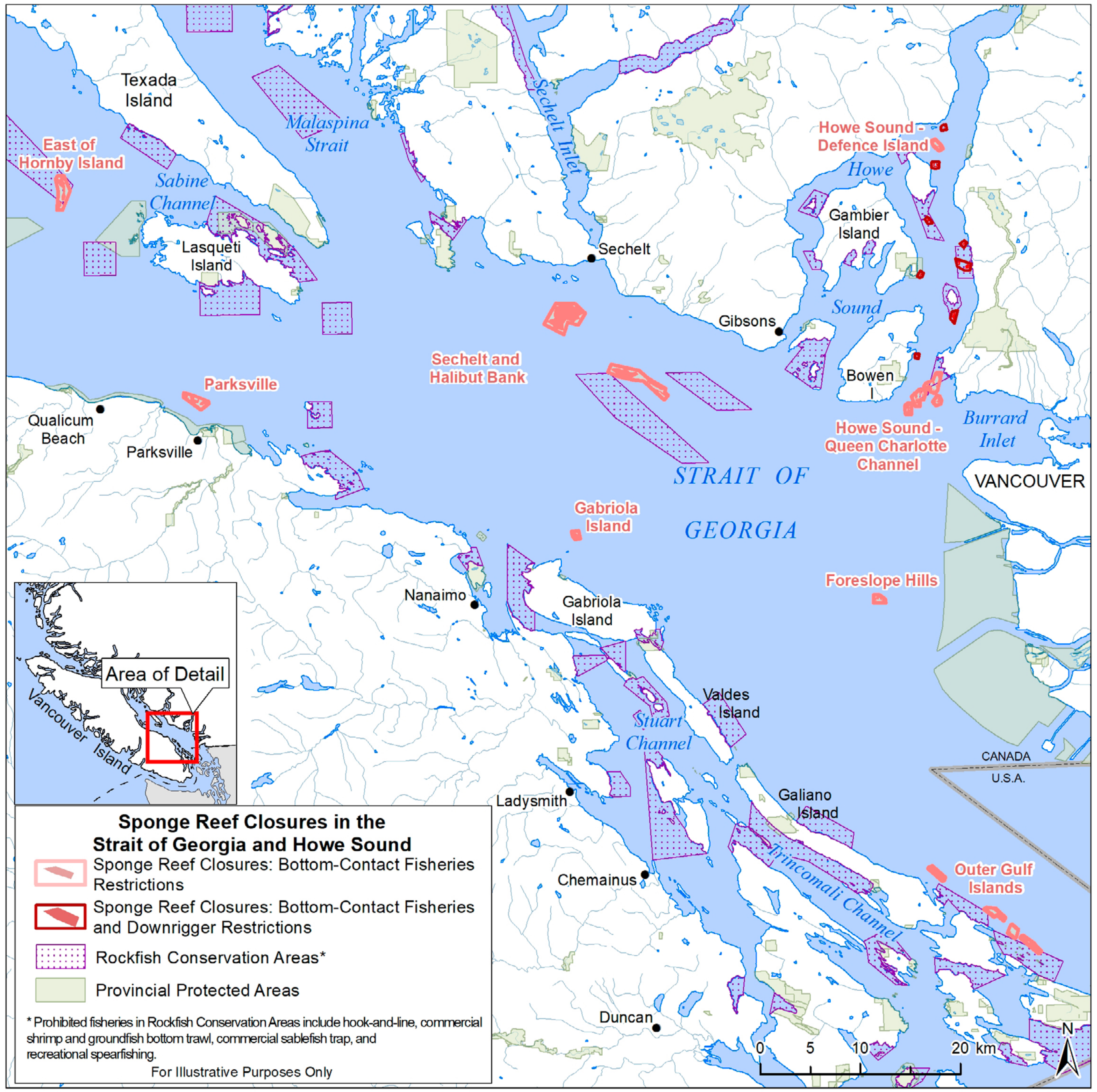
Because the reefs are only found in the northeastern part of the Pacific Ocean, it is believed they require very specific conditions to form. For example, cold water, low light, and high dissolved silica concentrations are all key to colonization and expansion. Levels of dissolved silica are especially high in waters off the Pacific Northwest and because >90% of a glass sponge's body structure is made of silica, it is critical for the growth of the organism and the reefs. Water temperatures at depths where reef-building glass sponges live are between 6°C and 12°C (43°F and 54°F). When glass sponges are exposed to temperatures outside this range they lose their ability to control how they pump water through their colonies, which is their primary means of feeding and waste removal.

Little light reaches the sponge reefs, as most are found below the photic zone where primary productivity occurs. One explanation for the lack of sponges in Puget Sound is the need for hard substrate for recruitment of larvae; the mostly soft-bottom substrates found in Puget Sound are not conducive to settlement (P. Johnson, University of Washington, personal communication). Sedimentation also has a key role in affecting sponge health and reef formation. For the bioherms to form, clay sediments are required to bury and cement the foundation of the reef, but excess sedimentation can smother and kill the live sponges. Puget Sound sees higher sedimentation than many parts of the Strait of Georgia; this may prohibit growth, although sponges can survive in elevated and sheltered parts of the seafloor. For example, live sponges are found on the leeward side of a submarine ridge in front of the Fraser River plume (Chu & Leys 2010).

The reefs contribute to the productivity of benthic ecosystems by forming complex habitat for diverse communities of invertebrates and fish. Surveys have shown over 100 species of fishes and invertebrates to be associated with glass sponge reefs, including rockfish (both juveniles and adults), shrimp, crabs, and other benthic organisms (Marliave et al. 2009; Chu & Leys 2010; Stone et al. 2013; Dunham et al. 2018). The reefs also play an important role in nutrient cycling. Glass sponges are efficient filter feeders removing up to 90% of bacterial cells from seawater they filter, and collectively, reefs can filter about 1% of the total water volume in the Strait of Georgia and Howe Sound daily, despite covering only <0.2% of the area of the seafloor (Dunham et al. 2018). Recent research has focused on the role of glass sponge reefs in carbon cycling, finding that they can remove up to 1 gram of carbon per square meter (g C/m^2) daily, which is impressive and comparable to terrestrial old growth forests and kelp forests (Dunham et al. 2018). As one of the densest known communities of deep-water filter feeders, this is one example of how glass sponge reefs link benthic and pelagic environments through nutrient (carbon and nitrogen) cycling. Because of their immense size and long-lived nature, the sponge reefs act as regionally important sinks of silicon and carbon (Chu et al. 2011; Kahn et al. 2015).

Glass sponges at the Galiano reef in the Salish Sea. Source: Jackson Chu, University of Victoria.

The uniqueness and fragility of these biogenic systems makes them susceptible to climate change and anthropogenic habitat loss. Recognizing that a better understanding of glass sponge reefs is needed and that trawling and other benthic disturbances threaten these important habitats, Fisheries and Oceans Canada has established a marine protected area encompassing the four largest reefs in Hecate Strait and has closed fisheries on 17 reefs in Howe Sound and the Strait of Georgia (Figure 2.9). These bottom-contact fishing closures have been in place since 2015, with the official conservation boundaries formalized in 2018. Ongoing research aims to address glass sponge trophic ecology, carbon sequestration potential, and other ecosystem functions. Meanwhile, recognizing glass sponge reefs as important biogenic habitats and protecting them by designating additional marine protected areas will contribute to their persistence, health, and perceived ecosystem value.



Above: Figure 2.9. Sponge reef closure designations in the Strait of Georgia and Howe Sound. Source: Fisheries and Oceans Canada (2021).

Right: Olympia oysters growing on a Pacific oyster shell Photo: Cheryl Lowe

Oysters

Olympia oyster (*Ostrea lurida*) is the only species of oyster native to the Pacific Coast of North America and the Salish Sea. Olympia oysters were once an important food source for Indigenous peoples (Arima 1983; Batdorf 1990) and, prior to European settlement, dense assemblages of Olympia oysters covered much of the Salish Sea's intertidal zone (Norgard et al. 2018). The Pacific oyster (*Crassostrea gigas*), a non-native species, is more commonly known because it is a commercial product produced by many shellfish growers in the Salish Sea; it was introduced as a faster growing alternative to the Olympia oyster when overfishing decimated native oyster stocks by the early 1900s (Steele 1957). Siltation from large-scale forestry operations and contamination from industry also contributed to decline of the Olympia oyster. Despite these obstacles, Olympia oyster (or native oyster) populations are resurging, and restoration efforts are underway in both Washington and British Columbia waters (see Vignette 4, Olympia Oysters).

Olympia oysters are found in estuaries, saltwater lagoons, tidal flats, and protected areas such as pocket beaches. They live lower in the intertidal zone than Pacific oysters, making them less visible to beachcombers. Like other bivalve mollusks, such as clams, geoducks, mussels, and scallops, oysters are filter feeders, filtering water and particulates (including phytoplankton and zooplankton) throughout the Salish Sea. Compared to the Pacific oyster, Olympia oysters are small, relatively flat, and usually less than 60 mm (2.4 in) in length. Olympia oysters are also well-adapted to upwelling environments, making them more resilient to ocean acidification (Waldbusser et al. 2016). In fact, experimental studies showed temperature and salinity to be more important than ocean acidification in determining larval success (Lawlor & Arellano 2020).

Although populations of Olympia oyster remain relatively small compared to other bivalve species, restoration of this once important native species (and maintenance of shellfish more broadly) is important to the overall health and functioning of the Salish Sea (White et al. 2009; Norgard et al. 2018). Beyond their helpful ability to filter large amounts of water and provide many other ecosystem services, oysters and other shellfish are important cultural and economic resources (Coen et al. 2011). However, these same beneficial attributes make oysters and other shellfish sensitive to natural and anthropogenic change, meaning they serve as important sentinels of change in the Salish Sea. For example, water temperature, ocean acidification, contaminants, and siltation all impair functional shellfish beds, indicating that ongoing monitoring efforts in both Canada and the United States are important, even if most studies are aimed at public health objectives in relation to shellfish harvesting rather than a broader ecological context.

BIOPHYSICAL CONNECTIVITY ACROSS THE SALISH SEA ECOSYSTEM

As discussed above, the intersection and coupling of biogenic habitats with the dynamic and nutrient-rich pelagic environment is partly what makes the Salish Sea such a productive estuarine ecosystem. As in many estuaries, the connectivity within the system is facilitated by filter feeders (e.g., oysters and glass sponges), while primary producers (e.g., eelgrass and kelp) convert nutrients into biomass and create habitats that in turn support numerous fish and invertebrate species. Through physical movement and trophic interactions, these species then transport organic matter from highly productive, shallow, photic zone habitats to deeper benthic or pelagic habitats within the Salish Sea.

While kelp and eelgrass habitats represent only a small proportion of the estuarine area in the Salish Sea, their importance in the food web and overall productivity in the ecosystem is assumed to be much greater (Mumford & Thomas 2007). Similarly, glass sponge reefs represent a very small proportion of area in the Salish Sea, but their function in carbon cycling is considerable (Dunham et al. 2018). The structure and protection these habitats provide for myriad species helps maintain ecosystem coupling and healthy ecosystem services. Their conservation is necessary for ecosystem function and resilience and monitoring their populations will be necessary to detect change (Loh et al. 2019).

Understanding the connectivity of organisms and habitats in this region continues to develop (Gaydos et al. 2009). Once considerable migrations of Pacific salmon with diverse life-histories brought marine-derived nutrients to watersheds (Ben-David et al. 1998; Gustafson et al. 2007). But the diminished runs of Pacific salmon (Bradford & Irvine 2000), especially Chinook and coho salmon, are one example of reduced connectivity between the estuary and watersheds, in this case the connectivity of both adults migrating landward and juveniles migrating seaward (Scheuerell et al. 2011). Within the estuary, organisms like shorebirds and juvenile salmon use shallow, productive tide flats like Padilla Bay, Washington, or Roberts Bank, British Columbia, to feed locally before moving to other habitats (Condon et al. 2013; Luxa 2013). The movement of birds, mammals, and fishes, and the physical transport of material (e.g., sediments, nutrients, carbon) from the surrounding watersheds, through the Salish Sea ecosystem, and out to the continental shelf and beyond makes it clear that the Salish Sea contributes to—and is reliant upon—a truly vast spatial scale.

Scientist measuring eelgrass bed
Photo: Ronald Thom

01 THE SALISH SEA ESTUARY SYSTEM

Dr. Bert Webber, Senior Fellow, Salish Sea Institute

The entirety of the Salish Sea is an estuarine ecosystem. Nested within the larger Salish Sea watershed, this estuarine ecosystem is the source of the rich biological structures and functions that make the Salish Sea of particular interest. It is the place where the freshwater from land drainages mixes with the waters of the Pacific Ocean and results in water with a measurable, although sometimes small amount of freshwater. One of the Salish Sea's unique characteristics is that in most places the water is quite salty. The Pacific Ocean off the Washington coast is around 34 PSU (practical salinity units, how salinity in water is measured), while most places in the Salish Sea have a surface salinity only a bit less—around 29 PSU. To most people's taste, this water would seem as salty as the ocean, but it is still a genuine estuary, where seawater is diluted with freshwater.

The Salish Sea is among the preeminent estuaries of North America, such as San Francisco Bay, the Florida Everglades, Chesapeake Bay, the St. Lawrence River, and Bristol Bay to name a few. All of these estuaries share the characteristic of high biological productivity. Estuaries are four times more productive than terrestrial grasslands, are twenty times more productive than the open ocean, and rival the most productive terrestrial crop, sugar cane, in terms of biological productivity. Like forests, grasslands, and intensively cultivated agriculture lands, estuaries produce high amount of organic material.

The food webs—pelagic, demersal, and nearshore—are diverse and rich. In the water of the estuary there is an abundant and complex array of species. The foundation of the pelagic zone is the photosynthesis of microscopic organisms—the phytoplankton. They create the food source that sustains the animal life, including the species we value as food, like the forage fish, and the larger species of fish, like salmon and rockfish. As well, many bird and mammal species depend on this complex food web. Near the shorelines the estuary supports rich beds of seagrasses and kelps, species with high value as habitat for many animal species.

We have known for some time (the 1970s and 1980s work of Curtis Ebbesmeyer and others) that there is a two-way circulation of waters in the Salish Sea. Surface waters move towards the ocean, and deeper waters move from the ocean into the Salish Sea. The movement is subtle and cannot be easily detected looking at the surface of the water on timescales in which we might make casual observations.

What causes the estuarine circulation? As the water from a river flows over the surface of the estuary, it moves seaward, pushed by the incoming river flow. As the freshwater moves across the surface of the estuary, the friction between the river flow and estuary below causes the deeper water to be pulled towards the surface, a process called entrainment. In a flat bottom estuary like Chesapeake Bay, entrainment continually pulls saltier water from below, and the salinity of surface water increases. In the absence of any other disturbance like wind, entrainment continues until the water is well-mixed and uniform.

The Salish Sea is different. Because of the irregular bathymetry, there are locations with active tidal currents where the water is agitated from surface to bottom. In these "washing machine" areas, water is vigorously mixed from surface to bottom, and surface water salinity increases. This is the mechanism that results in the surface water of the Salish Sea being so salty. Once through the tidal currents, the estuarine circulation is restored, with saltier water on the bottom and fresher water at the surface, and the journey to the mouth of the estuary continues.

So how much water is involved with the estuarine flow? The annual discharge of Salish Sea rivers allows us to calculate the total annual estuarine flow. The amounts are immense. Estuarine scientists have determined the entrainment of deeper water by the pushed surface water is between 10 and 20 times the river flow. This mixing of the rivers' freshwater and the deep Pacific Ocean water creates an immense movement of surface water towards the ocean mostly via the Strait of Juan de Fuca. A conservative estimate indicates that the amount of the outward estuarine flow from the Salish Sea through the Strait of Juan de Fuca is equal to a value that is eight times the annual flow of the Columbia River.

This freshwater flow drives estuarine circulation throughout the Salish Sea. We know that the replacement time of the total water of Puget Sound (the residence time) is around 3-6 months. That is, the volume of Puget Sound is replaced about tthree times a year by estuarine circulation. The outgoing estuarine flow is replaced by higher salinity, nitrogen-rich ocean water entering the Salish Sea at depth. This inflow works its way into all parts of the Salish Sea, providing the relatively high values of biological nitrogen that fuel the productive ecosystem.

While most of the biological nitrogen originates from the ocean waters, high concentrations of biological nitrogen remain in the outflow as well, stimulating primary productivity of ocean surface waters off Vancouver Island and the northwest coast of Washington.

The nature of this circulation, the rich biological systems dependent of the flow, and the resilience of the freshwater sources that drive estuarine flow are central to the Salish Sea Ecosystem.

The Salish Sea from space
Photo: NASA 2021

02 LOWER TROPHIC LEVELS IN THE SALISH SEA: RECENT FINDINGS FROM THE STRAIT OF GEORGIA

Dr. Ian Perry, Pacific Biological Station, Department of Fisheries and Oceans

Plankton form the base of the pelagic marine food web in the Salish Sea, and are eaten by fishes, marine mammals, and seabirds. Plankton include microscopic plants (phytoplankton) and very small animals (zooplankton). They drift in the water but can accumulate in very large numbers as a result of water currents, and growth and reproduction. In the Canadian waters of the Salish Sea (including the Central and Northern Strait of Georgia, and the Strait of Juan de Fuca), diatoms (which are single-celled algae that have a cell wall of silica) make up most (over 90%) of the phytoplankton during spring, but in the summer the phytoplankton are composed of a greater variety of species, in particular of small flagellates (which have cell walls composed of cellulose). Autumn has the greater diversity of phytoplankton species, with a mixture of flagellates remaining from the summer and diatoms beginning to grow again when storms mix nutrients back into the surface layers of the Strait (Nemcek et al. 2020).

Chlorophyll a is the main pigment in plants (it makes them green) and is used as a measure of the amount (or biomass) of phytoplankton. Seasonally, chlorophyll a in the Strait of Georgia is lowest during the winter when there are lots of nutrients but plant growth is limited by low light levels, highest during the spring when nutrients and light are optimal for growth, low during summer when nutrients are low, and higher again with episodic blooms during the autumn caused by wind events, which replenish the nutrients in the upper water layers (Figure 1, Suchy et al. 2019).

Phytoplankton chlorophyll concentrations have been monitored by satellites since 2003 and have been used to understand year-to-year changes in the amount of phytoplankton in the Strait of Georgia (Suchy et al. 2019). Moderate to high concentrations of chlorophyll a occurred in this region in 2005 and 2015, concurrent with early and strong flows of freshwater from the Fraser River into the Strait of Georgia, and with low numbers of windstorms. Chlorophyll a in the Northern Strait of Georgia over the period 2003 to 2016 was related to the temperature at the surface of the water and to the amount of light available for the plants to grow (which varies among years depending on cloud cover). In the Central Strait of Georgia over this same time period, Chlorophyll a concentrations were related to the amount of freshwater flowing from the Fraser River. All of these physical processes (sea temperature, amount of light for growth, and freshwater from the Fraser River) control the extent of vertical mixing in the Strait of Georgia, which in turn controls the amount and types of phytoplankton that grow in the Strait during the year. The median Chlorophyll a concentration in the Northern Strait of Georgia is also related to several atmosphere/climate indices, such as the Pacific Decadal Oscillation, but not in the Central Strait. This suggests that phytoplankton dynamics in the Central Strait of Georgia are more strongly influenced by local factors, such as flow from the Fraser River. While Chlorophyll a is an indicator of phytoplankton biomass, it does not tell the entire story of phytoplankton production because much of the phytoplankton is consumed by zooplankton.

Zooplankton are the small animals that largely feed on the phytoplankton, and in turn are eaten by other zooplankton, fishes, marine mammals, and seabirds. They have been monitored consistently in the Central and Northern Strait of Georgia since 1996 (Mackas et al. 2013). Total zooplankton biomass was highest in the late 1990s, then declined quickly to a minimum in 2005, and has recovered since 2010 to above normal

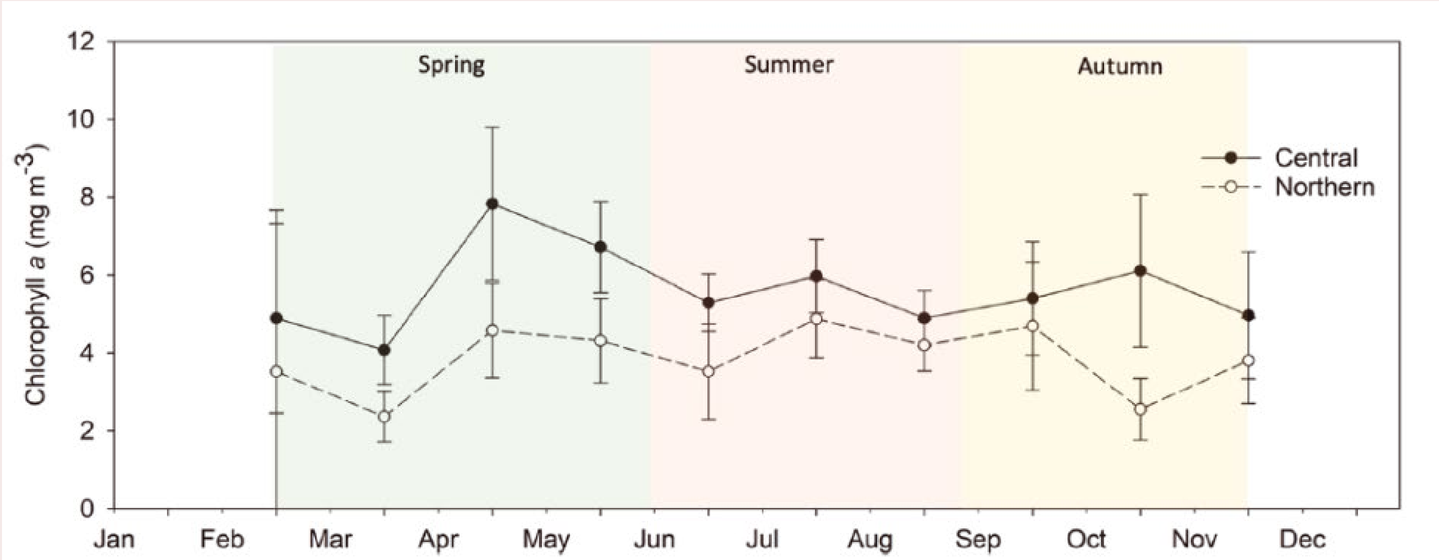


Figure 1. Typical pattern of monthly chlorophyll a concentrations in the Central and Northern regions of the Strait of Georgia as determined from weekly satellite remote sensing from 2003 to 2016. Vertical bars represent the 95% confidence intervals about the monthly mean values. Source: Reproduced from Suchy et al. (2019).

biomass levels (Figure 2; Perry et al. 2021). Most (76%) of the biomass of zooplankton are composed of four types of animals: medium and large copepods, euphausiids, and amphipods. Interannual changes in zooplankton biomass over this period were related to the salinity at the sea surface, the timing of the bloom of phytoplankton during the spring, and the Pacific Decadal Oscillation (a large-scale climate index).

Zooplankton abundance is important for the marine food web, and variations in the types of zooplankton and their abundance can impact growth and survival of fishes. Statistical models that included salinity, sea temperature, freshwater flow from the Fraser River, and the wind over the sea surface (all of which control the vertical mixing of the water column and the circulation in the Strait of Georgia), as well as zooplankton biomass, explained much (38-85%) of the interannual variability of the early marine survival rates of three populations of Chinook salmon in the Canadian waters of the Salish Sea. However, these analyses were based on conditions that occurred from 1996 to 2018; if climate change pushes conditions outside of those observed during this period, these statistical relationships may break down. Climate change—and the resulting change in river flow, temperature, or wind patterns—may lead to unusual and unexpected patterns of phytoplankton and zooplankton, which in turn could affect early marine Chinook salmon survival and the growth and development of other zooplankton-eating organisms.

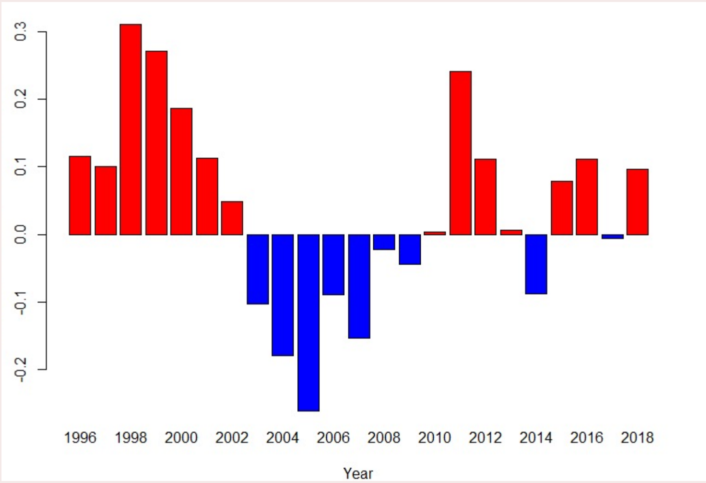


Figure 2. Total zooplankton biomass in Central and Northern Strait of Georgia, 1996 to 2018 (values shown are 'anomalies' or differences from the average values between 1996 to 2010). Source: Modified after Perry et al. (2021).

03 | BIRDS OF THE SALISH SEA

Dr. Rob Butler, Pacific WildLife Foundation

The Salish Sea—the largest inland sea on the west coast of Canada and the United States—supports jobs, supplies food, attracts tourists, provides recreation, is the basis of Indigenous cultures, and provides ecosystem services. Millions of people reside along its shores, and thousands of jobs are connected to the Salish Sea. Tourism and recreation related to bird watching and whale watching is a growing market. The Salish Sea is the ancestral home to Indigenous people whose ancient culture is connected to birds and mammals. The presence and abundance of birds and marine mammals indicates a healthy ecosystem and establishes a baseline for recovery. To sustain these animals and all they provide to us requires saving their homes, halting persecution, and preventing pollution of their food.

The significance of the Salish Sea comes into focus when we look at the diversity and abundance of its birds and mammals, some of which are globally, continentally, and nationally important. Of particular importance is the diversity and abundance of species on the Fraser River Delta. There are more species of birds on the delta than any comparable area in Canada, and nearly half of all 550 species of birds reported for British Columbia have been seen on the delta. Maximum single day counts for all species tallies to about 2 million birds, and the number that pass through on migration is several times greater. For example, over a million shorebirds migrate across the delta and through the Salish Sea annually, and hundreds of thousands of waterfowl spend their non-breeding season there.

Other areas in the Salish Sea attract large numbers of birds and marine mammals. When Pacific herring spawn on the east coast of Vancouver Island in late winter and early spring, tens of thousands of seabirds and seaducks, and hundreds of sea lions assemble to feed on fish and eggs. Channels and passages with high tidal flow can draw thousands of gulls. Whales from Hawaii and Mexico and seabirds from across the Pacific assemble in large flocks at the western entrance to the Strait of Juan de Fuca.

Among the 172 species of birds that use the waters of the Salish Sea each year (Gaydos & Pearson 2011) are waterfowl, loons and grebes, seabirds, herons, birds of prey, and shorebirds, whose collective annual ranges encompass the area bounded by Siberia, the Canadian High Arctic, Florida, and Peru.

Commonly encountered waterfowl in estuaries with agricultural lands in winter are the snow goose, trumpeter swan, American wigeon, northern pintail, green-winged teal, and mallard. Rocky shores yield thousands of surf scoters and Barrow's goldeneyes, and four Pacific Northwest endemic shorebirds: the black turnstone, black oystercatcher, surfbird and rock sandpiper. In spring and summer, mudflats are frequented by over 50 species of shorebirds, including hundreds of thousands of western sandpipers, and some rocky islands support a breeding cadre of Pacific Northwest species such as glaucous-winged gull, pelagic cormorant, pigeon guillemot and black oystercatcher. Late summer brings post-breeding common murres, Heermann's, Bonaparte's, and mew gulls. Ancient murrelets enter the Salish Sea in autumn and marbled murrelets spend the winter there. Killer whales come in search of salmon and marine mammals as prey, harbour porpoise, white-sided dolphins, and humpback whales seek schools of small fish, and gray whales plough up mudflats in pursuit of marine invertebrates.

The diversity and abundance of birds and marine mammals is built on an ecological foundation of marshes, mudflats, rocky shores, mixing of ocean currents, tides, and river flow that provide plankton, fish, and plants as food. High densities of plankton

A bald eagle takes off from tree branch
Photo: Taylor Bayly

occur off the Fraser River plume, serving as food for herring, sandlance, and anchovy that are eaten by diving birds, gulls, and marine mammals; biofilm forms on estuarine mudflats supplying energy needs for migrating sandpipers; eelgrass growth in spring provides a nursery for small fish for diving birds; and mussels and other marine invertebrates feed the large numbers of seaducks.

The abundance and diversity of marine birds and mammals has led to conservation initiatives to safeguard their presence. Twenty-two areas in the Salish Sea have been designated as Important Bird and Biodiversity Areas, of which the Fraser River Estuary has the greatest number of global, continental, and national species in Canada. Waters in the southern Strait of Georgia and the Strait of Juan de Fuca have been identified as an Important Cetacean Area for gray and humpback whales and critical habitat for endangered southern resident killer whales.

Despite all that has been learned about marine birds and mammals, large areas of the Salish Sea in Canada have not been systematically surveyed. The Salish Sea Marine Bird and Mammal Atlas is a project led by the Pacific WildLife Foundation with our partner Birds Canada, aimed at systematically mapping the distribution of marine birds and mammals in the Canadian waters. The atlas project used standard protocols to survey birds along the shore and at sea. The atlas will combine three decades of land-based bird surveys in Birds Canada's Coastal Waterbird Survey with surveys at sea led by Pacific WildLife Foundation. The atlas will be available online as an Esri storymap with links to technical reports and raw data of at sea surveys and the Coastal Waterbird Survey. The data will be useful for environmental assessments, sea level rise impacts, and tourism and recreation planning, and will serve as a baseline to measure change in the future.

04 | OLYMPIA OYSTERS

Dr. Jodie Toft and Betsy Peabody, Puget Sound Restoration Fund

Olympia oysters (*Ostrea lurida*) are our only native oyster species here in the Salish Sea. The namesake of Washington State's capital and a sought-after delicacy for miners during California's Gold Rush, Olympia oysters once covered an estimated 13-26% of the intertidal area in Puget Sound, mostly near the heads of inlets. A combination of overharvest, pollution, and habitat loss reduced the current population to less than 4% of historic numbers, though sparse numbers of Olympia oysters can still be found throughout most of their historic distribution. Looking to the future, as our region's marine waters experience effects of climate change and ocean acidification (OA), native species such as the Olympia oyster may prove to be a critical building block in overall resilience of the marine ecosystem. Not only do Olympia oysters provide a suite of ecosystem services including water filtration and creation of intertidal habitat structure, but they may have adapted over the eons to cope with wide fluctuations in the pH of Puget Sound, possibly making them hardy to OA-induced stress. In experiments conducted at Oregon State University, Olympia oyster larvae have shown themselves to be more tolerant to low pH levels than non-native Pacific oysters, perhaps due to Olympia oysters' relatively slow development (Waldbusser et al. 2015). By bringing back what was once abundant—our small but mighty Olympia oyster—we may also be bringing a more reliable stream of benefits that they provide—including improved water quality and local food—as they (and we) weather changing ocean conditions.

Olympia oyster restoration in Puget Sound has been underway since 1999. It has grown into a sustained priority for state, federal, tribal, and nonprofit partners working to improve the health of the Salish Sea. Puget Sound Restoration Fund (PSRF), a local non-profit dedicated to restoring foundational elements of Puget Sound's marine ecosystem, and many other partners have been restoring Olympia oysters in Puget Sound in several of 19 priority locations. Those locations are described in Washington Department of Fish and Wildlife's 2012 updated Olympia oyster stock rebuilding plan. The 19 sites are locations where Olympia oyster populations were once abundant and also sites that, once populations are restored, may serve as source populations, spilling over to repopulate other areas of Puget Sound.

The main methods for restoration are to add settlement substrate to areas where Olympia oyster larvae are found, and to distribute oyster seed as spat-on-shell or individual oysters. For the first method, the substrate most often used is clean Pacific oyster shell, which is distributed over the restoration site to provide habitat for Olympia oyster larvae to settle on. The second tool in the restoration toolbox is to distribute restoration-grade Olympia oyster seed as spat-on-shell or small, individual oysters across the restoration site. Spat-on-shell, as the name indicates, refers to small Olympia oysters that have settled onto Pacific oyster shells, which provide structure for the settlement of larval Olympia oysters. It turns out, Olympia oysters love the rough, craggy surface Pacific oyster shell provides. The bags of shell are then delivered to restoration sites, opened and spread across the area of interest. In areas without breeding populations, reintroduction of Olympia oyster seed serves as a jump start for the population. Spat-on-shell production happens either by catching Olympia oyster larvae in the wild or producing them in a conservation hatchery. If in the wild, bags of Pacific oyster shells are placed within the basin of interest in areas where monitoring has shown Olympia oyster larvae to be abundant. If larvae successfully settle, the spat-on-shell bags are then relocated to the restoration site. Alternatively, adult broodstock oysters are collected in the wild, from within the same basin as the prospective restoration site, and brought to a conservation hatchery, where larvae are produced and settled onto bags of shell following conservation genetic protocols. A key element of this strategy is having a conservation hatchery (or following conservation protocols within alternative settings).

In 2014, PSRF, the National Oceanic and Atmospheric Administration (NOAA) and other partners took a bold step forward for Olympia oyster restoration by establishing the Kenneth K. Chew Center for Shellfish Research and Restoration, which PSRF operates at NOAA's Manchester Research Station. The Chew Center is dedicated to research and production of native shellfish and other Pacific Northwest living marine resources. The development of a conservation hatchery was identified as a high-level need in both phases of the Washington Shellfish Initiative, as guided by the National Shellfish Initiative, and as a recommendation of the Blue Ribbon Panel on Ocean Acidification in the 2012 and 2017 reports. The facility is operated through a cooperative research and development agreement (CRADA) between NOAA and PSRF. With the Chew Center up and running, PSRF and partners could accelerate the pace of restoration and continue to ensure that restoration-grade spat-on-shell were produced, with genetic fidelity to the basins in which restoration was to take place. The collaboration was further solidified in 2017, when the state began providing base-level funding to cover 50% of hatchery operations through the Washington State Department of Fish and Wildlife.

The capacity to produce Olympia oysters for priority locations also supported an ambitious goal, set in 2010, to restore 100 acres of Olympia oyster habitat by the end of 2020, in partnership with multiple stakeholders. We successfully reached the restoration goal in 2020, buoyed by restoration in Sinclair Inlet, Liberty Bay, Port Gamble Bay, Fidalgo Bay, Dyes Inlet, and many other locations. The work is highly collaborative in nature, with partnership and support from a dizzying array of groups, including Washington State Departments Fish and Wildlife, Ecology, and Natural Resources, the Suquamish Tribe, the Swinomish Indian Tribal Community, the Jamestown S'Klallam Tribe, the Port Gamble S'Klallam Tribe, the Squaxin Island Tribe, the Skokomish Tribe, the Nisqually Indian Tribe, the Samish Indian Nation, the Tulalip Tribe, Northwest Straits Commission and Marine Resource Committees, NOAA, shellfish growers, tideland owners, University of Washington, and United States Department of Agriculture's Natural Resources Conservation Service. To put this collective accomplishment into perspective, only 150 acres of natural, dense Olympia oyster beds were estimated to exist in 2010.

In recent years, restoration of Olympia oysters has expanded and taken hold beyond the Salish Sea. In California, Oregon, and British Columbia, groups have been working to bring back assemblages of the West Coast's native oyster, building from lessons learned in Puget Sound, as well as early seeding efforts in Oregon in the mid-1990s. The group of oyster conservation and restoration practitioners that has developed on the West Coast is known formally as NOOC—the Native Olympia Oyster Collaborative. For the curious among us, NOOC has recently launched a story map to showcase nearly 40 Olympia oyster restoration projects, distill findings, and serve as a powerful and collective communication tool.

The success story of the return of Olympia oysters is beginning to unfold. The truth is that they have been here all along, just hidden away in small numbers—present, not abundant, yet a persistent part of our nearshore ecosystem. As this once high-profile species makes its way back into our region's conversations, it reemerges as part of our culture. And as we rebuild low density aggregations into complex, three-dimensional habitat, we rebuild a fundamental part of our marine ecosystem, one that supports fish, invertebrates, and ultimately, one that supports us.

SECTION 3

URBANIZATION AND HUMAN IMPACTS TO THE SEASCAPE

English Bay, Vancouver BC, with Mount Baker
Photo: Kimon Berlin

SECTION 3

EVIDENCE FOR SEASCAPE CHANGE

ECOSYSTEM CONVERSION, FRAGMENTATION, AND LOSS

Changing Watersheds
Development in Floodplains and along Shorelines
Shoreline Hardening and Disruption of the Shoreline Ecotone

INPUTS FROM HUMAN ACTIVITIES

Contaminants
Nutrients
Marine Debris
Vessel Traffic and Associated Concerns

VIGNETTES

5: Blocking Culverts Impact Salmonid Survival
6: Living Shorelines in Puget Sound
7: Stormwater Effluent Exerts a Key Pressure on the Salish Sea
8: Connection to Place: Indigenous Leadership in səlilwət
9: Derelict Fishing Gear
10: Biological Repercussions from Microplastics in the Salish Sea
11: Ecological Consequences of Built Shorelines in the Salish Sea

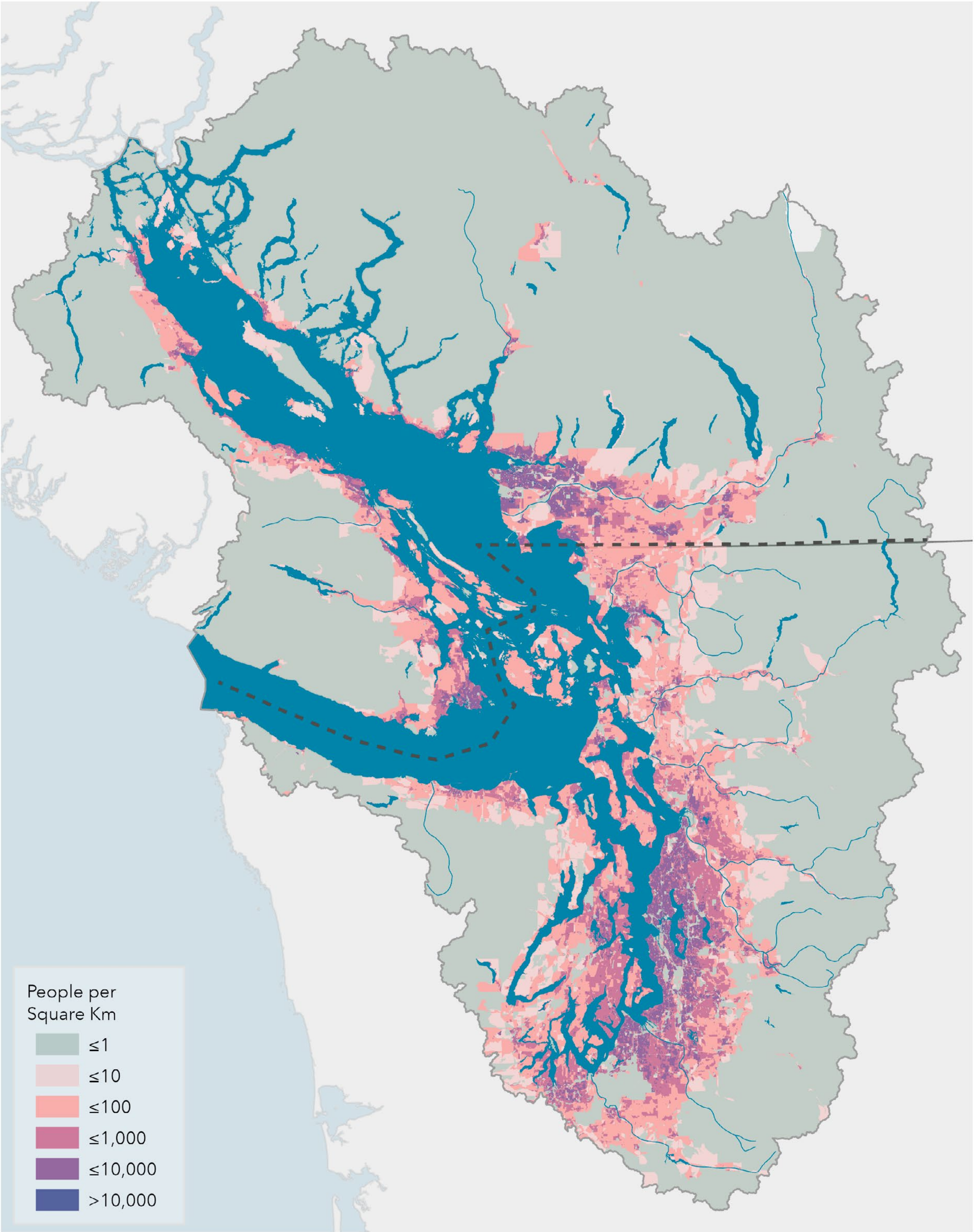


Figure 3.1. Human population density in the Salish Sea. People per square kilometer mapped for each census block. Data from 2010 in the US and 2011 in Canada.

Map by Aquila Flower, 2021

While the focus of this report is on the impacts to the Salish Sea seascape in the most recent 25 years, much of the region's landscape fundamentally changed more than a century ago. Since British and American colonists established trading outposts around the Salish Sea in the mid-1800s, there have been waves of settlers, urbanization, and concomitant population growth. By the early 1900s, the Salish Sea region saw rapid population growth: Seattle grew from 55,000 to 275,000 between 1897-1914 and Vancouver from 20,000 to 125,000 during the same period (MacDonald 1970). Population booms in this region occurred after World War II, and in the last two decades. With this population growth came extensive land-use change, with the building of railroads along the shorelines, conversion of land for agriculture, and the development of Seattle and Vancouver as major metropolitan areas. Both cities served and continue to serve as major ports, fostering the trade of goods, economic development, and the establishment of many residential neighborhoods feeding ever-greater population density.

Development continued over the course of the last 100 years, with expansion and renovation of existing infrastructure continuing to impact the estuarine ecosystem. Construction of roads, buildings and landscapes suited for human use drastically changed hydrology by increasing the extent of impervious surfaces while decreasing open space and forest cover. Additionally, stormwater runoff, industrial chemicals, and fertilizers and other chemical pollutants from lawns and agricultural lands entered regional estuarine waterways, fundamentally impacting the ecosystem. Meanwhile, access to the shoreline for recreation, subsistence harvest, and aesthetic value remained a high priority, but these uses were threatened by declining water quality, closed shellfish beaches, and limited access due to privatization as populations have continued to grow. While legislation in both countries in the 1970s improved water quality, many of these problems continue to this day through legacy pollutants, continued runoff from urban areas, and contaminants of emerging concern via wastewater treatment for a growing population.

In the Salish Sea region, nearly 9 million people reside within the Sea's greater watershed (8.76 million; S. Bartnik, Environment and Climate Change Canada, personal communication, Figure 3.1). The coastal population of British Columbia has grown to over 3.8 million people, from 2.9 million 20 years ago, with projections of 4.6 million by 2030 (Ip & Lavoie 2020). The population within Puget Sound, Washington is projected to exceed 4.8 million people this decade (Puget Sound Regional Council 2018). In addition to overall continued population growth in the Salish Sea, population in areas outside of cities has grown, shifting population demographics in suburban and exurban areas (Robinson et al. 2005). While urban growth in cities has continued, the additional growth in outlying areas has resulted in additional habitat fragmentation and loss. By the year 2025, the human population within the Salish Sea ecosystem is expected to expand beyond 9 million people, with an increasing trend through 2050.

Beginning with the Coast Salish peoples, who have been in the region for over 10,000 years, the landscape has been changed by human presence and activity (Suttles 1963; Carlson et al. 2001). The Coast Salish harvested cedar for buildings and canoes (Turner & Bell 1971; Lincoln 1990), fished local rivers, and built organized villages as the center of cultural and economic activities (Lepofsky et al. 2009; Schaepe 2009).

With each successive wave of growth after European settlement came increased conversion of native forests and wetlands to agricultural land, housing developments, and urbanization. Around the shores of the Salish Sea there has been extensive development of private and public infrastructure in support of the region's burgeoning population and economy ever since. Development of hard structures in estuarine and marine systems, from aquaculture infrastructure to ports and piers, has been termed "ocean sprawl" (Duarte et al. 2013; Firth et al. 2016; Bishop et al. 2017) and is growing at a rapid rate worldwide.

Thousands of species of birds, mammals, and other animals call the Salish Sea home and rely on intact habitats in both terrestrial and marine ecosystems for their lifecycles (Gaydos & Pearson 2011). Land use practices across the watershed impact the flow of water and biological materials, which then impacts connectivity among biotopes. These disruptions negatively impact estuarine biogeochemistry, flora, and fauna (Copping et al. 1994; Groulx et al. 2004). In response, the rising concern about cumulative environmental and social impacts of urban and suburban sprawl—and associated loss of habitats throughout the Salish Sea ecosystem—has given rise to "smart growth" approaches to land-use planning and development. Among many attributes, smart growth development and conservation strategies seek to integrate, and attempt to balance, protection of human health and enterprise, ecological health and function, and the long-term sustainability of both (BC Government 2006). For example, recent planning initiatives have resulted in mandated shoreline buffers (through the Shoreline Management Act in Washington, WAC 173-26-221), reduction of shoreline armoring and associated permit applications, and restoration of native habitats. Despite some progress, a lack of enforcement of code violations and weak regulations in some regions continue to result in ongoing impacts.

Unless efforts to curb human impacts increase at a pace greater than the losses induced by a growing population, a vision shared by many for "no net loss" of ecosystem function will be unmet. Further impacts to the estuarine ecosystem are inevitable in light of the growing human population. Slowing, mitigating, or reversing, where possible, the deterioration of the Salish Sea estuary, including river-mouth deltas, shorelines, marine habitats, and their ecological structure and function is a grand challenge for the next 25 years and beyond.

> *"I think here in our waters in... the Salish Sea, we're caught a bit in a vice grip. One arm is rapid climate change – our waters are warming and they're becoming more acidified. At the same time, we're piling on human population. Those two factors act synergistically, and both put a lot of stress on our marine ecosystem. Both factors contribute to... problems with sustainable ecosystems."*
>
> Dr. Drew Harvell
> Professor of Marine Ecology at Cornell University
> and affiliate faculty at the University of Washington
> School of Aquatic and Fishery Sciences

Logs rafted near the mouth of the Fraser River estuary, Iona Beach, BC
Photo: Yuri Choufour

EVIDENCE FOR SEASCAPE CHANGE

This subsection focuses on three key problems that a growing population has brought upon the Salish Sea: habitat fragmentation and loss, contaminants and other anthropogenic inputs to the marine ecosystem, and resource extraction. The emphasis is on direct impacts to the Salish Sea estuarine ecosystem, but the discussion recognizes that watershed and estuarine processes are tightly linked through flow of water, sediments, organisms, and detritus. Indeed, the Salish Sea watershed stretches from the mountain crests and extends across the coastal shelf, where marine waters influence and are influenced by activities in the Salish Sea.

ECOSYSTEM CONVERSION, FRAGMENTATION, AND LOSS

Changing Watersheds

The combined loss of native forest, conversion to timberland, and loss of vegetated cover to impervious surfaces has impacts to streamflow (volume and timing) and biogeochemical cycling. Additionally, as vegetated land is replaced by solid and paved surfaces resulting from urbanization (Figure 3.2), there are increased changes to hydrology. Large areas of impervious surfaces prevent the natural and gradual percolation of water into the soil, thereby increasing immediate runoff, flooding, erosion and sediment loading, and other impacts. The percent of impervious surface in a watershed has been correlated with low biological condition, while mixed-species and mixed-age-class forest cover has been associated with higher ecological function related to fish habitat, biological integrity, and hydrology (Booth et al. 2002).

Decades of industrial-scale timber harvest in the Pacific Northwest have converted what was once extensive multi-species and high-functioning old growth forest into mono-cropped timber plantations. Timber plantations lack the diversity and understory of native forests, affect the soil ecosystem, and reduce summer streamflow relative to mature and old-growth forest (Hicks et al. 1991; Jones & Post 2004). A study in Oregon showed that average daily streamflow in summer (July through September) in basins with approximately 35-year-old plantations of Douglas fir was 50% lower than streamflow from reference basins with old growth forests (>100 years old) dominated by Douglas fir, western hemlock, and other native conifers (Perry & Jones 2017). These studies imply that many forested watersheds in the Pacific Northwest are experiencing streamflow deficits caused by past and ongoing logging operations and replanting of monocultures, despite short-term increases in flow immediately following harvest (Segura et al. 2020). From a landscape perspective, extensively harvested and replanted watersheds are likely suffering sustained depletion of stream flows, especially during the summer and early fall months when precipitation is rare, prior to the annual onset of seasonal rains (Coble et al. 2020).

This reduction in streamflow has consequences for riparian vegetation and riverine and estuarine organisms, such as fishes. Threatened and endangered salmon seeking summer rearing habitat in streams and estuaries, such as steelhead trout, may be particularly affected (Scheuerell et al. 2021). The reduction of freshwater delivery into the deltas and estuaries within the Salish Sea also has impacts for those same salmon as they migrate downstream (Bottom et al. 2005). Outmigrating salmon are reliant on freshwater flows entering estuaries to ease their physiological transition to saltwater;

a reduction in streamflow in the summer months, when salmon are utilizing river mouth estuaries, may make this transition more challenging (Bottom et al. 2005; Morrice et al. 2020). Additionally, returning adults are challenged by low flows and high temperatures (Bowerman et al. 2017; Sergeant et al. 2017). Warming stream temperatures that are facilitated by lower flows and higher temperatures associated with climate change will further stress both resident and migratory species.

In addition to regulating flow, vegetated landscapes and riparian vegetation can provide a buffer from runoff containing pollutants. For example, impervious parking lots and roads collect pollutants, such as oils, which are then transported from these paved surfaces directly into streams and estuaries through the stormwater system (Klapproth & Johnson 2000). Contaminants washed off from these surfaces continue to flow downstream and into the Salish Sea (see the "Inputs from Human Activities" subsection below for an in-depth discussion). Where forests remain intact, natural waterways and riparian vegetation reduce this input by facilitating water absorption into the soil and by trapping pollutants and sediment before reaching the waterway (Everest & Reeves 2006).

River mouth deltas in the Salish Sea rely on riverine sediment supply for maintaining land surfaces (Church & Krishnappan 1998; Czuba et al. 2010). However, industrial-scale human activities in the watersheds, such as logging and construction, can cause erosion, with the excess sediment often deposited downstream in estuaries. This deposition is complicated by levees and dikes that do not allow stream and river sediment loads to disperse, which can lead to localized flooding (Grossman et al. 2011). Excess sediment deposited in some areas can smother emergent marsh vegetation, eelgrass, and bottom-dwelling animals, such as estuarine crustaceans, insects, and other invertebrates forming the base of the food web. Meanwhile, other areas are not getting the sediment supply needed to build beaches or account for subsidence from past human activities to keep up with rising sea levels (Nowacki & Grossman 2020).

Vegetative cover and hydrologic processes in watersheds may seem separate from marine and estuarine processes, but the disruption and loss of function in these upstream systems has direct and indirect impacts on many shoreline habitats in the Salish Sea. The most direct and intuitive of these impacts may be the human- and climate change-induced changes in the natural flow of water and sediment into the nearshore. The removal of the Elwha Dam in Washington was a large-scale demonstration of the importance of watershed processes (especially sediment supply) in building and maintaining nearshore habitats (Rubin et al. 2017). Over 3.5 metric tons of sediment accumulated along the shore within two years after dam removal, thus building an entirely new shoreline after 100 years of sediment sequestration behind dams had left the beaches sediment-starved (Gelfenbaum et al. 2015). While most connections between watersheds and the estuary are not this dramatic, they are nonetheless important.

Other impacts include undersized and broken culverts that impede outflow of freshwater and passage of materials from the watersheds, disrupting hydrologic processes. Organisms, especially salmon, are also impeded by the disconnection caused by culverts and otherwise diverted waters (see Vignette 5, Impacts of Culverts). In the lower watersheds and estuaries, tide gates impede inflow of saltwater to marshes and further impact outflow of freshwater from the watersheds, changing the hydrology of these important transition zones (Souder et al. 2018). Combined with habitat loss of important tidal wetlands, reduced function in those that remain further threatens their ability to maintain sediment surface elevation to keep up with sea level rise (Brophy et al. 2019).

Figure 3.2. Land cover in the Salish Sea bioregion. Land cover categories modeled using 30x30 meter resolution gridded satellite data from 2015.

Map by Aquila Flower, 2021

Development in Floodplains and along Shorelines

Floodplains (i.e., the broad areas located next to rivers, streams, and coasts) are dynamic natural systems constantly changing from reworking by river waters and deposited and eroded sediments. Floodplains provide essential habitat for wildlife, improve water quality, and protect human communities by allowing natural seasonal floodwaters to be absorbed by the surrounding landscape (Ward et al. 1999). At the same time, floodplains have long been considered desirable building sites, especially along navigable waterways and marine shorelines. The development of floodplains and estuarine wetlands has led to reduced capacity for buffering of floodwaters, resulting in increased diking and armoring of shorelines to (ostensibly) prevent flooding and erosion. Urbanization and armoring in floodplains and along shorelines have come at a net loss for wetland vegetation, like native swamp forests and emergent marshes that absorb floodwaters and are such vital habitats for many animals, from songbirds to salmon.

The shores of the Salish Sea and its contributing tributaries were once full of tidal wetlands, including tidal mud flats, emergent marshes, scrub-shrub wetlands, and tidal swamp forests. All of these habitats have suffered large reductions in areal extent in the last 150 years. For example, approximately 70% of wetlands in the Fraser River delta have been converted to developed land (BC Ministry of the Environment 2006), and less than 10% of tidal forests in Puget Sound remain, with only small relict patches remaining in some watersheds (Collins et al. 2003; Simenstad et al. 2011). Researchers conducting an extensive analysis of change to Puget Sound shoreline ecosystems found only 6.5% of the units they evaluated—more than 3,969 km (2,466 mi) of shoreline included in the study—had no documented changes (Simenstad et al. 2011). Much of the marsh and estuary areas have disappeared completely from their historical extent, with greater than 95% loss in some estuaries (Brophy et al. 2019). In British Columbia, a recent survey of all estuarine habitats showed the Strait of Georgia to be highly threatened in terms of integrity of estuarine area (Robb 2014).

Anthropogenic change through hardening of shorelines at the interface between the landscape and seascape is concentrated around urban areas throughout the Salish Sea, but even rural regions have experienced alterations to the shoreline like piers, floats, and other human impacts. The growth in urbanized areas from the city centers out toward surrounding, once rural areas, has been punctuated (Robinson et al. 2005). Fragmentation has occurred first, followed by increasing urbanization, and total habitat loss in areas proximal to major cities with high urban and suburban land use. Ecosystem fragmentation is not uniform throughout the Salish Sea, but the high degree of urbanization across the seascape has resulted in an indelible human fingerprint (Figure 3.2).

While ecosystem fragmentation and loss threaten the integrity of the Salish Sea ecosystem as a whole, specific ecosystem structures and functions are lost when natural landforms are converted. In the change analysis of Puget Sound mentioned above, the authors articulated a number of important ecological processes occurring on rocky shores, beaches, and in embayments and deltaic estuaries, especially related to sediment supply and transport and creation and maintenance of distributary channels in river-mouth estuaries (see Appendix B in Simenstad et al. 2011). The range of disruptions to ecosystem physical functions is wide, but impacts are primarily related to disruption of movement of sediment and biological material—the very processes that provide connectivity between the terrestrial upland and the estuarine coast.
Maintenance and movement of sediment supply is impeded by built structures that fragment the ecosystem and sever bluffs or river mouths from their adjacent habitats (Dugan et al. 2018). Freshwater input to the Salish Sea directly from hillslopes and rivers can also be disrupted and impacted, as can the important import and export of detritus driven by tidal movement (Heerhartz et al. 2014). Taken together, changes to coastal physical structures and processes from fragmentation of the Salish Sea landscape and seascape have led to impaired movement of geological and biogeochemical materials and, ultimately, disconnection among the fluvial, terrestrial, and marine realms.

Shoreline Hardening and Disruption of the Shoreline Ecotone

Shoreline armoring (i.e., the rock, riprap, and concrete structures intended to stabilize shorelines and protect human infrastructure) is one of the most obvious anthropogenic impacts to marine and estuarine shorelines around the world. The Salish Sea encompasses several large metropolitan areas, where armoring is generally more extensive, including seawalls protecting urban shorelines, revetments in front of single-family homes, and concrete structures in support of ports, marinas, and other commercial properties. Research on the impacts of armoring have been ongoing in the region since the early 2000s, and recent work has described the challenges with detecting changes that occur over long time scales and which are often non-linear (including thresholds associated with cumulative effects) (Dethier et al. 2016). In urban areas, like King County, WA more than 75% of the shoreline is hardened, causing associated loss of riparian vegetation and beach (Berry et al. 2001). A small stretch of hardened shoreline may have only localized impacts, but when armoring occurs over broad areas, impacting a high proportion of the shoreline, the cumulative impacts result in loss of function in the shore zone (Dethier et al. 2016).

Shoreline armoring in the Salish Sea has been shown to disrupt both biological (Romanuk & Levings 2003; Sobocinski et al. 2010; Heerhartz et al. 2014) and physical processes (Ruggiero 2010; Quinn 2010; Dethier et al. 2016). Armoring reduces retention of logs and beach wrack (algae, seagrass, leaf litter, and other organic and inorganic debris left by ebbing tides). While beach wrack may not be the most aesthetically attractive aspect of local beaches, it serves an important ecological function by harboring extensive invertebrate communities that consume the detritus and are in turn consumed by other organisms, such as birds, shore crabs, and small mammals.

Shoreline armoring fundamentally changes the interface between the marine and terrestrial ecosystems and disrupts spawning locations for beach-spawning fish, such as the surf smelt (*Hypomesus pretiosus*; Rice 2006). Spawning opportunities are reduced when armoring eliminates the intertidal zone, termed "relative encroachment" by Dethier et al. (2016), where these fish spawn on high tides. Additionally, the reduction in upland vegetation (overhanging trees and shrubs) increases beach temperatures and decreases sediment moisture, especially during the summer months, and results in surf smelt egg mortality (Rice 2006; Quinn et al. 2012). This reduction in vegetation also impacts nearshore species that rely upon insects and other fauna associated with that vegetation (Romanuk & Levings 2006). Shoreline armoring also has implications for migrating salmon; the installation of structures encroaching into the shallow intertidal zone where juveniles reside can disrupt their migration (Heerhartz & Toft 2015).

Physical impacts of armoring on beaches are evident in the Salish Sea and are especially pronounced when structures eliminate the foreshore (high-intertidal zone) and encroach lower into the intertidal zone. Such encroachment can cause increased interaction with wave energy and marine processes like alongshore transport, which impacts sediment exchange (Ruggiero 2010). At larger scales, when significant portions of shoreline are armored, there is reduction in direct sediment input from the bluffs being retained. The sediment supplied from natural bluffs is necessary to sustain beaches and maintain shorelines. The availability of this sediment will in itself protect shorelines, but when it is cut off by armoring, this function is lost. In yet another example, increased scouring around shoreline armoring changes sediment grain size in the intertidal zone due to waves, currents, and other physical processes (Dethier et al. 2016), which can impact the occurrence of biota and forage fish spawning. These types of physical effects are context dependent, contingent upon wave action, storm patterns, beach profile, and substrate type, as well as relative encroachment of armoring or other engineered structure into the intertidal zone. Recent work has shown that removal of armoring results in rapid restoration of some function, especially related to local invertebrate biota (Lee et al. 2018). The growing body of evidence related to impairment of ecological function due to shoreline armoring has strengthened enough to support changes in policy associated with shoreline management (Dethier et al. 2017). For example, as permits for hard structures are limited by regulations, structural alternatives like "living shorelines" are gaining attention (see Vignette 6, Living Shorelines). Creation of these so-called living shorelines use anchored logs, introduced sediment (through a process called nourishment), and native vegetation for preventing erosion when valuable infrastructure is threatened. The Green Shores initiative in both British Columbia (Stewardship Centre for British Columbia) and Washington (Washington Sea Grant) is one example of a science-based stewardship effort that provides support for best practices to minimize the impacts of new developments and restore shoreline ecosystem function. In Washington, where shoreline armoring is a more significant problem than in British Columbia, it is encouraging to see that new shoreline armoring projects are beginning to be outpaced by restoration efforts, thereby reducing the cumulative length of armored shoreline over time (Figure 3.3).

Disruption to the land-sea ecotone (that area of transition between the upland where terrestrial processes dominate, and the nearshore where marine processes dominate) is the primary result of shoreline armoring. Loss of sediment supply from naturally eroding bluffs and reduction of fauna that are critical to ecosystem function, such as terrestrial insects and intertidal benthic invertebrates, are ubiquitous effects of armoring. As urban growth and climate change continue, thoughtful regulatory limits on shoreline hardening are needed. Maintaining, or in many cases, restoring natural form and function to the nearshore will slow, mitigate, or reverse the impacts of cumulative land-use change around the Salish Sea.

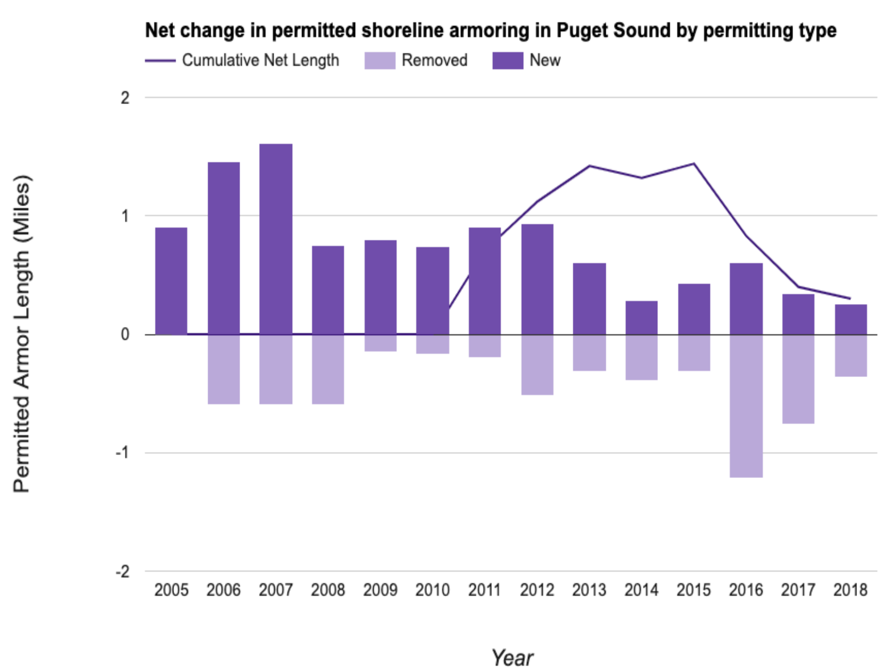
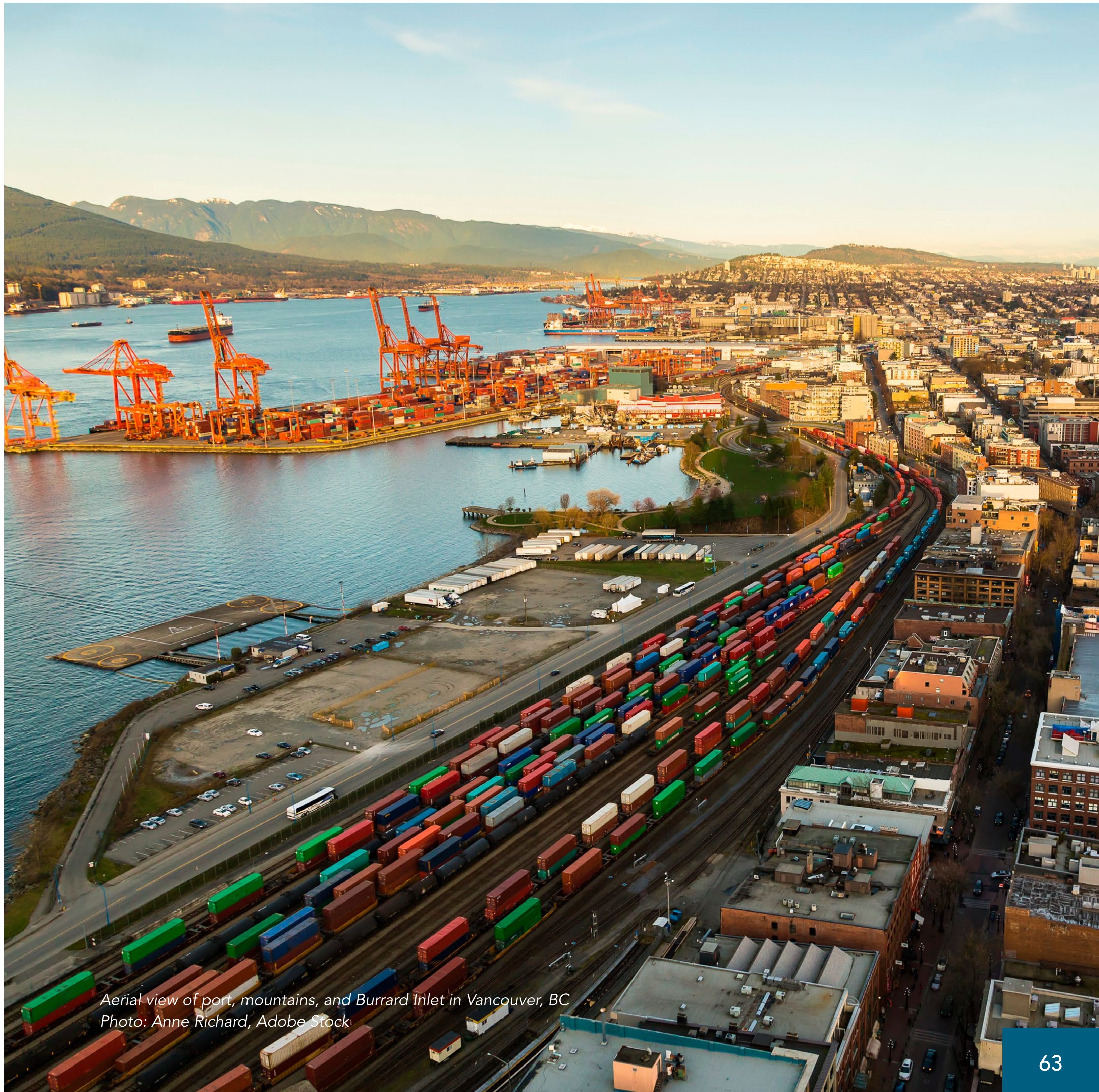


Figure 3.3. Net change in permitted shoreline armoring in Puget Sound over the last fifteen years. With removals and reduction of permitted new installations, the cumulative amount of shoreline armoring has declined in recent years. Source: Puget Sound Partnership (2019)



Aerial view of port, mountains, and Burrard Inlet in Vancouver, BC
Photo: Anne Richard, Adobe Stock

INPUTS FROM HUMAN ACTIVITIES

In addition to impairments brought about directly by fragmentation of natural shorelines and other ecosystem components, some regions of the Salish Sea are affected by poor water quality caused by human-driven inputs, such as excess sediment, nutrients, chemical pollution, and marine debris. Associated with land-use change, urbanization, agriculture, and other forms of development, these inputs and their impacts on the Salish Sea are discussed below.

Contaminants

Although water pollution is much reduced in the last half century due to the enacting of strict clean-water standards on both sides of the border, there remains legacy pollution from decades of industrialization, diffuse (non-point source) pollution from everyday runoff, and a suite of emerging chemicals of concern being released into local waters. Part of that loading comes from sewage treatment plants, shipyards, municipalities, and a multitude of commercial/industrial operations that have the legal right to discharge waste into the Salish Sea through permitting processes like the NPDES program (National Pollutant Discharge Elimination System) that was established by the Clean Water Act in the United States. Added to these permitted discharges is the massive load of chemicals and bacterial pollutants that enter the Salish Sea with stormwater runoff from roadways, lawns, farms, and parking lots. While we tend to think of contaminants as a local problem, contaminants also enter the inland waters of the Salish Sea through long-distance transport via ocean waters (Johannessen et al. 2009) and deposition from the atmosphere.

One of the primary terrestrial pressures on the Salish Sea estuarine environment is urban stormwater runoff. When rainfall runs across hard, impervious surfaces rather than soaking into the soil, it picks up and delivers materials on those surfaces (e.g., fertilizers, petroleum products, bacteria from pet waste) directly to nearby streams, rivers, and eventually the Salish Sea (see Vignette 7, Stormwater Effluent). The combination of physical, chemical, and biological degradation resulting from impervious surfaces has been termed "urban stream syndrome" (Paul & Meyer 2001). Surface runoff is the largest contributing source of toxic loading to Puget Sound (Washington State Department of Ecology & King County Department of Natural Resources 2011; Feist et al. 2017), and while the Strait of Georgia has relatively less urbanized area, runoff is an important source of contaminant contribution from the metropolitan areas of Vancouver and Victoria, BC (Marsalek & Schreier 2009). Stormwater runoff is a leading cause of impairment to waterbodies that do not meet local water quality standards, meaning the affected waters are not safe to swim in, they cannot be used for drinking water (if so designated), and/or the fish and shellfish living in the waters are not safe to eat.

Urbanization, industry, and agriculture in the watershed and along the shores of the Salish Sea have resulted in contamination by metals, organic pollutants, and pathogens. The long history of contaminants entering the ecosystem is evident in marine sediment cores that contain chemicals like PCBs (polychlorinated biphenyl), PAHs (polycyclic aromatic hydrocarbons), PBDEs (polybrominated diphenylethers), dioxins and furans, metals (e.g., mercury and lead), TBT (tributyl tin), and industrial detergents (Johannessen & Macdonald 2009; O'Neill & West 2009). Many of these chemicals are considered "legacy" pollutants with a very long history of entry and persistence in the environment. As shown in the conceptual diagram

Monitoring at Bowman Bay
Photo: Jason Toft

in Figure 3.4, legacy pollutants typically exhibit an initial entry date that may be decades in the past, followed by increases in use and discharge over time, and then decreases after the material is found to be toxic and subject to regulation and remediation (Johannessen & Macdonald 2009). Although regulatory action over the past several decades has been successful in limiting many so-called point sources of industrial pollution (e.g., discharge from a specific facility, pipe, or ditch), it's important to note that diffuse non-point inputs from stormwater runoff remain high. While these contaminants exist throughout the Salish Sea, accumulation in harbor seals provides some indication that Puget Sound has a more significant problem (Cullon et al. 2005).

In addition to the legacy pollutants that remain in the region's soil, water, air, and wildlife, and the common suite of metals and petroleum products and byproducts found in stormwater runoff, many new contaminants known as Contaminants of Emerging Concern (CECs) are posing additional threats to ecosystem health (USEPA 2021). Some of these emerging contaminants, like byproducts from vehicle tires, enter the Salish Sea via stormwater runoff (Tian et al. 2021). An additional pathway is via wastewater treatment plants that are ill-equipped to effectively remove these pollutants (and for some compounds, there are not yet regulatory standards set to guide methodology and compliance). The sheer number and breadth of chemical composition of novel contaminants passing through our wastewater treatment plants makes removal costly.

Recent awareness of pharmaceuticals and personal care products that are increasingly passing through treatment plants and into coastal waters is prompting new investigations of chemical interactions with marine organisms. A study from Puget Sound investigated CECs in wastewater treatment plant effluent,

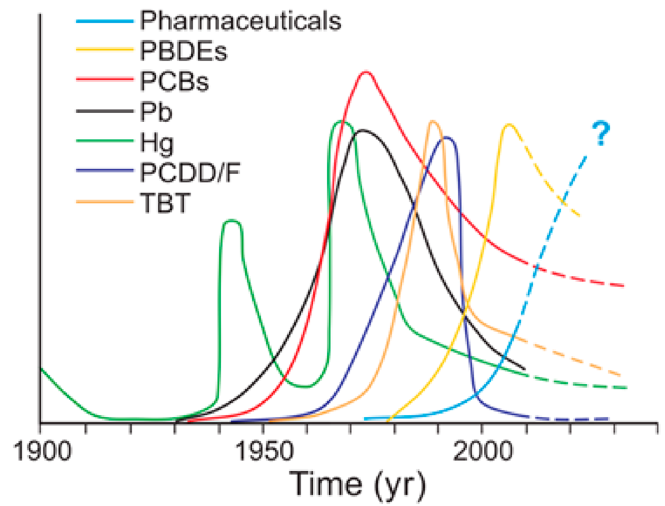


Figure 3.4. A schematic representation of the timelines for selected contaminant exposures in the Salish Sea. The sources of many contaminants have been reduced or eliminated, but in other cases they remain in the ecosystem. Newer emerging contaminants, like pharmaceuticals, have seen an increase in input starting in the latter part of the 21st century but their persistence is unknown. Source: Johannessen & MacDonald (2009)

in the water column, and in the tissues of two fish species (Chinook salmon and staghorn sculpin, *Leptocottus armatus*). The researchers found numerous CECs, including hormones, antibiotics, antidepressant and metabolic-regulating pharmaceuticals, and other compounds (Meador et al. 2016). The CECs identified in this study are common to many marine ecosystems and are likely to have adverse effects on fish and wildlife. The combined inputs to nearshore waters are substantial, likely on the order of 120 kilograms per day and approximately 44,000 kg annually (265 pounds per day and 97,000 pounds per year) for just Puget Sound (Meador et al. 2016). The development and use of new personal care products and pharmaceuticals is outpacing research into their effects on the environment, meaning not enough is known about cumulative effects and persistence of CECs in biota and the environment.

The addition of more people to the region means additional stresses to stormwater and wastewater treatment systems, with additional contaminants entering the marine system. As a consequence of population density, there are a relatively high number of wastewater treatment systems that discharge effluent into the Salish Sea. That count includes more than 100 treatment plants in Puget Sound, plus about 130 more in Canadian waters (BC Ministry of the Environment n.d.). Many Canadian systems treat wastewater to a lesser extent (primary or secondary treatment; Grant & Ross 2002) than their United States counterparts (which are required to have at least secondary treatment by Washington standards, WAC Chapter 173-221). As wastewater treatment plants are updated, they typically build to a higher treatment standard. For example, the recent $775 million (CDN) upgrade to the major wastewater treatment facility in Victoria, BC will benefit the Salish Sea with tertiary treatment capable of removing microplastics and contaminants. Even so, when secondary treatment bypasses, permitted flows, maximum outputs, combined sewer overflows, unmeasured compounds, and septic system contributions are all considered (on both sides of the border), CECs and other contaminants represent uncharted territory with potential to harm species and food webs within the Salish Sea in ways that are not yet fully understood.

The threats from stormwater to biota in coastal marine communities have been well-documented (Kennish 1997) and range from acute to chronic problems. Animals ranging from mussels to orcas are being evaluated for contaminant loads in the Salish Sea. River otters (*Lontra canadensis*) in the lower Duwamish River tidal zone near Seattle have shown high levels of PCBs in scat samples (9.1 to 19.3 mg/kg, which is above the level known to cause adverse effects; Wainstein et al. 2019). Mussels, which can be transplanted and sampled in certain locations, are being used to monitor PAHs and CECs, with total PAH concentration positively correlated with percent impervious surface in the adjacent watershed (Lanksbury et al. 2019), and CEC exposure is variable but high enough to be of concern (James et al. 2019). Mussels serve as passive samplers for the water they come in contact with, which is helpful in identifying areas of increased contaminant load and the thresholds that may be important for protection of human health associated with consumption.

In another example from the marine community, a recent study of juvenile Chinook salmon in Puget Sound showed unique chemical signatures indicative of wastewater sources. These fish also had high concentrations of persistent organic pollutants, suggesting that wastewater may be the source (O'Neill et al. 2020). The study highlighted the inferential power of combining multiple biomarkers to paint a more holistic view of conditions and potential linkages. Innovative technology and analytical approaches such as this will continue to shed light on the sources of contaminant burdens and allow for more informed decision-making and management.

Bioaccumulation and biomagnification of contaminants through the food web and impacts to human health from the consumption of fish and shellfish are of paramount importance in understanding ecosystem impacts as contaminants move up and through the food web (Figure 3.5). While biomagnification (the accumulation of toxicants as predators eat contaminated prey) has received much attention, especially related to the chronic health of orcas (Desforges et al. 2018), perhaps of equal or greater concern is the bioaccumulation of contaminants in shellfish, including those consumed by humans. Bioaccumulation refers to the process of a contaminant entering the food web and accumulating in specific organisms. While source control of PCBs was enacted many years ago, recent research is showing a persistence of these contaminants in fish and shellfish, confirming that these chemicals remain within the Salish Sea food web, do not easily break down, and are not safely sequestered in the sediments (West et al. 2017). This continued presence of chemicals threatens food security for Indigenous peoples who have traditionally harvested shellfish. The ongoing impacts of persistent contaminant loads in fish and shellfish combined with novel chemicals like CECs is an area of current investigation. It's also important to note that climate change may amplify some effects of food web bioaccumulation due to changing ocean chemistry and physical properties (Alava et al. 2018).

Contaminants will continue to enter the estuarine ecosystem as more agricultural and forest land is converted to impervious surfaces where common petroleum-based pollutants and many metals often originate. Increasing volumes of wastewater will continue to contribute nutrients and CECs to local waterways. Much regional research has focused on the effects of various contaminants on regional biota, but understanding how legacy pollutants interact with continuing and emerging contaminants to change toxicity will provide more insight into the harm being done through this human input. Continued population growth and urbanization brings with it additional stresses to stormwater and wastewater treatment systems and the capacity to prevent contaminants from entering the marine system. Meanwhile, beyond the catchment areas of stormwater and wastewater infrastructure systems, contaminants such as pesticides, nutrients, and other compounds will continue to enter the estuarine ecosystem from agricultural and forest land directly. From all sources, urbanization results in increasing contaminant loads to local waterways jeopardizing fish and shellfish and human well-

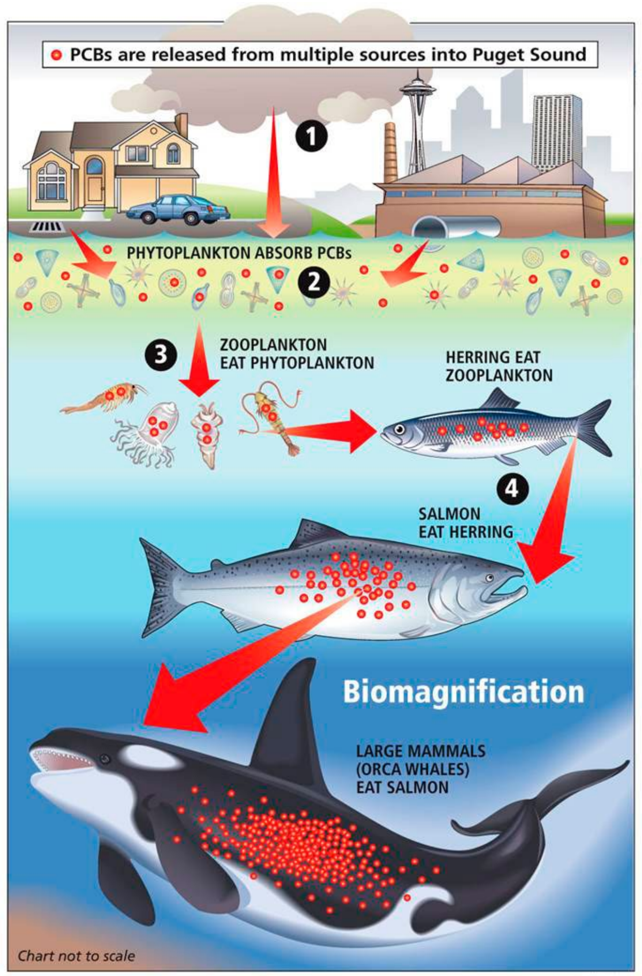


Figure 3.5. Biomagnification of contaminants (e.g., PCBs) through the Salish Sea food web, in this case in the context of Puget Sound. Source: Washington State Department of Ecology (2014)

being for the people who depend upon them (see Vignette 8, Connection to Place in səlilwət).

Nutrients

Nitrogen, phosphorous, and organic carbon (collectively "nutrients") are important naturally occurring elements in aquatic ecosystems that promote the growth of phytoplankton and drive the marine food web. In the Salish Sea, the primary source of nutrients, particularly nitrogen, is ocean water. Deep nutrient-rich water is upwelled along the coast. Driven by the outflow of freshwater at the surface of the Strait of Juan de Fuca, this deep water circulates in a counter-current deep into the Salish Sea, eventually exiting through the Strait of Juan de Fuca (see Section 2). Riverine inputs also account for a small portion of nutrients delivered to the Salish Sea. As the human population within the Salish Sea watershed has grown, nutrients from anthropogenic sources have become an increasing concern.

When nutrient loads are in excess of biological demand, the nutrient balance in a waterbody can tip from naturally occurring and necessary for ecosystem function to pollution. In the Salish Sea, excess nutrients can be trapped in poorly mixed embayments, resulting in lost ecosystem function. Anthropogenic nutrient sources that enter the marine ecosystem include runoff of fertilizers used in agriculture and lawncare, effluent from leaking septic tanks, and effluent from wastewater treatment plants (Mohamedali et al. 2011). Atmospheric deposition of nitrogenous compounds from fossil fuel combustion can also increase marine nutrient concentrations (Howarth 2007). The addition of these human sources of nutrients results in areas of nutrient enrichment, known as eutrophication. In these circumstances, phytoplankton respond to the excess nutrients with blooms, and then die-off in place. The decomposition process involves microbial activity that depletes oxygen, lowering bottom oxygen levels, resulting in regional low oxygen zones. Nutrient additions from human sources have grown with human population and may be tipping the balance toward larger and more frequent occurrences of algal blooms and zones of low dissolved oxygen (Newton et al. 2002).

A related but different problem is the input of nutrients from wastewater treatment plants that discharge to the Salish Sea. Even though the outfalls from these facilities are typically sited in areas of high flushing, there can be seasonal effects and pulses of added nutrients. For example, in late summer when circulation slows due to a reduction in freshwater input, nutrients from wastewater treatment facilities can result in reduced dissolved oxygen through a similar process of eutrophication. Increased human population has necessitated additional or expanded treatment facilities to handle the increased volume of waste. The volume of sewage associated with human population growth has been tied to closures of shellfish harvesting and an uptick in nuisance macroalgae (BC Government 2006). As the population continues to grow, we can expect additional contributions from wastewater facilities, particularly if there is no change in treatment technology to reduce nutrients and other contaminants in effluent. Looking forward, it's clear that more aggressive control and reduction of nutrients to the marine environment will be necessary to maintain (or ideally improve) marine water quality and meet water quality standards.

The ecological responses to nutrient enrichment are a function of the physical dynamics, residence times, and mixing within a system. Overall, the Salish Sea does not have the nutrient enrichment problem common to other estuaries because of the strong mixing and circulation within the Salish Sea. However, there are localized regions within the Salish Sea, such as Hood Canal and South Puget Sound, that are prone to eutrophication due to their physical setting (see Washington State Department of Ecology (2019) for a more detailed analysis). These inlets have naturally poor circulation that induces low oxygen conditions, as water stays in place for longer periods of time. Human sources of nitrogen and organic carbon in these areas exacerbate this low oxygen problem. In Puget Sound, the Washington Department of Ecology is leading an effort known as the Puget Sound Nutrient Source Reduction Project (Washington State Department of Ecology 2021) to develop a nutrient management plan with the goal of reducing anthropogenic nutrient sources in order to meet water quality standards for marine dissolved oxygen levels.

For many years (1998-2010), there was an increasing trend in nitrate concentrations in Puget Sound (as monitored by the Department of Ecology's Marine Waters program; Washington State Department of Ecology 2015), although that trend has not continued. Farther north, there is no increasing or decreasing trend in nutrients in the Strait of Georgia, which is largely influenced by marine-derived nutrients (Johannessen & McCarter 2010). In the Strait of Georgia, strong mixing and circulation (and less overall urbanization) in the subbasins contribute to less sensitivity to eutrophication, although some developed shorelines with poor circulation may be susceptible (Mackas & Harrison 1997).

While the natural oceanography and circulation of the Salish Sea may mitigate significant impacts throughout the ecosystem, anthropogenic nutrient inputs to the Salish Sea are expected to increase with the area's growing population. These increases in nutrient inputs combined with the impacts of climate change will result in localized ecosystem impairment. What is less certain is how land use, management actions, changing technology, and the natural oceanography of the region may mitigate significant impacts.

Creosote on beach
Photo: Ginny Broadhurst

Marine Debris

Throughout the history of human presence and industry in the Salish Sea region, a wide variety of debris has entered the ecosystem, much of it related to natural resource extraction (e.g., fishing and timber, which were a mainstay of the economy for many years). While much of the debris in the marine system can be considered legacy pollution, recent improvements in public awareness, regulatory tools, and best management practices are reducing inputs. Nonetheless, problems associated with this debris continue to impact the Salish Sea. New sources of pollution, namely plastics, have garnered widespread public attention, and studies quantifying the effects of plastic debris pollution are ongoing. Building upon this brief background and context, several sources of marine debris are discussed below: log booms/rafts and the associated wood waste deposits, derelict fishing gear (see Vignette 9, Derelict Fishing Gear), derelict piers and pilings that have not been removed, and plastics. Each of these issues involves a different set of impacts to the ecosystem, but all are broadly human inputs for which control and remediation are possible, given the public will and resources to do so.

Wood Waste

In the early days of logging operations, all logs were typically tied into large rafts and transported by water via rivers and estuaries to various regional mills. Some logs in the rafts would break away and drift where currents and tides deposited them upon riverbanks and the shore, sometimes in large aggregations. Even presently, log rafts are towed around the Salish Sea making their way from forest land to the few remaining mills. Large rafts are often tied to pilings in river-mouth estuaries while they await processing. When these rafts are tied in one place, they reduce light to the benthos, impacting benthic algae and plants like eelgrass. Also, they shed bark as tidal and wave action causes shifting and friction among the logs. Over time, wood waste negatively impacts the estuarine environment physically through accumulation of material and contact with the substrate, chemically through leachate, and biologically through disturbed habitat (Sedell et al. 1991). The abundance of benthic infauna is often reduced in areas with raft storage due to poor conditions and ongoing human inputs.

Management practices aimed at limiting the deleterious impacts of wood waste were put into place starting in the 1970s, but historic pollution of wood waste continues to affect estuarine habitats today. Many of the impacts are local, but numerous sites needing attention exist in British Columbia and Washington. The focus for these sites has turned to remediation and restoration, with an intent to regain ecological function lost to wood waste and lumber rafting practices. Restoration at these sites has taken many forms, from monitored natural recovery to capping and dredging (Breems & Goodman 2009). The environmental permitting process for remediation and restoration can be onerous given the variety of impacts from wood waste, including chemical contamination that can spread to surrounding waters. The Washington State Department of Ecology has an active wood waste remediation program through the Toxics Cleanup Program and localized efforts in British Columbia, such as the Esquimault Harbor Clean-Up Program overseen by the Department of National Defence, are targeting clean-up and restoration of these sites.

Derelict Pilings and Creosote

With shoreline industry in the Salish Sea came a variety of overwater structures, such as piers and docks, each with numerous pilings driven into the sediment to support them. The decking and buildings on these structures decayed before the pilings, which remain in nearshore areas as evidence of their industrial past. The pilings have historically been treated with creosote to prevent marine boring animals like marine isopods known as gribbles (*Limnoria* spp.). Creosote has been used as a wood preservative since the early 1900s to help prevent the decay of pilings, but it is also a known toxicant and has led to a legacy environmental problem. Hundreds of chemicals have been identified in creosote, with PAHs (known carcinogens) being of most concern. Creosote-treated pilings can leach chemicals into the water and sediments surrounding pilings, with adverse effects on biota. Many of these pilings remain in the environment, despite having no decking to support and serving no purpose. As these structures deteriorate, they can break off and wind up on public beaches where human exposure is of greater concern. But without action, many will continue for generations to expose marine organisms to toxicants as they remain in place.

This legacy of bygone industry may remind us of canneries and other waterfront economies of the past, but that legacy also presents ongoing environmental and human health hazards, as well as a safety concern related to recreation and navigation in coastal areas. In Washington State, the Department of Natural Resources (2021) Creosote Piling Removal Program has worked in conjunction with collaborating organizations to remove over 14,000 derelict piles and creosote logs landing on beaches. This effort has come at a significant cost of over $7 million (USD). But in both the United States and Canada, creosote-treated wood is still permitted for use in marine areas, despite being confirmed as harmful to wildlife and even though alternatives such as steel and concrete are preferred under various Best Management Practices (from Fisheries and Oceans Canada, see Hutton & Samis 2000; and

USEPA, see USEPA 2016). In British Columbia, an innovative effort at the Squamish Terminals wrapped creosote-treated wood pilings in a plastic fabric that prevents contact with chemicals leaching out from the pilings and also provides habitat for spawning herring (Hume 2012). The long-term viability of this approach is not clear, but it demonstrates that some ecological function can be returned even with pilings left in place and that solutions like this may be locally feasible. In some cases, standing pilings do provide wildlife habitat, especially for birds, and the Washington Department of Natural Resources has replaced contaminated pilings with non-treated structures to help maintain this habitat. Meanwhile, continued removal of creosote-treated wood pilings will reduce inputs of contaminants in nearshore areas, reducing the overall pollutant load in the coastal environment.

Plastics

While plastic pollution was first reported many decades ago, it has only recently come more fully into public and regulatory awareness, especially related to the marine environment (Law 2017). When plastics enter the marine environment, they may wash up on beaches (Corcoran et al. 2009), fall to the substrate (Keller et al. 2010), or remain entrained in the water column (Desforges et al. 2014). A study of Puget Sound beaches showed 61 pieces of anthropogenic marine debris per square meter, with an estimated total of 5.8 metric tons of debris along Puget Sound shorelines (Davis & Murphy 2015). While this study included multiple materials, foam, primarily expanded polystyrene, and plastic fragments were the dominant pollutants. This study also showed that most anthropogenic debris on beaches is generated within the region, as abundances increased near urban centers (Davis & Murphy 2015), although this could be a function of oceanography. As plastics—whether in the water column, at depth, or on beaches—remain in the environment, they break into fragments over time because of weathering (Cole et al. 2011). Exposure to ultraviolet radiation furthers degradation, which results in ever smaller and smaller particles that pollute our waters, sediments, and biota.

Plastic particles smaller than 5 millimeters are known as microplastics, and they're ubiquitous in samples taken from all over the world. These particulates pose a potential danger through direct ingestion (Jovanović 2017). A lesser understood pathway is as a potential vector for contaminant transfer (Hartmann et al. 2017). Weathering and biofouling processes continually alter the particle surface in ways that increase the accumulation of chemicals onto plastic debris. Thus, accumulation can increase with time in seawater, potentially making the particles more hazardous to animals that consume them (Law 2017; Rochman 2015). In a recent study from Puget Sound, microplastics were detected in sediments from all 25 locations sampled (Spanjer et al. 2019), indicating just how widespread plastic and microplastic pollution is.

It is thought that filter feeders (organisms that filter their food from the water), like krill, oysters, and mussels, also inadvertently capture tiny microplastics, and the plastics accumulate in their gut and circulatory system (Van Cauwenberghe & Janssen 2014). The ingestion and accumulation of these microplastics can have negative effects on the animal's health and may also be passed to other animals, including humans, through the food chain. However, recent research from the Salish Sea has shown that while microplastics are widespread in the environment (occurring at 50% of the sites sampled in this study), accumulation by Pacific oyster (*Crassostrea gigas*) is much less than previously thought, with only 2% of the particles confirmed to be plastics (Martinelli et al. 2020). While this may be good news for oyster lovers, it could mean that oysters are very good at rejecting plastic particles as non-food and releasing them back to the environment where they will once again persist, weather, and degrade further. Once degraded into nanoparticles, detection is more difficult, and our understanding of the resulting acute and chronic effects on affected biota is incomplete.

Given the large human population in the Salish Sea watershed and the proliferation of plastics in the last 50 years, there is concern that significant plastic contamination—from degrading single-use bottles to microfibers commonly used in outdoor clothing—may be harming fish and wildlife (see Vignette 10, Microplastics in the Salish Sea). Desforges et al. (2014) found widespread microplastic particles, especially nearshore. But recent work analyzing microfiber particles in fishes (sand lance, *Ammodytes hexapterus*, and Pacific herring, *Clupea palassii*) commonly consumed by seabirds (rhinoceros auklets, *Cerorhinca monocerata*), found large variation in burdens from one year to the next (Hipfner et al. 2018) and that the forage fishes did not commonly consume microfibers. The impacts of microfibers and other microplastics breaking down into nanoplastics may make fish and wildlife less able to reject these particles (Peng et al. 2020) and deserves more attention.

The topic of marine plastics has certainly garnered public attention. It's also certain that there is more work to be done in understanding the pathways into the food web, the fate and health effects of these materials in biota and biotic processes, and the related implications for the greater Salish Sea ecosystem.

Plastic bag floating in seawater
Photo: Adobe Stock

Vessel Traffic and Associated Concerns

Around the world, an increase in coastal population has brought with it increased vessel traffic in coastal waters. The Salish Sea is no exception, with major shipping lanes running through the heart of the estuary, from the Pacific Ocean to the major ports of Seattle and Vancouver. Vessel traffic and associated impacts like underwater noise, ship-strikes of whales and other marine mammals, and risk of oil spills are of growing concern. In addition to the numerous cargo ships and tankers using the designated shipping lanes, maritime traffic includes tugs, fishing vessels, ferries, government vessels like Coast Guard and Navy ships and research vessels, and numerous recreational vessels transiting the extent of the estuary (Figure 3.6). In the Salish Sea, recreational vessel traffic and ferry traffic increases in the summer months when tourism is at its peak, but overall vessel traffic has increased in recent years and is projected to continue to increase given population and economic growth (McWhinnie et al. 2021).

For many years, the risk of petroleum spills has been recognized as a significant concern for the region, especially given the shared waters through which vessels must pass to and from the Pacific Ocean. Proposed expansion of Canada's Trans-Mountain Pipeline and other proposals have raised new concerns about significant increases in shipping traffic—specifically tankers carrying fossil fuels and fossil fuel products—in the international shipping channels and the ability of the region to respond to a spill, given multiple jurisdictions that would be involved. The Oil Spill Task Force (2021) was established as a means of coordinating spill response. While the exact cost to marine life and the ecosystem from a spill would be dependent upon the nature of the spill and conditions at the time, there is no doubt that remediation of a major spill would be an enormous economic burden to the region. Several modeling efforts to predict oil fate and transport exist (e.g., Salish Sea Model with General NOAA Operational Modeling Environment coupling; Model of Impact of Dilbit and Oil Spills in the Salish Sea (MEOPAR)) but actual impacts to the estuarine ecosystem from an event are dependent on critical factors at the time such as: size of the spill, type of product (e.g., diesel, crude oil, dilbit, etc.) and its physical and chemical properties, agency response time, location of the spill, sea state, season, weather conditions, and many more variables. While a spill may be a rare event given the number of ship passages made daily, it is not without tremendous consequences.

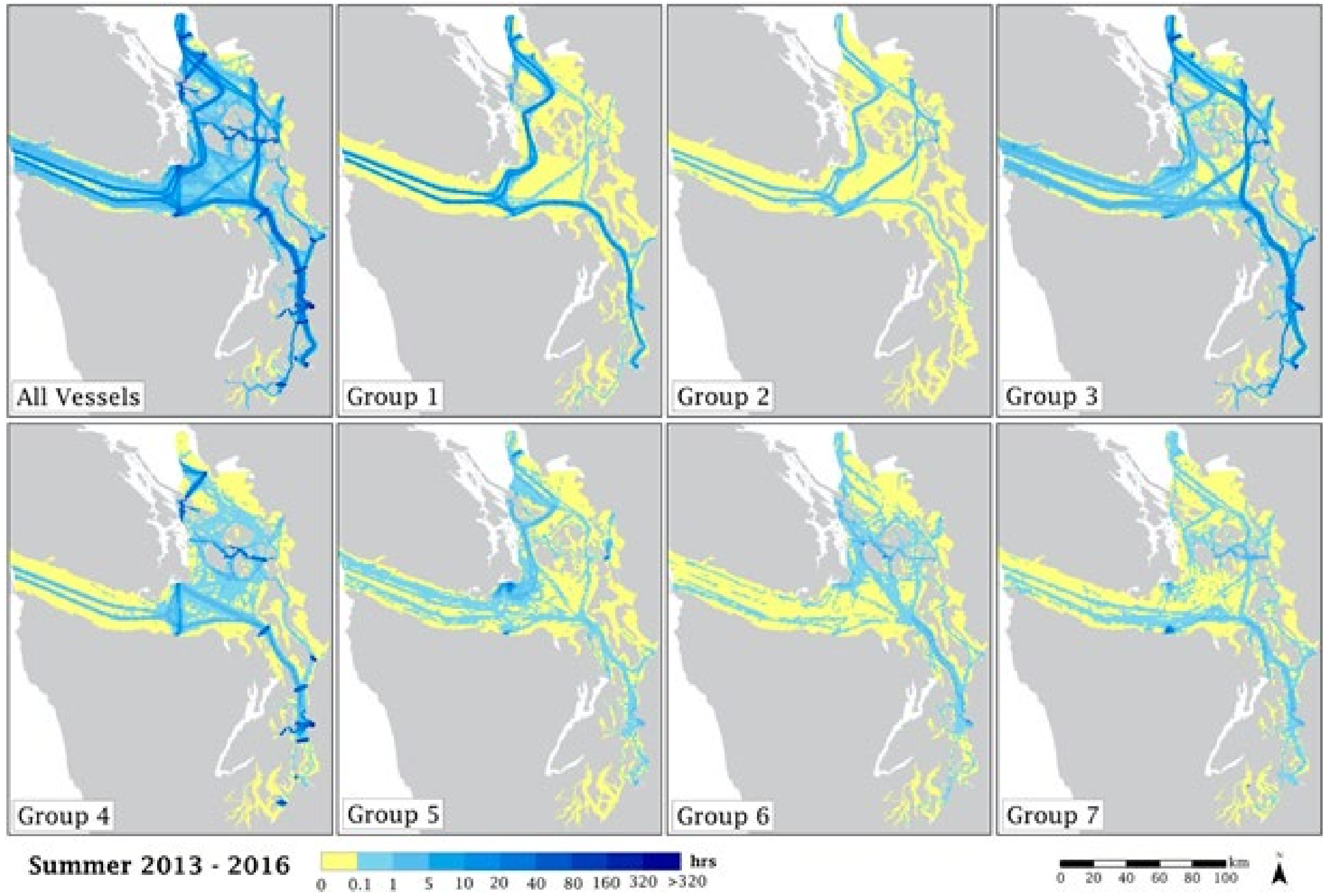


Figure 3.6. Vessel traffic in the Salish Sea during the summer season over four years, 2013-2016. Groups shown are as follows: 1 = Cargo ships, 2 = Tankers, 3 = Fishing vessels/tugs, 4 = Ferries, 5 = Government vessels, 6 = Recreational/tourboats, 7 = Miscellaneous. Data are from the Automatic Identification System (AIS), which not all vessels employ, so are likely under-representations, especially for smaller vessels that are less likely to utilize AIS. Source: McWhinnie et al. (2021)

An increase in ship traffic—even vessels not carrying petroleum products—brings other risks for marine life. A recent report documenting causes of killer whale deaths in the Pacific Ocean showed human impacts implicated in many of those deaths, with trauma associated with vessel interactions to be a leading cause of injury and death (Raverty et al. 2020). Whales, including killer whales and humpbacks in the Salish Sea, are at risk of ship strike, with several documented occurrences in recent years. Many more strikes, especially by large cargo ships, go unreported. Vessel speed is one factor, but noise associated with vessel propulsion is also a concern. Underwater noise may disorient mammals, and transiting vessels can disrupt behavior (Erbe et al. 2019).

Underwater noise as a result of vessels and other maritime activities is of growing concern. The seascape has become noisier over time, at a pace that surpasses the evolutionary adaptive capacity of many animals, especially marine mammals (Duarte et al. 2021) but also fishes (Nikolich et al. 2021). Noise includes the vessels themselves, the use of sound-emitting equipment like active sonar commonly employed by the military, and research and fishing operations (Figure 3.7). Other sources of noise include pile driving and other construction, noise from seismic surveys, and energy exploration and extraction. The impacts to marine life range from behavioral and physiological to, in extreme cases, death. Many actions are underway to reduce vessel noise, including redesigning propeller systems, electrifying vessels, and creating "go slow" zones (Port of Vancouver ECHO program; Vancouver Fraser Port Authority 2021) and "no go" zones (e.g., west side of San Juan channel in Washington) to protect southern resident killer whales. As human activities in the seascape continue to increase, marine spatial planning and other ocean management schemes should aim to consider migratory routes and minimize cumulative seascape noise through technological advancement and planning.

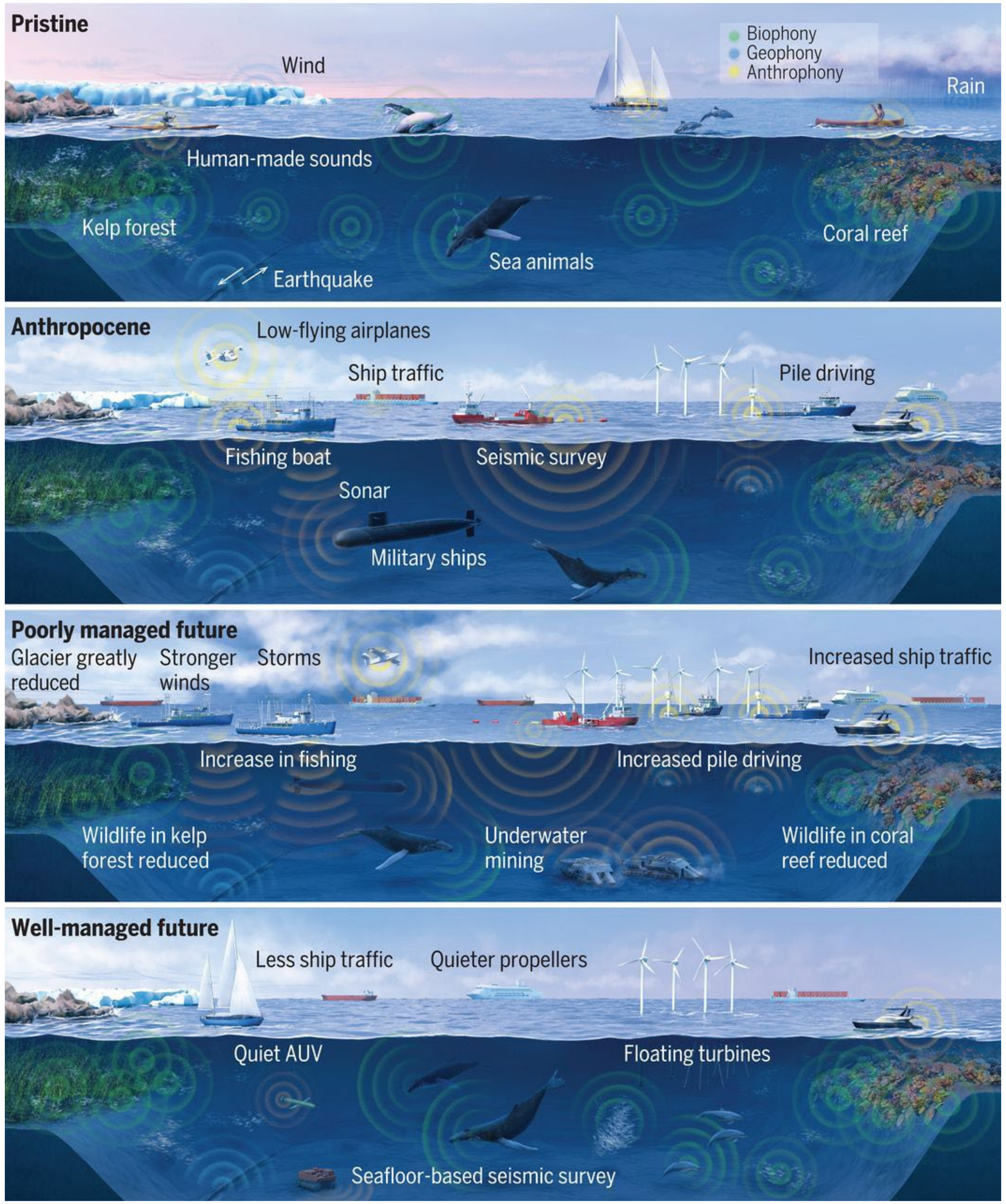


Figure 3.7. Underwater noise in the seascape. This series of illustrations conceptualize conditions from before the industrial revolution when noise was largely composed of sounds from geological (geophony) and biological sources (biophony), with minor contributions from human sources (anthrophony), to the present where anthropogenic noise and reduced biophony owing to the depleted abundance of marine animals and healthy habitats have led to impacts on marine animals. Source: Duarte et al. (2021)

EXTRACTION

The Salish Sea economy was once driven by extraction of natural resources. Beginning with fur trappers and continuing through the heyday of the fishing and timber industries, extraction of the plants and animals living within the Salish Sea and its watersheds was a hallmark of the regional economy and identity. Maritime industries still define many communities, and timber harvest remains a profitable industry in both British Columbia and Washington, with steady harvests over the last 25 years after peak production in the late-1980s (Environmental Reporting BC 2018). Newer sectors, like marine renewable energy, may help drive shifts away from fossil fuel consumption in the region, but tradeoffs related to the marine ecosystem will have to be carefully considered. Examples of continuing and emerging extractive industries within the Salish Sea estuarine ecosystem are discussed below.

Energy

An emerging energy source for Salish Sea communities is the proposed extraction of energy from the strong currents and tides that define the oceanography in the region. Tidal energy projects have been proposed for Admiralty Inlet and other smaller tidal channels, like Agate and Rich Passages in Puget Sound and in the constricted channels of the northern Strait of Georgia. These projects would utilize turbines to convert the kinetic power in fast moving tidal currents to electrical power. The interactions between tidal energy devices and the physical environment can lead to localized and system-wide changes in currents and sediment transport (Hasegawa et al. 2011; Wang & Yang 2017). The Pacific Marine Energy Center (2021) is a consortium of universities and public and private partners promoting responsible development of marine renewable energy.

The impacts of tidal energy systems on Salish Sea biota are unknown, but concerns arising from systems deployed in other parts of the world include various effects of the turbines in the water column. Of obvious concern is the risk of strike or entanglement of organisms in energy infrastructure. Tidal turbines also produce sound as part of their operation. As the implications of underwater noise on marine biota gain more attention (Williams et al. 2015), it is important to bear in mind the impacts on endangered and threatened marine mammal species as well as behavioral responses from other species, like fishes. While no large-scale system yet exists in the region, cumulative effects of multiple energy systems may impact circulation within the Salish Sea. As renewable energy solutions remain desirable—and will help combat climate change—it is important to consider the ramifications for marine organisms and habitat and the maintenance of functional ocean processes.

Harvest of Finfish and Shellfish

The rich biota of the Salish Sea meant sustenance for Indigenous populations, who relied upon salmon, herring, oysters, clams, and other estuarine fish and shellfish species for food (Kuhnlein & Humphries 2017). At the time of European settlement, salmon was extensively harvested by Indigenous people using a variety of gear types, yet it remained a sustainable resource (Lichatowich 1999; Atlas et al. 2021). After the arrival of European settlers and the growth of human population in the Salish Sea, overfishing ensued (Quinn 2010). At the turn of the 20th Century, depletion of upland forests, salmon, oysters, and other resources resulting from unregulated extraction from a growing population was already recognized.

After World War II, with the continued growth in human population and the global industrialization of fisheries, both recreational and commercial fishing expanded. By the mid-1970s, several species were beginning to decline (Schmitt et al. 1994). Three gadoids—Pacific cod (*Gadus macrocephalus*), walleye pollock (*Theragra chalcogramma*), and Pacific hake (also called whiting, *Merluccius productus*)—are now nearly absent from Puget Sound and were the subject of a petition for protection under the United States Endangered Species Act in 2000. Pacific cod and pollock are also less abundant in the Strait of Georgia than they were historically, but hake remain an abundant fish there, although in a unique resident population which has shown reduced size-at-age (King & McFarlane 2006), likely from lack of prey availability. The exact causes of decline for these species are unknown, but the decline is likely the result of overharvest, changing food webs, and shifting environmental conditions. Some evidence suggests that declines in Puget Sound demersal fishes (living close to the seafloor) may have resulted from a distributional shift rather than a demographic shift (Essington et al. 2013), but more extensive sampling is needed to fully reveal the dynamics of populations within the Salish Sea.

Given the declines in many species, harvest reductions were introduced for herring and multiple demersal species (rockfishes, cod, and flatfishes) in the 1980s by the Washington Department of Fish and Wildlife (Palsson et al. 1997). Bottom trawling was banned entirely in Puget Sound in 1989. In the Strait of Georgia, demersal fisheries were productive through the mid-1990s before succumbing to a series of depletions (Johannessen & McCarter 2010); harvest control rules were enacted there as well, and the fisheries remain limited in scope (King et al. 2013). In both cases, most restrictions on harvest occurred only after populations were severely reduced (Schmitt et al., 1994). A legacy of the fishing industry boom time included extensive amounts of derelict fishing gear (see vignette on derelict fishing gear), some of which continued to induce fishing mortality long after regulations were put in place.

Fishing is part of Tribal and First Nations cultures and identities. For thousands of years, Tribes and First Nations have harvested fish and shellfish, eelgrass, birds, crabs, and other organisms from the waters of the Salish Sea, for subsistence, for ceremonial purposes, and commercially. Indigenous peoples today are engaged in fisheries for herring and salmon, for groundfish such as Pacific halibut (*Hippoglossus stenolepis*), Pacific whiting (*Merluccius productus*), and many species of rockfish (*Sebastes* spp.) and flatfish, as well as many important invertebrate species, like Dungeness crabs (*Metacarcinus magister*) and clams. The loss of biodiversity—through overharvest, contamination-related harvest closures, and habitat destruction—threatens food security (Bernhardt & O'Connor 2021).

In British Columbia, the First Nations Fisheries Council works with on behalf of BC First Nations to protect First Nations' rights and title related to fisheries and protection of aquatic resources, including the right to Free, Prior, and Informed Consent with respect to projects proposed on or near their territories. In the United States, Treaty Tribes are co-managers of fisheries resources. In coordination with the Northwest Indian Fisheries Commission, Tribes work closely with the State of Washington and the U.S. federal government to develop and implement species conservation plans for many stocks in Puget Sound and along the Pacific Coast.

Salmon remain an important species for Coast Salish peoples and the 1985 Pacific Salmon Treaty, developed cooperatively by the United States and Canada and implemented by the Pacific Salmon Commission (PSC), includes representatives of federal, state, and tribal governments across both borders. These treaties, agreements, and programs are critical to Tribal and First Nations customs, yet Tribal and subsistence use of fishery resources continue to be jeopardized by loss of habitat, low species abundances, pollution, disease, and the lack of recognition of their rights, title, and jurisdiction in their homelands.

Pacific oysters on a beach in near Shelton, WA
Photo: Duane Fagergren

Large-scale commercial fisheries are no longer removing substantial finfish biomass from the Salish Sea, but the lasting impacts of overharvest during the late 20th century are still felt today, as many species have failed to rebound, likely due to some combination of overharvest and ecosystem change. The recent book *Fishes of the Salish Sea* (Pietsch & Orr 2015) is part of current efforts to protect and restore fishes in the Salish Sea by bringing attention to the diversity of species that call this estuary home. Recreational, Tribal, and commercial fisheries remain for spot prawn (*Pandalus platyceros*), Dungeness crab, geoduck (*Panopea abrupta*), salmon of many species, herring, and rockfishes. Regulatory action has led to more robust creel surveys and reporting, but illicit harvest, changing ocean conditions, and continued impacts from urbanization threaten populations of valued species.

High rise construction in Seattle
Photo: Ginny Broadhurst

SUMMARY OF URBANIZATION AND HUMAN IMPACTS TO THE SEASCAPE

The number of people living within the Salish Sea region is growing rapidly, but the population and its impacts are not evenly distributed in time and across the ecosystem. The multiple examples and lines of evidence discussed above support the observation that population growth drives urbanization and development, which in turn triggers structural changes to the landscape and seascape like habitat fragmentation, shoreline armoring, conversion of vegetated areas to impervious surfaces, and profound changes in watershed and wetland hydrology. These gradual but damaging trends also drive nutrient and contaminant loading to the estuarine waters and limit the scope and scale of local fisheries.

Some may perceive human impacts to the estuarine ecosystem to be limited to our shorelines, but connectivity among the watersheds and the estuary via movement of organisms and water make it clear that these impacts extend much farther. Coastal development can alter ecosystem connectivity by creating barriers or interrupting the natural movement and biophysical processes of organisms and resources. Coastal development also introduces new materials and contaminants like bio-accumulative chemicals and concrete infrastructure (Bishop et al. 2017). In some cases, development may in contrast bring new novel habitats to urbanized areas, offering opportunities for restored or regenerative ecosystem function (see Vignette 11, Built Shorelines).

The challenge ahead for policy makers, resource managers, and residents is how best to balance the pace and scale of new structures and impacts that, over the past 100 years or more, have outpaced and replaced the existing natural habitat with something very different: human infrastructure that is typically incapable of providing one or more ecosystem functions and services that the original landscape and seascape provided.

The combination of legacy, continuing, and emerging impacts to Salish Sea flora, fauna, and ecosystem processes means a myriad of decisions and actions ahead to slow, mitigate, remediate, or restore lost function in the most urban areas and to preserve, monitor, and protect existing function in less populated areas. To bolster public and political will for regulatory change, clearly demonstrated relationships between stressors and biological condition are necessary (Rice 2007). The Salish Sea will remain an urbanized ecosystem, with increasing development and habitat loss outside of city centers, and some land managed in a way that complements conservation, including within urban areas. An awareness of how individual actions of the almost nine million people residing in the region impact the estuary is necessary. But without consideration of the cumulative impacts of these activities and the structural, systemic changes needed to address these multiple factors, ecological integrity and resilience will continue to suffer.

05 | BLOCKING CULVERTS IMPACT SALMONID SURVIVAL

Excerpted from *State of Our Watersheds 2020*, authored by the Northwest Indian Fisheries Commission

During the first six years of implementing the U.S. v. Washington culvert case injunction, the State of Washington has corrected 150 fish-blocking culverts in the Puget Sound Region. At the current rate, if additional support is not gained, the corrections of the remaining 799 culverts would be completed in 32 years or the year 2052.

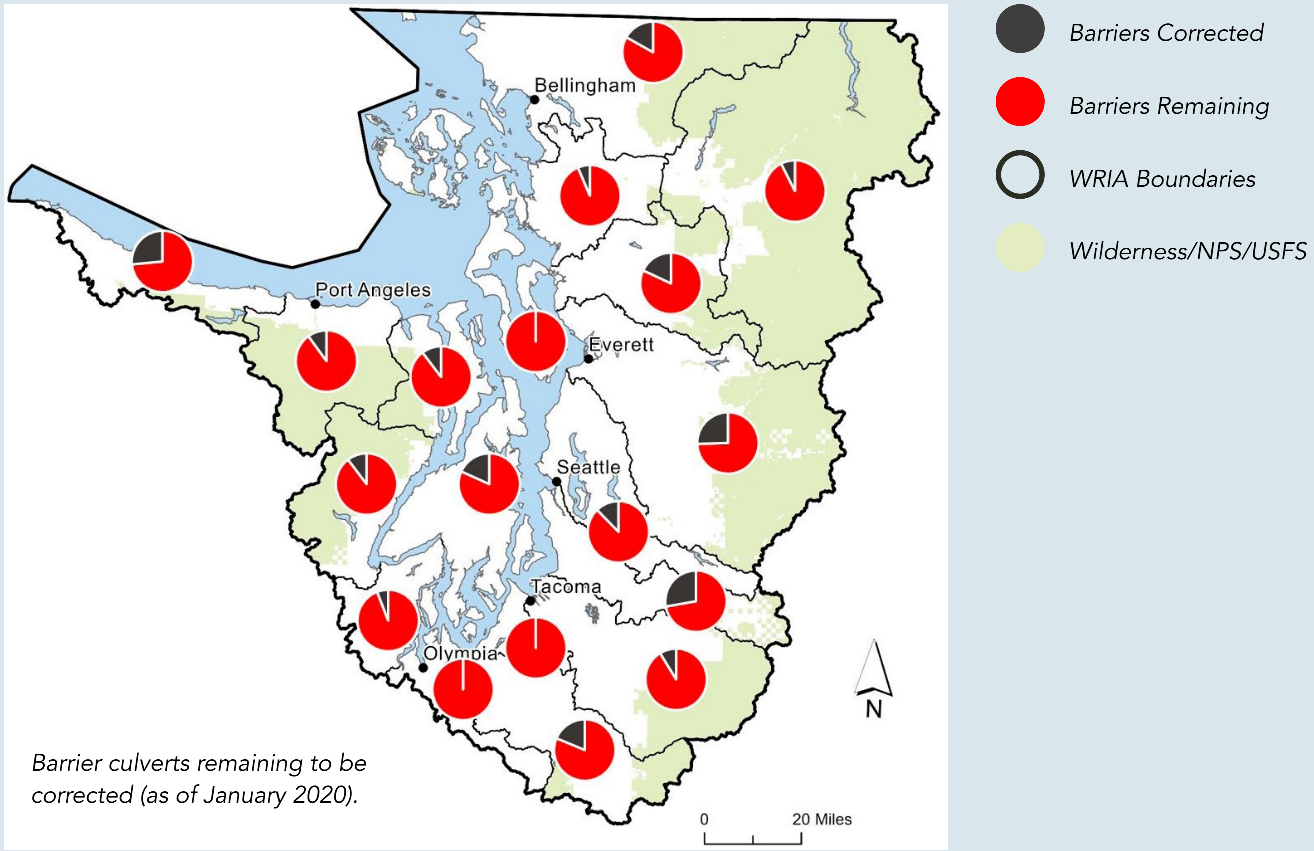
Usable habitat for Puget Sound salmon is a fraction of what it once was, and our ability to recover the salmon populations directly depends on the recovery of habitat (National Marine Fisheries Service 2007). "Impaired fish access is one of the more significant factors limiting salmonid productivity in many watersheds" (Joint Natural Resources Cabinet 1999). In 2013, the U.S. District Court ruled that "the Tribes and their individual members have been harmed economically, socially, educationally, and culturally by the greatly reduced salmon harvests that have resulted from State created or State-maintained fish passage barriers" (United States v. State of Washington 2013).

The Puget Sound Salmon Recovery Plan states that "the loss of rearing habitat quantity and quality is the primary factor affecting population performance," and that the status quo is unacceptable (National Marine Fisheries Service 2007). Not only do physical barriers limit fish passage and available habitat, they can also damage water quality and disrupt sediment deposition (Joint Natural Resources Cabinet 1999).

Because of this damage, "In 2001, the United States and western Washington Tribes brought an action against the State of Washington for their failure to construct and maintain fish passage on state-owned culverts." In 2007, the court ruled that the right of taking fish as secured by the Treaties, means that the State must "refrain from building or operating culverts that hinder fish passage" (United States v. State of Washington 2013).

In March 2013, the U.S. District Court granted the permanent injunction requested by the Federal Government and Tribes, holding that the Tribes "have suffered irreparable injury in that their Treaty-based right of taking fish has been impermissibly infringed. The construction and operation of culverts that hinder free passage of fish has reduced the quantity and quality of salmon habitat, prevented access to spaw ning grounds, reduced salmon production in streams in the Case Area, and diminished the number of salmon available for harvest" (United States v. State of Washington 2013).

Multiple state agencies were affected by this ruling. Washington State Parks and the Department of Fish and Wildlife were required by state law to fix injunction culverts by Oct. 31, 2016 (Joint Natural Resources Cabinet 1999). This deadline was nearly met, but because some barrier culverts have been identified since the 2016 deadline, a few corrections still need to be made. Some Department of Natural Resources' culverts have a longer timeline for correction (United States v. State of Washington 2013).



Barrier culverts remaining to be corrected (as of January 2020).

Owner	Barriers Repaired	Barriers Remaining	Planned to be Repaired	Repaired between 2016-2019	Added to List	Removed From List
DNR	62	7	4	20	4	5
DOT Total	67	787	17	42	107	43
DOT < 200	2	152	1	1	28	11
DOT > 200	64	633	16	41	77	27
DOT *Unknown*	1	2	0	0	2	5
Parks	13	0	0	9	0	1
DFW	8	5	0	4	5	5
Total	150	799	21	75	116	54

Washington Department of Transportation (DOT) is required to fix culverts that block 200 meters or more of habitat by 2030. DOT culvert repair funding is less than 12% of where it needs to be to complete repairs by the court appointed deadline. DOT still needs to fix over 600 barrier culverts (>200m of habitat) in the PSR region; 16 are planned for repair in the 2020-2021 construction season.

Source: Map and table data comes from Washington State Department of Fish and Wildlife (2019), Washington State Department of Natural Resources (2019a; 2019b), Washington State Department of Transportation (2019; 2020), Curtis (2019), Washington State Department of Ecology Regions (2000), and Washington State Parks and Recreation Commission.

06 LIVING SHORELINES IN PUGET SOUND

Jason Toft , University of Washington

Armor removal and restoration at Seahurst Park, a site of longer-term monitoring as highlighted in the press.

Nearly one third of Puget Sound's shorelines are armored (e.g., seawall, bulkhead, riprap). Armoring has documented negative impacts on the flora and fauna that benefit from healthy intertidal beaches. Although shoreline armor may be necessary in some cases to protect people and property, there are often promising "living shoreline" options to restore natural features, also referred to as soft or green shorelines. These options can be applied to situations where complete restoration is either impractical or not feasible given human constraints. Living shoreline techniques often include a mix of design options, including armor removal, sediment nourishment of beaches, log placement, planting vegetation, and moving seawalls further inland. Depending on site characteristics, some engineering may be required for stability. Through regular monitoring, we can determine the effectiveness of these restoration efforts and their value to the nearshore ecosystem, applying what we learn to future management scenarios.

Summary of Monitoring Efforts

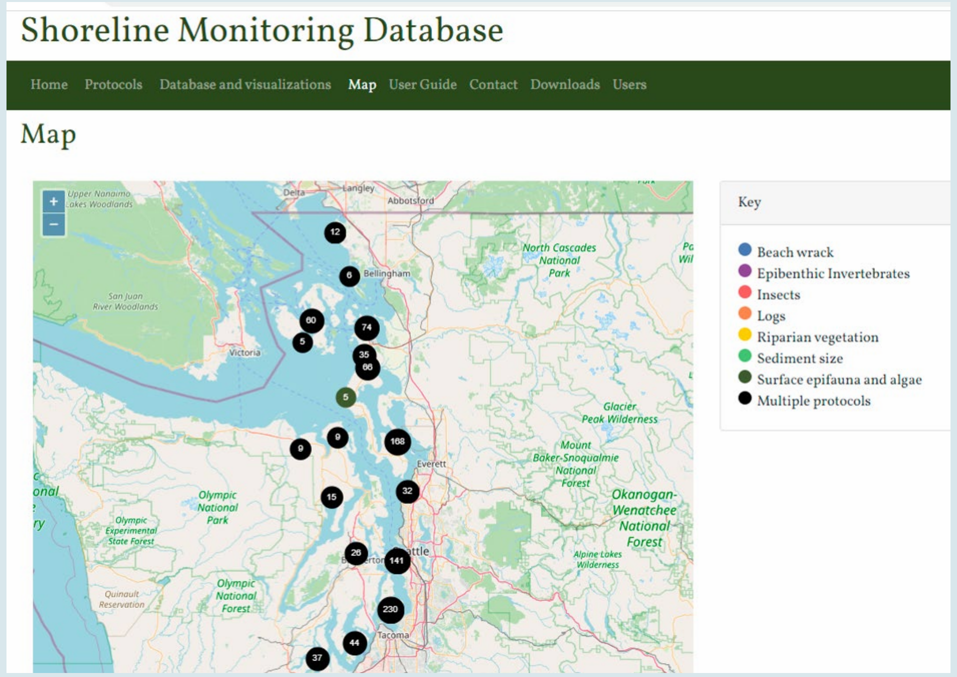
The Puget Sound Ecosystem Monitoring Program (PSEMP) Nearshore Work Group recently compiled a list of sites that have been restored and monitored since 2005. The focus was on sites where shoreline armor has been or will be removed, and also included other living shoreline techniques from the Marine Shoreline Design Guidelines (MSDG) and Your Marine Waterfront. The list details 54 sites, of which 38 had armor removed as of February 2020, totaling 21,132 feet of armor removed. A total of 26 different groups helped with monitoring efforts, a striking demonstration of the participation breadth across Puget Sound. Further information on armor removal can be found at the Shoreline Armoring Puget Sound Vital Sign, and the Washington Department of Ecology's web app for soft shore projects.

Current efforts support coordination of data collection, stewardship, and analysis.

Development of standardized monitoring protocols and a centralized Shoreline Monitoring Database (shoremonitoring.org) enables multiple groups to collect and upload data (e.g., citizen science groups, agencies, and academics), combining datasets and ensuring data longevity and compatibility across groups. Ongoing efforts support addition of more protocols to the database, incorporation of historical data, improvement to database features, addition of data visualizations, and analysis of data to evaluate restoration effectiveness. This tool could be adopted to include all shorelines of the Salish Sea, an important goal to integrate efforts across the United States-Canada border. Often, citizen scientists and students are engaged in monitoring activities. As an example of citizen science engagement, the Northwest Straits Foundation has been leading volunteer surveys at Bowman Bay since 2013, documenting success stories such as forage fish spawning four years after restoration. Overall, 87 volunteers have contributed over 1,980 hours monitoring the project. The Vashon Nature Center BeachNET program engaged 177 volunteer hours in 2019, monitoring restoration effectiveness across five sites. These citizen scientists were a mix of community volunteers, students, and land trust interns, and have changed the views of local citizens.

Current Gaps and Priorities for Future Monitoring

Funding is instrumental not only for living shoreline design and implementation, but for monitoring to measure effectiveness, as successful volunteer and student involvement requires ongoing training, staff time for organizational support, and stewardship and analysis of the data. Expansion of data collection and interpretation will provide an adaptive management framework to evaluate project effectiveness and will generate information that can inform future living shoreline applications. Although we have made large strides in recent years in coordinating efforts and standardizing protocols across diverse groups, given the range of organizations and geographic scope involved, continued support would help make levels of effort consistent across regions. Future efforts should focus on maintaining long-term monitoring of before and after restoration data, in order to learn from the temporal trends that can inform management actions. Living shorelines are often unique in their setting and design application. New sites should be incorporated to expand our spatial framework for analysis and address specific design details. By addressing both physical and ecological functions of beach restoration, we will be able to better plan for restoration actions that will be sustainable, especially when faced with coastal resiliency and sea level rise.



Shoreline Monitoring Database - Map Feature.

07 STORMWATER EFFLUENT EXERTS A KEY PRESSURE ON THE SALISH SEA

Dr. Emily Howe, The Nature Conservancy

What is Stormwater?

One of the primary terrestrial pressures on the Salish Sea estuarine and marine environment is urban stormwater runoff. When rainfall runs across hard, impervious surfaces, rather than soaking into the soil, it picks up and delivers toxic contaminants directly to nearby streams, rivers, and eventually the Salish Sea. In fact, for most toxic substances, surface runoff is the largest contributing source of loading to Puget Sound (Washington State Department of Ecology & King County 2011).

Unfortunately, the Salish Sea's relationship with stormwater effluent is no outlier; stormwater is the fastest growing cause of surface water impairment in the United States as urbanization transitions forested and other natural landscapes to hard, impervious surfaces (USEPA, 2019). Given that the Salish Sea is expected to house another 5 million people by 2040, stormwater interventions will be necessary in order to break the relationship between urbanization and stormwater-caused ecological degradation.

Fortunately, researchers have uncovered a variety of successful techniques to reduce stormwater impairment of surface and receiving waters, including street sweeping, pervious pavement, and green stormwater infrastructure wherein stormwater is filtered by soil and plant mixtures on its way between the streets and the sea. These interventions are costly (approximately $65-132 billion is needed to restore Puget Sound to hydraulically function like a forest), but the costs of stormwater pollution are high as well: the sickening and deaths of Salish Sea organisms. Annual losses due to one contaminant (polycyclic aromatic hydrocarbon exposure) alone are estimated to be between $4.4 to $12.1 billion (Ecology & Washington State Department of Health 2012; Simmonds & Wright 2014).

Urban stormwater runoff is a two-fold problem, impacting the quantity of water pulsing off the land, as well as the quality of that water. As a result of stormwater's twin problems, urban watersheds and marine receiving waters suffer from "urban syndrome"—a condition that results in low abundance and survival of sensitive aquatic and coastal species (Walsh et al. 2005). Virtually all urban streams and rivers in Puget Sound have been harmed by stormwater pollution (Booth et al. 2004).

Water Quantity

Watersheds with as little as 5-10% impervious surface area, such as rooftops, roads, and paved parking areas, exhibit aquatic habitat degradation as a result of increased surface runoff (Walsh et al. 2005). This changes the timing, magnitude, and frequency of high flow events, making urban streams "flashier" than those with natural surrounding landcover conditions. These hydrological changes cause combined sewer overflow events, flooding, erosion, and scouring of stream and riverbeds. Flashy hydrology disrupts habitat structure and alters the ecology of freshwater ecosystems themselves, but also disrupts larger ecosystem processes in marine environments, such as nutrient flux, organic matter processing, and ecosystem metabolism (Palmer & Rubi 2019). While coastal food webs rely on rivers to deliver organisms, nutrients, and detritus from the land to the sea, these fluxes increasingly result in negative impacts, such as eutrophication, hypoxia, and harmful algal blooms.

Water Quality

In addition to altering hydrological flow regimes in watersheds contributing to the Salish Sea, urban stormwater also delivers a suite of contaminants that severely impact the water quality of streams, rivers, estuaries, and the Salish Sea itself. Urban runoff contains complex and unpredictable mixtures of chemicals, including persistent organic pollutants (e.g., PCPs), heavy metals (e.g., copper, zinc), hydrocarbons (e.g., motor oil, tailpipe emissions, rubber tire particles), nutrients (e.g., nitrogen, phosphorous), pesticides, and pharmaceuticals (Noël et al. 2011). Toxic pollutants entering the Salish Sea may be metabolized in plant and animal tissues, bioaccumulated in tissues, incorporated into sediments, volatized, degraded, or conserved in marine waters.

Toxic Stormwater Impacts

Researchers have documented toxic effects of stormwater exposure for a diverse range of aquatic and marine species, ranging from primary producers to high trophic-level predators. Some effects are sublethal, reducing species fitness and long-term survival. For example, heavy metal accumulation is common among marine macroalgae and eelgrass (*Zostera marina*), reducing photosynthetic function (Lyngby & Brix 1984; Jarvis & Bielmyer-Fraser 2015). Other sublethal impacts of stormwater on marine organisms include the reduction of byssus strength in marine mussels (Gaw et al. 2014), reduced olfactory function in juvenile salmonids (Baldwin et al. 2003), reduced growth and lipid storage in juvenile Chinook (Meador et al. 2006), reduced pathogen resistance in juvenile salmon (Arkoosh et al. 2001), cardiotoxicity in juvenile fish (Incardona 2015), decreased reproductive function and immune response in benthic fishes (Rice et al. 2000), seals (Anan et al. 2002), and Southern Resident killer whales (Washington Department of Fish and Wildlife 2011).

Some effects are acutely lethal, as is the case for adult coho salmon, where pre-spawn mortality rates in urban streams can be as high as 90% (Scholz et al. 2011; Tian et al. 2021). These fish end their years-long journey to the ocean and back with their bellies still full of unfertilized eggs, missing their single chance to spawn. For coho, it appears that pre-spawn mortality is linked to the human transportation network, where contaminants, like tire wear leachates, are generated (Feist et al. 2017; Tian et al. 2021). Development expansion and increasing use intensity of the built environment is thus significantly impacting the long-term viability of local coho populations, with far-reaching ramifications for both freshwater and marine food webs alike. And while it is tempting to focus on lethal impacts to iconic species such as coho, road runoff is similarly lethal to lower trophic level organisms, such as mayfly larvae, sea urchins, and amphipods, which all play important roles in upholding marine, freshwater, and terrestrial food webs (Anderson et al. 2007; Kayhanian et al. 2008; McIntyre 2015).

Rainwater hitting a stormdrain in Seattle, WA
Photo: The Nature Conservancy

Moving Forward—Identifying Where Stormwater Pollution Is Generated on the Landscape
A much-repeated phrase from stormwater managers is "how much and where" do we need to implement stormwater BMPs (Best Management Practices)? This is a difficult question to answer until we identify our ecological and social goals for stormwater management. The amount and spatial configuration of stormwater interception techniques will look very different depending on whether the goal is to meet permit regulations, recover coho salmon, or recover Southern Resident killer whales because biological organisms are susceptible to stormwater contaminants for different reasons, in different locations, at different scales, and at different points in time according to their life history traits (Levin et al. 2020). Incorporating robust monitoring programs, such as MusselWatch, the Benthic-Index of Biotic Integrity (B-IBI), and coho pre-spawn mortality observations, and considering the ecological scales at which different biota operate can help identify the biotic response to stormwater runoff, adding valuable ecological information to stormwater monitoring and loading data.

One starting place to answer the "how much and where" question is to build a predictive map quantifying levels of stormwater pollution generated across the landscape. This type of 'threat' heatmap can be coupled with ecological data to produce action maps for stormwater intervention. We have started building the predictive map; we statistically link local stormwater monitoring data to landuse and land cover characteristics, and then calculate the pollution load using local precipitation patterns at 15-minute timesteps for the 32 different hydrologic response units (soil types, landcover types) existing in Puget Sound. We use Big Data capabilities to model surface hydrology across the entirety of the Puget Sound watershed at a 1 m^2 spatial resolution, and aggregate data at several spatial scales for local, watershed, and regional-scale planning.

Areas with high percent cover of impervious surfaces, such as hard cityscapes, as well as industrial and commercial zones, tend to produce higher pollutant loads than high-density residential, low-density residential, and rural areas, which tend to have less impervious surface cover. Transportation networks—roads and highways—generate very high levels of stormwater contaminants, especially those with higher traffic intensity. Traffic behavior (e.g., congestion points) also plays a role, indicating that a combination of a static landscape structure and dynamic anthropogenic behavior layered atop that structure can combine to create stormwater pollution hotspots throughout the landscape. Once we finish building this baseline heatmap, we can begin to add in the ecological layers to understand exactly where on the landscape stormwater interventions will be most efficient and effective at breaking the link between urbanization and aquatic degradation.

08 CONNECTION TO PLACE: INDIGENOUS LEADERSHIP FOR HOLISTIC RESEARCH, RESTORATION, AND GOVERNANCE IN SƏLILWƏT (BURRARD INLET)

Tsleil-Waututh Nation's Treaty Lands and Resources Department, with contributions from Carleen Thomas, Anuradha Rao, Sarah Dal Santo, Lindsey Ogston, and Spencer Taft

Tsleil-Waututh means "People of the Inlet"; Tsleil-Waututh People were born with a sacred obligation to protect the waters of Burrard Inlet. Our first grandfather was transformed from a wolf into a human being. As he grew into a young man, he became lonely. The Creator gave him a vision that he was to dive off one of the tallest cliffs in Indian Arm, grab two handfuls of sediment from the floor of the Inlet, and bring them back to the beach. Our first grandmother was transformed from that. Our ties to this Inlet run deep. It's important that we hold that responsibility, that as a Nation we gather people around who see our vision, and that our work resonates with their own spirit.

Since time out of mind, Tsleil-Waututh have used and occupied Burrard Inlet and surrounding watersheds. Generations of Tsleil-Waututh people were brought up with the teaching, "When the tide went out, the table was set." About 90% of our diet was once derived from Burrard Inlet and the Fraser River, but today the Inlet is unable to support our needs. Cumulative effects of colonial settlement and development have eroded the ecological health, integrity, and diversity of the Inlet. Urbanization and industrialization have brought a complex cocktail of contaminants, transforming Burrard Inlet from our primary food source into a heavily polluted system. By 1972, sanitation and contamination concerns led to the closure of the Inlet to bivalve harvesting. Tsleil-Waututh Nation (TWN) has a goal to restore the health of the Inlet so that we, and future generations of Tsleil-Waututh People, can once again harvest wild marine resources and continue to practice our cultural and ceremonial activities in a clean and healthy environment. The return of herring and orcas shows us that the Inlet is coming back, but there is more work to be done, and we need to do the work together.

TWN is a leader in weaving western and Indigenous science to inform integrated, inter-disciplinary governance and stewardship of natural systems. The science-based, TWN-led Burrard Inlet Action Plan (BIAP) brought together teams of knowledge holders, researchers, practitioners, decision-makers, and community members to share scientific knowledge about the state of Burrard Inlet, to foster development of a shared vision for environmental stewardship, and to identify actions to improve the health and integrity of Burrard Inlet by 2025 so that:

- healthy, wild marine foods can be harvested safely and sustainably;
- water and sediment are safe and clean for cultural and recreational activities;
- important habitats are productive, connected, and support biodiversity; and
- healthy populations of key species are viable and will continue to persist in the long-term.

Applying an Indigenous lens to re-focus water quality science, monitoring, and decision-making, TWN values are starting to reshape on-the-ground research and water quality policy. TWN, in collaboration with the Province of British Columbia, is leading an update to the Provincial Water Quality Objectives for Burrard Inlet, and has co-developed and co-approved provincial water quality policy. TWN established a multi-sector, regional roundtable, as well as technical advisory teams, to review this work. Discussions and relationship building at these tables are proving to be as important as the updated policy.

TWN's holistic approach to water quality improvement has enriched the understanding of the nature and extent of marine pollution, and opportunities to reduce it, through:

- compiling comprehensive water, sediment, and tissue quality data for Burrard Inlet from available scientific sources;
- mapping watershed-wide spatial data for Burrard Inlet water quality (including point and non-point sources of pollution), and drawing linkages between terrestrial activities and marine impacts; and
- developing water, sediment, and tissue objectives for a wide array of legacy and emerging contaminants, and ensuring that these objectives are protective of key values including health of aquatic life, and consumption of seafood by coastal Indigenous peoples.

Oral histories and community values inform all TWN projects. For example, TWN's Climate Change Resilience Project used a community values-based approach to inform identification of the key community vulnerabilities to the impacts of climate change, including sea level rise, coastal and creek flooding, and erosion. A community-based advisory committee is helping to inform development of practical solutions for climate action.

Burrard Inlet
Photo: Anuradha Rao

Knowledge sharing and relationship building are important objectives for TWN work. To restore a traditional relationship with the Inlet, with benefits for all, TWN is breaking down silos and bringing together cultural values, disparate data sets, and diverse actors in a way that hasn't been done before. We have hosted three Burrard Inlet Science Symposia, each attended by approximately 150 participants from dozens of organizations, with the most recent (held in 2019) focused on stormwater management solutions. Building relationships and sharing knowledge increase understanding and connections in our stewardship programs and initiatives.

From eelgrass to elk, TWN takes a watershed-scale approach to leading ecosystem monitoring and restoration, and working in partnership with others to improve the health and integrity of marine and land-based ecosystems. Restoration projects have included eelgrass transplants, re-establishment of the first community shellfish harvests since 1972, inland salmon habitat restoration, invasive species removal, elk re-introduction, and the re-establishment of community elk harvests. These projects embody Tsleil-Waututh principles of environmental stewardship, build community connection to the lands and waters, and work to ensure current and future community access to natural and cultural resources.

A littleneck clam held in a person's hand
Photo: Tsleil-Waututh Nation

Connecting past, present, and future, TWN's Cumulative Effects Monitoring Initiative employs mapping and modelling of available data on environmental monitoring with cultural and archaeological analysis to reconstruct historical ecosystem states, food web dynamics, and shoreline uses. This work is supported by TWN-led field programs to monitor contaminants, underwater noise, marine plants and algae, invertebrates, fish, and terrestrial systems. This work will build an understanding of the cumulative environmental effects of two centuries of development and industry (since European contact) and help predict future states associated with regional development and climate change. This work will be used to inform complex management decisions in and around Burrard Inlet and reveal opportunities for environmental protection, restoration, and enhancement toward ecosystem health and food security.

Tsleil-Waututh Nation and culture are rooted in the lands and waters surrounding Burrard Inlet. Since thousands of years pre-contact, our stewardship laws, Indigenous knowledge, and practices have enabled us to govern, manage, and protect these lands, waters, and resources. More recent pressures of unprecedented regional growth, development, and climate change have created new challenges and reinforced the urgency of environmental stewardship and restoration. In working to address these challenges, TWN has been making strides to integrate Indigenous knowledge, science-based research, inter-disciplinary thinking, community values, knowledge sharing, relationship building, and collaboration within ongoing TWN stewardship programs and initiatives to improve the health of Burrard Inlet and surrounding areas.

09 | DERELICT FISHING GEAR

Jason Morgan, Northwest Straits Foundation

Derelict fishing gear—those nets, pots, and other gear lost during fishing operations or vessel transit—has been implicated in several aspects of degradation in the Salish Sea. Derelict gear can degrade marine habitats by scouring or preventing habitat access through accumulation of gear or by fundamentally altering habitats by trapping fine sediments and changing the substrate. This gear has also been implicated in the deaths of countless fish, marine mammals, seabirds, and invertebrates in the Salish Sea, either from entanglement or "ghost-fishing"—whereby the gear is capturing both targeted and non-targeted organisms but is not retrieved (Good et al. 2010). The use of gillnets with monofilament fibers in once-booming salmon fisheries has resulted in thousands of lost monofilaments nets, but purse seines, trawls, and crab and shrimp pots also litter the substrate, especially in areas with high relief rocky reefs.

Where complex topography and ocean currents converge in the Salish Sea, gear accumulates in areas where it catches on rocky reefs or similar and entrains other gear.

The problem of derelict fishing gear in the Puget Sound region was identified as a high priority by the Northwest Straits Initiative (Initiative) in 2002. It was during this time that the Initiative worked collaboratively with the Washington Department of Fish and Wildlife, tribes, the fishing industry, and other partners to develop a no-fault reporting system that includes a 24-hour hotline, a database, and state-approved guidelines for the safe and environmentally sensitive removal of derelict fishing gear. The Initiative's Derelict Gear Program, created to eliminate harm from derelict fishing gear in Puget Sound, was established and managed by the Northwest Straits Commission, and later passed on for management by their non-profit partner the Northwest Straits Foundation from 2009 to present.

Since 2002, the Initiative has removed 5,811 derelict fishing nets and 5,964 derelict crab pots from the marine waters of Puget Sound. The removal of derelict fishing gear provides immediate and long-term benefits to the Salish Sea ecosystem. Removal of derelict gear eliminates the present and future threat of entanglement to marine birds, fish, mammals, and invertebrates, and restores the full-service benefits of the marine habitat it has degraded. A post-derelict gear removal monitoring project showed that marine habitat dominated by kelp achieved 90% recovery over one growing season without further management actions (Northwest Straits Marine Conservation Initiative 2009). By removing 5,811 derelict nets, the Initiative has restored more than 860 acres of marine habitat.

Perhaps most compelling is the number of marine animals found entangled and prevented from entanglement through removal of this harmful gear. A total of 84 marine mammals, 1,119 birds, 5,717 fish, and 478,599 invertebrates were found entangled in the derelict fishing nets at the time of removal. These numbers provide only a snapshot of the long-term effects of derelict fishing gear. Observed entanglements do not account for previously entangled animals that have decomposed, been eaten by predators or scavengers, or fallen out during gear removal operations. Applying a catch rate model developed by researchers at University of California, Davis using data from the Initiative's Derelict Gear Program, it can be estimated that the 5,811 derelict nets removed were entangling more than 11 million marine animals annually (Gilardi et al. 2009). See table for estimated annual catch rates by major animal groups and examples of species found.

The decline of commercial fishing in Puget Sound has largely reduced the number of nets lost each year. To prevent the re-accumulation of derelict fishing nets in Puget Sound, the Initiative's newly lost net Reporting, Response, and Retrieval Program was launched in 2012. This program allows fishermen, resource managers, and the general public to report lost fishing nets through a 24-hour hotline or online reporting system. The reports are subsequently investigated and verified derelict nets are removed at no-fault or cost to the fishermen. Since the program's inception in 2012, 133 reports of potential derelict nets have been received, resulting in the verification and removal of 86 nets.

The issue of derelict fishing gear extends beyond the Puget Sound region to all reaches of the Salish Sea, albeit on different scales, and the Initiative has provided its experience and expertise to others working to address the problem. The Province of British Columbia worked in collaboration with the Northwest Straits Initiative in 2011 on a pilot project to remove derelict fishing gear in Canadian waters, and recently DFO has initiated The Ghost Gear Fund, providing grants to support 26 projects across Canada over two years (2020-2022). Several non-governmental agencies and fishing industry groups are involved with derelict gear removal on both sides of the border, indicating that this issue has gained attention and prompted action. Fisheries have been reduced but are still active, which means the likelihood of gear loss remains and efforts to remove derelict gear and prevent gear loss will be needed into the future.

Numbers of animals estimated entangled annually by 5,811 derelict nets

Group	Annual catch for 5,811 nets	Examples of species found entangled
Marine Mammals	2,210	Harbor porpoise, Stellar sea lion, river otter
Birds	29,441	Cormorants, grebes, scoters, pigeon guillemots
Fish	163,459	Canary and other rockfish, Chinook salmon, lingcod
Invertebrates	11,781,085	Dungeness crab, red rock crab, octopus, geoduck
Total	**11,976,195**	

10 BIOLOGICAL REPERCUSSIONS FROM MICROPLASTICS IN THE SALISH SEA

Ashley Bagley and Iris Kemp, Long Live the Kings

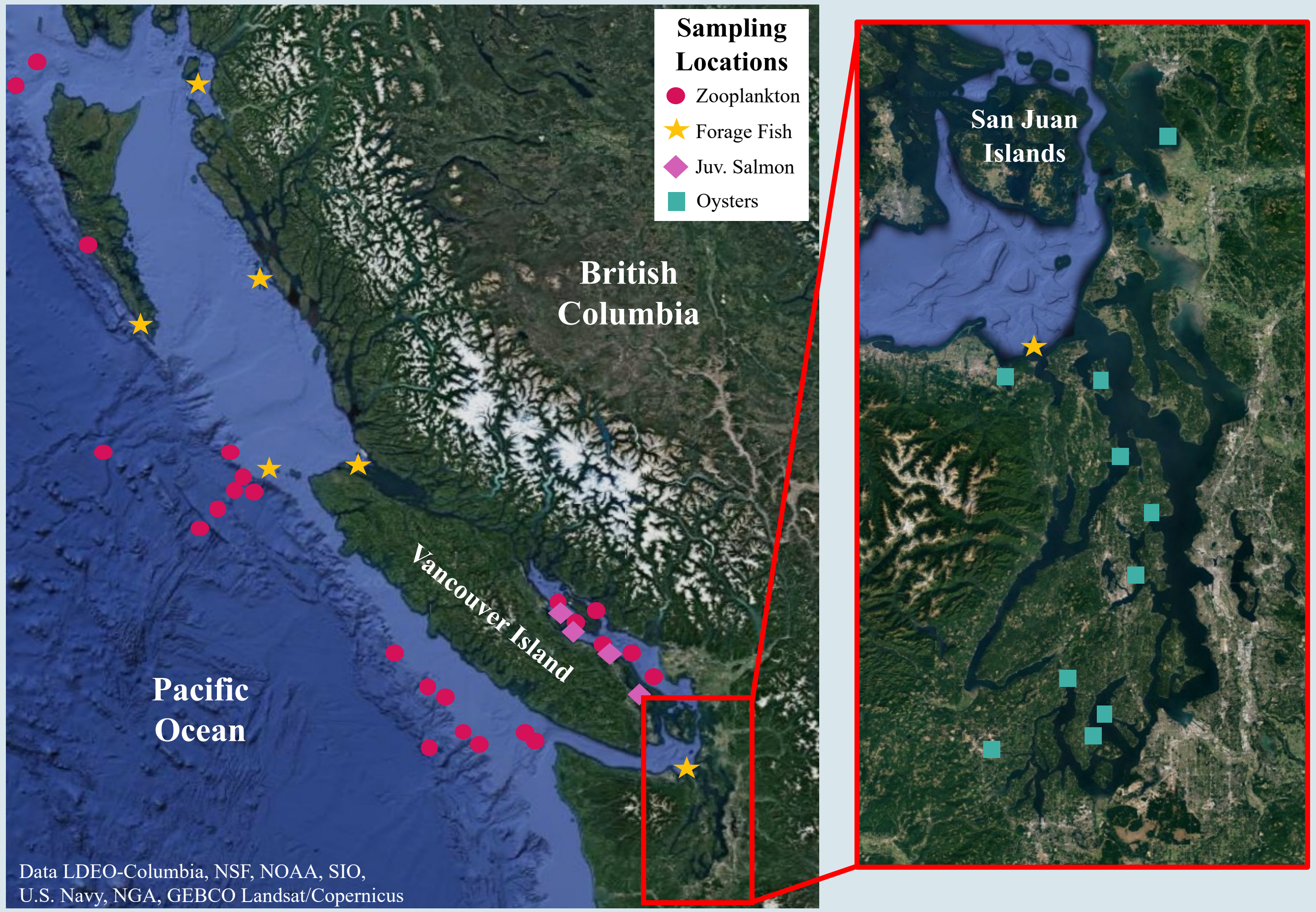
Microplastic (< 5 mm) consumption and the movement of microplastic through the marine food web is an emerging concern in the Salish Sea. Upon consumption, marine plastics can physically and chemically affect marine organisms. Physical effects from eating it include obstructing an organism's mouth and/or throat, blocking its digestive tract, artificially filling its stomach, and absorbing into other parts of its body (Cedervall et al. 2012; Cole et al. 2013; Rochman et al. 2013; Desforges et al. 2014, 2015). Chemical pollutants in seawater can bind to microplastic particles and "hitchhike" their way into marine organisms only to leach after consumption. This can cause: (1) male fish to produce proteins commonly found in female fish, a process known as feminization; (2) endocrine disruption, which can lead to developmental malformations or disturbances in the immune and nervous systems; and (3) bioaccumulation within an organism (Tian et al. 2021). It is important to note that effects from plastics may be unique among species, types of contaminants, and types and sizes of plastics (Desforges et al. 2015; Ašmonaite et al. 2018).

Few surveys of microplastics in marine organisms in the Salish Sea have been conducted to date (see map figure, adjacent page). Zooplankton, bivalves, forage fish, salmon, and orcas are species of concern for direct microplastic consumption or secondary consumption via trophic transfer. Species at the base of the food web, like zooplankton, are likely to pass consumed microplastics on to their predators. Feeding behavior and physical characteristics influence the quantity and size of microplastics eaten by zooplankton (Cole et al. 2013). A field study in British Columbia determined encounter rates were one particle per every 34 copepods and one particle per every 17 euphausiids, but found that exposure and consumption were not correlated (Desforges et al. 2015).

Filter-feeding bivalves can retain microplastics directly from the water or indirectly by consuming zooplankton that have eaten microplastics. Oysters appear to have low retention time of microplastics, and a recent observational study determined only 2% of particles found in wild Pacific oysters were identified as plastic (Martinelli et al. 2020). Mussels treated with microplastics and algae under laboratory conditions had inhibited clearance rates when high concentrations of microplastics were present; however, the concentrations of microplastics observed in the Salish Sea likely do not negatively affect mussel clearance rate (Harris & Carrington 2020).

Research on microplastic consumption in forage fish, salmon, and orcas is limited. Observational research has shown that low percentages of sand lance (1.5%) and herring (2.0%) on the coast of British Columbia consumed microplastics and that consumption varied according to body size, with larger forage fish less likely to consume microplastic (Hipfner et al. 2018). This study concluded it is unlikely forage fish are a conduit for microplastic consumption in predatory species, like salmon. Another observational study in the Salish Sea discovered the average microplastic concentration per juvenile Chinook salmon was 1.15 pieces, which is unlikely to cause direct mortality (Collicutt et al. 2019). A laboratory study by the United States Geological Survey (USGS) concluded most juvenile Chinook that consumed microfibers—thread-like fibers less than 5 mm in diameter—were able to excrete them and that the fish did not experience altered digestion rates (A. Spanjer, USGS, personal communication). Scientists with the National Oceanic and Atmospheric Administration and University of Washington are examining fecal samples to determine microplastic consumption by southern resident orcas. Preliminary results reveal microfibers and small microparticles in the feces. This research is important in furthering our understanding of the chemical effects associated with microplastic consumption.

The existing body of research suggests that current microplastic concentrations within the Salish Sea are not a significant threat to marine organisms. However, factors such as increasing urbanization and climate change may create or exacerbate microplastics impacts on Salish Sea species, and microplastic exposure and consumption rates across local and regional spatial scales and seasonal and interannual timescales remain largely unquantified.



Approximate sampling locations for zooplankton, forage fish, salmon, and wild Pacific oysters within Salish Sea and coastal waters (left) and Puget Sound waters (right) representing surveys conducted by Desforges et al. (2015), Hipfner et al. (2018), Collicutt et al. (2019), and Martinelli et al. (2020). Four sampling locations outside this geographic area were excluded from visualization.

11 | ECOLOGICAL CONSEQUENCES OF BUILT SHORELINES IN THE SALISH SEA

Dr. Stuart H. Munsch, Ocean Associates, Inc., under contract to Northwest Fisheries Science Center, National Oceanic and Atmospheric Administration

Waterfronts are important ecosystems and busy places. Shallow waters are often productive and densely inhabited by fish. Along shore, terrestrial, aquatic, and benthic realms provide a diversity of habitats for primary producers, invertebrates, and fishes. Indeed, ecologists often characterize nearshore ecosystems as fish nurseries because they provide small fish with plentiful, diverse food sources and protection from predators (Beck et al. 2001).

However, the world's population is disproportionately located near water, where people aggregate industrial, residential, and commercial activities. Consequently, many nearshore ecosystems are highly modified. This is the case in the Salish Sea where many species rely on shoreline habitats, but people have modified shorelines. By appreciating habitat impacts and how to mitigate them, we may steer toward a future than enables people and nearshore ecosystems to coexist.

One of the major modifications to the Salish Sea's shoreline is armoring (e.g., seawalls, riprap). Armoring is hard, heavy material such as concrete or boulders that prevent erosion and allow people to build close to shore. Over 25% of Puget Sound's shorelines are armored, approaching 100% in urban areas (Simenstad et al. 2011). Armoring can replace backshore vegetation, truncate intertidal zones, simplify benthic substrates, and eliminate transition zones connecting land and sea.

The ecology of armored shorelines is different from their unarmored counterparts. Severing the connection between land and sea prevents mutual exchange of nutrients and energy (e.g., seagrass, logs, leaf litter) across shore (Dethier et al. 2016; Heerhartz et al. 2014). The limited, less diverse habitats of armored shorelines are inhabited by less abundant and diverse invertebrate assemblages (Sobocinski et al. 2010; Heerhartz et al. 2016). This translates to a limited prey field available to fish, and fish along armored shorelines must switch from their primary prey of terrestrial (e.g., flies) or epibenthic invertebrates (e.g., harpacticoids) to presumably less valuable plankton (Toft et al. 2007; Morley et al. 2012; Munsch et al. 2015a).

Armoring also influences fish composition. Along armored shorelines, species that prefer deep, rocky waters are present, while species preferring sandy substrates are absent (Toft et al. 2007; Morley et al. 2012; Munsch et al. 2015b). Additionally, along intact shorelines, tiny fish use the shallowest waters to avoid predators before they grow large enough to use deeper waters. However, these tiny fish avoid armored shorelines, presumably because their deeper waterfronts do not offer extreme shallows and predator refuge (Munsch et al. 2016). In addition to removing predator refuge, armored waterfronts attract small fish predators (Munsch et al. 2015b). Another issue is that armored beaches lack backshore vegetation, which keeps intertidal zones cool and damp. As a result, survival of beach spawning fish embryos is lower along armored shorelines compared to vegetated shorelines (Rice 2006). Overall, there are many ecological impacts of armoring on the Salish Sea, and these effects are primarily negative.

Another common modification to shorelines is overwater structures (e.g., bridges, docks, piers). Overwater structures shade shallow waters, limiting photosynthetic species and creating areas too dark for fish to see. This can reduce abundances of invertebrates that associate with algae and seagrasses, including invertebrates common in fish diets (Cordell et al. 2017a). In addition, fish avoid shaded areas under large piers (Munsch et al. 2014; Ono et al. 2014). This is particularly concerning for juvenile Pacific salmon, which migrate along shore but often swim in circles next to piers rather than under them. When salmon do use areas under piers, they rarely feed (Munsch et al. 2014). Similarly, large floating bridges are physical barriers that can disrupt migratory movements of salmonids and increase their risk of predation, potentially by attracting predators to migratory bottlenecks (Moore et al. 2013). Overwater structures are thus another stressor to the Salish Sea's nearshore ecosystems.

By appreciating negative effects of shoreline modifications, we can mitigate them, even along shores heavily used by people (Munsch et al. 2017). Restoring shorelines by removing armoring can recover many lost habitat functions (Toft et al. 2014; Lee et al. 2018). Indeed, many of the Salish Sea's shorelines are not exposed to rapid erosion and do not require conventional armoring. In such cases, property owners may employ alternative shoreline designs that are more aesthetic than armoring, allow people to access the beach, and retain habitat functions (Washington Department of Fish and Wildlife 2016). Where true restoration is not practical, built pocket beaches and artificial intertidal zones can mimic some habitat functions of intact shorelines (Toft et al. 2013). These efforts to improve habitat can directly benefit people, for example by providing recreational beach space within urbanized landscapes. In areas where conventional armoring is necessary, seawalls can be textured to provide habitats for algae and invertebrates including fish prey (Cordell et al. 2017b). Similarly, where large overwater structures are necessary, people can construct them using translucent surfaces to avoid shading (Cordell et al. 2017b). Pocket beaches, artificial intertidal zones, textured seawalls, and translucent pier materials have recently been employed along the downtown Seattle waterfront to enhance habitats without reducing the waterfront's utility to people. Ongoing research is examining their effectiveness. Overall, we may protect the Salish Sea's nearshore ecosystems by appreciating ecological consequences of building along shore, conserving shorelines where human use constraints are low, and developing and employing approaches to mitigate negative effects of built shorelines in urban areas.

Railroad tracks and rip rap armoring along the shoreline at Marine Park, Bellingham WA Photo: Ginny Broadhurst

SECTION 4

CLIMATE CHANGE

A GLOBAL PROBLEM WITH LOCAL IMPACTS

Downtown Bellingham, WA from the Lummi Nation
Photo: Nick Pinkham

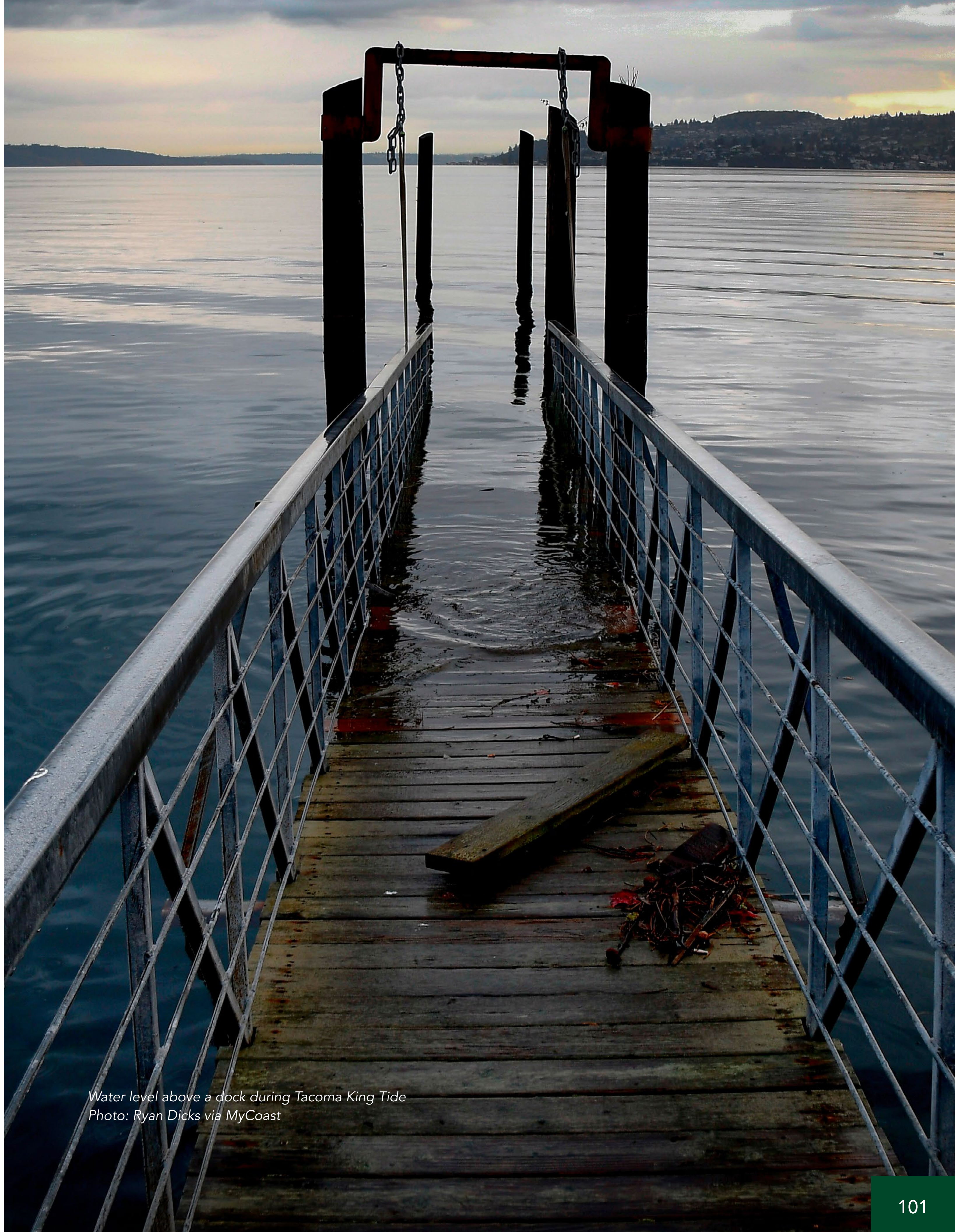
SECTION 4

PHYSICAL EVIDENCE OF CLIMATE CHANGE

ECOLOGICAL EVIDENCE OF CLIMATE CHANGE

SUMMARY OF CLIMATE CHANGE IN THE SALISH SEA

VIGNETTES



Water level above a dock during Tacoma King Tide
Photo: Ryan Dicks via MyCoast

Twenty-five years ago when *The Shared Waters Report* was written, scientists were beginning to identify concerns associated with climate change in the Salish Sea. Today, scientists more fully recognize, catalog, and quantify the ongoing impacts of climate change and are working to predict what further effects it might trigger in the coming decades.

Observed changes to the Salish Sea ecosystem include documented long-term trends across several critical atmospheric, hydrologic, biologic, and geophysical parameters, and also include more abrupt and anomalous conditions like the 2014-2016 marine heat wave known as "the Blob." Modeling studies that incorporate climate projections and concomitant changes to physical processes supplement those empirical observations to provide additional indications of regional changes that have already occurred and that are probable with continued global climate change.

Climate change modeling and projections are understandably uncertain, and the resulting responses from biota are even more uncertain because multiple impacts may change organism populations and communities in nonlinear ways. However, as recognized by numerous researchers and studies cited in this report, predictions about ecosystem impacts will continue to be vital and will benefit from more transboundary cooperation, additional carefully designed small-scale experiments, and development of truly integrated models where large-scale simulations are possible and likely to generate new insights leading to sustainable solutions.

Climate vs. Climate Change

Climate is the slowly varying aspects of the atmosphere-hydrosphere-land system. Climate is determined by the long-term pattern—averages, variability, and extremes—of temperatures, precipitation, and winds at a location and can be variable even over short distances. Climate descriptions can refer to various spatial scales (local, regional, or global) and temporal scales (decades, years, seasons, months, or specific dates). Climate change, on the other hand, is any systematic change in the long-term statistics of climate elements from one system state to another, where the new state is sustained (over several decades or longer). Climate change may be due to natural external forcings, such as changes in solar emission or slow changes in the earth's orbital elements, natural internal processes of the climate system, or anthropogenic forcing (American Meteorological Society n.d.). Vernacularly, climate change refers specifically to the rise in global temperatures and associated physical and chemical forcings from the mid-20th century to present that result from anthropogenic causes, and that is the sense it is used herein.

PHYSICAL EVIDENCE OF CLIMATE CHANGE

Increasing greenhouse gas emissions, and the resulting increases in atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are driving changes to the earth system, referred to as climate change. The impacts of climate change are largely driven by physical forcing (changes and drivers of change in physical processes), the first and foremost of which is global temperature of the air, water, and soil.

Those drivers and their impacts alter much more than just temperature in the marine environment by affecting ocean currents, salinity, water density, pH, and other structural elements of marine systems. Discussed below are several examples of physical and chemical impacts, how they force changes within other inter-connected elements, and how those changes impact ecosystems.

Air Temperature

Globally, air temperatures on Earth have warmed by about 0.75°C (1.5°F) since 1900 (Intergovernmental Panel on Climate Change 2014; 2018) and by nearly 1.1°C (2°F) in the Pacific Northwest (May et al., 2018; Figure 4.1). This warming is attributable to human-caused emissions of greenhouse gases, such as CH_4, N_2O, and CO_2 (Intergovernmental Panel on Climate Change 2018; Oreskes 2004). The Salish Sea region has shown a warming trend in recent years (1980 to present), with average temperatures for almost all years since 1980 above the 100-year average (Mauger et al. 2015). In 2015, during the "the Blob" heat wave event, the Salish Sea region experienced its warmest air temperatures on record at 1.9°C (3.4°F) above normal for the year and 3.4°C (6.2°F) warmer during the winter (May et al. 2018). Going forward, the projected average temperature increase over the next 25 to 50 years ranges from 2.0° to 3.3°C (4.2° to 5.9°F) (Mauger et al. 2015; PCIC 2018), signaling that the temperatures experienced in 2015 were a preview of projected change for this region (see Vignette 12, The Blob).

While warming from climate change is expected for all seasons and is projected to be greatest in summer (Mauger et al. 2015), wintertime warming air temperatures could lead to profound changes in snowpack, and in turn, to water delivery to the estuarine waters of the Salish Sea (Figure 4.2). For example, in 2015 the region experienced abnormally warm air temperatures throughout the year, which led to an extremely low snowpack, pronounced water scarcity, and wildfires. These types of impacts are predicted to increase in occurrence and severity over time.

Changes to temperature and precipitation will have impacts on freshwater delivery in terms of availability, scarcity, and timing. For each 1°C (1.8°F) of air temperature warming, peak snow-water equivalent (the amount of water contained within the snowpack, which can be thought of as the depth of water that would theoretically result if the entire snowpack was melted instantaneously) in the Cascades is expected to decline 22% to 30% (Cooper et al. 2016).

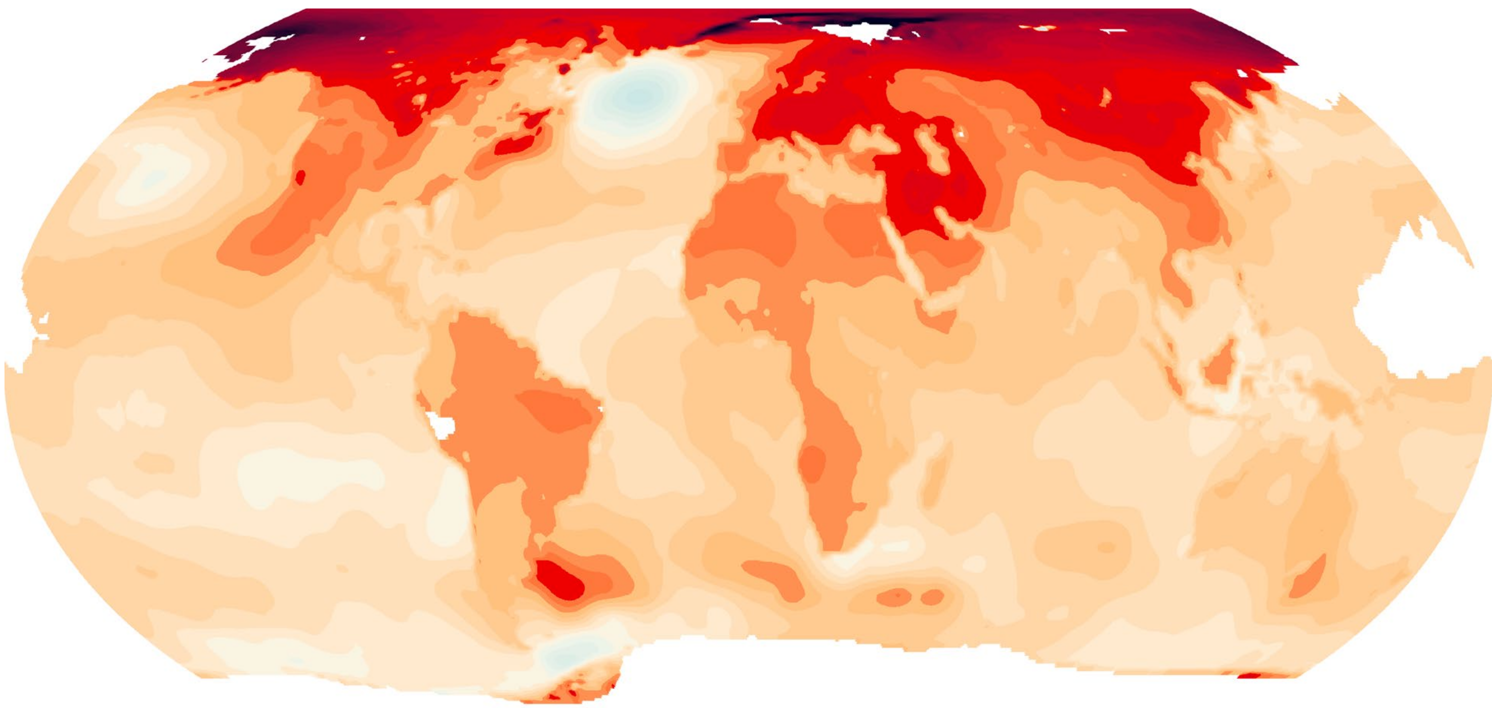


Figure 4.1. Global temperatures in recent years are some of the warmest on record. This static image of a dynamic map of Berkeley Earth data shows how the temperature average of the last five years compares with the years 1880 to 1899 (refer to the source to view an interactive map with this and other data). Source: Mooney & Muyskens (2019)

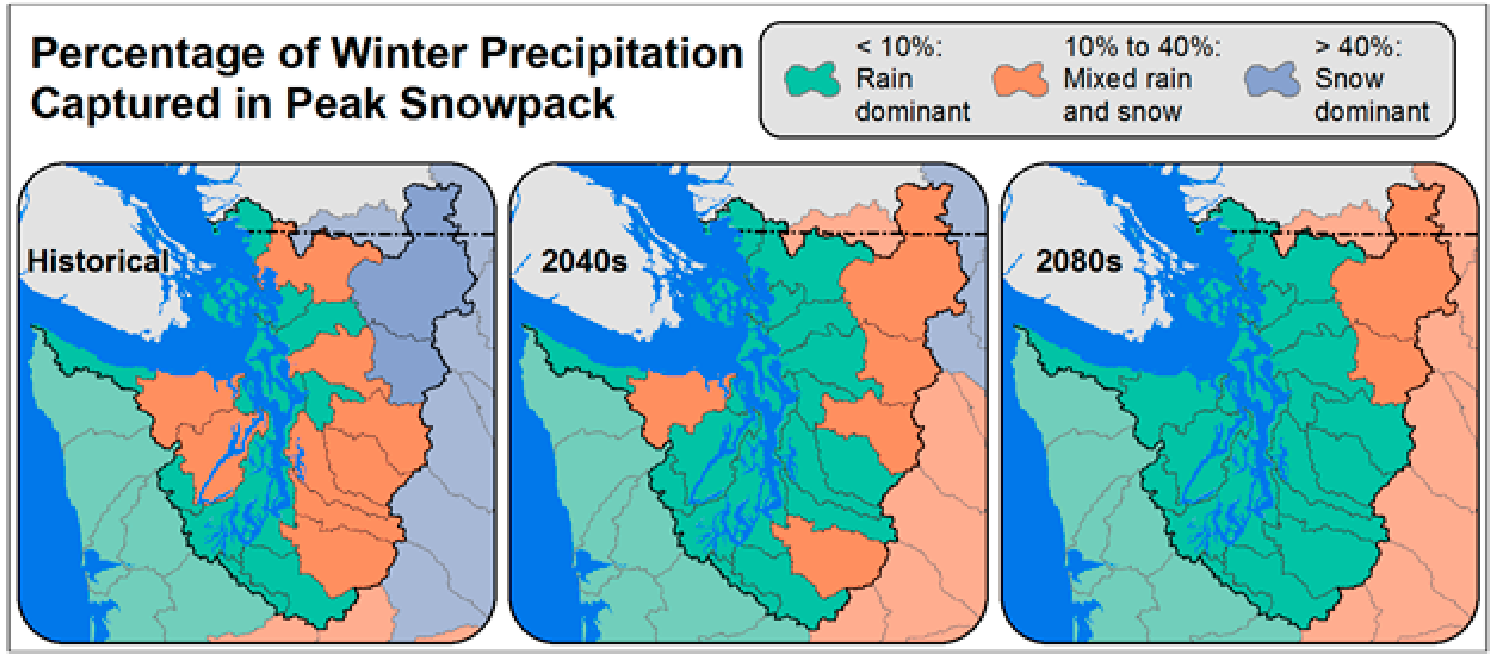


Figure 4.2. Percentage of winter precipitation captured in peak snowpack. Models project a dramatic shift to more rain-dominant conditions in Puget Sound watersheds from a recent historical time period (1970-1999) forward 100 years to the 2080s. Maps indicate current and future watershed classifications based on the proportion of winter precipitation stored in peak annual snowpack. Source: Mauger et al. (2015)

The loss of snowpack has implications for water delivery in the spring and early summer, as lower snowpack will mean less melt-off (volume of runoff) and earlier melt-off.

Warming air temperatures have affected and will continue to directly affect stream temperatures (Isaak et al. 2012). Temperature is one aspect governing the kinds of organisms that can live in freshwater systems and it impacts metabolic processes of these animals (higher temperatures typically involve higher metabolic costs; Clark & Fraser 2004). Additionally, temperature influences water chemistry by governing dissolution of minerals and gases (water at higher temperatures can hold less dissolved oxygen), which is an important consideration for aquatic life. Temperature effects in streams can be subtle increases over time or more pronounced short-term, discrete, or acute effects. For example, water temperature in the Fraser River has increased by an average of 3.3°C (5.9°F) over the last century (Riche et al. 2014), representing a gradual increase over time. Meanwhile, the number of days when Fraser River water temperatures exceed a threshold for salmon migration (believed to be 18°C, Martins et al. 2011) has increased over the last 50 years (Riche et al. 2014), representing an acute effect.

As global climate change continues, we are likely to experience similar combinations of persistent and acute increases in air, water, and soil temperatures, leading to complex changes in the biota dependent upon those systems.

Both persistent and acute temperature changes can impact stream chemistry, biota, and more, but the impacts on the receiving waters of the Salish Sea are currently not well understood. Model downscaling (the use of large-scale climate models to make predications at local scales) is necessary to resolve predictions for coastal areas that often have different dynamics than the open ocean. Local predictions of physical conditions can then be used to investigate impacts to biota at the local scale. Although the complex oceanography within inland waters like the Salish Sea makes predictions particularly challenging, it's clear that impacts from warming freshwater will likely be most pronounced in areas where freshwater and saltwater mix in river-mouth estuaries. For example, recent modeling work in the Snohomish River estuary projected a 4°C (7.2°F) increase by the end of the century in the estuary headwaters (upriver region) and a 2°C (3.6°F) increase in temperature in the mixing zone in Possession Sound (seaward region; Khangaonkar et al. 2019).

Freshwater Delivery

Inflow from the Fraser River, Skagit River, and the many smaller rivers emptying into the Salish Sea, together with direct precipitation, drives many aspects of physical oceanography within the inland waters. These include stratification and saltwater dilution. Most importantly in the Salish Sea, incoming freshwater (mostly from the Fraser River) helps drive estuarine circulation (Masson & Cummins 2000), which transports organisms, circulates nutrients and oxygen, and transports sediments. Thus, changes in freshwater delivery can have impacts on physical gradients (e.g., water density) and biological processes within the estuary.

As air temperatures continue to increase, there are two aspects to precipitation that will directly impact freshwater delivery, and thus the estuarine waters of the Salish Sea: 1) more intense precipitation events will periodically increase freshwater delivery and 2) increasing rain (rather than snow) in alpine areas will result in increased freshwater delivery, especially during the winter months. Regarding the first impact, intense precipitation events are historically atypical because the region normally receives rainfall as a steady drizzle or light rain over the winter months rather than episodic torrential downpours (multiple inches in a 12-hour period). An increase in rain event intensity means more rainfall in short periods of time, increasing the variation in water delivery timing (Ward et al. 2015) and increasing runoff and flooding as water flows from the upper watersheds, through the coastal lowlands, and into the Salish Sea.

For the second effect, snowfall is expected to decline as temperatures warm, and will be replaced with rain events in the mountains (Figure 4.3). This will result in increased winter streamflow, as snowpack typically serves as a water reservoir to hold freshwater until seasonal temperatures warm enough to begin seasonal melting. This is a critically important disruption because snow and ice serve as hydrological stabilizers, reducing variation in freshwater flow from the mountains to the coasts (Johannessen & Macdonald 2009). Without this reserve of frozen water built up in snowpack over the winter months, spring freshets (the annual peak in flow associated with snowmelt) in major snow-influenced rivers, such as the Fraser and Skagit Rivers, will likely be reduced. In short, water delivery will increase throughout the winter season, but will be seasonally reduced during the spring melt-off. This change will likely have significant implications for estuaries, leading to changes in the circulation and transport of nutrients, oxygen, sediment, and biota.

Another aspect of a changing hydrograph (freshwater discharge over time) is the projection of a significantly lower peak flow occurring much earlier in the year (Figure 4.3). Johannessen and Macdonald (2009) show this to be about 24 days earlier by 2080 than during the 1961 to 1990 reference period for the Fraser River. An earlier study conducted more broadly in the Pacific Northwest found shifts of 10-30 days earlier already occurring in their 50-year period of study, 1948 to 2000 (Stewart 2004). These studies provide an indication of changes in water delivery already occurring and projected for the future.

How changes in streamflow timing will influence the estuarine waters of the Salish Sea is not well understood and will likely vary by river system and location. For example, a modeling study in the Snohomish River estuary (Yang et al. 2013) suggests that salinity intrusion points will change with changing river discharge and sea level rise. However, given the dynamic nature of estuaries with respect to salinity, the impacts of these changes to biota are unknown and may depend upon the time scales at which they occur.

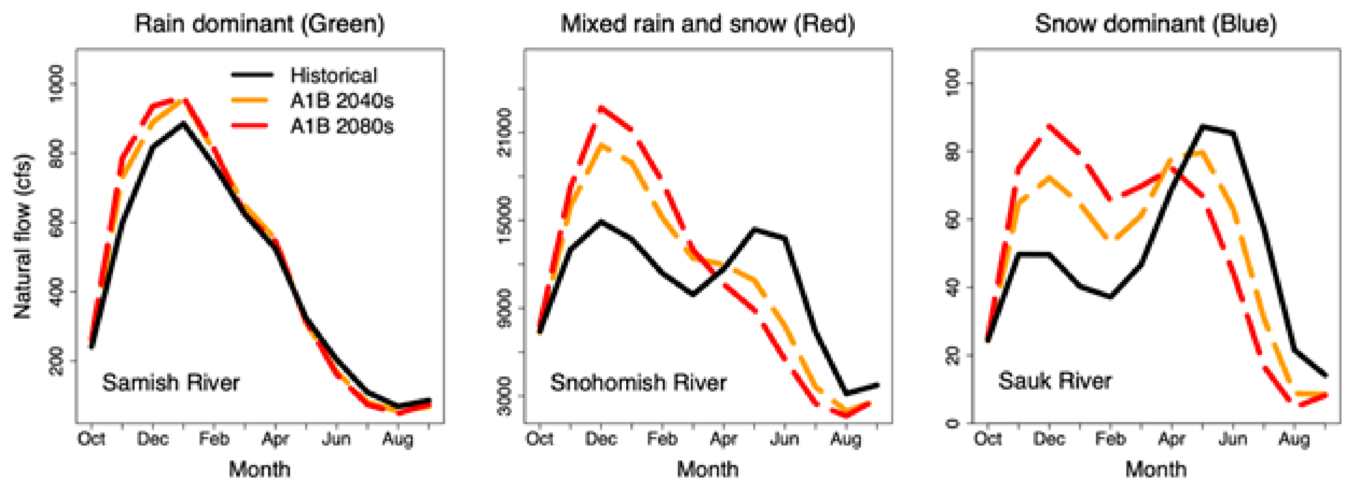


Figure 4.3. Changing freshwater discharge in three different watershed types. Colors in graph titles refer to those in Figure 4.2, which provides a spatial depiction of rain dominant, mixed rain and snow, and snow dominant watershed types. Graphs indicate average historical (1970-1999, black line) and future average monthly streamflow. Average projected future conditions are from ten global climate models during two time periods: the 2040s (2030-2059) and the 2080s (2070-2099) using a moderate greenhouse gas scenario (A1B). Streamflow is projected to increase in winter and decrease in spring and summer for all basin types, with the biggest changes occurring in mixed rain and snow watersheds. Source: Mauger et al. (2015); data from Hamlet et al. (2013)

Racehorse Falls in Deming, WA
Photo: Nick Pinkham

Sea Water Temperature

Global ocean surface waters have warmed between 0.5 and 1.0°C (0.6-1.8°F) since 1970, with warming observed at all depths. Due to the ocean's heat capacity and circulation, the rise in ocean temperatures lag those of air, river, and lake water (Intergovernmental Panel on Climate Change 2007). In addition, changes in ocean temperature are not evenly distributed across the globe. Time-lapse animations and static maps, like the series shown in Figure 4.4, make it clear that the Northern Hemisphere has disproportionately warmed, with some of the highest rates of warming across the globe observed in the North Pacific (+5.0 to 6.0°C; Figure 4.5).

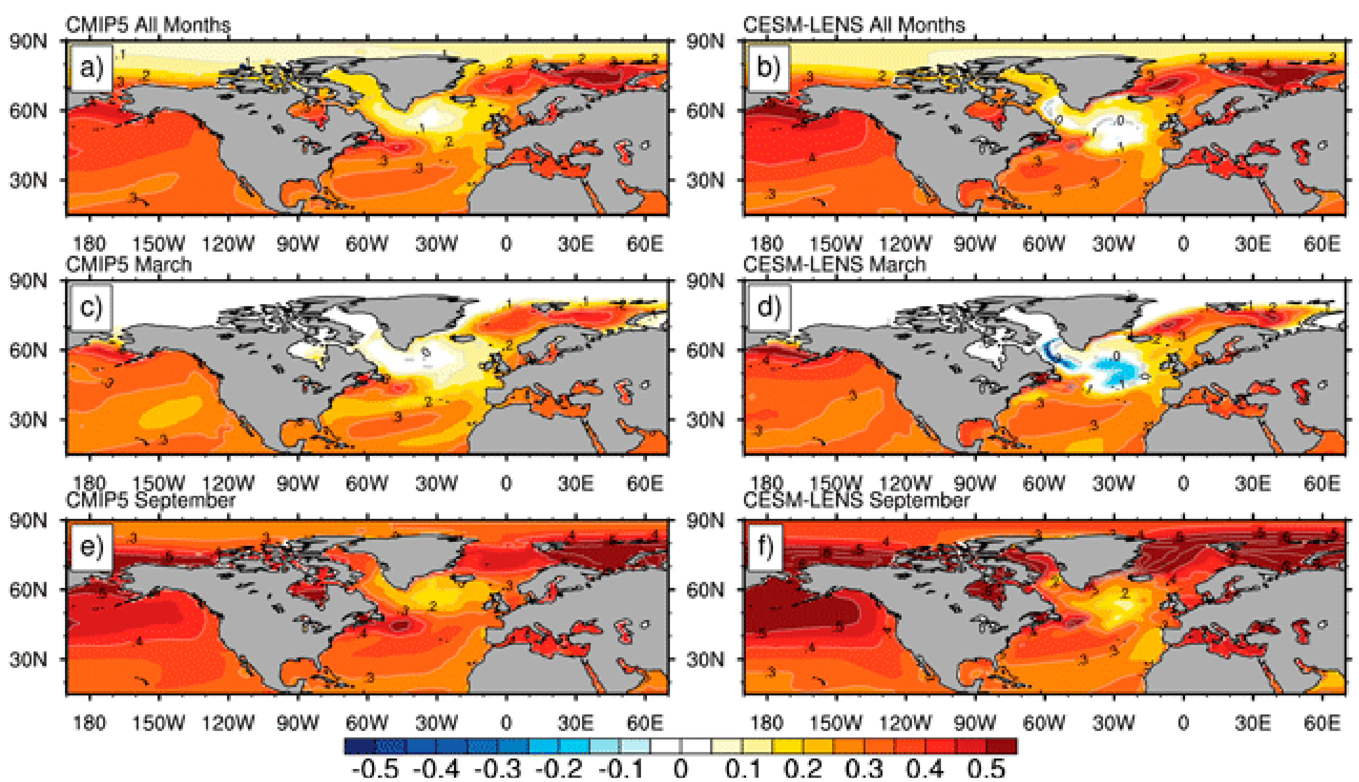


Figure 4.4. Ensemble mean sea surface temperature trends predicted from climate models (CMIP5 and CESM-LENS) over the period 1976-2099. Trends are shown for all months (a, b), for March (c, d), and for September (e, f) based on CMIP5 (a, c, and e) and CESM-LENS (b, d, and f). Color bar indicates trends in °C per decade with positive values in shades of red and negative values in shades of blue. Only trends that are significant at a 95% level using a Mann-Kendall test are shown. Trends are positive and significant in most areas except the North Atlantic and Arctic Oceans in March. Source: Alexander et al. (2018)

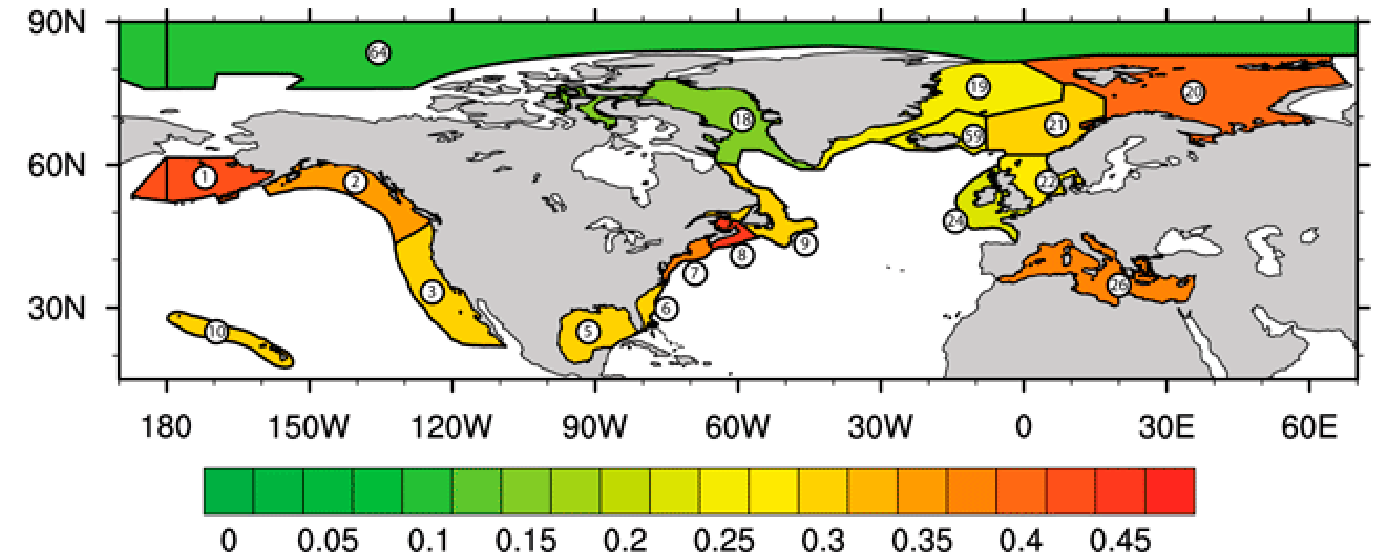


Figure 4.5. Sea surface temperature trends in Large Marine Ecosystems in the northern hemisphere. Colors denote the climate model (CMIP5 ensemble) mean area-averaged SST trends (°C per decade) during 1976–2099. All trends are significant at the 95% level using a Mann-Kendall test. Regions are numbered following the LME convention: 1) Bering Sea, 2) Gulf of Alaska, 3) California Current, 5) Gulf of Mexico, 6) Southeast US Shelf, 7) Northeast US Shelf, 8) Scotian Shelf, 9) Newfoundland-Labrador Shelf, 10) Hawaii, 18) West Greenland, 19) Greenland Sea, 20) Barents Sea, 21) Norwegian Sea, 22) North Sea, 24) Celtic-Biscay Shelf, 26) Mediterranean, 59) Iceland Shelf and Sea, and the 64) Central Arctic. Source: Alexander et al. (2018)

In the Salish Sea, one of the best time-series of sea surface temperature (SST) is from the network of British Columbia lighthouse stations (Fisheries and Oceans Canada 2021). Daily observations of SST and salinity started at the Pacific Biological Station in Departure Bay, BC, in 1914. Observations were made daily using the time-tested technique of measuring seawater collected in a bucket. This sampling apparatus was lowered into the surface water at or near the daytime high tide and the temperature and salinity were measured. The methodology has remained the same throughout the time-series for consistency, offering one of the best long-term records of measurement in the region (White et al. 2016). More recently, researchers have used satellite (MODIS) derived temperature data to measure temperature across broader areas (Amos et al. 2015). Monthly averaged satellite data show that trends in SST at two sites in the Strait of Georgia are very similar to the Lighthouse measurements; this correspondence supports spatial extrapolation of the Lighthouse measurements to the broader basin, extending further the value of the time-series.

The stations in the Strait of Georgia show a mean increase in SST of about 0.56°C per decade (Amos et al. 2015). This is higher than the global average (Intergovernmental Panel on Climate Change 2007; Solomon et al. 2009) and contrasts markedly with the trends from the more northern stations in British Columbia, which have shown less warming. The warming trends of the southern stations are significant in all months of the year but are most evident during summer (July–September). The summertime anomalies in temperature at Active Pass are significantly correlated with the temperature of Fraser River water, suggesting that warming freshwater in this major tributary has an influence as it flows into the Salish Sea. Temperature differences between the Strait of Georgia and the outer continental shelf are increasing in time, especially since 2000. At present rates of SST rise, the southern coastal waters of British Columbia are projected to be about 3°C warmer by the end of the 21st century.

The Salish Sea Model (Figure 4.6; see Vignette 13, Salish Sea Model) is a complex hydrodynamic model developed for the Salish Sea and serves as a tool with which to assess changes in Salish Sea conditions given some inputs to forcing (climate or other) (Khangaonkar et al. 2012). As part of a recent study (Khangaonkar et al. 2019), the authors used climate forcing to determine changes in circulation, sea level rise, and other attributes in the Salish Sea. Similar to work from the Strait of Georgia (Amos et al. 2015), their model showed a projected increase in sea surface temperature of 2.6°C by the end of the century. Mixing and circulation driven by ocean water mediate some of the temperature increases resulting from increasing air temperature and temperatures of inflowing freshwater, but as the ocean warms, the mediating properties may diminish.

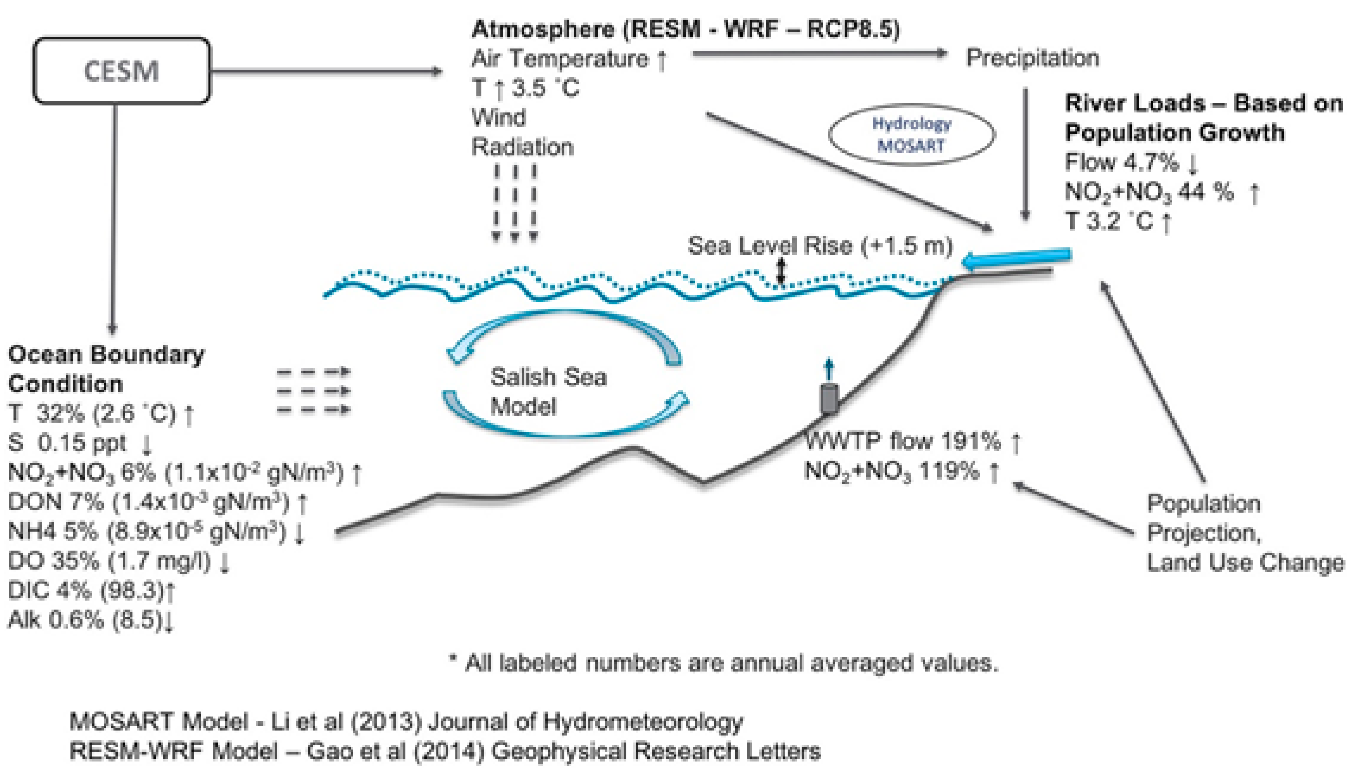


Figure 4.6. The Salish Sea Model is a three-dimensional computer tool that can simulate hydrodynamic and water quality processes in the Salish Sea. Shown here is a summary of the projected changes for temperature, salinity, freshwater inflows, and water quality variables for the future (75 years from now, 2095) relative to inputs for 2000. The model uses climate scenario RCP8.5 and includes several input models including: CESM = Community Earth System Model; RESM = Regional Earth Systems Model; WRF = Weather Research and Forecasting; and MOSART = Model for Scale Adaptive River Transport. Variables include: T = temperature, S = salinity, NO2 and NO3 = Nitrite and Nitrate (nutrients), DON = dissolved organic nitrogen; NH4 = Ammonium, DO = dissolved oxygen; DIC = dissolved inorganic carbon; Alk = Alkalinity, and WWTP = wastewater treatment plant. Source: Khangaonkar et al. (2019)

Anomalies

Climate data, whether air or sea surface temperature or other metrics, are often presented as anomalies. An anomaly is the deviation in a quantity from its expected value, such as the difference between an observation (measurement) and a mean, or the difference between a mean and a model prediction. It is important to understand the reference period used to understand the scale of change.
In climate science, the present-day climate is compared to a period in the recent past (typically 1980 to 1999, but other time periods like 1950 to 2000 may be used). Current observations or model predictions for the future are generally shown as deviations from the average for this reference period and will be represented as values greater than or less than zero, with zero being the mean from the reference period and therefore a form of baseline from which to compare. Datasets that are local (for example, from the Salish Sea as described in this report) or don't have long time-series may use different reference periods, but still present data as anomalies.

Our understanding of the effects of climate change, particularly warming sea surface temperatures, is aided by natural experiments. The marine heat wave in the northeast Pacific Ocean of 2014 to 2016, known as the "Blob" is one such natural experiment. While the Blob has subsequently diminished; it's important to note that the effects of that event persisted in observed biota on the coast for several years after the most extreme temperature rise (Sutherland et al., 2018).

A new heat wave was observed in the fall of 2018 due to delayed and reduced winter cooling (Boldt et al. 2019), and it continued into 2019, prompting concerns about the return of very high sea surface temperatures in the region. But weather events in the fall of 2019 resulted in the warm mass being driven offshore into the North Pacific. The frequency and duration of these warm water events will be of much interest to scientists in the coming years.

The Blob

Strongly positive temperature anomalies developed in the northeast Pacific Ocean during the winter of 2013–2014. These anomalies were caused by lower-than-normal rates of the loss of heat from the ocean to the atmosphere and of relatively weak cold advection in the upper ocean. Both of these mechanisms can be attributed to an unusually strong and persistent weather pattern featuring much higher-than-normal sea level pressure over the waters of interest. The region of warm sea surface temperature anomalies subsequently expanded and reached coastal waters in spring and summer 2014 and persisted through 2016. This warm water mass became known as the "Warm Blob" or the "Blob." (See Vignette 12, The Blob, for more detail.)

The consequences of short-term and long-term changes in water temperature for the Salish Sea are not yet fully understood. What is apparent is that the inland waters of the Salish Sea are unique and do not follow lockstep with coastal oceanographic phenomena, but they do exhibit some of the same signals. The influence of local urbanization in the region's many watersheds and the variable inputs of freshwater are defining features of the system, but those features also make it challenging to predict or fully resolve complex interactions between atmospheric and oceanographic conditions (Roop et al. 2020). Additionally, reductions to circulation driven by climate change, and the system's unique and varied oceanography, could exacerbate effects of increasing temperatures at local scales.

We do know that warming sea water temperature interacts with other physical, chemical, and biological processes to shift species distributions (Hazen et al., 2013), increase metabolic costs (Deutsch et al. 2015), change phenology (the timing) of events such as phytoplankton blooms or migrations (Brown et al. 2016), and destabilize food webs (Nagelkerken et al. 2020). In the Salish Sea, these changes are happening simultaneously, with impacts to salmon (Hinch et al. 1995; Shelton et al. 2020), phytoplankton (Moore et al. 2008), and likely many other species that are yet unstudied. Additionally, increasing sea water temperature increases susceptibility to marine diseases (Harvell et al. 2019; Burge & Hershberger 2020; and see Vignette 14, Eelgrass Wasting Disease) and amplifies bioaccumulation of contaminants (Alava et al. 2018). Without a doubt, many effects are occurring simultaneously and, in some cases, synergistically.

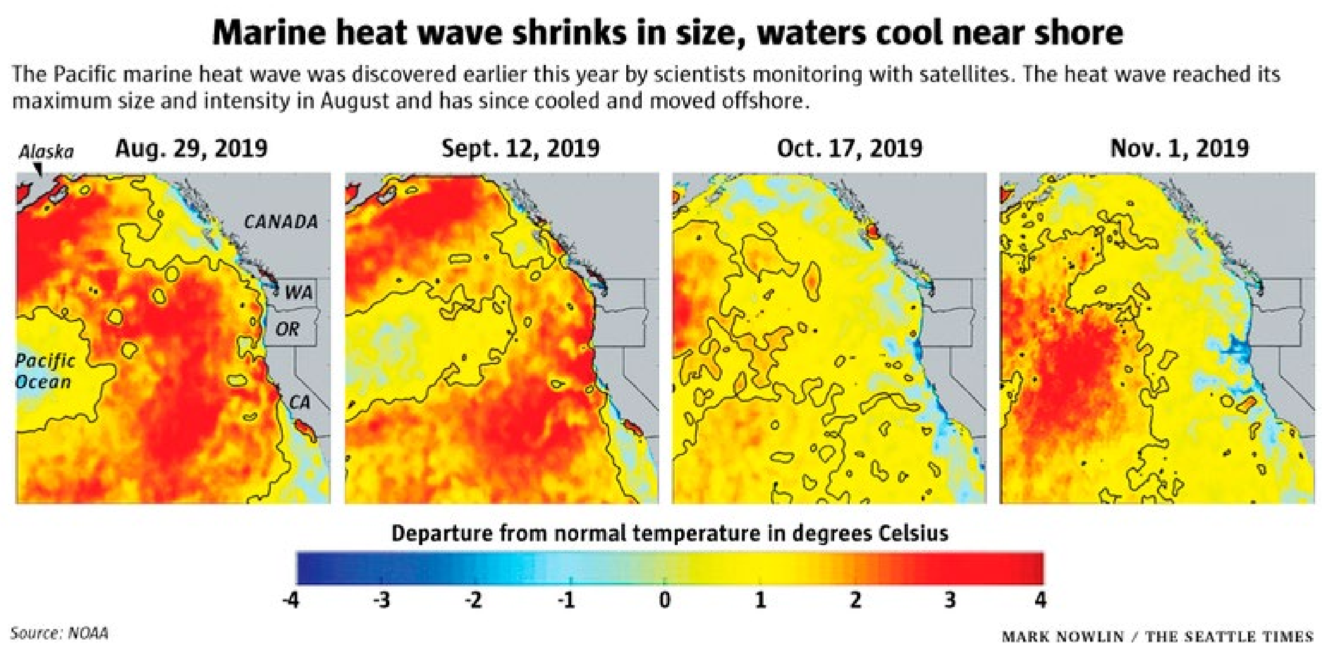


Figure 4.7. A new marine heat wave after the Blob in 2014-2016. After the Blob event in 2014-2016, a new marine heat wave set in during the summer of 2019 but dissipated that autumn. Source: Mark Nowlin & the Seattle Times (2019)

Ocean Acidification

Ocean acidification refers to the chemical changes in the ocean caused by the absorption of CO_2 from the atmosphere (Figure 4.8). Predictions for the next 100 years indicate that the oceans will continue to absorb CO_2, further increasing ocean acidity. Since the beginning of the Industrial Revolution when anthropogenic carbon emissions began to increase significantly, the global average pH of surface ocean waters has declined by 0.1 pH units from an average of 8.2 to 8.1. This may not seem like much, but the pH scale (measured from 0-14, with lower values representing acidic conditions), like the Richter scale, is logarithmic, meaning this change represents an approximate 30% increase in acidity (Pacific Marine Environmental Lab 2021). Estimates of future CO_2 levels, based on business-as-usual emission scenarios, indicate that by the end of the 21st century, the surface waters of the ocean could show acidity levels 1.5 times what they were prior to the Industrial Revolution.

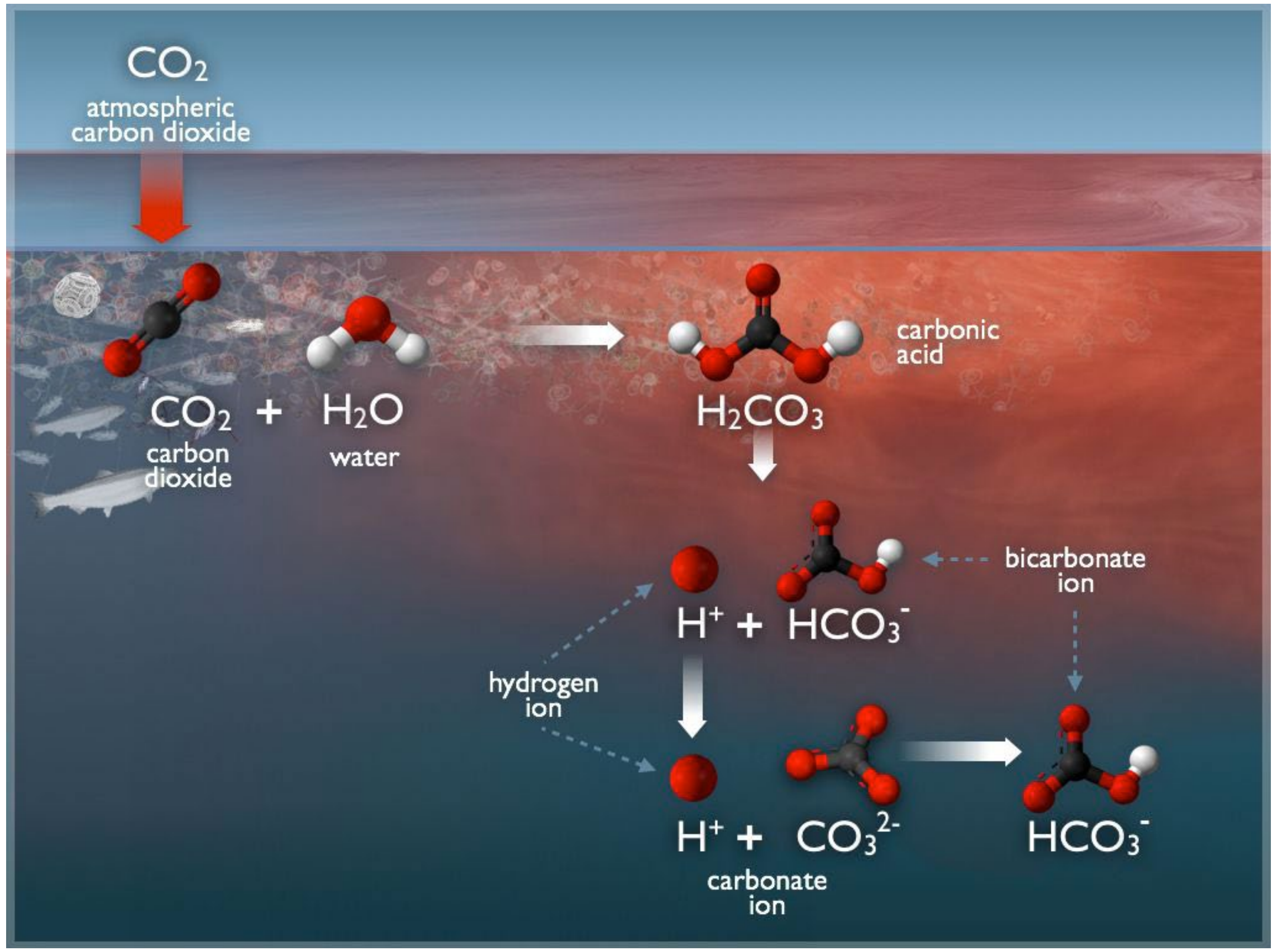


Figure 4.8. Carbonate dynamics in the Salish Sea are driven by a number of physical processes occurring along the Pacific Coast and in the inland waters. CO_2 from the atmosphere is absorbed by the ocean and mixes with seawater to form carbonic acid. This carbonic acid then quickly dissolves to form an acid (H+ ion) and bicarbonate (HCO_3-), which is a base. This is the process known as ocean acidification. Source: Center for Environmental Visualization (2014)

Pacific Northwest coastal waters are among the most acidified worldwide (Feely et al. 2010; Feely et al. 2012; Mote et al. 2014). In the Salish Sea, pH is largely regulated by natural mixing, circulation, and biological processes. The geography, bathymetry, and natural physical forcing in the Salish Sea put it at similar risk of acidification as the nearby coastal waters. The features contributing to the risk of ocean acidification include incursion of upwelled waters that are naturally low in pH and rich in CO_2 (Crummett et al. 2020), restricted circulation within the Salish Sea caused by shallow sills between basins, inputs of naturally low pH river water, and inputs of nutrients from humans (Cai et al. 2021).

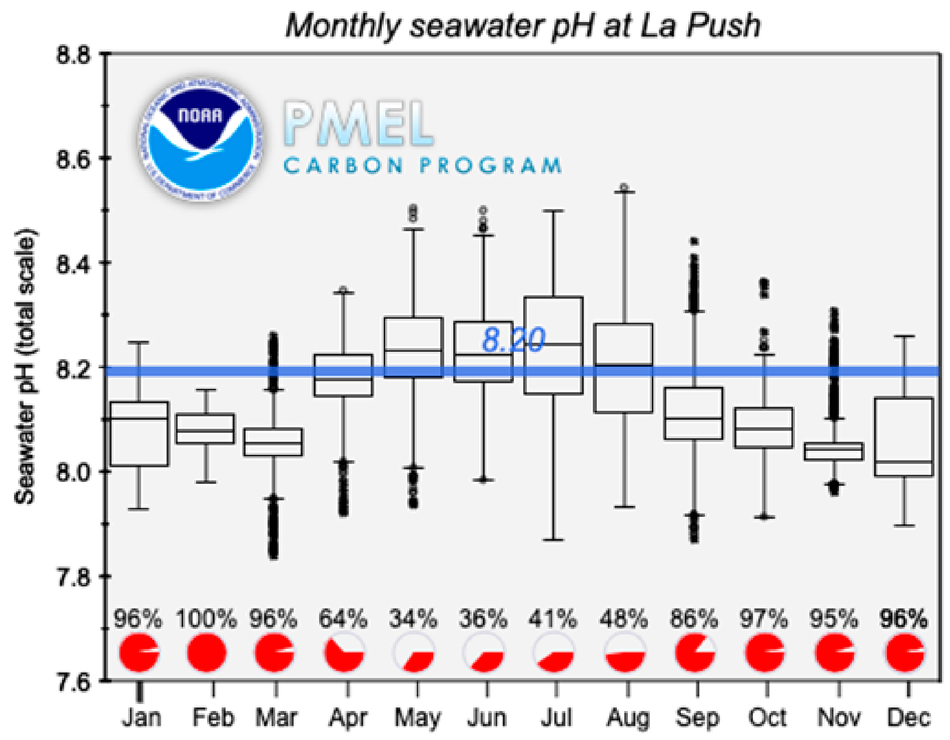


Figure 4.9. Monthly climatology of surface seawater pH at La Push, WA. Box plots are observations binned by month as described in Sutton et al., 2016. Pie charts represent percent of observations within each month that fall below the baseline (here 8.2, which is considered neutral seawater based on pre-industrialization levels). Source: NOAA Pacific Marine Environmental Laboratory (2021)

Ocean acidification currently plays a small but significant role in reducing the pH of Salish Sea waters and is somewhat seasonally driven. At La Push, WA, the NANOOS (Northwest Association of Networked Ocean Observing Systems) buoy monitors pH and several other water quality parameters (NANOOS 2021). The data from this buoy show a seasonal pattern to pH, with more acidified (lower pH) water present in the winter months compared with the summer months (Figure 4.9), observations also made in the Northern Salish Sea (Evans et al. 2019). This seasonal pattern is driven in part by phytoplankton production taking up CO_2 and thereby modulating pH during the summer months.

In addition to reduced seawater pH, there are three other major chemical changes caused by CO_2 absorption: increase in inorganic (total) carbon, reduced carbonate ion concentrations, and reduced saturation states of biologically important calcium carbonate minerals. Calcium carbonate minerals are the building blocks for the skeletons and shells of many marine organisms and aragonite is the primary mineral used as an indicator of ocean acidification. The formation of calcium carbonate is sensitive to the concentration of carbonate ions in seawater. In most areas of the coastal ocean, there is ample calcium carbonate ion and therefore abundant material for calcifying organisms to build their skeletons and shells. However, ocean acidification is causing carbonate ion to decline, which is likely to negatively affect the ability of some organisms to produce and maintain their shells. There is already evidence of reduced calcification among pteropods (pelagic mollusks) in the Salish Sea (Bednaršek et al. 2020a). Many organisms at the base of the food web rely on calcium carbonate to build shells, meaning any disruption to these abundant organisms will ripple throughout the marine food web.

Key biological processes, including photosynthesis, growth, respiration, recruitment (the addition of juveniles to a population), reproduction, and behavior are sensitive to high CO_2 and low pH (Whitely-Binder & Washington State Blue Ribbon Panel on Ocean Acidification 2012). While ocean acidification is generally considered a negative impact in marine ecosystems, in some cases, increased carbon may benefit ecological processes. For example, increases in total carbon can stimulate photosynthesis, resulting in blooms when other limiting nutrients are also available (Boyd et al. 2018). This increase in primary production can also positively affect zooplankton communities (Taucher et al. 2017), although this has not been demonstrated for the Salish Sea (McLaskey et al. 2019). In some places, phytoplankton blooms may include harmful algal species, posing a health risk or producing unknown consequences for other organisms (Hattenrath-Lehmann et al. 2015). These and other studies are identifying direct impacts of ocean acidification to biota and clarifying the mechanisms causing change, with much more yet to be learned.

Ocean acidification has the potential to directly affect a wide range of organisms in the Salish Sea, from primary producers including phytoplankton and seagrasses, to marine invertebrates (e.g., shellfish) and vertebrates (e.g., fishes). Increased concentrations of CO_2 in the marine environment impede calcification processes for organisms like clams and oysters (Figure 4.10; Waldbusser et al. 2015) and can influence the physiology of marine organisms by changing their internal acid-base balance, potentially leading to changes in protein synthesis, growth, development, and neurophysiology—and reduced oxygen transport capacity (Kroeker et al. 2013). Invertebrate prey important to salmon and herring, including gammarid amphipods, harpacticoid and calanoid copepods, euphausiids, and decapod larvae could be also affected by increased ocean acidification. Recent work on Dungeness crab larvae on the Pacific Coast showed risk of carapace dissolution (chemical degradation of the shell, resulting in structural deformities), which has implications for growth (Bednaršek et al. 2020a). Dungeness crab is a valuable and important fishery in the region, and reduced condition of larvae could have serious impacts to the sustainability of the fishery. Using predictions from the Salish Sea Model, the same researchers identified South Puget Sound as a potential hot spot for damage from acidification for larval crab, driven by the uptake of atmospheric CO2 (Bednaršek et al. 2020b).

There are also potential direct effects on fish, which have been shown to experience olfactory disruption and other physiological impacts as a result of acidified waters (Williams et al. 2019). Many estimates of species at risk from ocean acidification are based on projections from laboratory exposure experiments or laboratory experiments in combination with model predictions. With the exception of pteropods (Bednaršek et al. 2020a), few studies have clearly demonstrated changes in abundance or condition for Salish Sea species in the wild as a direct consequence of changes in ocean chemistry from increasing CO_2, but the decrease in ocean pH from anthropogenic CO_2 is well documented and the projected decrease in pH is well understood. However, the biological response to these changes is much less clear and is the ongoing focus of research efforts around the world and here in the Salish Sea. Anthropogenic acidification due to eutrophication (described further below) is where nutrients of anthropogenic origin enhance organic matter production in shallow coastal areas, which is then respired to produce CO2. While not as prevalent a mechanism in the Salish Sea as in other regions (e.g., Chesapeake Bay; Zimmerman & Canuel 2000), this type of acidification is observed locally. An example is from the southern part of Hood Canal, Washington where there is concern that nutrients from terrestrial runoff may stimulate additional production of organic matter that is respired to CO_2 (Feely et al. 2010). Irrespective of anthropogenic nutrient inputs, seasonal phytoplankton cycles (Pelletier et al. 2018) and annual variability in circulation will also influence CO_2 uptake and pH in inland waters. Understanding the synergistic responses to elevated CO_2 and impacts when combined with low oxygen, warming SST, and localized eutrophication is necessary to fully understand the impacts of acidification.

There are concerns about future impacts of acidification in oceans and the Salish Sea, given the predicted trajectory for atmospheric CO_2 and long-term local trends in seawater pH. The extremely rapid and accelerating pace of change in ocean pH and the susceptibility of a wide variety of taxa to changes in ocean carbon chemistry suggest that while the precise effects of ocean acidification are largely unresolved, they could substantially compound throughout the food web. The indirect effects of ocean acidification are likely to be even more pervasive, as are the interactions between ocean acidification and other effects of global climate change. For example, deoxygenation and increasing seawater temperatures will be complex, with synergistic or antagonistic responses that are typically difficult to measure in the field (Gao et al. 2019). Experimental work and field-based investigations on the cumulative effects of climate change are underway, but deserve increasing attention given the accelerating pace of the impact.

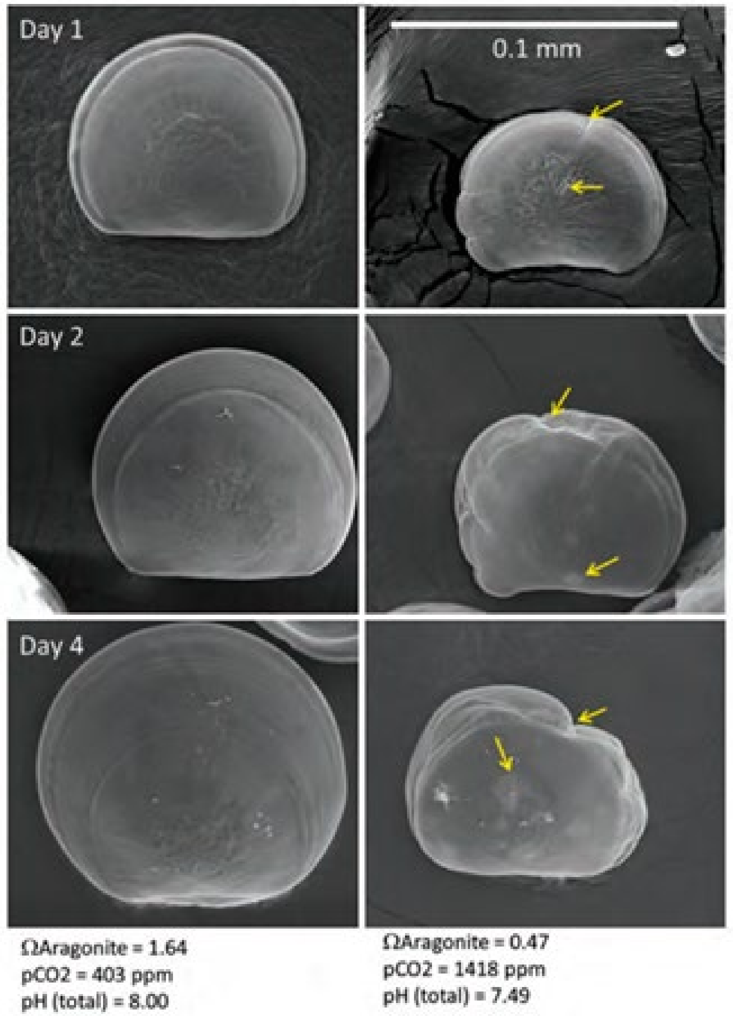


Figure 4.10. Pacific oyster larvae from the same spawn, raised by the Taylor Shellfish Hatchery in natural waters of Dabob Bay, Washington, under favorable total pH = 8.00 (left column) and unfavorable total pH = 7.49 (right column) carbonate chemistry. Under more acidified conditions (right column) development of shell is impaired; arrows show defects (creases) and some features (light patches on shell) that are suggestive of dissolution. The scale bar in the upper right panel is 0.1 mm, or approximately the diameter of a human hair. Source: Whitely-Binder & Washington State Blue Ribbon Panel on Ocean Acidification (2012); photo credit: Brunner/Waldbusser

Clam nets on a beach near Shelton, WA
Photo: Duane Fagergren

Dissolved Oxygen

To survive, most marine organisms must have sufficient levels of dissolved oxygen (DO) in the water. Oxygen (O_2) enters the water through two natural processes: diffusion from the atmosphere and photosynthesis by phytoplankton and aquatic plants. The mixing of surface waters by wind and waves increases the rate at which oxygen from the air can be dissolved or absorbed into the water. Cold water can hold more oxygen than warm water, but dissolved oxygen concentrations are also driven by biological processes. While oxygen is consumed by animals throughout the ocean, the majority of consumption is caused by bacterial respiration of organic matter as it decomposes. These and other complex interactions among physical, chemical, and biological processes ultimately determine DO concentrations.

The processes and dynamics governing DO in the Salish Sea are important to understand because decreases in dissolved oxygen are a concern for maintaining aquatic life. As briefly explained below, decreases in DO manifest in three different forms: 1) global deoxygenation, 2) naturally occurring oceanic low-oxygen zones, and 3) eutrophication-induced low oxygen in coastal ecosystems. The mechanisms that drive each of these forms of reduced DO are distinct, but also all interrelated in the ecosystem.

Global Ocean Deoxygenation

Deoxygenation of the open ocean is one of the major marine manifestations of global climate change. Global deoxygenation is due largely to changing ocean currents. Oxygen minimum and limiting zones (natural areas of oceanic low oxygen) may incur into coastal waters like the Salish Sea. When these low-oxygen ocean waters mix with coastal low-oxygen waters, dissolved oxygen conditions worsen locally. Those variations in marine oxygen concentrations can induce major changes to remineralization processes (chemical breakdown of particles) and associated sources and sinks of important nutrient elements, such as nitrogen, phosphorus, and iron in the water column and underlying sediments (Oschlies et al. 2018). The consequences of deoxygenation on water chemistry in the Salish Sea are largely unknown but there is evidence from other regions that dissolved oxygen loss has potentially broad impacts on pelagic and benthic fisheries, tourism, and ocean nutrient cycling (Schmidtko et al. 2017).

According to a recent estimate, the ocean lost 2% of its oxygen inventory between 1960 and 2010 (Schmidtko et al. 2017; Oschlies 2019). While increasing global ocean temperature is often cited as the cause, changing ocean circulation, mixing, and/or biochemical processes are also considered primary drivers for observed changes in ocean oxygen (Ito et al., 2017). In fact, Oschlies (2019) found that only about 15% of the oxygen loss is attributed to lower solubility of O_2 in warmer sea water (due to the direct effects of warming sea water), while a greater proportion of the decline (>50%) is due to changes (in most cases a slowing) in circulation and mixing resulting from temperature-driven increases in stratification. This stratification results in less exchange of high DO waters from the surface layer to the deeper bottom water. While rising global ocean temperatures may be the ultimate cause of these changes, the processes are complex and vary considerably among locations.

Overall, deoxygenation is an ongoing process and accompanies ocean warming and ocean acidification as one of the three major oceanic consequences of rising atmospheric CO_2 levels (Levin & Breitburg 2015). Decreasing O_2 in subsurface waters is normally accompanied by increasing acidity on the British Columbia coastal shelf, and both trends are of great concern to marine life (Crawford & Peña 2013). Deoxygenation is expected to continue as increasing global temperatures reduce the capacity of the ocean to hold oxygen, decrease the degree of mixing in the upper water column, and reduce the ocean-overturning circulation.

Stratification

Ocean stratification is when water masses with different properties form layers that act as barriers to water mixing. The structuring properties are salinity and temperature, which drive differences in water density. The layers are normally arranged according to density, with the least dense water masses (typically fresher water) sitting above the denser layers (typically saltier water). Stratification can create barriers to mixing between layers, which can affect the primary production in an area. Phytoplankton need sunlight and nutrients, which accumulate in the deeper layers as particles are broken down, but without mixing, productivity is diminished because nutrients aren't available in the surface layer where sunlight is abundant. Additionally, stratification can cause anoxia or hypoxia, when oxygen-depleted waters (resulting from microbial processes consuming oxygen) are unable to mix with oxygen-rich surface waters. Indexes of stratification generally provide information about the difference in density between the surface water and water at depth.

Naturally Occuring Low-Oxygen Zones

Time-series have revealed a more extensive oxygen decline in the Northeast Pacific Ocean than in other parts of the ocean (Whitney et al. 2007). The marine waters that enter the Salish Sea via the Strait of Juan de Fuca and Johnstone Strait reflect conditions in the northeast Pacific Ocean that are influenced by complex global circulation patterns. In general, deep water off the Pacific Coast of North America is old (it has been circulating around the globe for centuries without contact with the atmosphere). This water is cold, dense, nutrient rich, and of most relevance here: oxygen depleted (Reid & Mantyla 1978; Hellya & Levin 2004).

On the continental shelf and slope off Washington and British Columbia, the lowest O_2 values are found in deeper waters (O_2 generally decreases with increasing depth and increasing water density in this region; Crawford & Pena 2013). But during summer, deep ocean water comes to the surface due to seasonal upwelling. Upwelling is driven by seasonal wind patterns that push surface waters away from shore, resulting in deep water rising to replace the water that has been displaced (see description at Center for Science Education 2008). Upwelling is an important component of oceanography and dissolved oxygen concentrations in the Salish Sea.

Ocean water typically enters the Strait of Juan de Fuca at depth and mixes due to tides and currents. As with ocean water on the continental shelf, the deeper portions of the Strait of Juan de Fuca tend to be low in DO, especially in the summer during strong upwelling. Dissolved oxygen at any depth is determined by vertical mixing and stratification, but it tends to be greater in surface waters and lower at depth as it enters the Strait of Georgia (Riche et al. 2015).

Once in the Salish Sea, oxygen-depleted but nutrient-rich ocean water mixes with warmer, oxygen-rich surface water, creating optimal conditions for seasonal productivity. But low dissolved oxygen within Salish Sea basin waters, partly imported from the shelf and partly driven by biological processes (e.g., carbon cycling) within the Salish Sea, could reduce benthic and pelagic habitat (Johannessen & Macdonald 2009) and disrupt biological productivity.

Coastal Eutrophication and Hypoxia

In addition to global changes in DO, declining oxygen concentrations have also been found in coastal oceans. These "hypoxic" zones are areas of very low O_2 concentration (<2 mg/L, compared with 8 to 12mg/L for oxygen-saturated waters). Coastal hypoxia is largely fueled by riverine runoff of fertilizers, but other anthropogenic inputs like failing septic systems and deposition of nitrogen emitted to the atmosphere by fossil fuel combustion are also important sources (Nixon 1995). The nutrients from these sources—primarily nitrogen and phosphorous, with nitrogen being the most limiting in marine ecosystems—contribute to eutrophication. Eutrophication is the process of increased organic enrichment of an ecosystem, generally through increased nutrient inputs (Nixon 1995). In short, nutrient input results in excessive primary production (phytoplankton and/or algae), which in turn leads to increased metabolism (bacterial activity), which is demanding of oxygen and results in local oxygen depletion. This hypoxia changes community structure (food webs and habitats) through remineralization, microbial processing, and respiration that can result in ocean acidification.

Some of the impacts of hypoxia beyond direct declines in available oxygen include increased sedimentation (from decomposing material that would have broken down if oxygen were available), reduced depth distribution of submerged aquatic vegetation, and redistribution of fish and invertebrates to avoid low oxygen (hypoxic) or no oxygen (anoxic) areas. In coastal ecosystems like the Salish Sea, there is a delicate balance between having enough nutrient inputs and primary production to sustain life and a healthy food web, versus nutrient enrichment that accelerates primary production to the point of excess.

In many cases, eutrophication is a locally generated problem with local impacts. It typically results in declines in available oxygen, especially in the bottom waters. These hypoxic events can be episodic, occurring seasonally (most common in summer/autumn) in the coastal zone. In the Salish Sea, the overall anthropogenic contribution of nitrogen (typically thought of as "nutrient input") is minimal relative to natural sources coming from ocean waters. While this makes widespread eutrophication unlikely, anthropogenic nitrogen sources, such as wastewater outfalls and leaking septic systems, may have significant local effects, especially during periods of low circulation.

Some inlets and subbasins are more susceptible to hypoxia because sills at the mouth of the subbasin slow mixing and increase residence time. Puget Sound has hypoxia hotpots including South Puget Sound, Hood Canal, and Quartermaster Harbor. However, hypoxia in these regions is largely driven by ocean-derived nitrogen and a reduction in flushing (reduced circulation, seasonally); although additional nutrients entering these regions from the land may exacerbate the problem (Khangaonkar et al. 2018). Studies done in the Strait of Georgia showed anthropogenic nitrogen inputs to be minimal (Sutton et al. 2013) with strong tidal mixing ameliorating low dissolved oxygen by mixing in oxygenated surface water (Ianson et al. 2016); both studies suggested that widespread eutrophication is unlikely. However, as in Puget Sound, local anthropogenic activities, such as aquaculture and sewer outfalls, may produce enough additional anthropogenically-derived nutrients that short-lived local events may occur. In some locales and seasons, local hypoxia may be exacerbated by larger-scale oxygen changes, such as the global deoxygenation and upwelling-driven low-oxygen ocean waters described above.

Hypoxia and Dead Zones

Hypoxia refers to low oxygen in aquatic ecosystems, usually a concentration of less than 2 or 3 milligrams of dissolved oxygen per liter of water (mg/L). Dissolved oxygen concentration is highly dependent upon temperature, but normal concentrations are typically 8 to 12 mg/L. A complete lack of oxygen (0 mg/L) is called anoxia. Typically, when waters become hypoxic, mobile organisms relocate to more favorable areas.

If the changes are sudden or widespread, the animals may become trapped and perish. Similarly, sessile (immobile) organisms are not able to escape hypoxic zones and will die if their oxygen demand exceeds the available oxygen. Areas where hypoxia is severe are called anoxic zones, sometimes referred to as "dead zones." Often the only organisms alive in these anoxic dead zones are the ones that can live without oxygen (e.g., some microbes).

Waves crashing into wood debris, San Juan Island, WA
Photo: Ginny Broadhurst

Sea Level Rise

Globally, sea level has risen about 20 cm (7.9 in) on average over the past century, with average rates accelerating from 1.4 mm/yr (0.06 in/yr) until about 1970 to 3.6 mm/yr (0.14 in/yr) in the most recent period of observation from 2006 to 2015 (Intergovernmental Panel on Climate Change 2019). In the Salish Sea, sea level change has varied from -2 to 2 mm/yr (-0.07 to 0.07in/yr).

At most locations in the Salish Sea, sea level has risen over the same period, but a number of factors make rates of relative sea level rise variable (i.e., RSLR, represented by the rate of eustatic sea level rise combined with vertical land movement to result in the net change in height of the sea relative to land). Rates of sea level change vary depending on local land vertical motion, weather patterns, and ocean conditions, all of which may amplify or mute changes in sea level at local scales. Land movement can counteract or exacerbate rates of RSLR, depending upon which vertical direction the land is moving (Figure 4.11). For example, active tectonics are causing uplift of the land on the northwest tip of the Olympic Peninsula in Washington. Areas around Neah Bay in the Strait of Juan de Fuca are experiencing a relative decline in sea level of -1.8 cm/decade (-0.71 in/decade) for a total of about -13.2 cm (5.2 in) over the last 75 years due to uplift of the land exceeding the rise in eustatic sea level (the height of the water surface irrespective of the land; Mauger et al. 2015). In other areas in the Salish Sea, land is subsiding (downward movement of the land mass) due to sediment compaction, groundwater withdrawal, or erosion. Subsidence in conjunction with eustatic sea level rise leads to greater RSLR.

Much of the region is subsiding and most areas within the Salish Sea are seeing relative sea level rise. For example, Victoria has seen moderate increases in sea level (+9.1 cm or 3.6 in) over the last 50 years (NOAA Tides and Currents Sea Level Trends 2017; Vadeboncoeur et al. 2016) while Seattle has experienced greater change, +24.7 cm (9.7 in) of RSLR since 1900 (NOAA Tides and Currents Sea Level Trends 2017; NOAA 2021). These measurements exemplify the local-scale variation in the region and stress the importance of accurate measurements of sea level to fully understand the impacts on developed land, infrastructure, and coastal habitats.

Global average sea level is projected to rise further, and at accelerating rates, with climate change, and the Salish Sea region is no exception. RSLR in the Salish Sea is expected to exceed 15 cm (5.91 in) by 2050 and 45 cm (17.7 in) by 2100 (Miller et al. 2018). When projecting relative sea level rise, several factors including global climate models, greenhouse gas scenarios, and estimates of the rate of vertical land motion all play a role in arriving at projections. As climate models are further refined, and as additional sea level monitoring and measurement data are collected, new projections are likely. Irrespective of predictions, sea level rise is not expected to rise in a consistent linear fashion, meaning relative slowing in RSLR may be temporary before an acceleration in RSLR that may have profound effects on low-lying coastal areas (Bromirski et al. 2011).

Increasing sea level will interact with tides, storm surges, and freshwater delivery from rivers leading to more frequent and more extreme coastal flooding. This will be especially apparent during extreme high tides, commonly known as king tides, which are normal (but very high and very low) tides that occur twice a year. If these high tides coincide with storms, water levels will increase even further. The Witness King Tides Project is using citizen science to collect photographs of how king tides are impacting coastal resources (Witness the King Tides 2021). In Vancouver, BC, king tides overtop low-lying parts of a seawall that was designed based on sea level heights from the 1970s and 1980s. Sea level in Vancouver is expected to rise by as much as 50 cm (19.7 in) by mid-century, making the occurrences of flooding more likely.

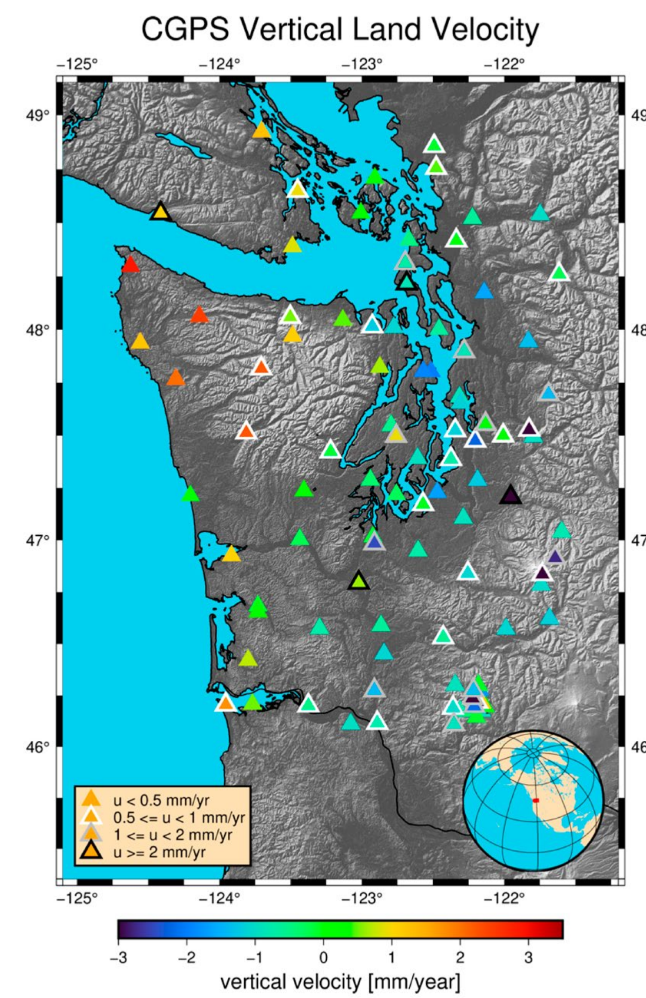


Figure 4.11. Relative rates of vertical land movement in the Salish Sea. Positive numbers and warm colors (red and orange) show uplift in land movement, while negative numbers (blue and teal) show subsidence. Areas with the greatest subsidence are likely to have the greatest impacts from relative sea level rise. Fine-scale understanding of land movement is important for predicting relative sea level rise locally. Source: adapted from Newton et al. (2021)

Sea level rise and storms are expected to threaten coastal development and critical habitat, such as low-lying estuaries, intertidal zones, and mudflats (Johannessen & Macdonald 2009). A higher sea level increases high-tide water levels and allows more wave energy to reach farther shoreward, enhancing the potential for coastal flooding and associated impacts (Bromirski et al. 2011; Figure 4.12). Inundation and erosion exacerbated by sea level rise are expected to cause habitat losses or shifts in habitat types, such as salt marshes, beaches, tide flats, eelgrass beds, and river deltas (see Vignette 15, Eelgrass Variations). Locations more likely to experience habitat loss include low-lying areas, locations with highly erodible sediments, and areas where inland migration of coastal habitats is hindered by bluffs or sea walls and other structures impeding sediment distribution (Mauger et al. 2015). Many of these locations are at the center of Indigenous communities, threatening personal and cultural property, as well as natural resources like shellfish beds (see Vignette 16, Climate Change Adaptation).

Sea level rise and the associated habitat changes in the marine environment are projected to also affect the geographical range, abundance, and diversity of Pacific Coast marine species and habitats, some of which use shallow water areas for rearing, although the extent to which this will be the case is still largely unknown. Shellfish and eelgrass beds are likely to change distribution with longer inundation times.

Climate Change: Combining Forces

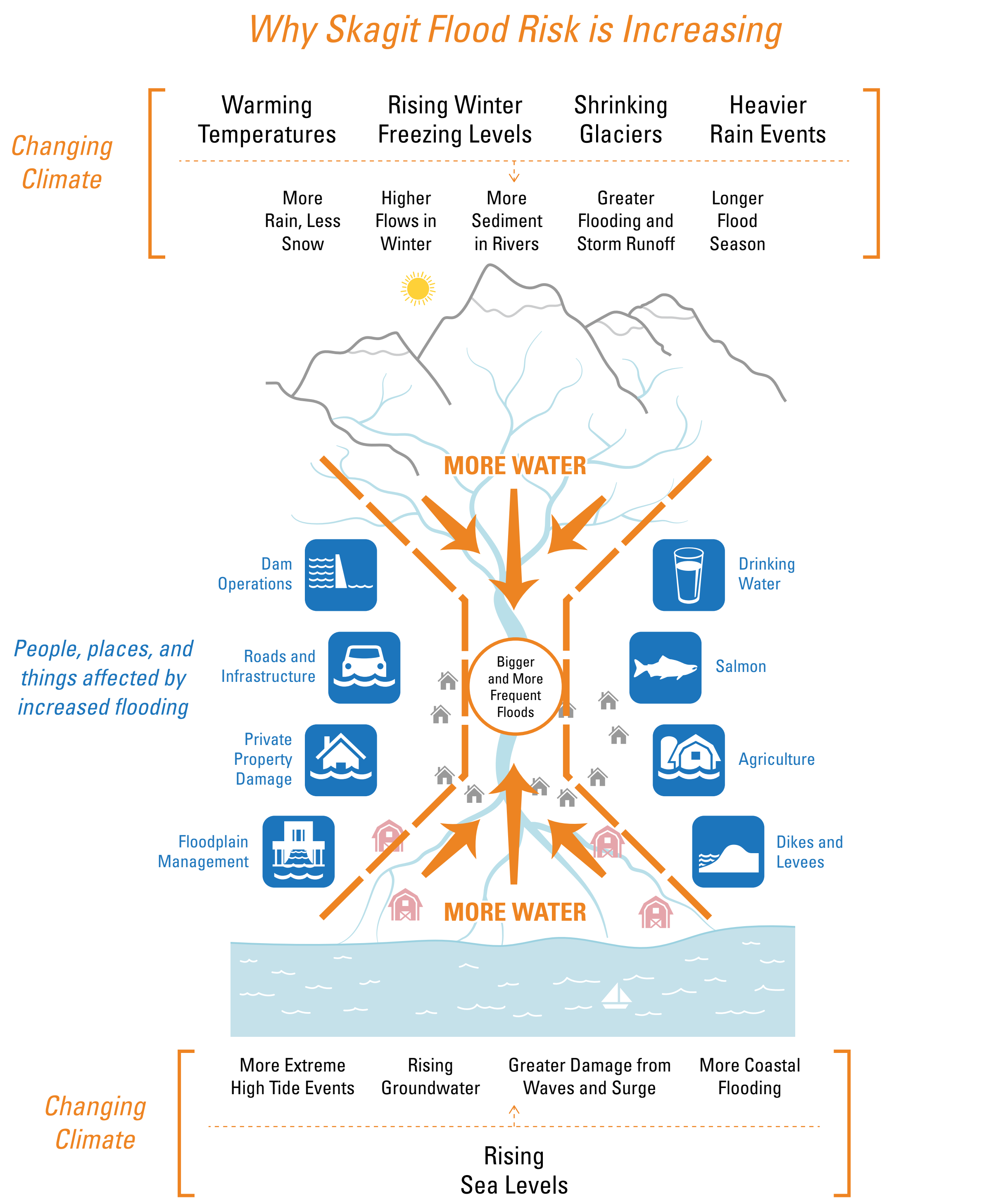


Figure 4.12. The intersection of climate change impacts. Increased freshwater flow will combine with rising sea level to result in increased coastal flooding and numerous secondary impacts. Source: Skagit Climate Science Consortium (2021)

Physical Impacts from Climate Change Occurring in the Salish Sea Ecosystem

A partial list of physical impacts occurring or projected for the Salish Sea ecosystem from changing climate is provided below. Both the Climate Impacts Group at the University of Washington and the Pacific Climate Impacts Consortium at the University of Victoria are leading extensive programs on actionable climate science in the region (Climate Impacts Group n.d.; Pacific Climate Impacts Consortium 2021).

- Warmer air temperatures
- Shrinking glaciers
- Less snowfall
- Decreasing summer streamflows
- Increasing winter peak flows
- Changes to timing of peak and base flows
- Higher freshwater temperatures
- Lower levels of dissolved oxygen in streams
- More sediment delivered into streams and ultimately to the Salish Sea nearshore
- Drying out of wetlands
- Regional drought
- Increased frequency and size of wildfires
- Greater probability of landslides
- Warmer ocean temperatures
- Rising sea levels
- Ocean deoxygenation
- Stronger storms and greater storm surge
- Changing ocean chemistry, including ocean acidification
- Changing, and slowed, currents

ECOLOGICAL EVIDENCE OF CLIMATE CHANGE

Habitats, processes, and biota within the Salish Sea are showing evidence of climate change impacts, and this trend will continue. Research over the last two decades, combined with observations made during the marine heatwave in 2015-2016 and since, provide tangible evidence and useful insights into how local ecosystem structure, processes, and individual species are affected by climate change. The likely effects on other oceanographic, hydrologic, and biotic components are suggested by models, theory, and evidence from other regions and applied locally. Those emerging effects will become more apparent (and more fully documented) in coming years, especially as temperature, acidification, and other indicators continue to increase to points that become stressful for native species and species that play a critical role in the food web. The examples discussed below are not intended to be an exhaustive cataloging of all climate change-related impacts in the Salish Sea, and in fact, while we suspect climate may be driving changes in some organisms and populations, evidence is still emerging and indirect effects are largely unknown (see Vignette 17, Salish Sea Jellyfish). But we briefly highlight several important ecosystem components for which climate-related impacts are documented as an entry-point for understanding biological response to climate change.

Phytoplankton

Although phytoplankton forms the base of the Salish Sea estuarine food web, there is much uncertainty about how phytoplankton production will change in the Salish Sea in response to climate change. In general, changes to phytoplankton dynamics may include changes to phytoplankton community composition (the species that dominate the phytoplankton), the timing of blooms (phenology), and abundance of species and communities. Projected changes in nutrient concentrations and light conditions, the limiting factors for primary production, as a result of climate change are thought to be minimal and are not anticipated to change primary production (Johannessen & Macdonald 2009). But primary production in the northern Salish Sea is linked to large-scale climate indices and whether this relationship remains or shifts is of interest (Ji et al. 2010). In more southerly locations in the Strait of Georgia, local impacts of climate drive annual changes in primary production (Suchy et al. 2019); the same is thought to be true for Puget Sound, driven mostly by estuarine circulation. Comprehensive time-series on phytoplankton production do not exist, so evaluating recent trends is not possible. However, the mechanisms of change include increased temperature and CO_2, decreased pH and dissolved oxygen, and changes in timing and extent of freshwater input, which drives estuarine circulation and residence times.

Local variability in production is driven primarily by freshwater runoff, but also by winds and solar radiation, all of which affect water exchange, air-sea gas exchange, mixing, and estuarine circulation (Riche et al. 2014). Together these processes provide the setting for primary production, and alteration could disrupt the annual onset and evolution of phytoplankton production. For example, the change in annual freshwater discharge (flattening of the hydrograph) from the Fraser River, the dominant freshwater source in the Salish Sea (Thomson 1981), may drive changes in timing of phytoplankton production (Johannessen & MacDonald 2009). Fraser River discharge is associated with circulation throughout the Salish Sea. With more of the discharge occurring in spring and less in summer, there may be an earlier spring bloom (Riche et al.,2014) and an overall change in primary production resulting from changes in circulation. Local inputs of nutrients might lead to increased production locally, and result in eutrophication in enclosed bays (Mackas & Harrison 1997).

Composition of the phytoplankton community is also subject to change, with climate change potentially bringing more frequent occurrences of harmful algal blooms (Johannessen & MacDonald 2009). Harmful algal blooms or HABs are occurrences of algal species that cause toxic effects or physical harm. For example, large blooms of spinose form algae can clog fish gills. In another example, certain algal species produce noxious and toxic substances that can accumulate in food chains and cause illness or death in animals and humans. Mudie et al. (2002) suggested that observed increases in harmful algal blooms in the Strait of Georgia in the last several decades might have been caused by climate change. In a modeling study on *Alexandrium* spp. (a dinoflagellate), Moore et al. (2015) concluded that by 2050, global warming would lead to 30 more days a year with conditions favorable for *Alexandrium* blooms in Puget Sound. Additionally, suitable conditions for blooms could occur up to two months earlier and extend a month later (Moore et al. 2011). Warmer water in regional estuaries (e.g., South Puget Sound inlets) may contribute to a higher incidence of harmful blooms of algae linked to paralytic shellfish poisoning. These types of ecosystem impacts may then cause adverse economic impacts, such as beach closures affecting recreational or commercial harvesting of shellfish (Mote et al. 2014).

Changes to physical conditions that influence phytoplankton growth may also lead to an altered coupling between phytoplankton and zooplankton if bloom timing changes and zooplankton are slow to adapt. This type of change is very difficult to observe without high resolution data, and even when collected, it tends to be on a small spatial scale that limits inference, especially in a diverse ecosystem like the Salish Sea.

Kelp

In recent years, attention has turned to kelp and the ecological role it plays in the Salish Sea ecosystem. While stressors related to land-use induced changes to the seascape (e.g., overwater structures) have reduced growing habitat for kelp, increases in air and water temperature associated with climate change are of particular concern for Salish Sea kelp species. Growth has been correlated with sea surface temperature, where higher temperatures produce lower growth and poor recruitment (Pfister et al., 2018). Intertidal kelps may be especially susceptible to rising air temperature, which can lead to more rapid desiccation and inability to withstand the ambient temperatures on a given tide cycle.

Research in Barkley Sound, BC (outside the Salish Sea along the west coast of Vancouver Island), may be indicative of what kelp experience within the Salish Sea: species loss, declines in kelp cover, and declines in recruitment coinciding with warm temperatures (Starko et al. 2019). This study showed kelp in inlets with low wave exposure, restricted circulation, and warmer temperatures to be especially hard hit by the 2014 to 2016 warming event. Emerging data from Puget Sound also show declines in kelp cover to be most pronounced in inlets in South Puget Sound where circulation is restricted and temperatures are elevated (Berry et al. 2021).

In some cases, climate change may lead to positive responses from organisms. As photosynthetic organisms reliant on CO_2 but living in a generally low-CO_2 environment, kelp and eelgrass may benefit. Increased CO_2 has been experimentally shown to increase the net primary production in eelgrass and kelp (Thom 2005; Palacios & Zimmerman 2007). In another study, satellite data showed the kelp, *Nereocystis luetkeana*, to be resistant to the heat wave on the Oregon coast (Hamilton et al., 2020).

As these examples help illustrate, changes in distribution and abundance of biogenic habitats like eelgrass and kelp will be driven by local change, global change, and the intersection of the two at discrete spatial and temporal scales. Fluctuation in kelp abundance has been linked to both broad-scale oceanic conditions, as indicated by the Pacific Decadal Oscillation and North Pacific Gyre Oscillation, and to local-scale impacts on water quality, temperature, and increased herbivory (Taylor & Schiel 2005; Foster & Schiel 2010; Burt et al. 2018; Pfister et al. 2018; Schroeder et al. 2020), illustrating that failure to account for the local or global scale could dramatically change inferences about populations.

Coastal Wetlands

Coastal ecosystems are already impacted by the combination of climate-related ocean changes and adverse effects from human activities. Sea level rise will continue to have profound impacts on coastal wetlands, including salt marshes, freshwater marshes, forested swamps, and seagrass beds. These are valuable ecosystems, providing habitat for invertebrates, fishes, and birds and contributing a range of ecosystem services related to coastal protection. Coastal wetlands store carbon in aboveground and belowground biomass, and are important for buffering stormwater, filtering excess nutrients and other contaminants, and absorbing floodwaters during periods of high precipitation and runoff.

Much of the region's coastal wetland habitat has been lost due to urbanization (85% of historical area along the United States West Coast; Brophy et al. 2019), sharply reducing coastal protection and habitat provisioning. A recent study showed that within moderate sea level rise scenarios, most coastal wetlands will be reduced in size or lost by the end of the century (Thorne et al. 2018). Wetland response to sea level rise is a function of available sediment supply and adequate hydrodynamics to maintain marsh height. Some coastal wetlands will decline in quality as periods of inundation lengthen.

The intersection of urbanization and climate change is especially detrimental for low-lying coastal areas. Many coastal wetlands, tide flats, and beaches will decline in extent as a result of sea level rise, particularly where coastal wetlands cannot adapt by shifting inland due to geography or infrastructure such as roads and ports. These physical constraints are known as "coastal squeeze." In some cases, marshes will be able to migrate landward, but many regions will experience coastal squeeze because extensive coastal development limits the extent to which marshes can migrate and adapt. Species such as shorebirds and juvenile salmon could be impacted by further loss of this already limited habitat.

The communities most likely to be impacted by rising sea level and the resulting loss of coastal wetlands include many Tribal and First Nations communities who have lived along the shores of the Salish Sea for thousands of years. Settlement trends, first by Indigenous peoples and later by European settlers, have played an important role in increasing low-lying coastal communities' exposure and vulnerability to sea level rise and extreme sea rise events (Pörtner et al. 2019). The attributes that made settlement locations desirable at the outset (e.g., proximity to waterways and harvest sites) are their very vulnerability. Loss of shellfish habitat, inundation of dwellings and infrastructure, and increased coastal erosion on Indigenous lands are just some of the impacts already affecting Indigenous communities in the Salish Sea (Northwest Indian Fisheries Commission 2016; Vadeboncoeur et al. 2016). Salmon fisheries have long played an important role in Tribal and First Nations communities by supporting cultural activities and providing food security. Loss of rearing habitat in coastal wetlands will further compromise the sustainability of already stressed salmon runs, and increasing inundation will threaten shellfish resources as well. Tribes are considering the ability of coastal wetlands to adapt or maintain resilience to sea level rise as part of their climate mitigation plans (Northwest Indian Fish Commission 2017; Ramirez & Simenstad 2018; Swinomish Indian Tribal Community 2010), but the ability to respond is compromised by existing development.

Salmon

Pacific salmon are intimately linked with the identity of Coast Salish peoples and are more broadly identified as an icon of the Pacific Northwest. In their assessment of Pacific salmon vulnerability to climate change, Crozier et al. (2019) identify a number of climate-related factors threatening the existence of Pacific salmon in the Salish Sea and beyond. These factors include: increasing stream temperatures that influence rearing duration and adult holding and upstream migration timing; summer water deficits that limit upstream migration; increased streamflow variability and flooding that could scour redds and increase egg mortality (Ward et al. 2015; Weinheimer et al. 2017); increased ocean acidification that impacts the salmon sensory system directly (Williams et al. 2019) and food resources (Busch et al. 2013); and changing ocean conditions that impact what can be a lengthy ocean residency of several years for some species and life history types (Crozier et al. 2021; Sobocinski et al. 2021).

Adaptive capacity within salmon populations, including the life-history diversity that allows for adaptation as conditions change, could help mitigate climate impacts. In an analysis of Fraser River sockeye, an important component of salmon biomass in the Salish Sea, Reed et al. (2011) found that evolutionary adaptation may be more rapid than the rate of climate change, allowing sockeye to change their migratory behavior as they have in the Columbia River (Beechie et al. 2006; Crozier et al. 2011).

In much of the region, the expression of life history diversity in migratory behavior and habitat use has been reduced from historical levels (Burke 2005). For example, where protracted outmigrations once meant salmon migration downstream and into the saltwater from late winter through fall, we now see pulses of homogeneous, transient, and predominantly hatchery fish migrating in a more constricted period of May to July (Rice et al. 2011; Greene et al. 2021). The repercussions to wild populations from hatchery practices are a topic of ongoing research (e.g., density-dependence in habitat-limited estuaries). Additionally, a recent evaluation has shown implications of hatchery practices on predation that may be detrimental to wild stocks in the marine waters (Nelson et al. 2019).

In the vulnerability assessment, Puget Sound stocks were considered less vulnerable than others along the Pacific Coast due to their life-history diversity, extensive use of multiple habitats types, and shorter freshwater migrations (less time in warming rivers) than other populations (Crozier et al. 2019). But coho and Chinook salmon and steelhead trout all show high sensitivity and exposure to the metrics assessed-and all three species have shown population declines (Sobocinski et al. 2018). Furthermore, there has been an overall decline in marine survival over the last 40 years (Zimmerman et al. 2015; Kendall et al. 2017; Ruff et al. 2017) to levels so low that additional mortality could be devastating to populations. The marine ecosystem is projected to continue to undergo major changes, with potentially significant consequences for Pacific salmon in the years to come (see case study on salmon marine survival).

Marine Birds

There are over 170 species of birds that rely on the Salish Sea for foraging, rearing, or nesting (Gaydos & Pearson 2011). Birds integrate across the seascape by using different habitats throughout their life cycle and within any single feeding or rearing season. Shorebirds, like sandpipers (*Calidris mauri*), may stop on tidal flats rich with invertebrates and marine biofilm (a thin layer of microbes and benthic diatoms on the surface of mudflats) as a stopover prior to nesting (Schnurr et al. 2020). Other birds, like surf scoters (*Melanitta perspicillata*) rely on herring spawn found on eelgrass and algae (Lok et al. 2012). Nesting on islands or in Salish Sea watersheds and foraging in the marine waters and on tideflats means birds, like salmon, rely on multiple intact and productive habitats for survival as individuals, populations, and communities.

Since the 1990s, the abundance of wintering marine birds has been declining, with birds dependent upon forage fishes as prey (especially those that dive for their food) experiencing the most severe declines (Vilchis et al. 2015). Recent work from Canada showed downward trends in abundances for many bird species within the Salish Sea, but stable trends in those same species from the Pacific Coast (Ethier et al. 2020). These species were primarily piscivores (those that rely on fish prey), but marbled murrelets (a bird that relies on both fish and microzooplankton prey) has also shown evidence of prey limitation (Norris et al. 2007). Forage fish abundances in the Salish Sea have varied in recent years, are currently below historical levels, and are also thought to be sensitive to environmental change (see case study on Pacific herring). If the current distribution and abundance of sandlance, surf smelt, and herring is driven by environmental change, there may be an indirect climate effect for birds if the prey abundances are low enough to impede productive foraging for marine birds, an activity that is regulated by metabolic costs. The loss of forage fish spawning habitats as nearshore conditions degrade may be driving low forage fish abundances (Vilchis et al. 2015), although in many cases the fish are not habitat limited. Pollution and disturbance are other potential causes of seabird decline.

Any climate impacts are likely compounded by other anthropogenic effects, especially given the differential trends from animals primarily foraging within the Salish Sea and those outside (Ethier et al. 2020). This same differential mortality has been observed in salmon (see case study on Pacific salmon marine survival) and underscores the need to better quantify the impacts of human presence and activity on biota. Climate impacts are likely to be both direct and indirect and will be difficult to isolate from other existing stressors. Ecosystem integrators like seabirds (e.g., scoters, loons, mergansers, and gulls) and Pacific salmon—species that move across the landscape and seascape—are important sentinels of ecosystem change, thus sea bird monitoring (e.g., Norris et al. 2007) could provide an indication of functional ecosystem changes resulting from landscape (Allen et al. 2019) and seascape change (Diamond & Devlin 2003; Vilchis et al. 2015).

SUMMARY OF CLIMATE CHANGE IN THE SALISH SEA

Evidence for human influence on the climate system has grown since the first assessment report was presented by the Intergovernmental Panel on Climate Change in 1990. Growing populations and fossil fuel-based economies around the world are responsible for increasing greenhouse gas emissions, driving large increases in the atmospheric concentrations of CO_2, CH_4, and N_2O. About half of the cumulative anthropogenic CO_2 emissions between 1750 and 2011 have occurred in the last 40 years (high confidence; Intergovernmental Panel on Climate Change 2014) and the global ocean has absorbed about 30% of the emitted anthropogenic CO_2 since the industrial era began (Pörtner et al. 2019). In these recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. This human influence is evident in warming of the atmosphere and the ocean, in changes in the global water cycle, and in global mean sea level rise—all effects contributing to changes within the Salish Sea ecosystem. While the Salish Sea is nested within the larger Earth system where these global-scale changes are occurring, the rapid pace of local population growth, urbanization, and associated carbon emissions have direct impacts on the Salish Sea and contribute to climate change both globally and locally.

While the causes of climate change are global and primarily from greenhouse gas emissions, impacts of climate change manifest locally. The Salish Sea and its physical and biological components are already experiencing some of the effects of global climate change, including changing precipitation regimes, increasing sea water temperatures, and ocean acidification. Scientists are beginning to understand some of the predicted near-term effects of global climate change from climate models that continue to improve in their accuracy and applicability at the regional scale. However, what's lagging behind is our understanding of how organisms, ecosystem processes, and interactions are affected by global climate change today and more so into the future. Combined with increasing disruption from local human impacts, the dynamics of the Salish Sea estuarine ecosystem will undoubtedly change, and making predictions about these changes will remain a challenge.

This section of the *State of the Salish Sea* report has provided a snapshot of the many physical factors driving climate change impacts in the Salish Sea. Each of the projected impacts has associated uncertainty, but climate models and empirical observations from recent years provide confidence in the general trends seen to date and expected in the future within the Salish Sea ecosystem. What is less certain is the biological response and response of complex ecosystem processes like food web dynamics, energy and nutrient cycling, and biomass production. Changes in many of these biophysical processes are not easily detected due to a high degree of natural variability.

Complex processes often exhibit nonlinear dynamics, hysteresis (a lag in response before reaching a tipping point; Selkoe et al. 2015) and potentially a new stable state (Carpenter et al. 2000; de Young et al. 2008). Many have suggested the Salish Sea, and the North Pacific Ocean more broadly, experienced a regime shift in the late 1980s related to changing global climate (Benson & Trites 2002; Hare & Mantua 2000; Möllmann & Diekmann 2012; Perry & Masson 2013). Since that time, a growing body of scientific and anecdotal evidence suggests structural changes within the Salish Sea are driving changes in species distribution and abundances, from benthic invertebrates (Partridge et al. 2018) to groundfish (Essington et al. 2021), although time-series for many organisms do not exist. Continued monitoring and assessment is the only way to capture natural variability and discriminate signals from perturbations.

There is growing evidence from around the world that an organism's sensitivity, as well as exposure, drive that organism's vulnerability to climate change and realized ecosystem changes (Hare et al. 2016; Jones et al. 2018; Hughes et al. 2019). It's important to keep in mind that the rate of change in the system and an organism's ability to adapt, known as adaptive capacity, may be as important in determining long-range outcomes as the magnitude of the change itself. Indeed, some species may be climate "winners" and thrive on a warming planet. For example, species that are at the northern extent of their range in the Salish Sea may benefit as sea water warms and the center of their distribution moves north (Pinsky et al. 2013; Morley et al. 2018). Many of the organisms in the Salish Sea are found within the larger California Current ecosystem and are not at the southern (warmest) extent of their range within the Salish Sea. In contrast, some species may be climate "losers" and not have sufficient adaptive capacity to keep up with the rate and type of changes underway. An example is Pacific Cod (*Gadus macrocephalus*), which was once common in the Salish Sea. Today they are found in lower abundances than in the past and may be extirpated from the region with warming water temperature.

Given the nonlinear dynamics of change, the lags from hysteresis, and our inability in some cases to clearly identify key trends and thresholds, early detection of significant changes is a challenge. Changes in multiple species taken collectively can lead to asynchrony in species interactions and disrupt the entire ecological community (Sydeman & Bograd 2009). Both iconic species and those lesser known in the Salish Sea will continue to be affected by changes in physical conditions in the Pacific Ocean, changes in watershed hydrology and freshwater input, and increases in temperature, sea level, and ocean acidification (Burkett et al. 2005; Hewitt et al. 2016; Samhouri et al. 2017). To improve our ability to detect these changes early and quickly develop adaptive management strategies, a combination of experimental work and modeling with forecasting capabilities based on strong observational data collection efforts, will be needed. Combined with "rapid-response" type studies during natural experiments, these will be the best tools for understanding how climate change is impacting the Salish Sea ecosystem and its associated human systems.

In addition to ecosystem changes, we cannot ignore that there are also economic and cultural consequences for human communities (Adger 2010), many of which will not be equitably distributed (Islam & Winkel 2017). Some of these consequences are related to sea level rise, land and habitat loss, and changing distributions of organisms that people in this region have relied upon for generations (Lynn et al. 2014; Marushka et al. 2019). Our ability to respond to the inevitability of climate change will be somewhat dependent upon the resilience of the ecosystem and its ability to adapt, but also on our own individual and collective will to reduce the local impacts and perturbations that will potentially compound the globally driven change.

12 | THE BLOB: WHAT WERE ITS IMPACTS ON THE SALISH SEA?

Dr. Nicholas Bond, Cooperative Institute for Climate, Ocean and Ecosystem Studies, University of Washington

A marine heat wave (MHW) of unprecedented severity, areal extent and duration occurred in the Northeast Pacific Ocean during 2014-2016. This event, known as the "Blob", had a wide variety of far-ranging effects on physical, chemical, and biological ocean properties; here we focus on the Salish Sea. The Salish Sea is connected to the open ocean, of course, and so it stands to reason that the Blob must have influenced our local waters. However, it is not necessarily obvious how, and to what extent. Because the Blob was such a massive perturbation, it represents an attractively large signal for inquiry. Conceivably it represents a dress rehearsal for typical conditions in future decades due to global climate change. With those ideas in mind, the purpose of this piece is to briefly review what happened and the lessons learned.

The near surface waters of the Northeast Pacific began warming substantially, relative to seasonal norms, in the winter of 2013-2014. This warming, which actually entailed less seasonal cooling than usual, can be attributed to a persistent ridge of higher than normal pressure that set up shop over the Gulf of Alaska. The ridge disrupted the usual parade of storms that cross the Northeast Pacific that time of year, with lower wind speeds as a result. The consequence was less heat drawn out of the upper ocean (one cools off a bowl of soup by blowing on it) and suppressed mixing of colder water from below, and ultimately surface temperatures that were as much as 2-3°C on the warm side by early spring 2014 over a large area offshore of the Pacific Northwest. Once formed, this mass of warm water was maintained by an overall reduction in low cloud coverage, and hence enhanced solar heating, in the warm seasons of 2014 through 2016. It was also reinforced by a weather pattern in the winter of 2014-2015 that featured anomalous winds from the south, of sub-tropical origin, and a shift in the overall pattern to include positive sea surface temperature (SST) anomalies along the coast of western North America (Figure 1). For the most part, the Blob ended in late fall of 2016, in association with an active storm track that brought a preponderance of cool winds out of the northwest. On the other hand, a lingering hangover from the Blob was still noticeable through 2019 at depths roughly between 100 to 300 meters, particularly in the Gulf of Alaska.

The Blob both directly and indirectly impacted the Salish Sea. The Salish Sea's primary exchange with the open ocean is at the west entrance of the Strait of Juan de Fuca; ocean conditions at that location both impact the properties of the inland waters and modulate their ventilation (i.e., residence times). The Northeast Pacific also indirectly influences the Salish Sea through its effects on the weather. Because the prevailing winds usually include an onshore-directed component, sea surface temperature anomalies off the coast of the Pacific Northwest tend to be reflected in air temperature anomalies of the same sense. The record high temperatures in Washington State during the winter of 2014-2015 can be attributed in part due to the Blob.

With that lead-in, let us now consider what happened in the Salish Sea. Much of the following information is cribbed from the "Puget Sound Marine Waters" annual overviews produced by the National Oceanic and Atmospheric Administration's (NOAA) Northwest Fisheries Science Center for the Puget Sound Ecosystem Monitoring Program's Marine Waters Workgroup, and interested readers are encouraged to check out those overviews.

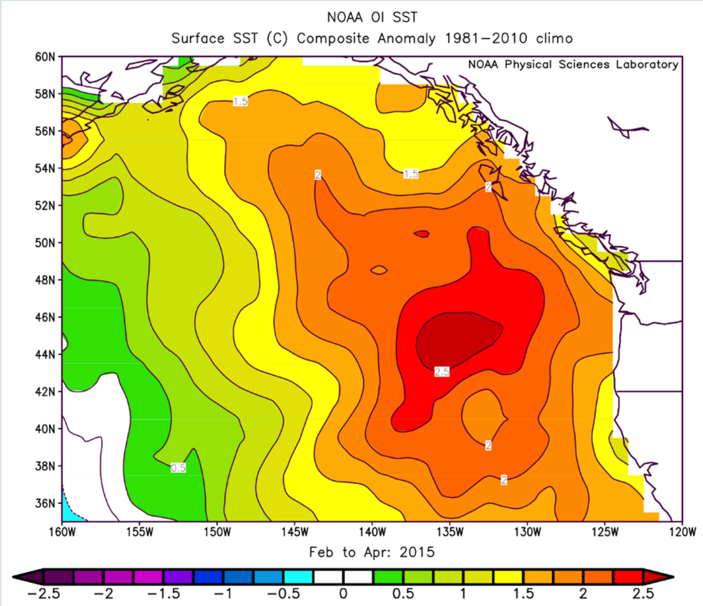
The Blob really began rearing its ugly head in fall 2014 when the seasonal transition in the coastal winds from upwelling to downwelling shoved the extremely warm water lurking offshore right up to the coast. The warm water entering the Strait of Juan de Fuca at that time meant that the density differences driving the estuarine circulation were weakened. An important consequence of the lack of flushing was abnormally low oxygen concentrations in some locations, especially in lower Hood Canal. The relatively warm and sunny weather during fall 2014 was accompanied by a prominent phytoplankton bloom.

The heyday of the Blob was during 2015. The aforementioned warm winter of 2014-2015 resulted in the most paltry snowpack for the Pacific Northwest in the historical record. Because the precipitation was much more in the form of rain rather than snow, there was greater freshwater runoff than usual in early 2015, leading to low salinities in the upper part of the water column, and very low streamflows in summer 2015, resulting in high salinities. The latter had the positive effect of promoting vertical mixing, and hence helped in some locations to keep oxygen concentrations at depth from cratering. That being said, the open ocean conditions associated with the Blob imply that there were relatively long residence times for the waters of the Salish Sea with a host of incompletely known consequences. This was a year that will long be remembered for harmful algal blooms of Pseudo-nitzschia spp. along the west coast of North America, but the Salish Sea also got in the act with an amazingly early bloom of *Alexandrium* spp. in Hood Canal in April and numerous examples of Vibrio-contaminated oysters. Impacts on higher trophic levels also became apparent, including herring, seabirds (e.g., rhinoceros auklets) and some species of marine mammals.

The year of 2016 was less extreme as the Blob wound down, but the Salish Sea definitely remained on the warm side. This year also featured a continuation of the recent trend for warmer spring weather and rapid snowmelt, with the result being earlier freshening of the near-surface waters of the Salish Sea. Herring populations and some seabird and marine mammal species continued to struggle.

The post-blob period of 2017-2019 represents a mixed bag. The return of more normal conditions—whatever that means during a time of inexorable trends in physical and chemical ocean properties—was accompanied by recovery in some populations and continued declines in others. A telling example here is the plight of the southern resident orcas, who apparently spent relatively little time in the summer of 2019 in their usual haunts in the Salish Sea, perhaps because of the Blob's longer-lasting impacts on Chinook salmon runs.

In terms of takeaways, perhaps the Blob can serve as a wake-up call. The climate community appreciated the overall warming that was occurring, but still was stunned by the magnitude of this recent event. The marine ecosystem response was complex, especially at higher trophic levels, and it is proving to be no cinch to tease out the interplay between all the potential factors. Better understanding of the Salish Sea's response to the climate forcing through improved monitoring and further research is necessary. We know that the Salish Sea will experience future events, and that they are liable to be even more extreme and with profound effects, given the background warming and changing ocean chemistry.



Sea surface temperature (SST) anomaly distribution (°C) for February-April 2015 from NOAA's Optimal Interpolation Sea Surface Temperature dataset. Source: NOAA/ESRL Physical Sciences Laboratory from their website at http://psl.noaa.gov/.

13 THE SALISH SEA MODEL – FOR DIAGNOSTIC BIOPHYSICAL ASSESSMENTS SUPPORTING ECOSYSTEM RESTORATION AND WATER QUALITY MANAGEMENT

Dr. Tarang Khangaonkar, P.E., Salish Sea Modeling Center, University of Washington, Tacoma, and Pacific Northwest National Laboratory

"Why is there persistent annual occurrence of hypoxia in Hood Canal but not in Saratoga Passage? Why does Padilla Bay support a healthy eelgrass meadow while Skagit Bay and Port Susan appear to be losing vegetation? Why do we continue to detect PCBs in fish tissue and the food web despite many years of source control and sediment remediation efforts? Will nutrient reduction strategies be effective in managing dissolved oxygen near algal blooms? And will they also provide ocean acidification relief? What do we know about the operation of net-pens and potential spreading of released particulate matter and disease, and how does Salish Sea circulation and transport affect accumulation of microplastics and marine debris?"

These are examples of some of the leading questions currently being addressed by our water quality management and regulatory agencies. Given numerous concerns related to the health of the ecosystem and the possibility of anthropogenic impacts—from population growth to climate impacts, such as sea level rise—scientists, engineers, and planners seek an improved basic understanding of the biophysical behavior of the Salish Sea. The Salish Sea Model (SSM) development was motivated by this urgent need for a comprehensive predictive model that could diagnose water quality issues and concerns and serve as a planning tool in support of Puget Sound restoration efforts. The model framework and formulation were selected specifically to allow assessments of concerns, such as recurring hypoxia in Puget Sound, loss of eelgrass meadows, loss of nearshore habitat, and persistence of toxic contaminants in sediments and tissue. The SSM was developed by the Pacific Northwest National Laboratory in collaboration with the Washington State Department of Ecology (Ecology) and with support from the United States Environmental Protection Agency (USEPA) (Khangaonkar et al. 2018).

The SSM was designed to function at an academic/scientific research level of quality, but with practical applications and use by the broad Salish Sea community in mind. It uses an unstructured approach in which the model domain is represented by a grid/mesh made up of triangular cells over which Navier-Stokes equations of continuity and momentum are solved. This provides flexibility, encompassing regions with complex shorelines and the presence of multiple islands. The approach also allows the model resolution to be refined locally for site-specific applications. Right from early-developmental stages, SSM sub-domains with the finite volume community ocean model (FVCOM) framework have been deployed in support of feasibility analyses for nearshore restoration projects. Despite best intentions, efforts to restore nearshore habitats can result in poor outcomes if water circulation and transport are not properly addressed. Land use constraints can lead to selection of suboptimal restoration alternatives that may result in undesirable consequences, such as flooding, deterioration of water quality, and erosion, that require immediate remedies and costly repairs. Quantitative models designed for application to the nearshore

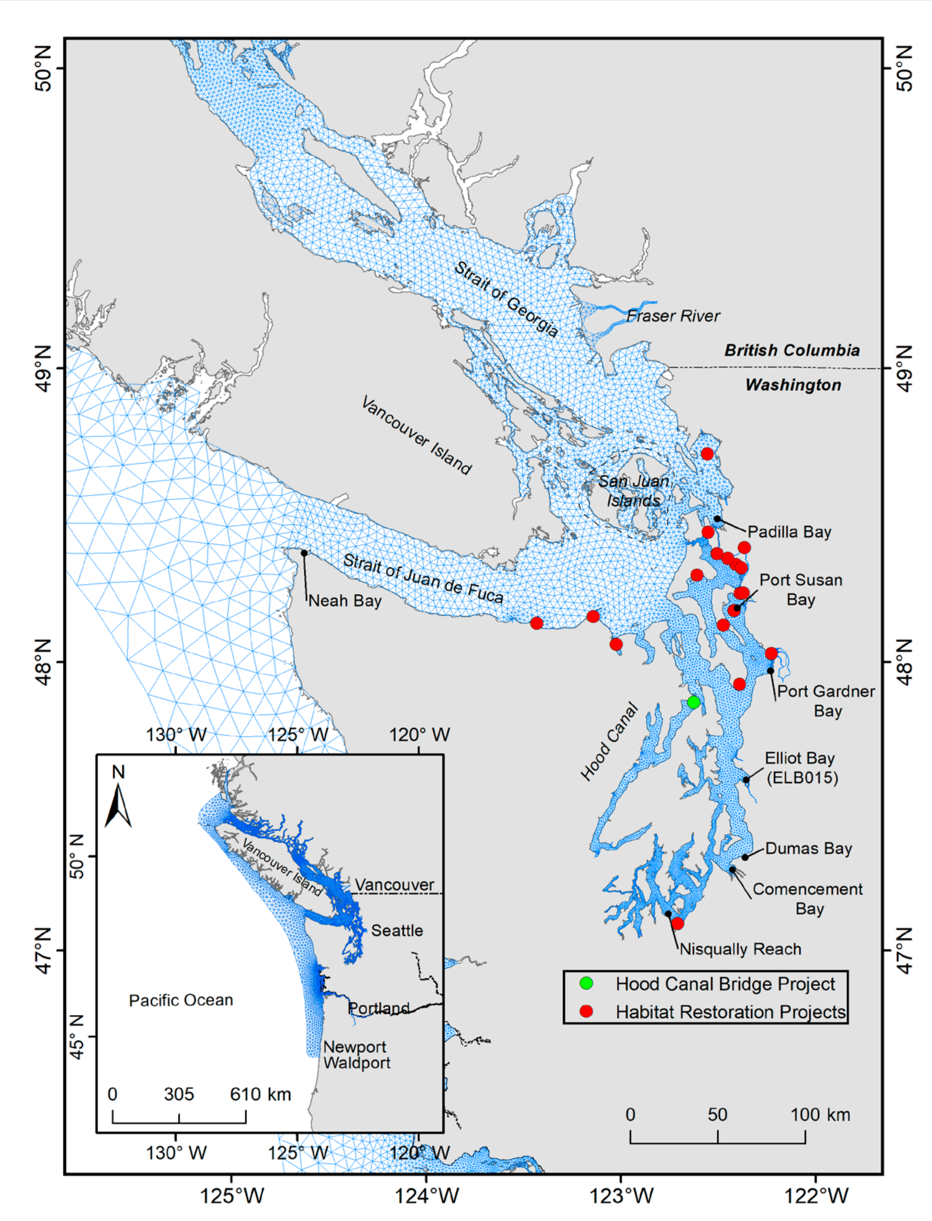


Figure 1: Project sites in the Salish Sea where site-specific applications of FVCOM based hydrodynamic models were developed as part of restoration feasibility or environmental assessment and design efforts. These applications included stand-alone as well high-resolution sub-basin applications embedded within SSM. Source: Tarang Khangaonkar

environment can minimize uncertainty about restoration goals, such as recovery of tidal exchange, supply of sediment and nutrients, and establishment of fish migration pathways. Starting with one of the earliest and largest restoration efforts in Puget Sound (Nisqually National Wildlife Refuge) to recent projects in the Whidbey Basin, the model has provided hydrodynamic simulations in the intertidal nearshore environment, predicting cumulative effects of multiple dike-removal, dike breach, and dike-setback scenarios on tidal currents, inundation frequency, connectivity, and sedimentation and erosion processes. Figure 1 shows locations of various sites in the Salish Sea where SSM was used with high resolution (≈10-25 m) in sub-basins of interest, either in stand-alone (cut-out) mode or embedded within SSM as part of restoration feasibility or impact assessments prior to project implementation.

The familiarity with the Salish Sea environment and years of on-water experience sometimes convinces us of potential remedial actions based on intuition, personal convictions, and desired expectations. However, this inland fjord is complex, and the nearshore intertidal reaches where most development activity and anthropogenic impacts first occur—with tidal ranges greater than 3 meters over most of the domain—are too complex and challenging to rely on scaling inferences and past project experiences alone. For example, having recognized that the anthropogenic nutrient loads to the Hood Canal basins were relatively small, many of us were convinced that hypoxia in Hood Canal was somehow tied to the Hood Canal floating bridge. The hypothesis was that bridge presence directly obstructed surface currents and therefore likely impacted large-scale circulation and flushing (Khangaonkar & Wang 2013). Application of the SSM as part of the Hood Canal Bridge Impact Assessment showed that the floating bridge indeed creates a zone of influence which affects currents, salinity, and temperature patterns in the near field (3-6 km; Khangaonkar et al. 2019). However, it also demonstrated that the original intuitive conviction that the bridge contributes to hypoxia in the Lynch Cove region of Hood Canal approximately

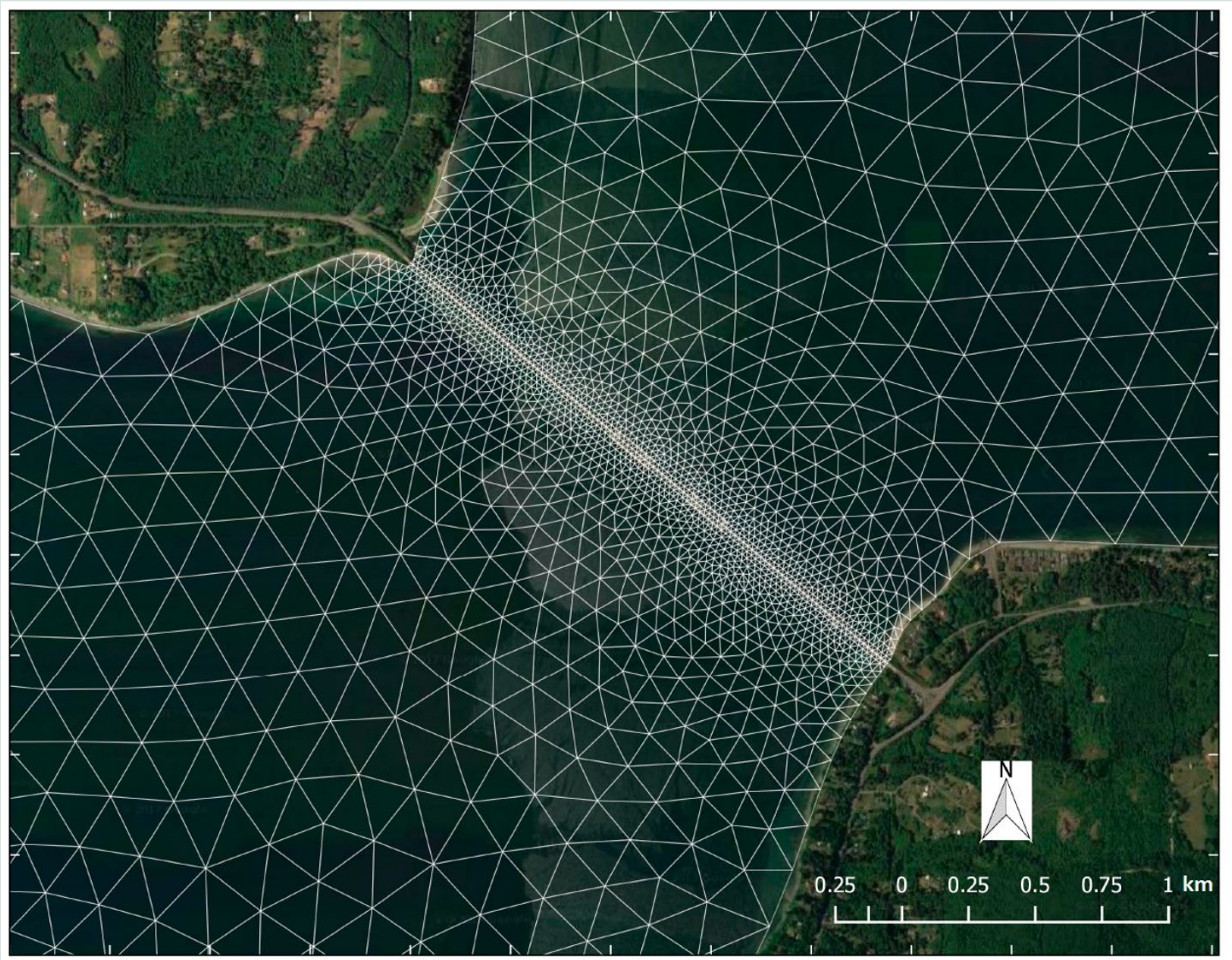


Figure 2. Salish Sea Model grid with refinement near the Hood Canal Bridge region to facilitate incorporation of the bridge block effects on circulation and water quality (biogeochemistry).

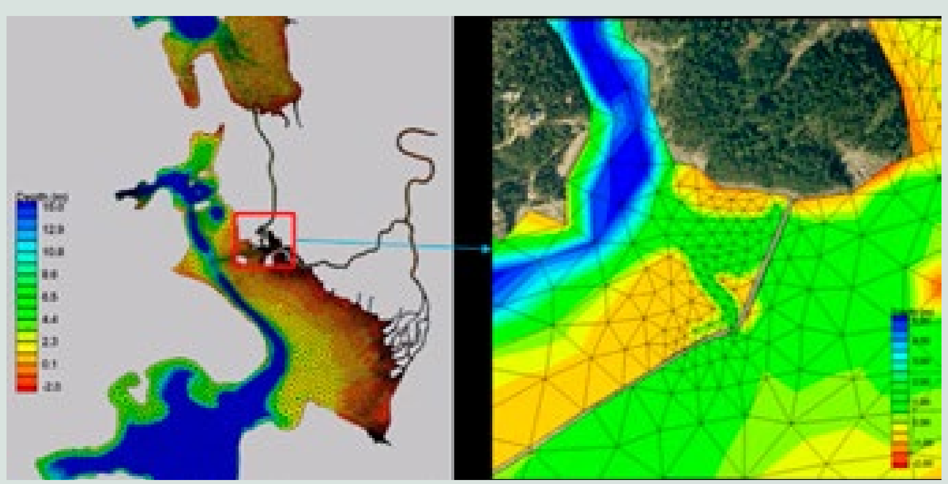


Figure 3. A closeup of model grid near McGlinn Island jetty near the mouth of North Fork Skagit River.

80 kilometers away was likely incorrect. The magnitude of hypoxia and overall basin flushing time appeared to be unaffected by the presence of the bridge based on numerous model tests. However, the SSM-based modeling effort did show that the hypoxia magnitude (exposure in area-days) was instead directly affected by overall nutrient pollution entering the Salish Sea and the resulting increase in algal growth. In other words, improvement to Hood Canal hypoxia will require overall improvement in Salish Sea water quality and cannot be addressed by Hood Canal sub-basin focused actions alone. Figure 2 shows a SSM grid with site-specific refinement down to 18-meter scale for embedded simulation of the Hood Canal Bridge block along with the rest of the domain.

This ability of SSM to conduct high resolution applications with shoreline structures has proven particularly useful in providing information to decision makers in situations where ecosystem goals may conflict with regional infrastructure needs. For example, the 16-kilometer Swinomish Federal Navigation Channel, which provides navigation access to Northern Puget Sound by connecting Skagit and Padilla Bays requires periodic maintenance dredging and dikes to train Skagit River flow and sediments away from the channel.

The Swinomish Channel is in need of repairs to dikes/jetties, as sedimentation has increased, but the wear and tear and resulting breaches are seen as beneficial to migrating fish. The proposed repairs and dike constriction actions for channel maintenance appear to be in conflict with salmon habitat restoration goals aimed at improving access, connectivity, and brackish water habitat. The model was applied to assess the feasibility of achieving the desired dual outcome of (a) reducing sedimentation and shoaling in the Swinomish Channel and (b) providing a direct migration pathway and improved conveyance of freshwater. Figure 3 shows a closeup of model grid refinement and application to evaluate impacts on sediment deposition and salinity patterns. The results showed that connectivity and the desired brackish environment could be restored effectively through one of the scenarios considered but would come at increased dredging and maintenance costs (Khangaonkar et al. 2017).

For the scientific and the regulatory community in the Salish Sea, a key performance measure for acceptance of biogeochemical models has always been their ability to reproduce nutrient-algae annual cycles and dissolved oxygen (DO) levels. DO is often regarded as an indicator of water quality, and the ability of the model to reproduce recurring hypoxia in sub-basins, such as Lynch Cove, Penn Cove, and East Sound, and responsiveness to anthropogenic nutrient loads from watershed runoff and wastewater loads is desired. This elusive goal had stymied ecosystem modeling research and nutrient management efforts in the region for decades. The SSM has successfully reproduced estuarine circulation, inter-basin exchanges, and annual biogeochemical cycles in the inner waters of Puget Sound, Georgia Basin, the San Juan Islands, and the Northwest Straits. SSM-based results have shown that nutrient loads from land-based sources are responsible for approximately 62% of exposure to hypoxic waters in the Salish Sea (Khangaonkar et al. 2018). The model has since been selected as the tool of choice by the USEPA and Ecology for developing the Marine Water Quality Implementation Strategy (MWQ IS) and is currently supporting the Puget Sound Nutrient Source Reduction Project (Ahmed et al. 2019).

In recent years, several new capabilities have been added to SSM in preparation for its use in sea level rise and climate change impact projections. The model now includes explicit simulation of turbidity, zooplankton, and eelgrass, and performs at a higher skill level for dissolved oxygen (DO) and ocean acidification (OA) or pH predictions. The SSM had previously demonstrated that the effects of the altered ocean chemistry in the upwelled shelf waters as a result of climate change would propagate into the inner Salish Sea and impact biogeochemistry, resulting in higher predicted algal biomass, a potential species shift from diatoms towards dinoflagellates, and increased regions of hypoxia and acidification (Khangaonkar et al. 2019). Since then, to improve ecological response predictions, micro- and meso-zooplankton kinetics have been incorporated, along with eelgrass, which may compete with phytoplankton for available nutrients in the photic zone along the shorelines. Figure 4 provides updated projections for ocean acidification impacts in the Salish Sea for Y2095. Results point to the possibility that the bottom layer of the Salish Sea water column (lower 15% of water depth) will be exposed to low pH waters with $\Omega A < 1$, 100% of the time. For the bottom layer, which already experiences exposure to corrosive water in present condition, this represents an increase of approximately 20%. However, for the surface waters including the photic zone, the projection for the future Y2095 scenario represents a near doubling, over a 114% increase in exposure to waters with ΩA < 1 (Khangaonkar et al. 2021; Note: these results are limited in that they are based on projections from a single ensemble member run of the National Center for Atmospheric research (NCAR) Community Earth System Model (CESM) and must be interpreted with appropriate caution. However, we believe that the results still provide a useful peek into the type of response one may expect over the Salish Sea in the future.)

In collaboration with University of Washington (UW) and Washington State Department of Fish and Wildlife, and with USEPA support, a toxics fate and transport module for SSM is currently under development. The SSM-toxics module development effort targets tracking of PCBs and metals from sources such as outfalls through the water column, to produced organic particles, and through the food chain to fish tissue data that has been collected by the Washington Department of Fish and Wildlife over many years. The model was also used by the same team in connection with tracking of toxics in Puget Sound, which includes pharmaceuticals such as opioids and the chemotherapy drug melphalan, along with a suite of 62 other contaminants (James et al. 2020). The SSM was used to compute a Salish Sea-wide map of effluent concentration from 99 wastewater outfalls over a one-year period to examine cumulative effects. An outfall effluent plume module FVCOM-Plume has been developed to provide dynamic plume dilution and transport analysis in tidal environments (Premathilake & Khangaonkar 2019). We expect that dynamic application of SSM with FVCOM-Plume will help regulatory agencies with accurate aquatic and human health exposure assessments in the Salish Sea.

In collaboration with NOAA Center for Operational Oceanographic Products and Services (COOPS), Ecology, UW-NANOOS, the PNNL SSM team is developing a high-resolution version of SSM towards SSM-OFS, an Operational Forecast System for the Salish Sea, for navigation and maritime emergency response support. Community access to SSM is available through the Salish Sea Modeling Center that was recently established through a memorandum of understanding between University of Washington, Tacoma and PNNL with support from USEPA, Puget Sound Partnership, City of Tacoma, and the University of Washington.

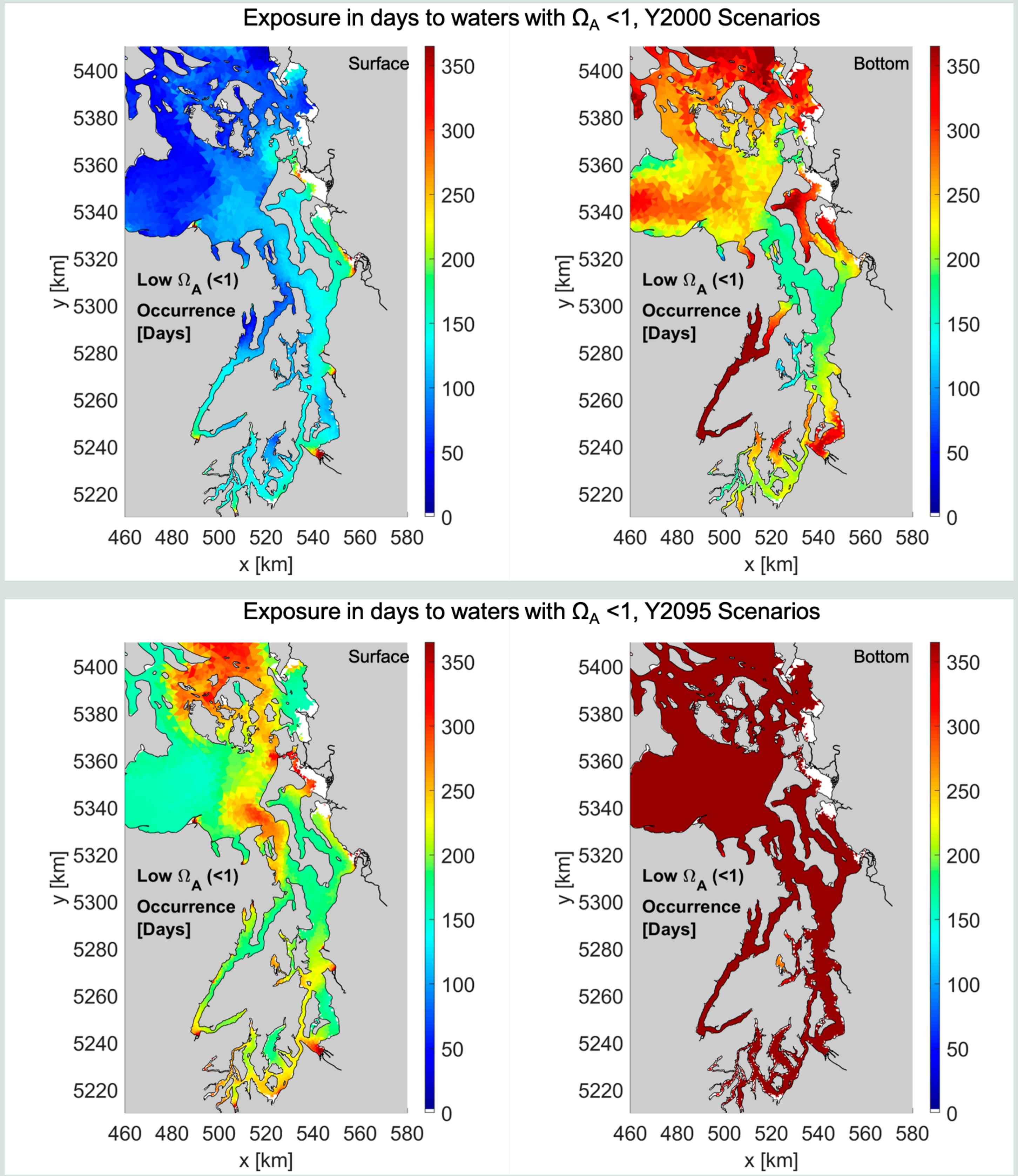


Figure 4. Projected exposure in days to waters corrosive to shell forming organisms with aragonite saturation ΩA < 1 for surface and bottom layers of Salish Sea. Top panel: Historical Y2000 scenario simulation, surface and bottom layer. Bottom panel: Future Y2095 simulation, surface and bottom layer. Surface layer corresponds to upper 3% of the water column and bottom layer corresponds to lower 15% of the water column.

14 EELGRASS WASTING DISEASE

Olivia Graham, Morgan Eisenlord, and Dr. Drew Harvell, Department of Ecology and Evolutionary Biology, Cornell University

Rising seawater temperatures can increase the risk of disease outbreaks in many taxa (Burge et al. 2014; Maynard et al. 2016; Burge & Hershberger 2020). In addition, heat waves, which occur when seawater temperature exceeds a threshold, are increasing in severity, duration, and intensity (Hobday et al. 2016; Oliver et al. 2018) and have been associated with numerous ecological changes in our waters. For example, documented impacts from the longest heat wave described to date, which occurred in the Northeast Pacific Ocean from 2014 to 2016, include mass mortality events of planktivorous seabirds, widespread harmful algal blooms, ecosystem regime shifts from bull kelp forests to sea urchin barrens, massive shifts in plankton productivity and composition, and an outbreak of seastar wasting disease in numerous species including the sunflower star (*Pycnopodia helianthoides*), a pivotal predator (Cavole et al. 2016; Gentemann et al. 2017; Harvell et al. 2019; Rogers-Bennett & Catton 2019).

Pathogens are potentially the ultimate keystone species in that their small biomass can have massive impacts that ripple through ecosystems. However, the triggers to epidemics are likely multivariate and complex, involving a combination of host stress, environmental conditions, and changes in biological communities. Progress in understanding the conditions that lead to epidemics has been hindered by a lack of integration among these various components that determine susceptibility and resilience to pathogens. Disease outbreaks can be particularly damaging when they affect ecosystem engineers, such as corals and seagrasses (Burge et al. 2014; Harvell & Lamb 2020). Outbreaks of wasting disease in seagrasses are one of a myriad of stressors associated with declining temperate and tropical seagrass meadows around the globe (Short et al. 1988; Waycott et al. 2009; Sullivan et al. 2013; Martin et al. 2016; Sullivan et al. 2018). The largest outbreak of wasting disease occurred in the 1930s along the European and American coastlines of the Atlantic Ocean (Renn 1936; Godet et al. 2008). During this outbreak, eelgrass meadows suffered up to 90% mortality. Impacts of the outbreak include altered sediment distribution and disrupted coastal food chains, fisheries, and migratory waterfowl (Short et al. 1988). These examples demonstrate the cascading ecological impacts of infectious diseases in foundation species (Hughes et al. 2008; Waycott et al. 2009; Plummer et al. 2013).

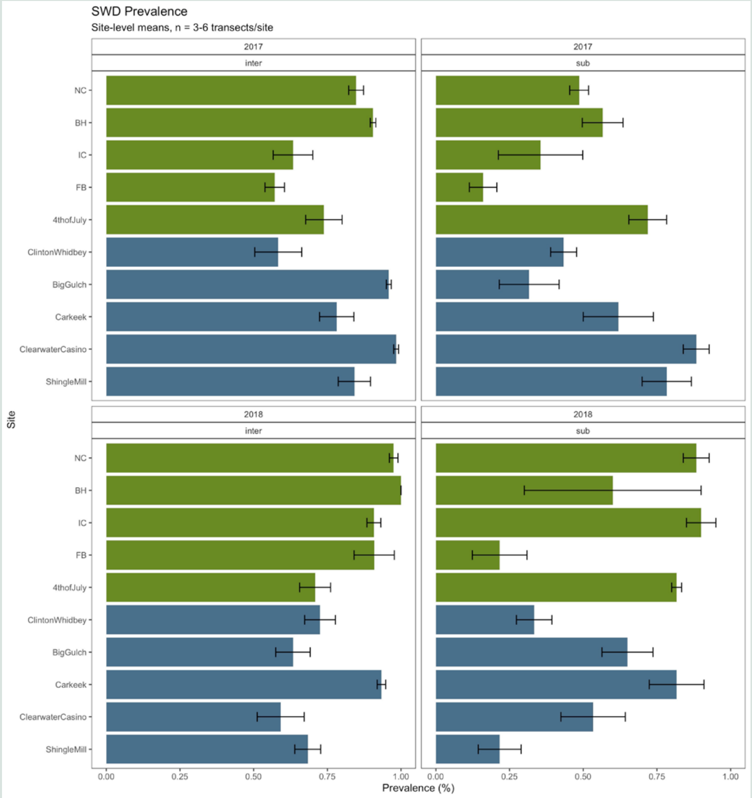
In recent years, eelgrass in critical estuaries on both the United States Atlantic and Pacific coasts has declined. Eelgrass meadows are affected globally by a wasting disease caused by the protozoan *Labyrinthula zosterae*. There are other disease agents under investigation that can also damage eelgrass, but wasting disease caused by *L. zosterae* is currently the most damaging in our waters.

Levels of eelgrass wasting disease are high in the San Juan Islands (Groner et al. 2016) and Puget Sound. Intertidal and subtidal seagrass wasting disease prevalence and severity were extremely high at field sites in the San Juan Islands (North Cove, Beach Haven, Indian Cove, False Bay, and 4th of July) and Puget Sound (Clinton-Whidbey, Big Gulch, Carkeek, Clearwater Casino, and Shingle Mill) in 2017 and 2018 (and ongoing). Prevalence exceeded 50% at all intertidal sites in both years and was higher in most intertidal than subtidal sites. Severity of infections were higher in intertidal than subtidal sites in the San Juan Islands and more variable in Puget Sound.

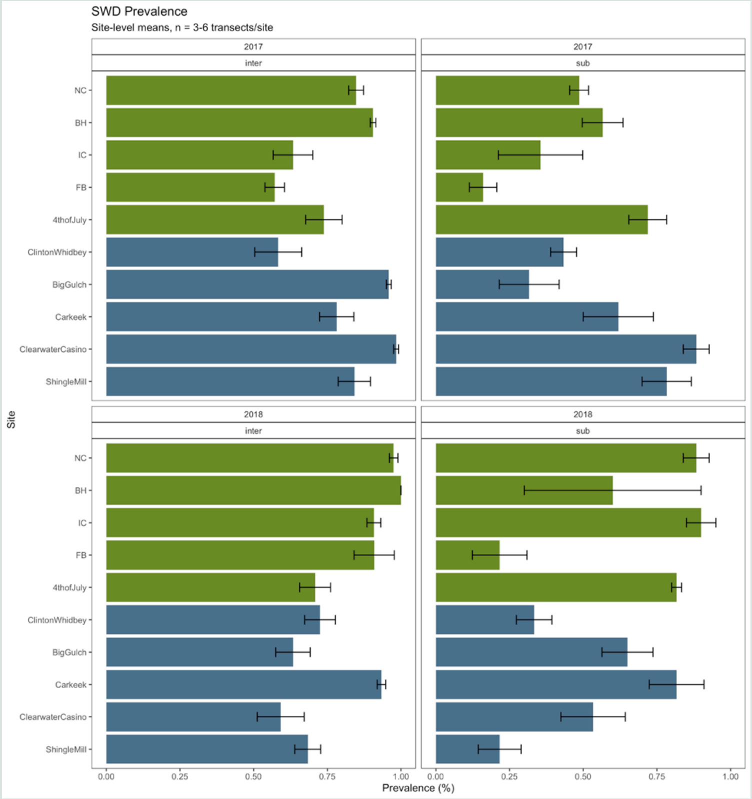
Our time-series studies from 2012 to 2017 (and ongoing) show sharply increasing levels of disease correlated with warming winter and spring temperatures (Groner et al. under review).

These increasing levels of disease are a threat to sustainability of eelgrass meadows, our most valuable marine habitat, vital for fish development and filtration services and blue carbon mitigation.

Shallow intertidal eelgrass with bubble snail eggs at False Bay, San Juan Island, WA. Photo credit: Sarah Petrini.



Prevalence (proportion of diseased blades, n = 40/transect, 3 transects per site) of disease in intertidal and subtidal eelgrass meadows in the San Juan Islands and Puget Sound.



Severity (percent of a blade damaged by lesions) of disease in the San Juan Islands and Puget Sound eelgrass meadows.

15 EELGRASS VARIATIONS TIES TO SEA LEVEL VARIATIONS

Dr. Ronald Thom, Staff Scientist Emeritus, Pacific Northwest National Laboratory

In the summer of 1991, out of curiosity and to train interns in measuring the fundamental ecological process of primary production, we started measuring the growth rate of eelgrass (*Zostera marina*) every two weeks in a lush meadow near our lab at the mouth of Sequim Bay. In all but two summers since then, with the help of student interns and volunteers, we have continued to measure the growth rate between May and August. After about ten years, we started to look at the data. Although visually we did not see obvious differences in the meadow, we found that the growth rates varied substantially between summers. We wondered why.

In an effort to explain the results, we first organized the knowledge on the factors that affect eelgrass. It is well established that eelgrass is found at the dynamic interface between the lower intertidal and the shallow subtidal zones where suitable conditions of the sediment, wave energy, salinity, temperature, and light occur. The fact that eelgrass does not like to dry out (desiccate) limits its upper extent in the intertidal zone. Because it needs light to live and grow, and because light decreases in water with depth as well as turbidity, the lower depth it can exist at is a function of the amount of light reaching the bottom. So that explains the broad range of distribution, but does it help explain why eelgrass grew faster some years than others in our study plot? We enhanced our monitoring of growth by including light and temperature measurements, and collected data throughout Puget Sound on depth distribution of eelgrass. We also examined the data developed by the Washington State Department of Natural Resources eelgrass monitoring program, which began in the early 2000s and engaged eelgrass experts in discussions about our question.

During the 1990s, the issue of sea level rise (SLR) driven by global warming began to be studied more closely. We had an early interest in the effect of SLR on tidal marshes and studied accretion rates of marshes in our region in 1991. Sea level obviously could affect eelgrass also. The SLR scenarios under investigation were largely steady increases in sea level, with nuances associated with local conditions such as land subsidence and isostatic rebound. Based on the studies by the Washington State Department of Ecology and others, it turned out that the relative SLR rate on the shoreline in the Sequim Bay area was close to zero; there was no effect on eelgrass based on this scenario. However, while exploring the sea level variation tracked by NOAA, we noticed that the tide level recorded by sensors in Port Angeles and Port Townsend varied from the tide level predicted by tide models on many days. Short-term variations appeared to be caused by localized storm events pushing water levels higher via storm surge. We also noticed that longer-term (i.e., weeks to months) differences in mean sea level were occurring. We termed these longer-term variations mean sea level anomalies.

Several conditions can cause anomalies in mean sea level, among them being local storms and El Nino and La Nina events. El Nino events result in heating and thermal expansion of the North Pacific Ocean. The Oceanic Nino Index (ONI) is basically the temperature of the surface water in a region near the equator compared with the long-term mean. An ONI between -0.5 and +0.5 indicates a neutral ONI. Values of the ONI above and below that range indicate El Nino and La Nina conditions, respectively. The monthly mean sea level anomalies recorded near Sequim Bay between 1990 and 2013 ranged from -0.16 to +0.38 meters—a total range of 0.54 meters or almost 2 feet.

This longer-term variation could influence eelgrass growth by sustained periods of either low water levels or high water levels. Knowing the factors that control eelgrass growth, higher tides could enhance growth of the plants at our intertidal site by reducing the period of drying during summer, whereas extended lower tides could slow growth via greater desiccation. Plotting the growth rates over a period of 1991 to 2013 against mean sea level and the ONI showed a reasonably consistent pattern, with higher growth rates during periods of higher mean sea level, especially during El Niños and vice versa with La Ninas. Also, plotting growth rates against desiccation stress (measured in percent of daytime hours the plants were emerged) as well as the mean maximum temperature showed strong negative correlations with growth.

So we think we have at least part of a plausible explanation for the variation in growth rate. We examined old long-term data on eelgrass shoot density from Willapa Bay and near the Clinton Ferry Terminal on Whidbey Island and found that the variation seen there could be at least partially explained by sea level and/or temperature variations. In a study of Padilla Bay, Kairis and Rybczyk (2010) found that the steady increase in sea level would result in an increase in eelgrass area. This is because as the sea rises, the area above the current limit of eelgrass would be subjected to less desiccation stress and should be suitable for eelgrass. At the lower depth distribution of eelgrass, the typically clear water should allow eelgrass to persist (not decline), at least until depths and/or turbidity increase substantially.

The portion of the eelgrass meadow where our long-term growth studies were conducted inexplicably started to become less dense in 2014 and finally disappeared in 2016. This collapse of approximately $700m^2$ corresponded with the anomalous warm water conditions termed the Blob. Although we are still trying to figure out the mechanism for this collapse, our observations indicated that Canada geese had started to congregate during this period in numbers we had never seen before. They tended to congregate in the area of our sampling plot, where they were observed eating eelgrass. Unlike Brant geese that only eat the leaves, Canada geese pull up the leaves and the rhizome. Importantly, eelgrass regenerates its shoots from the rhizome, and with that gone, the eelgrass cannot quickly recover. We are not sure if the geese were the primary cause of the collapse or why they suddenly started to show up on the site, but they surely contributed to it.

Although the collapse necessitated that we relocate our monitoring plot, perhaps one of the things we learned that can be applicable elsewhere is the advantage of monitoring something for a long time (28 years so far) in the same place as where factors influencing variation can be studied. We had the advantage of using a site located within 150 meters of the laboratory to conduct these studies. It has allowed us to tease out causal factors causing eelgrass variation and collapse, and to link these to events occurring hundreds to thousands of miles from the site. Coupling these local long-term findings with research and monitoring done in Salish Sea and globally will help us better understand the longer-term effects of global warming and perhaps other human and natural-derived pressures on coastal ecosystems, and provide clues on how to make these system more resilient to these pressures.

16 VULNERABILITY ASSESSMENT AND CLIMATE CHANGE ADAPTATION PREPARATION

Excerpted from State of Our Watersheds 2020, authored by the Northwest Indian Fisheries Commission and the Jamestown S'Klallam Tribe

The Jamestown S'Klallam Tribe is on the forefront of addressing tribal vulnerabilities and preparing for climate change. The 2013 Jamestown Climate Vulnerability Assessment and Adaptation Plan provides an assessment of vulnerabilities of tribal resources to the negative impacts of climate change. The plan also identifies adaptation measures that the tribe is working to complete. Sea level rise, ocean acidification and climate models show potential for increased risks to critical habitats, tribal infrastructure and tribal health.

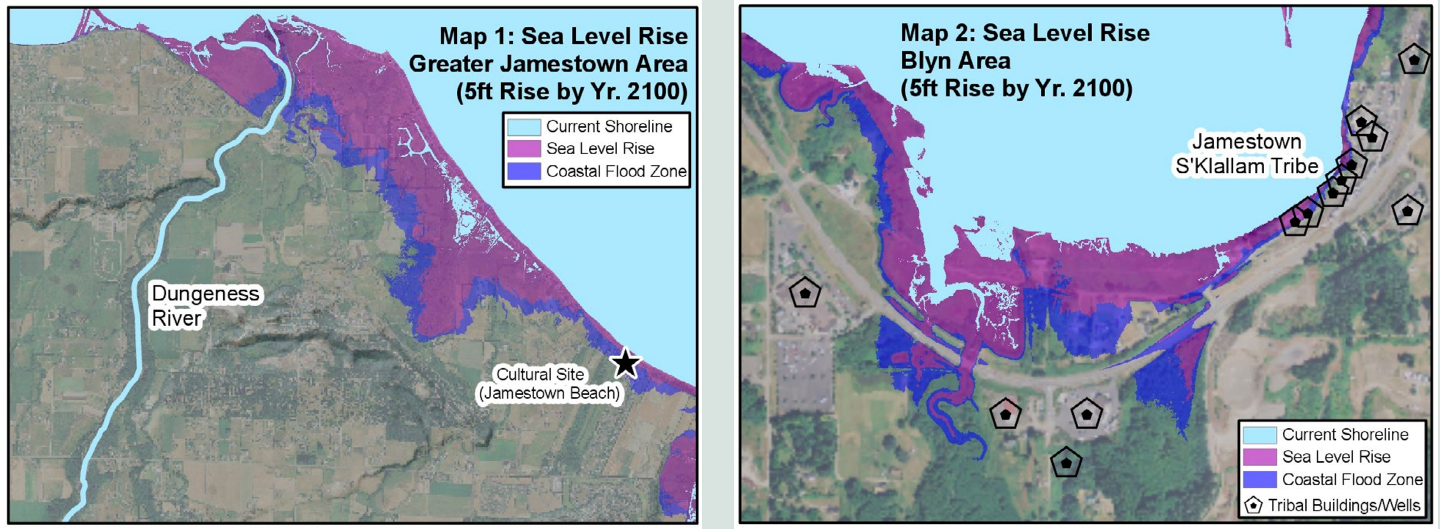
As one of the first tribes in western Washington to complete a climate adaptation plan and vulnerability assessment, the Jamestown S'Klallam Tribe has identified and prioritized areas where the changing climate conditions (i.e., changing precipitation patterns, sea level rise, ocean acidification) will leave tribal resources, infrastructure, economy and health most vulnerable (Adaptation International 2013), Climate vulnerability depends largely on climate exposure, sensitivity and adaptive capacity (Adaptation International 2013).

The tribe identified many vulnerabilities:
Impact to Salmon which is the foundation for almost all aspects of tribal cultural life and also serve as economic and nutritional resources for the tribe. Salmon will be impacted by the change in timing and amount of winter rains and flooding, scouring of egg redds (nests) during high flows, thermal stress from higher water temperature, and less water availability in the summer.

Oysters and clams also are highly vulnerable under expected conditions. Projected impacts include higher water temperatures and ocean acidification. There will also be an increased occurrence of shellfish poisoning associated with harmful algal blooms (which warmer conditions may favor), diminished health and wellness, economic loss, and increased flooding of tribal buildings, sacred historical places and infrastructure (Adaptation International 2013).

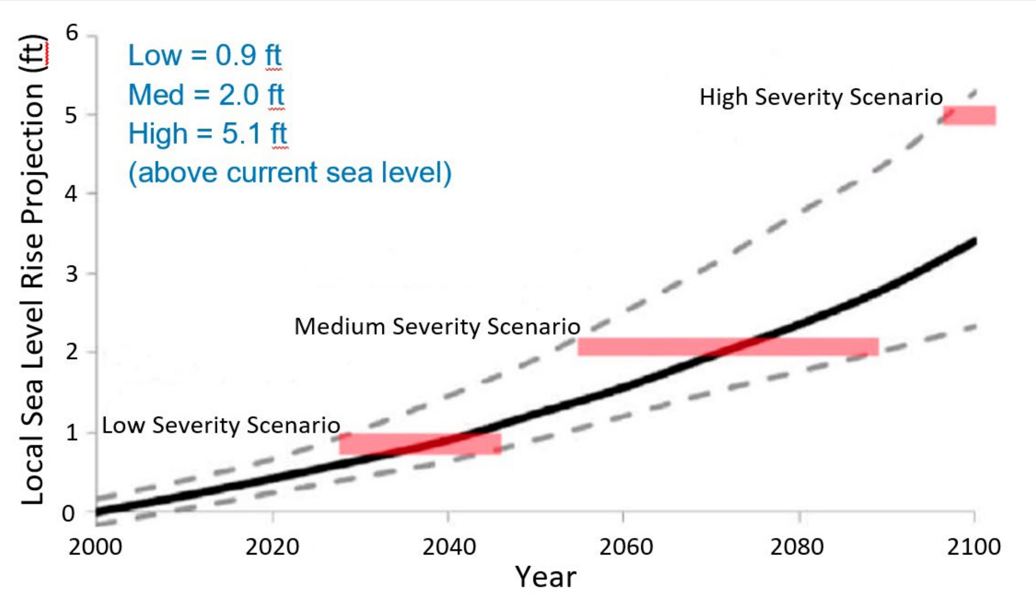
Traditional ways of life and health are extremely vulnerable. The loss or displacement of traditional plants necessary for food and fibers needed for traditional practices is likely. There are potential impacts to Indian health from forest fire smoke and loss of important traditional agricultural food and natural resources.

> To ensure continued economic growth, promote long-term community vitality, and protect sensitive resources and assets, it is essential that we incorporate climate change preparedness into our planning efforts and operations.
>
> W. Ron Allen
> Jamestown S'Klallam Tribe Chairman



Maps 1 and 2. The maps show flood conditions with a sea level rise model under the high severity scenario (Map 1). They show the potential inundation of a vital water source, closed roads, an important cultural site at Jamestown Beach (Map 1), and buildings on the tribal campus in Blyn (Map 2) where flood risk is projected to increase by the end of the century. Map data sources: Adaptation International (2013), National Agriculture Imagery Program (2013). Source: Washington State Department of Ecology Regions (2011) and United States Geological Survey (2019)

Ocean acidification (decrease in ocean pH) will cause waters to become "corrosive to shell-forming organisms such as oyster larvae, clams, mussels and crabs," posing serious threats to the shellfish in the Strait of Juan de Fuca (Adaptation International 2013). Pictured are the pteropod shells dissolving because of the decreasing ocean pH. Source: Washington State Department of Ecology (2012)



Sea level rise in three scenarios (low, medium, high). This graph is from page 16 of the Jamestown Climate Vulnerability Assessment and Adaptation Plan (Adaptation International 2013). The tribe has identified areas most susceptible to rising sea levels. The assessment has helped the tribe relocate several storage buildings that would have been otherwise affected.

17 | SALISH SEA JELLYFISH

Dr. Correigh Greene, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration

The Salish Sea is home to a diverse community of gelatinous zooplankton (or "jellies") composed primarily of species from the phyla *Cnidaria* and *Ctenophora*. These include conspicuous large scyphozoan medusa such as lion's mane (*Cyanea capillata*) and egg-yolk jellies (*Phacellophora camtschatica*), to smaller hydrozoans such as crystal jellies (*Aequorea* spp.) and ctenophores (e.g., *Pleurobrachia* spp.). One abundant species is the moon jelly (*Aurelia* labiata), which forms huge aggregations (or "smacks") easily observable from the air as well as in the water (Figures 1 and 2; see Eyes Over Puget Sound, Schaub et al. 2018).

In their adult forms, jellies comprise a relatively large proportion of the biomass in the Salish Sea. For example, the Puget Sound Ecopath model (Harvey et al. 2010) estimated total biomass at nearly 8.5 and 6.4 mt/km^2, for "jellyfish" and "small gelatinous zooplankton", respectively. These values were comparable to other invertebrates ("shrimp", 8.1 mt/km^2) as well as the more abundant fishes such as Pacific herring (5.9 mt/km^2 in total) or "small-mouthed flatfishes" like English sole (7.9 mt/km^2). Hence, they likely play important roles as predators and competitors in the Salish Sea's pelagic ecosystem.

Figure 1. Aurelia smacks (left) seen from the air and on the water in South Puget Sound from the Eyes Over Puget Sound program. Source: Christopher Krembs, Washington Department of Ecology.

Figure 2. Underwater view of Aurelia in a smack. Mature adults are typically 10-30 cm diameter and have been found in densities >170 m-3. Source: C. Greene, Unpublished data.

Around the world, scientists have observed increases in the abundance of jellies over the last 50 years. These patterns have been associated with eutrophication, intensive fishing, and changing climate (Purcell et al. 2007), although other research has pointed to large-scale climate variation driving jellyfish blooms (Purcell 2012; Condon et al. 2013; Greene et al. 2015). Are similar changes occurring in the Salish Sea? Are these changes having large impacts to the ecosystem?

These questions have been difficult to address, in part because of a lack of consistent monitoring. Jellies are often ignored as uninteresting bycatch in monitoring studies of pelagic fishes, although interest has recently grown in part due to large blooms recently observed in the northern California Current (Ruzicka et al. 2016). Data synthesized from historical and recent surface trawl data in two sub-basins of Puget Sound indicate that jellyfish catches may have increased since the 1970s (Greene et al. 2015; Figure 3).

While these patterns may appear ominous, they may also reflect natural annual variation (e.g., anomalously high abundances could have occurred in 2003 and 2011), and continuous monitoring can better address long-term changes in biomass. Figure 4 summarizes the only continuous time-series of jellies in the Salish Sea (Greene & Munsch 2020), based on annual surface trawling in Skagit Bay (Northern Puget Sound). Estimates of total jelly biomass per tow illustrate that substantial annual variation exists. High biomass was observed during the marine heatwave of 2015–2016. In subsequent years, however, biomass declined to the second lowest level observed since recording started in 2003, and has subsequently remained below average through 2019. This occurred despite above-average water temperatures in 2019, indicating that water temperatures are not the sole predictor of blooms. Furthermore, individual species appear to respond differently to warming. As exemplified in the lower panel of Figure 4 by the two largest species, the egg yolk jelly and the lion's mane jelly exhibited strikingly opposite patterns during the 2014-2016 marine heatwave period. Occurrence of both large species was low in the last three years, when smaller jellyfish dominated the biomass. Collectively, these results suggest that the jellyfish community is sensitive to climate signals such as marine water temperatures, although jellyfish do not appear to be systematically increasing in abundance over time.

Whether jellies are on the rise or are episodic in the Salish Sea, the question of their role(s) in the pelagic ecosystem remains an important one with respect to managed species such as Pacific salmon. In this

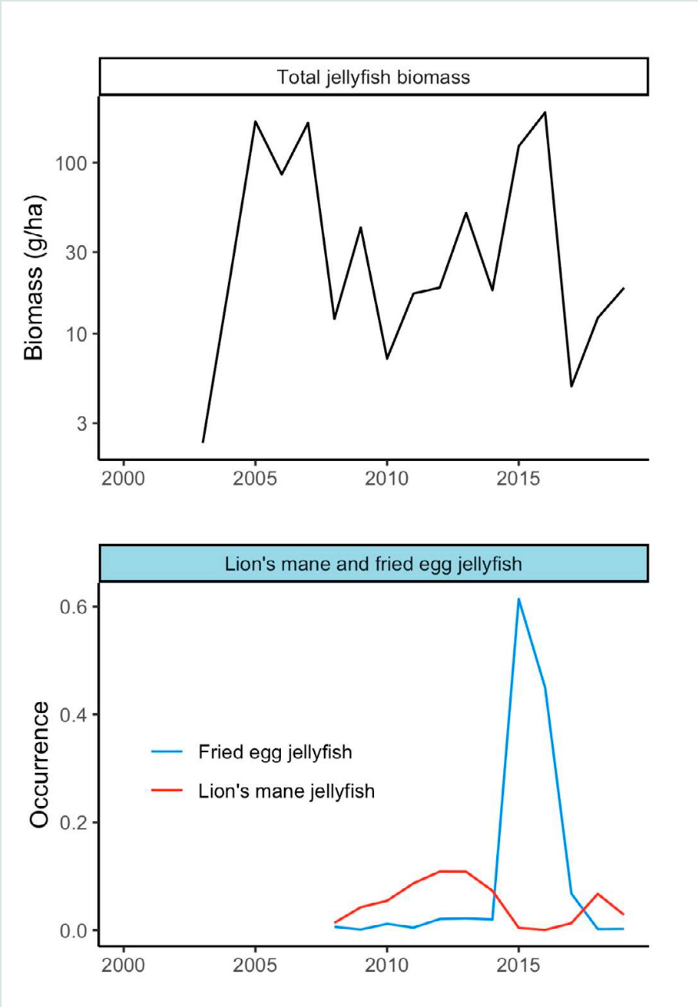


Figure 3. Annual trends in A. total jelly biomass (average g/hectare on a logarithmic axis, top panel) or B. occurrence (probability of presence, bottom panel) of lion's mane (red line) and fried egg (blue line) jellies from surface trawls in Skagit Bay. Predicted trends account for seasonal variability, spatial autocorrelation, and water volume swept through net tows. Source: C. Greene, unpublished data.

respect, one of the key species may be the moon jelly, whose huge aggregations can occupy large portions of inlets in the Salish Sea. Species of the genus *Aurelia* are found worldwide and are among those that commonly form huge, nuisance blooms. *Aurelia* have been reported to clog fishing nets and power plant intakes, deter tourism, and interfere with aquaculture (Purcell et al. 2007), all leading to significant regional economic losses. *Aurelia* are also indicators of degraded ecosystem health, often associated with eutrophic habitats, and sometimes low oxygen conditions (Arai 2001).

Aurelia entrain their prey through fluid motions created during swimming, the relative velocity of which, compared to the escape response of their prey, primarily determines prey selection (Costello & Colin 1994). In one study, *Aurelia* shifted their diets from primarily small jellyfish to include more copepods as they grew (Sullivan et al. 1994, Suchman et al. 2008). Mid- to large-size medusae may preferentially select copepods and fish eggs (Pereira et al. 2014) and also can prey on ichthyoplankton (Bailey & Batty 1983; Figure 5 upper panel), simultaneously serving as competitors and predators of fish.

Aurelia also have the potential to increase primary production by removing zooplankton grazers (Figure 5, middle panel). The increase in turbidity commonly associated with eutrophication gives an advantage to non-visual predators such as *Aurelia* (Purcell 2012), particularly when feeding on prey with good visual acuity, such as fish larvae. Hence, *Aurelia* may impact forage fish, Pacific salmon, and pelagic early life stages of demersal fish species via both direct and indirect pathways through predation and competition, respectively. Note that changing turbidity levels might also provide benefits to fishes from visually orienting predators such as birds and pinnipeds.

Large aggregations of *Aurelia* may also affect water chemistry and nutrient levels through their metabolism, and through decomposition after death. Through their metabolism, aggregations may reduce dissolved oxygen, increase ammonium levels, and allow phytoplankton to proliferate. Hence, *Aurelia* may facilitate bacterial production (Figure 5, bottom panel) that promote eutrophic conditions, to which jellyfish are relatively insensitive compared to fish species (Richardson et al. 2009). Because *Aurelia* has few natural predators, jellyfish medusae may accumulate biomass and in death transfer pelagic carbon to the benthos, acting as trophic "dead ends" and fueling benthic detritivores (Richardson et al.

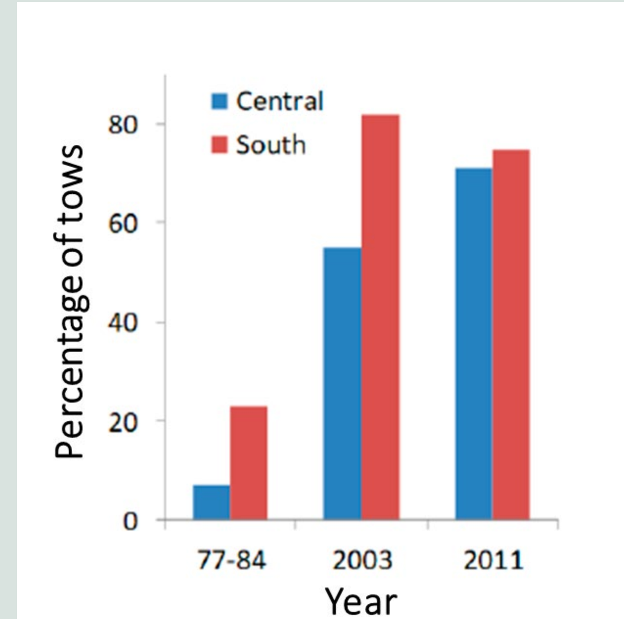


Figure 4. Percent of surface trawl sets in which jellyfish were >75% of the catch biomass in Central and South basins of Puget Sound in 1977-1984, 2003, and 2011. Source: Data from Greene et al. (2015).

2009). Alternately, proliferation of pelagic jellyfish parasites such as hyperiid amphipods may result in retention of carbon biomass within pelagic ecosystems (Hamilton 2016) as they are consumed by fishes (Riascos et al. 2012; Weil et al. 2019).

In sum, multiple pathways may link jellies to components of the Salish Sea's food web that are more important to people. As we learn more about these trophic linkages through ongoing experimental and field research, we are also improving our ecosystem models, which will allow us to put jellies in the context of species like Pacific salmon, geoducks, and rockfish. Combined with better monitoring of distribution and abundance (Eyes Over Puget Sound; Schaub et al. 2018), these models will allow us to examine cascading effects of jellies in the ecosystem and to test scenarios like increasing long-term trends or episodic changes in jelly abundance. Within the next few years, we may have a much better perspective on the roles jellies play (and have played) on the Salish Sea's pelagic ecosystem as these ongoing studies develop.

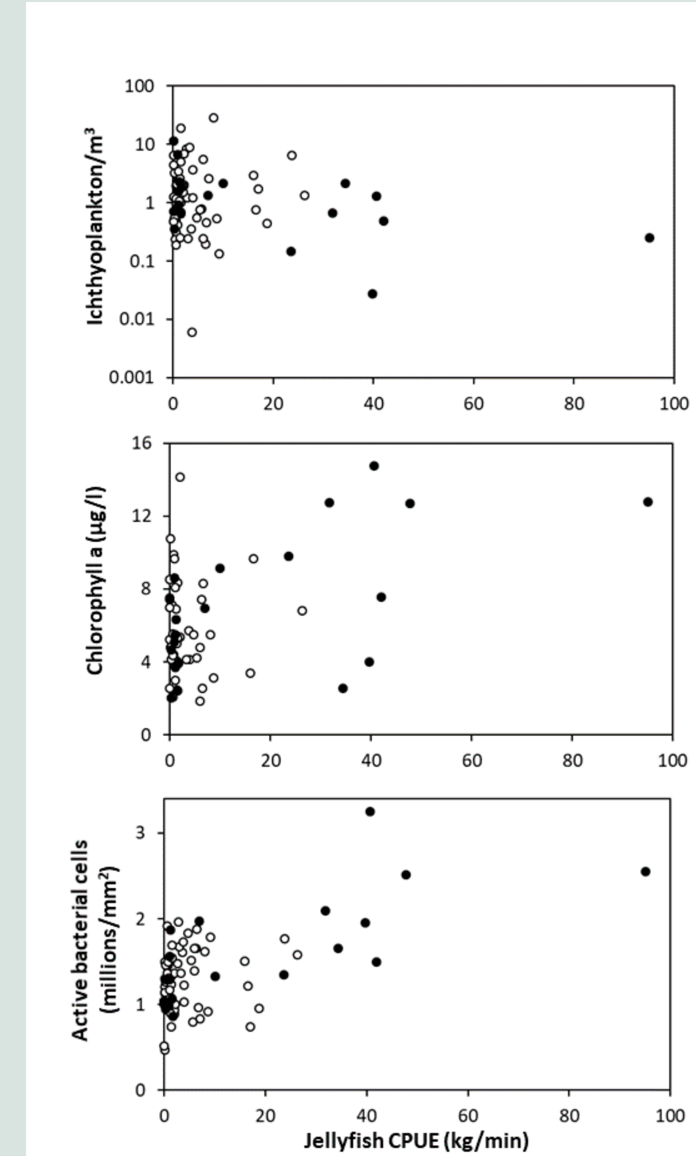


Figure 5. Relationships between ichthyoplankton density, chlorophyll concentration, and metabolically active bacteria as functions of total jellyfish catch per unit effort (CPUE) sampled at 85 sites across Puget Sound in 2011. Filled circles are large embayments, where Aurelia aggregations tend to occur within Puget Sound. All measurements of total jellyfish CPUE surpassing 35 kg/min were dominated by Aurelia biomass; hence those sites were sampled in the vicinity of Aurelia aggregations. Source: C. Greene, Unpublished data.

SECTION 5

CUMULATIVE ECOSYSTEM EFFECTS

Whytecliff Park, West Vancouver, BC
Photo: Nick Pinkham

SECTION 5

CUMULATIVE EFFECTS CASE STUDIES

PERSISTENT, CONTINUING, AND EMERGING IMPACTS

SUMMARY OF CUMULATIVE EFFECTS IN THE SALISH SEA

VIGNETTES

The many impacts identified in this report caused by urbanization locally and climate change globally intersect and generate cumulative ecosystem impacts in the Salish Sea. Cumulative effects are defined as the collective impacts of past, present, and future human activities on the environment (Spaling & Smit 1993). There is great uncertainty in measuring and predicting cumulative effects, especially considering the unknown interactive effects of multiple stressors on ecological components (Figure 5.1; Murray et al. 2014). Stressors interact with each other and can be additive, non-additive, or can multiply (synergistic) or reduce effects (antagonistic) predicted from single stressors and combinations of stressors (Crain et al. 2008). Interactions can be direct or indirect and may be modulated by other unrelated factors. Additionally, non-linear responses can result in changing interactions in both time and space as thresholds or other inflection points are approached. For these reasons, understanding and describing cumulative effects in ecosystems is particularly challenging (Darling & Côté 2008), but nonetheless an important

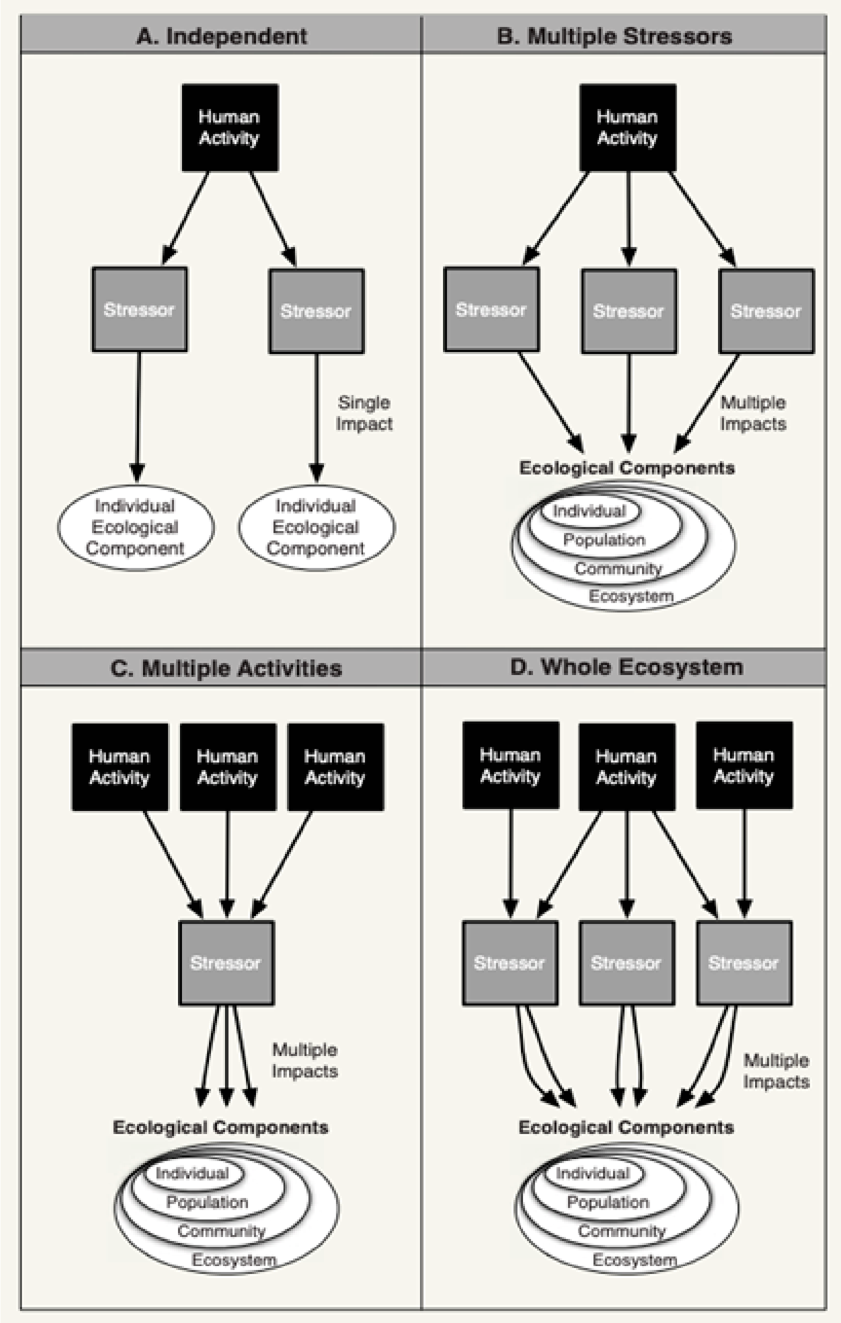


Figure 5.1. Theoretical framework of pathways by which independent and cumulative effects impact ecological components. A) human activities produce multiple stressors that impact ecological components, B) a single human activity produces multiple stressors that impact a suite of ecological components, C) multiple activities each produce a common stressor that has multiple impacts on a suite of ecological components or multiple impacts on a single ecological component over space or time, and D) accounting for the whole ecosystem, where multiple activities produce multiple stressors that have multiple impacts on a suite of ecological components. Stressors from activities can accumulate across space (local, regional, and global stressors) and time (past, present, and predicted future activities). Source: Clarke Murray et al. (2014)

consideration in science and management as ever more complex problems threaten our ecosystems.

In a laboratory, we may investigate the effects of temperature, dissolved oxygen, and ocean acidification on a species, but the complexities of the cumulative stressors in the environment, such as changing tides, weather conditions, contaminant concentration, productivity, and interactions among species, make the reality of identifying and understanding cumulative effects *in situ* much more challenging. The complex oceanography of the Salish Sea also means that effects are likely to vary from region to region, as oceanographic conditions change.

Cumulative effects studies—even those that are well planned and executed—are frequently limited in spatial and temporal scope. This makes understanding the interaction of legacy, continuing, and emerging stressors difficult to assess. Historical or legacy stressors have likely altered ecological components in the system, making the effects of the continuing disturbances more profound and rendering any habitat or organism less resilient to future impacts (Levin & Lubchenco 2008). For example, it's known and documented that previous overfishing exacerbates climate-induced temperature effects on fish population resilience (Free et al. 2019). This type of temporal evolution of ecosystem problems is a fundamental challenge in addressing cumulative effects, especially where decades of human impacts have critically altered organisms, biotopes, or ecosystem processes.

The interaction of global and local stressors is borne out on our coasts. One such intersection in the Salish Sea is the increased risk of coastal flooding due to climate change-induced sea level rise and urbanization. Rising sea levels are fundamentally altering our low-lying saltwater habitats by increasing inundation time, bringing saltwater farther inland and flooding new areas (Nicholls et al. 2007). Increases in intensity of precipitation resulting from climate change will change hydrology and water delivery timing, bringing floodwaters to our coasts (Pacific Climate Impacts Consortium 2015). If you've visited a tropical city where rainfall during storms comes at rates of more than an inch per hour, you may know that the stormwater collection systems are typically built to handle these deluges. Here in the Pacific Northwest, the existing infrastructure is built to handle historically consistent amounts of input, not the rapidly increasing intensity of precipitation or sea level rise that are currently observed and predicted to increase with climate change (Raymondi et al. 2013).

As time goes on, urbanization, sea level rise, and the increasing intensity of precipitation will further challenge shoreline armoring, roads, stormwater conveyance, sewage treatment facilities, bridges, and buildings along our shorelines. In addition, the intersection of increased flooding (driven by climate change) and increases in impervious surfaces (associated with land-use change) will combine to yield increased coastal flooding.

Additional sea level rise and flooding and will bring increased desire for shoreline armoring. But policy changes can result in more robust alternatives for long-term coastal ecosystem resilience (Kittinger & Ayers 2010). While most of the literature on cumulative effects in marine ecosystems is on the cumulative impacts of stressors (Korpinen & Andersen 2016), it should also be noted that cumulative impacts can be net positive when applied to restoration (Hall et al. 2018; Diefenderfer et al. 2021). While restoration can remediate some effects of urbanization, accounting for persistent changes resulting from global climate change presents an additional challenge and will require long-term solutions.

While this direct intersection of our two focal impacts—urbanization and climate change—is the most obvious illustration of cumulative impacts, there are many other manifestations of cumulative effects. There are also many approaches to evaluating cumulative effects: stressor or activity-based approaches (e.g., understanding the cumulative impacts of marine shipping; Transport Canada 2019), area-based approaches (e.g., Marine Spatial Planning; Foley et al. 2010; Collie et al. 2013; Washington Marine Spatial Plan 2021), and species-based approaches (Andersen et al. 2017; Fu et al. 2020). There is active research on how best to understand and manage cumulative effects in marine ecosystems and development of new methods (Hodgson & Halpern 2019).

Here we use a species-based approach and three case studies to highlight cumulative impacts of ecosystem change and response in three iconic Salish Sea species: herring (*Clupea pallasii*), salmon, and orcas. Each of the three taxa highlighted below is impacted in myriad ways by humans living in the Salish Sea region and, in the case of climate change, far beyond the region due to teleconnections across the globe (i.e., climate variability links between non-contiguous geographic regions). Examining the mechanisms of depletion and abundance helps highlight the ways in which human activities interact with ecological processes to impact these icons of the Salish Sea.

Emergency workers placing warning signs on flooded road
Photo: ML Harris, Adobe Stock

CASE STUDY:

PACIFIC HERRING IN THE SALISH SEA

Dr. Jennifer Boldt, Fisheries and Oceans Canada
Dr. Todd Sandell, Washington Department of Fish and Wildlife
Jaclyn Cleary, Fisheries and Oceans Canada

Background

Pacific Herring (Clupea pallasii; hereafter referred to as herring) are small, schooling, silver fish that play an important role in the food web of the Salish Sea. These forage fish transfer energy from plankton to predators, such as piscivorous fish (e.g., Chinook and coho salmon), seabirds, and marine mammals (Pikitch et al. 2012). Herring are also culturally and commercially important; they have been utilized by First Nation peoples in British Columbia and by Native American Tribes in Washington for food, social, and ceremonial purposes for thousands of years and harvested commercially since at least the early 1900s (Thornton 2015; Sandell et al. 2019). As is the case for many forage fish species, herring abundance is often highly variable from year to year and abundance trends may vary geographically. For example, Puget Sound's Cherry Point herring stock showed a 97% decrease in stock biomass since 1973 (Gustafson et al. 2006; SeaDoc 2018); whereas, Strait of Georgia's (SOG) aggregate migratory stock increased from 2010 to 2016, was comparatively stable, and, in 2020, was relatively high compared to historic levels (Fisheries and Oceans Canada 2021). Herring abundance and distribution can be affected by many factors, including climate change, environmental conditions, ecosystem productivity, fishing, and habitat changes. Understanding how these factors individually and cumulatively affect the abundance, recruitment, age structure, size, condition, and distribution of herring presents a challenge to the assessment of these species.

Life History

The aggregate stock of migratory SOG herring spend summers in feeding areas on continental shelf waters off the west coast of Vancouver Island before migrating to nearshore spawning areas in the SOG in winter (Taylor 1964). Herring in the southern Salish Sea (US waters) exhibit a mixture of life histories, with stocks in South Puget Sound exhibiting year-round residency while most northern stocks migrate to the ocean to feed during the summer. The migratory habits of a few stocks, such as Cherry Point and those in Hood Canal, are unclear, based on stable isotope and analyses of toxic chemicals (Sandell et al. 2019). Pacific Herring are generally zooplanktivores, consuming small, early-life history stages of copepods and switching to larger and later life history stages of copepods and euphausiids as they grow. In March-April each year, herring return to spawn in the same geographical region but not necessarily to the same spawning beach or bay. Herring spawn in nearshore areas where each female deposits 20,000-40,000 eggs on macrophytes, such as eelgrass, rockweed, kelps, and other algae, and males release sperm to fertilize the eggs (Haegele et al. 1981; Humphreys & Hourston 1978). Egg hatching time is temperature-dependent, but generally takes a couple of weeks (Alderdice & Hourston 1985). Young herring spend their first summer in nearshore areas (Haegele & Armstrong 1997; Emmett et al. 2004). Herring generally become sexually mature between the ages of 2 to 3 and can live up to 15 years of age, but most live to less than 10 years of age (Cleary et al. 2017). Herring population abundance is determined largely by the annual recruitment of young fish to the adult spawning stock. Recruitment in turn is heavily influenced by survival during the early life history (Taylor 1964; Schweigert et al. 2009).

Indicators

In British Columbia, herring are managed as five major stocks (Strait of Georgia, SOG; West Coast of Vancouver Island, WCVI; Prince Rupert District, PRD; Haida Gwaii, HG; and Central Coast, CC), and two minor stocks (Area 2W and Area 27) (Fisheries and Oceans Canada 2021; Figure 5.2). Fisheries and Oceans Canada (DFO) conducts annual scientific surveys for each of the five major herring stock areas. These scientific surveys, which include egg surveys and biological sampling, inform a yearly peer-reviewed scientific stock assessment with up-to-date advice on the status of all five major stocks. DFO also works with Indigenous communities and harvesters in the Strait of Georgia to better understand herring distribution, spawn dynamics and traditional harvest areas. In 2020, the stock assessment model was used to provide estimates of herring spawning biomass, an important indicator of stock status (Fisheries and Oceans Canada 2021). Additionally, DFO reports annually on spawn distribution and biological indicators like weight-at-age.

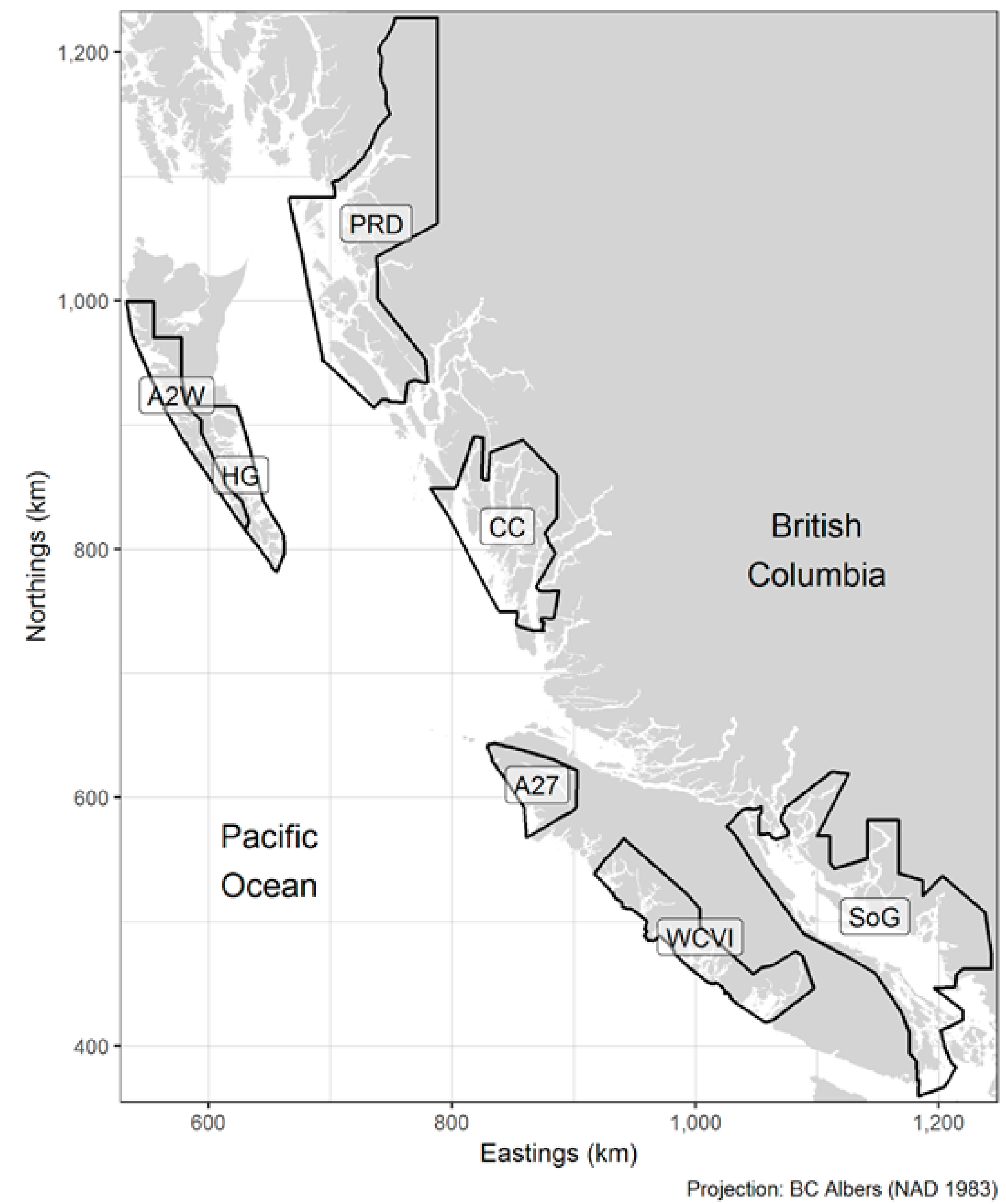


Figure 5.2. Boundaries for the Pacific Herring stock assessment regions (SARs) in British Columbia. The major SARs are Haida Gwaii (HG), Prince Rupert District (PRD), Central Coast (CC), Strait of Georgia (SoG), and West Coast of Vancouver Island (WCVI). The minor SARs are Area 27 (A27) and Area 2 West (A2W). Source: Fisheries and Oceans Canada (2019)

Southern Salish Sea (SSS, including Puget Sound and Hood Canal) populations are managed individually, and the management focus is on maintaining viable populations at each spawning location (Siple & Francis 2016; Sandell et al. 2019; Figure 5.3). A minimum spawning biomass has been identified for each of the populations and status is determined by

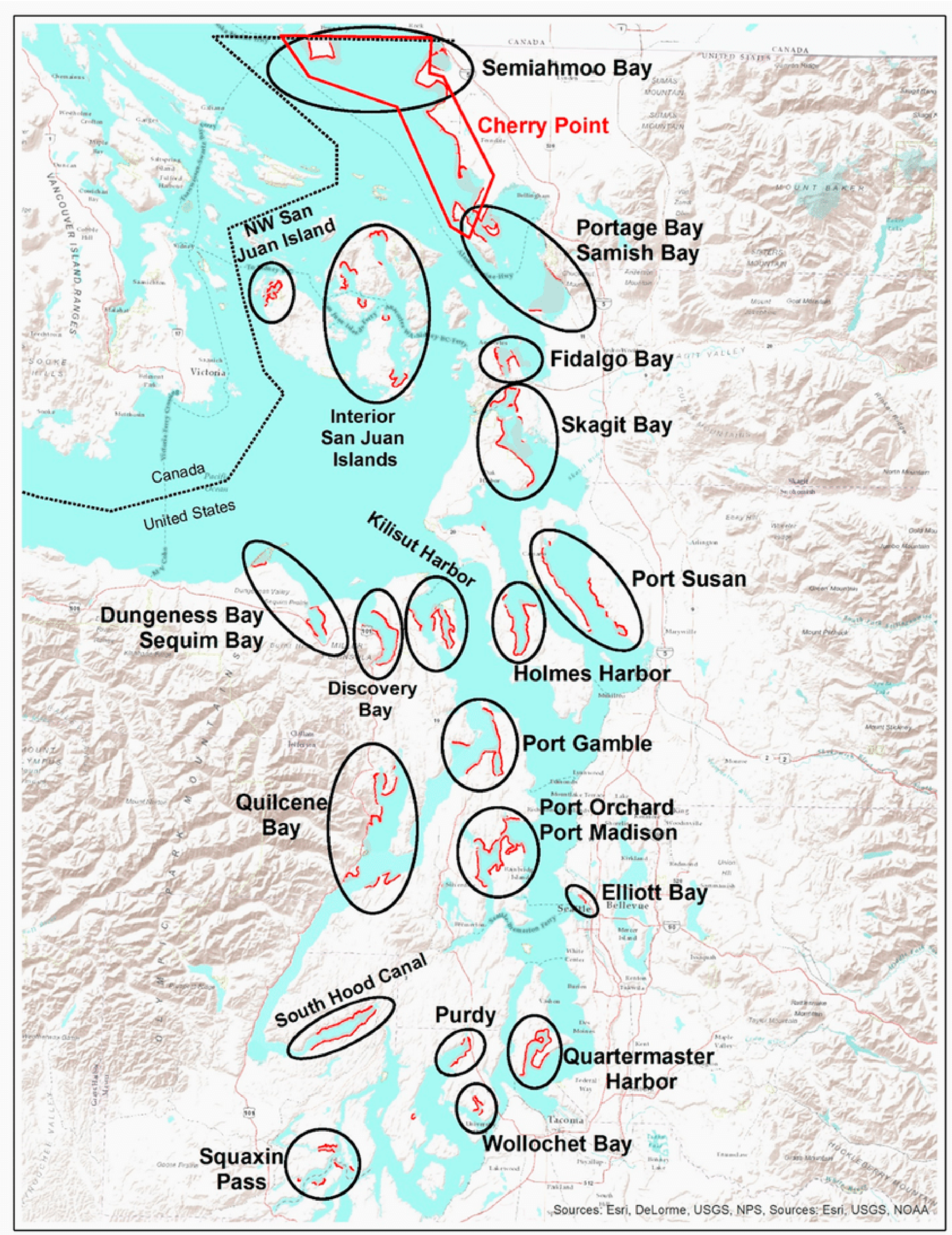


Figure 5.3. Known spawning stocks of Pacific herring in United States waters of the Salish Sea as of 2018. Source: SeaDoc Society (2018)

annual monitoring. Annual monitoring generates spawning biomass estimates derived from acoustic-trawl surveys (discontinued in 2009 due to budget restraints) and egg deposition surveys.

Status and Trends

In British Columbia, the overall biomass of herring is much greater than that of Puget Sound/SSS (SeaDoc Society 2018). DFO's stock assessment model estimate of herring spawn biomass in the Strait of Georgia region showed a strong increasing trend from 2010-2016, after which it was comparatively stable until 2020, when biomass was relatively high compared to historic levels (Fisheries and Oceans Canada 2021; Figure 5.4). For at least the past 15-years, herring spawning has been concentrated in northern areas of the Strait of Georgia, primarily from Nanaimo to Comox. The weight-at-age of SOG herring declined from the 1980s to 2010, with an increase in recent years. This general pattern in weight-at-age has been observed in all major herring stocks of British Columbia.

As in British Columbia, the weight-at-age of SSS herring declined from the 1980s to 2012 (Stick et al. 2012); due to the cessation of acoustic trawl surveys, weight-at-age estimates are no longer available. In the SSS, overall herring biomass declined 23% from 2018 to 2019, largely due to declines in Hood Canal stocks (mainly Quilcene Bay), which had comprised over 50% of the total beginning in 2015 (Figure 5.5). The 2019 total was 9% lower than the five-year average, and six stocks had no spawn detected in that year, although the Quilcene Bay and Port Orchard-Port Madison (PO-PM) stocks increased in biomass. 2020 brought dramatic changes, with record highs recorded at Quilcene Bay, PO-PM, and Purdy (in south Puget Sound); the total was the highest recorded since 1980 (18,559 tonnes, compared to a ten-year average of ~9,250 tonnes), even though surveys were curtailed due to the pandemic (making the total a known underestimate). However, most stocks continued to spawn at low levels, reflecting the overall

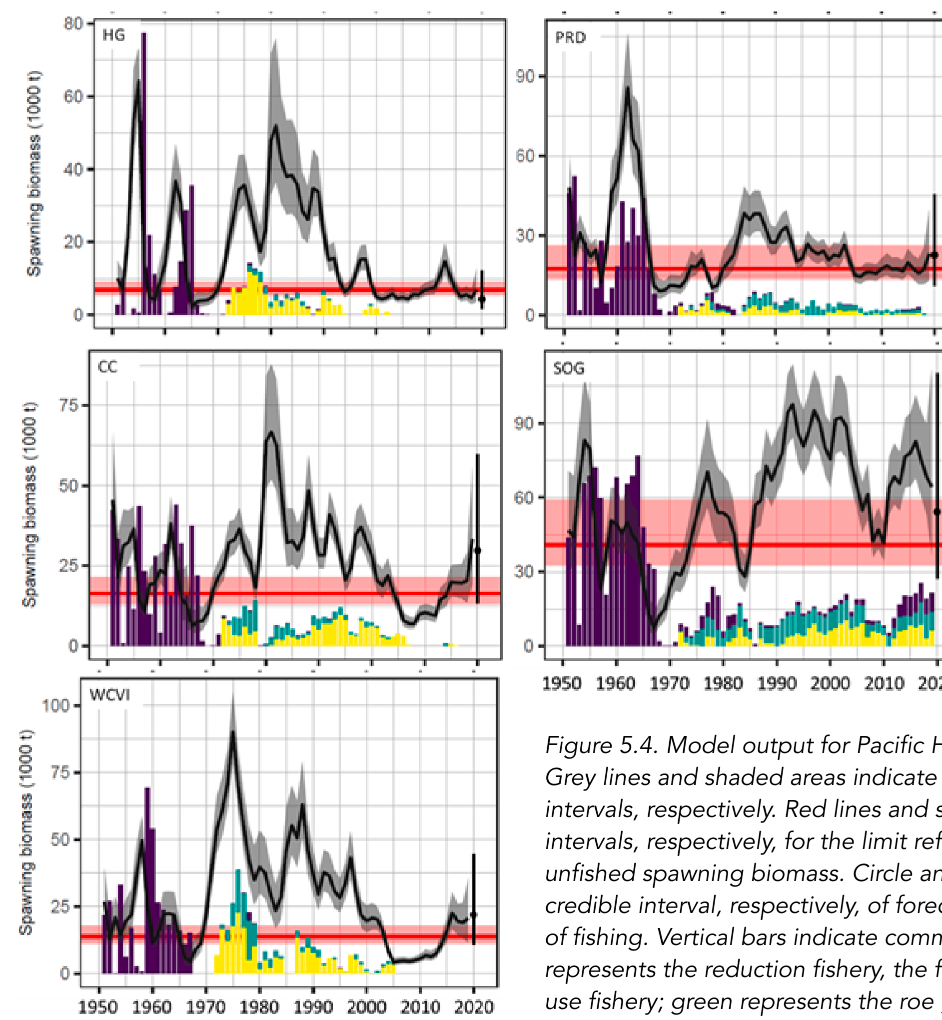
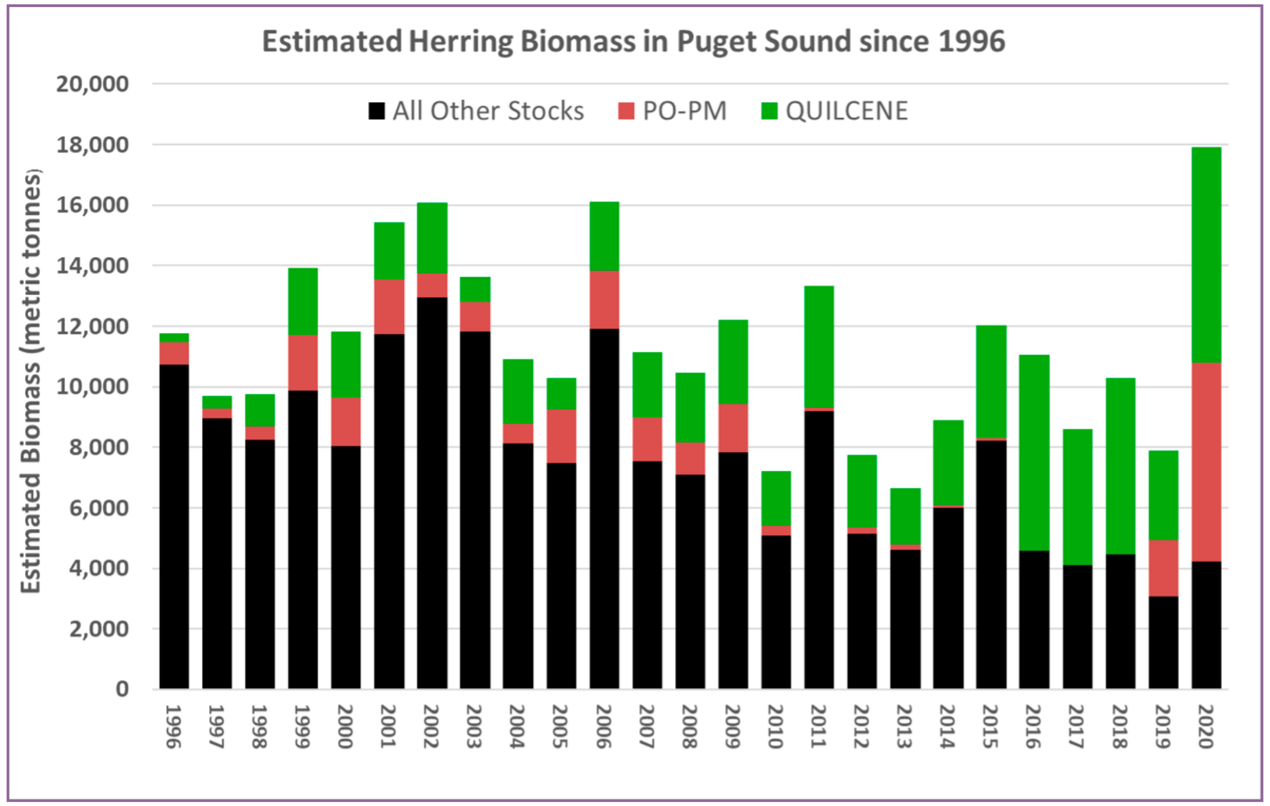


Figure 5.4. Model output for Pacific Herring in the major stock assessment regions. Grey lines and shaded areas indicate spawning biomass medians and 90% credible intervals, respectively. Red lines and shading indicate medians and 90% confidence intervals, respectively, for the limit reference point 0:3SB0, where SB0 is estimated unfished spawning biomass. Circle and vertical line indicate the median and 90% credible interval, respectively, of forecast spawning biomass in 2021 in the absence of fishing. Vertical bars indicate commercial catch, excluding spawn-on-kelp; purple represents the reduction fishery, the food and bait fishery, as well as the special use fishery; green represents the roe gillnet fishery; and yellow represents the roe seine fishery. Source: Adapted from Figures 6-8, 10, and 11 in Fisheries and Oceans Canada (2021)



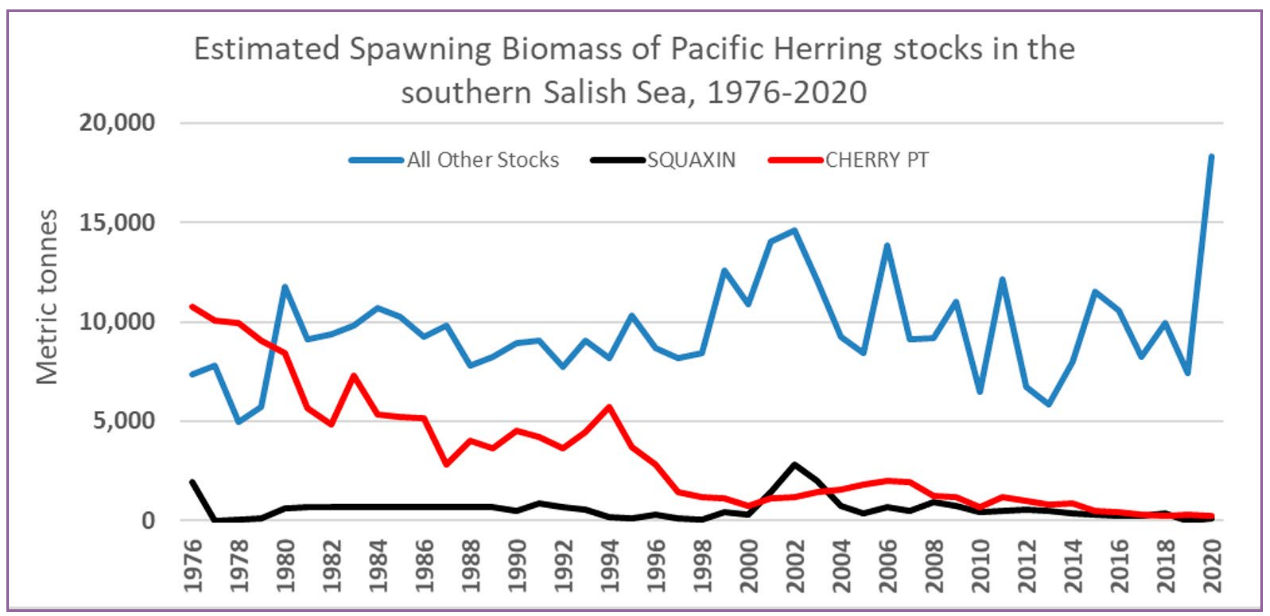


Figure 5.5. Estimated herring stock biomass estimates for the Southern Salish Sea. Source: Adapted from Sandell et al. (2020)

shift from widely dispersed spawning to the dominance of a few stocks in the biomass estimate (Figure 5.5) Forage fish populations are notorious for having extreme annual variations in population abundance and recruitment, but the increase seen in 2020 is striking. The most likely explanation is that, during the anomalously warm "Blob" years (~2014-17), when surface waters in the Northeast Pacific Ocean were much warmer than average, surface waters in the SSS were also higher and we had more sunlight than normal in the region. This led to increased phytoplankton blooms and zooplankton biomass that created a larger food supply for larval fish. Research by Dr. Julie Keister's lab at the University of Washington showed the increases in zooplankton abundance were particularly large in the Main Basin of Puget Sound (which includes the PO-PM/Bainbridge Island area) and Hood Canal (Quilcene Bay). As a result, there may have been "jackpot recruitment" years for herring in 2016-17 due to increased zooplankton abundance. Herring return to spawn at age 2-3, so this may explain the abundance of spawning fish in 2020, although it does not explain why only a few stocks had such high recruitment.

The Cherry Point stock, which is genetically unique, increased 16% from 2018-19 and dropped slightly in 2020 (poor survey coverage due to the pandemic) but remains at critical levels in comparison to its historical run size-once the largest in the SSS.

Factors Causing Trends

Herring abundance, distribution, and weight-at-age can be affected by multiple factors, such as climate change, environmental conditions, system productivity, fishing, and habitat changes. These factors act at local, regional, and ocean-basin spatial scales and during different life history stages of herring. For example, local- or regional-scale toxic contaminants from legacy pollution sites and stormwater runoff may be affecting central and South Puget Sound populations (West et al. 2008; West et al. 2014; see also Encyclopedia of Puget Sound (2021) for more about stormwater). The observed trends in herring weight-at-age in all British Columbia stock areas suggest that ocean-basin-scale factors may also be influencing herring population trends. When and where multiple pressures (i.e., cumulative effects) act on different life history stages of herring complicates our understanding of herring population dynamics.

It is thought that early life history stages (egg to juveniles) are the most critical in determining herring abundance and condition (Sinclair & Tremblay 1984; Shelton et al. 2014). Bottom-up processes (prey-driven) are the main factors affecting interannual variability in juvenile herring abundance and condition in the SOG (Boldt et al. 2018). Bottom-up factors include zooplankton prey availability, herring spawn biomass, temperatures, and the date when most herring spawn relative to the spring bloom date. The timing or match-mismatch between herring and their prey appears to be important in determining abundance of age-0 herring in the fall (Schweigert et al. 2013; Boldt et al. 2018). There is some evidence that top-down (predator-driven; e.g., juvenile coho and Chinook Salmon) processes may also affect age-0 herring condition (but not age-0 herring abundance).

Herring recruitment and survival has also been linked to water temperatures (Tester 1948; Ware 1991) and bottom-up control of production (Schweigert et al. 2013), prey availability, and competition with other fish (Godefroid et al. 2019). Changes in ocean conditions, such as temperature or currents, could affect the amount and types of prey available. For example, a northerly current direction could result in the presence of California Current waters off the west coast of Vancouver Island where SOG herring feed in the summer; the California Current waters bring zooplankton species that have a lower energetic value, creating poorer feeding conditions for herring (Mackas et al. 2004; Schweigert et al. 2010).

There are a wide variety of herring predators, including Pacific Hake, Lingcod, Spiny Dogfish, Pacific Cod, Sablefish, Arrowtooth Flounder, Pacific Halibut, Steller Sea Lions, Northern Fur Seals, Harbour Seals, California Sea Lions, and Humpback Whales (Schweigert et al. 2010). As of 2010, off the WCVI, fish predator abundance had decreased in recent years, while the abundance of most marine mammal predators increased (Olesiuk et al. 1990; Jeffries et al. 2003; Olesiuk 2008). Research into predator consumption of herring indicated that a significant proportion of the herring population could be consumed annually by predation, although it was not clear if this could cause the observed estimates of natural mortality of WCVI herring (Schweigert et al. 2010). When examined both spatially and temporally, it was found that the summer distribution and abundance of herring off the WCVI (this includes SOG herring) may be driven by Pacific Hake abundance, zooplankton prey availability, and competition with Pacific Sardine (Godefroid et al. 2019).

Implication of Trends

Trends in herring biomass have implications for First Nations in British Columbia and Tribes in Washington, commercial and recreational fisheries, and the marine ecosystem and its predators. The SOG stock comprises more than 50% of the total herring biomass in British Columbia waters, and this stock has supported commercial fisheries in the SOG annually since the 1950s. Opportunities for commercial herring fisheries in the other four stock areas have been more variable over the same time period and have at times included full commercial closures due to low herring abundances and/or restricted opportunities (e.g., for First Nations spawn-on-kelp harvest only).

The only commercial fishery for herring in the SSS is the sport-bait fishery (supplying herring for recreational salmon and groundfish fishers); no fishing is allowed north of Admiralty Strait to protect the Cherry Point stock. The sport bait fishery mostly targets 1+ to 2+ year old (juvenile) herring assumed to be an aggregate of stocks within the main basin. This fishery has a harvest guideline of less than 10% of the cumulative adult herring spawning biomass estimate of stocks that spawn in South/Central Puget Sound, Hood Canal, and the Whidbey Basin (Bargmann 1998), but usually only achieves 2% to 6% of the spawning biomass because of market conditions and processing/holding capacities (Sandell et al. 2019). Hood Canal has been closed to all commercial herring fishing since 2004 due to concerns about the impacts of low dissolved oxygen and elevated summer temperatures on fish health and abundance.

Trends in herring biomass have implications for herring predators, such as fish, marine mammals, and seabirds. Age-0 herring are an important part of juvenile Chinook and coho salmon diets (Beauchamp & Duffy 2011; Chamberlin et al. 2017). Herring may also represent up to 88% of Lingcod diet (Pearsall & Fargo 2007), 40% of Pacific Cod and Pacific Halibut diets (Ware & McFarlane 1986), and 35% to 45% of pinniped diets (Olesiuk et al. 1999; Lance et al. 2012; Olesiuk 2008). Depending on the level of diet specialization and ability to switch to alternate prey, herring abundance and condition may affect predators' growth and abundance.

Future Research

Northern Salish Sea

DFO is committed to a Precautionary Approach in the management of Pacific Herring, which includes establishing biological limit reference points (a fisheries management tool) and the use of harvest control rules. Harvest control rules define harvest rates, which are reduced to zero when herring spawning biomass is below a pre-defined low biomass level (Cleary et al. 2017). Recently, DFO has been using simulation models to test the ability of harvest control rules to meet conservation objectives by maintaining stocks above the limit reference point. These simulations are part of a coast-wide Management Strategy Evaluation (MSE) process, focused on establishing conservation objectives and renewing the management framework. The herring MSE process engages First Nations and the fishing industry in the development of objectives and management strategies for sustainable fisheries. Additionally, uncertainties in stock structure (i.e., existence of smaller sub-stocks) and climate change impacts can also be explored as "scenarios" or "hypotheses" within herring MSE.

Southern Salish Sea

Recognizing the many data gaps in our knowledge of forage fish, the Washington Department of Fish & Wildlife has also adopted a Precautionary Approach to the management of forage fish in Puget Sound and the SSS. The precautionary approach "utilizes caution when the agency is faced with a decision and a lack of information. The approach calls for reducing fishery or other activities if there is reason to believe that the activities will cause significant harm, even if such a link has not been established by clear scientific evidence. Treaty Indian tribes are not part of this policy and are not bound by it" (Bargmann 1998).

The Salish Sea Pacific Herring Assessment and Management Strategy Team identified several factors in 2018 that could potentially limit herring recovery. These include exploitation (fisheries), human population growth (with effects on water quality, nearshore light pollution, habitat loss, and nutrient enrichment, among others), toxics (including pollution from legacy sources, which continue to contribute toxics regardless of human population), vessel traffic/noise, Allee effects (positive correlation between population size or density and mean individual fitness), predation, competition, disease, climate change, and ocean acidification. One area that may be conducive to management action is jellyfish, which act as both competitors and predators of herring during various life stages. Recent reports suggest jellyfish are becoming more abundant in Puget Sound (Greene et al. 2015; see Vignette 17, Salish Sea Jellyfish), and resources should be directed to quantify jellyfish abundance and establish the timing of jellyfish blooms, which may be occurring earlier in the year as water temperatures warm. In Puget Sound, at least one proposal has been forwarded to initiate jellyfish fisheries for Asian markets, although concerns about bycatch have slowed progress on this front.

CASE STUDY:

SALMON MARINE SURVIVAL

Michael Schmidt, Long Live the Kings
Dr. Isobel Pearsall, Pacific Salmon Foundation
Iris Kemp, Long Live the Kings
Dr. Brian Riddell, Pacific Salmon Foundation

Our Northwest culture, economy, Tribal and First Nation title, rights, and treaty rights, orca whales, and the overall health of our ecosystem are at risk without thriving salmon populations. We have invested hundreds of millions of dollars in habitat restoration, significantly reduced harvest, and improved the way we manage hatcheries. Yet we are still struggling to recover salmon in the Salish Sea. This includes Puget Sound Chinook salmon and steelhead trout (both listed as threatened under the United States Endangered Species Act) Puget Sound coho salmon (which have declined substantially in abundance) and many populations of Chinook, coho, and steelhead in the Strait of Georgia basin that are listed as Species at Risk in Canada.

In 2013, the Pacific Salmon Foundation (PSF) and Long Live the Kings (LLTK) launched the Salish Sea Marine Survival Project (SSMSP): a US-Canada research collaboration to identify the primary factors affecting the survival of juvenile Chinook salmon, coho salmon, and steelhead trout in the Salish Sea marine environment (Salish Sea Marine Survival Project 2021). It was established in response to unique declining patterns in Salish Sea Chinook, coho, and steelhead production compared to the Washington and British Columbia coast (Zimmerman et al. 2015; Kendall et al. 2017; Ruff et al. 2017), ecological changes in the Salish Sea, and the belief that once salmon leave the freshwater environment, their marine survival or overall survival in the saltwater to adulthood is largely determined by the early marine period (described as their critical period, *sensu* Beamish & Mahnken 2001).

From 2014 to 2018, a multidisciplinary international collaborative of over 60 federal, state, Tribal, nonprofit, academic, and private entities implemented a concurrent, coordinated research effort that encompassed numerous hypothesized impacts on Chinook, coho, and steelhead as they entered and transited the Salish Sea. The SSMSP operated under a single overarching research framework with shared hypotheses and aligned sampling and analyses strategies. Ultimately, over 90 studies were initiated and some of the research continues.

The project aimed to determine the extent to which early marine survival in the Salish Sea was limiting population recovery and whether it was driven by local factors or global processes, or more likely, some cumulative, synergistic combination thereof. Local impacts result in recommendations to improve the Salish Sea ecosystem, whereas globally driven impacts result in recommendations to adapt to our changing environment.

Survival Declines and the Critical Period

The Salish Sea appears to once have been a productive place for salmon compared to the coast. Chinook, coho and steelhead generally have declining trends in marine survival from the late 1970s to present, whereas northwest coastal and Columbia River populations generally began with lower marine survival and either show less of a decline or none at all over the same time period (Zimmerman et al. 2015; Kendall et al. 2017; Ruff et al. 2017). Chinook survival rates varied significantly by population within the Salish Sea, with Strait of Georgia populations exhibiting clearer declines in survival (Ruff et al. 2017). Coho salmon populations had similar survival declines throughout the Salish Sea (Zimmerman et al. 2015; Sobocinski et al. 2021). This is consistent with salmon distribution patterns in the Salish Sea that suggest different Chinook populations rear in specific areas of the Salish Sea, whereas coho are more widely distributed and mixed (C. Neville, Fisheries and Oceans Canada, personal communication). Like coho, steelhead marine survival and adult abundance declined among Salish Sea populations although the strength of synchrony in trends was slightly less (Kendall et al. 2017).

The 'critical' aspect of the early marine phase for individuals may be to achieve a growth threshold or specific condition in their first summer at sea in order to survive the subsequent fall/winter period (Holtby et al. 1990; Tovey 1999; Beamish & Mahnken 200; Beamish et al. 2004; Tomaro et al. 2012). Alternatively, direct mortality during the early marine phase may signify the importance of the critical period in regulating survival. For steelhead, which migrate quickly through the Salish Sea to the open ocean, direct mortality as smolts in the Salish Sea appears more important (Moore et al. 2015; Moore and Berejikian 2017). For Chinook and coho, growth during the first summer in the Salish Sea is likely a greater determinant of overall marine survival (Beamish et al. 2008; Duffy & Beauchamp 2011; Claiborne et al. 2020). That said, during this early marine phase there are signs of high juvenile Chinook and coho mortality due to seal predation (Chasco et al. 2017; Nelson et al. 2019b; Nelson in prep; Nelson in press) and little evidence that size-selective mortality is occurring on Chinook (Gamble et al. 2018; K. Pellett, FIsheries and Oceans Canada, personal communication). Work to collect additional data and assess relationships with first summer growth is ongoing.

Factors Affecting Marine Survival during the Salish Sea Critical Period

Numerous factors can affect salmon survival during this critical period. Broadly, the primary hypotheses of the SSMSP were:

1. Early marine survival is determined by bottom-up ecological processes: **weather, water conditions, and productivity that determine the food supply for salmon and result in variation in size and growth rate.** Salmon may also compete among themselves or with other fishes for food.
2. Early marine survival is determined by top-down ecological processes. **Predation is likely the direct cause of mortality,** but salmon may be affected by other biological factors (e.g., disease and contaminants), increasing their susceptibility to predation, directly killing them, or affecting their condition such that overall marine survival is reduced.
3. **Multiple factors interact and have cumulative effects** in determining early marine survival. These may be additive, synergistic, or dampening.

Humans have also influenced salmon productivity and marine survival through our impact on habitats and related losses of life history diversity in salmon.

Key Findings of the Project

Salish Sea-wide factors affecting food supply and predation are the most critical, whereas other impacts are significant at population or sub-basin levels. Findings of the SSMSP clearly illustrated that changes in environmental conditions influence zooplankton (Keister & Herman 2019; Keister et al. 2019; Perry et al. 2021) and forage fish production (Chamberlin et al. 2017; Boldt et al. 2018; Duguid et al. 2021), which in turn, regulate salmon growth and survival (Duffy & Beauchamp 2011; Chamberlin et al. 2017; Keister & Herman 2019; Greene et al. 2020). Populations of harbor seals have increased concomitantly with declines in salmon marine survival (Jeffries et al. 2003; Nelson et al. 2019). Growing evidence suggests that direct predation is a significant contributor to steelhead mortality (Berejikian et al. 2016) and is likely contributing to increased mortality in coho and Chinook salmon as well (Chasco et al. 2017; Nelson et al. 2019; Nelson in prep; Nelson in press). Other contributing factors include contaminants (O'Neill et al. 2019, O'Neill et al. 2020) and disease (Stentiford et al. 2017; Mordecai et al. 2019), which for some populations are limiting growth and/or causing sub-lethal stress.

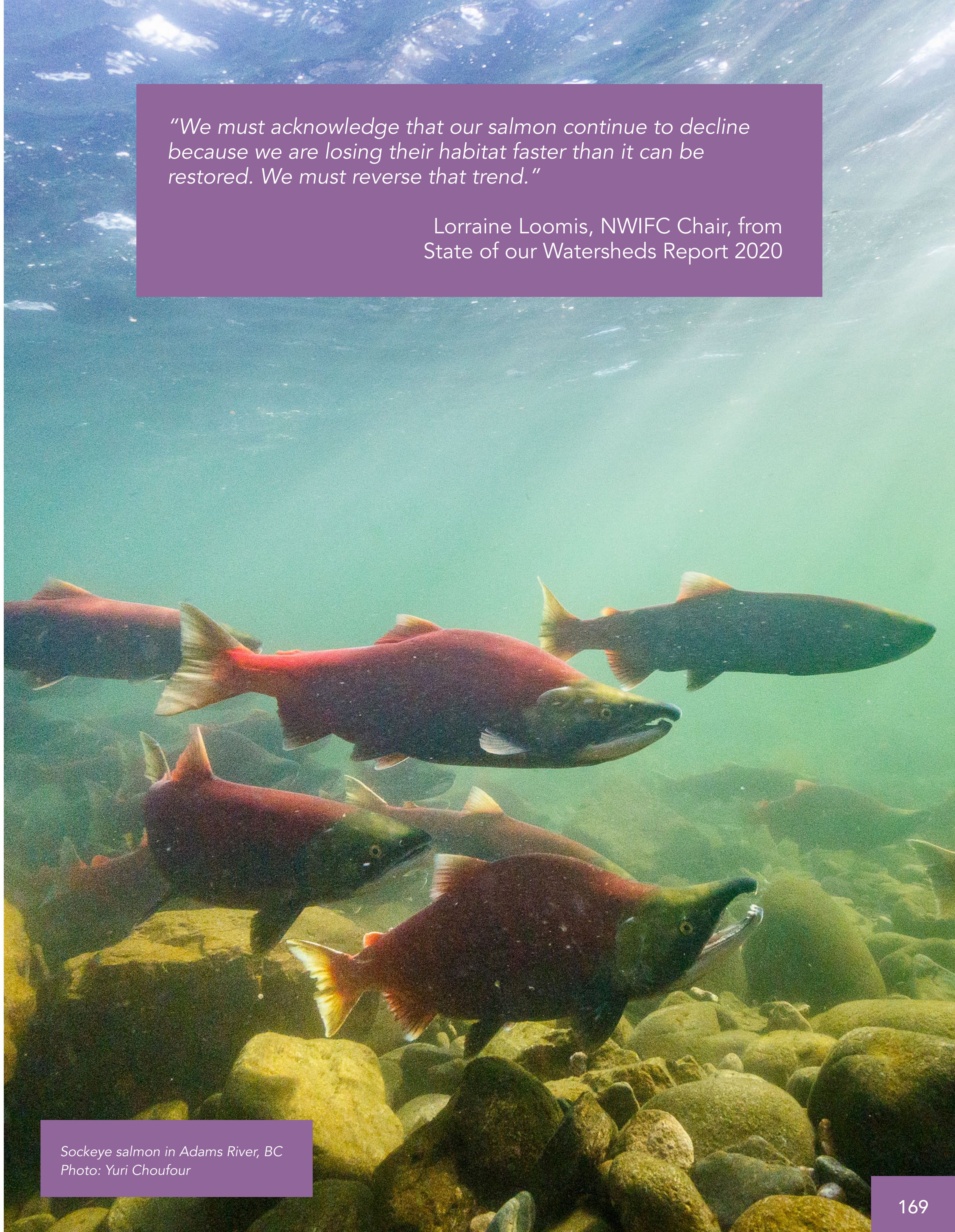
In all, empirical findings and modeling efforts suggest multiple interacting causes of declines in marine survival in the Salish Sea (Sobocinski et al. 2020; Sobocinski et al. 2021). There are substantial concerns about the role of climate change in both the Salish Sea and North Pacific Ocean and how changing conditions impact salmon, but the difficulties in isolating its impacts are considerable, especially in the inland waters where numerous other factors are at play.

A synthesis report titled *Factors limiting survival of juvenile Chinook salmon, coho salmon and steelhead in the Salish Sea: synthesis of findings of the Salish Sea Marine Survival Project* will be completed in 2021 (Pearsall et al., in prep). It will present a synthesis of the findings to date and the perspectives of the lead scientists regarding the primary factors affecting survival and the next steps in research and management.

Potential Management Actions and Research Needs

In many cases, the suite of management actions chosen will be dependent upon species and populations targeted. All actions should be treated like experiments given the uncertainty around outcomes and should take an adaptive management approach (monitor, analyze, adjust). These actions include but are not limited to:

- Reduce damage to and restore estuary and nearshore (e.g., kelp and seagrass) habitat for salmon, Pacific herring, sandlance, and crab. Ensure that connectivity of marsh, eelgrass, and kelp habitats is accounted for. Support soft-shore initiatives.
- Recover, protect, and maintain diversity in herring populations. Better understand early year class dynamics.
- Support salmon life-history variability through habitat restoration, population management, and testing various hatchery rearing and release strategies. This may build resilience to variation in food supply and reduce the potential for density-dependent impacts including competition, disease, and predation.
- Investigate various approaches to reducing predation by seals including: facilitating passage at migration barriers where predation is an issue; obstructing or removing log booms and other seal haulouts; using predator deterrents; and, if necessary, performing experimental removals.
- Take targeted actions to reduce contaminant burdens in juvenile salmon and steelhead where those impacts are greatest (e.g., PBDEs affecting Chinook in the Snohomish estuary). Focus larger-scale remediation efforts on PCB hotspots to reduce impacts



"We must acknowledge that our salmon continue to decline because we are losing their habitat faster than it can be restored. We must reverse that trend."

Lorraine Loomis, NWIFC Chair, from State of our Watersheds Report 2020

Sockeye salmon in Adams River, BC
Photo: Yuri Choufour

to Chinook residing in Puget Sound. Also, assess contaminant inputs and impacts in the Strait of Georgia, prioritizing the lower portions of the Fraser River and its estuary.
- Optimize fish health in hatcheries, especially as increasing temperatures associated with climate change continue to be a concern. This includes disease management and smolt readiness.
- Protect and manage flows in freshwater to reduce predation-based mortality of outmigrating salmon smolts (e.g., under British Columbia's Water Sustainability Act 2014).
- Use newly compiled environmental data to improve adult return forecasting and harvest management, and new ecosystem models to broadly guide ecosystem recovery actions.

Uncertainties

We still have many questions about what is affecting salmon survival in the Salish Sea. In particular, we have substantial evidence that impacts to the food supply of Chinook and coho salmon are occurring but have yet to iron out the mechanistic relationships that explain how and why. This includes understanding the relative impact of climate variation on temperature, nutrients, winds, shifts in primary productivity (e.g., diatoms versus dinoflagellates), and conditions that affect light attenuation underwater. It also includes having a more refined understanding of salmon rearing locations, as SSMSP results suggest that different rearing locations within the SOG may be associated with variation in survival. This information is critical for improving our ability to predict adult returns for fisheries management and recovery and for refining our recovery actions for resilient salmon and a resilient ecosystem.

To continue to integrate multiple environmental changes within the Salish Sea and assess impacts to salmon in a cumulative fashion, an ongoing effort within the SSMSP is the development of food web and end-to-end models that simulate full ecosystem processes from oceanography up through trophic dynamics and fisheries. These include an Ecopath with Ecosim model being developed by the University of British Columbia, and an Atlantis model led by NOAA and LLTK. End-to-end ecosystem models are increasingly being used to consider cumulative impacts, to evaluate fishery management options, and to evaluate impacts of nutrient loading, oil, and other contaminants. These models are now a core part of the toolbox for supporting ecosystem-based management of fisheries and marine resources. Due to the uncertainty in understanding complex natural systems with limited data, using multiple models to evaluate and inform policy choices and management decisions is an emerging best practice.

The quality of model outputs and other analyses of the impacts of ecosystem change are tied to the quality and quantity of data available. Therefore, we must continue to collect and improve upon the empirical data available. Specific monitoring recommendations derived from the SSMSP, as well as several new and innovative assessment techniques are described in detail in the forthcoming paper titled, *Novel Assessment Techniques, Monitoring Recommendations, and New Tools for Ecosystem-Based Management Resulting from the Salish Sea Marine Survival Project* that will be available at www.marinesurvivalproject.com.

Community science was a novel part of British Columbia's endeavors to increase capacity to collect oceanographic data. The PSF Citizen Science Oceanography Program developed via the SSMSP collects an unprecedented amount of oceanographic data at spatial and temporal scales not previously attainable, and at a fraction of the cost. Other groups of citizen scientists sample forage fish embryos and identify forage fish spawning habitat in collaboration with PSF, local Shore-keepers, World Wildlife Fund, and Vancouver Island University. Plus, a new PSF-supported community science initiative through the University of Victoria was established to sample adult Chinook and coho diets in the Strait of Georgia to assess seasonal, regional, and inter-annual variability in herring and other forage fish availability.

An Achievement in Science and Transboundary Collaboration

The SSMSP has already been extremely influential. Findings have already guided over 20% of recommended orca recovery actions put forth by the Washington State Governor's Southern Resident Orca Task Force and many actions in NOAA's Puget Sound Steelhead Recovery Plan. However, one of the greatest achievements from the SSMSP has been the development of an integrated and broad community of researchers, across disciplines and borders. This network of professional and community scientists was necessary to undertake the most comprehensive study of the salmon's Salish Sea marine ecosystem conducted to date. Strong transboundary collaboration among researchers—in government, academia, and nonprofits—was facilitated through program funding, annual workshops, and working groups. For more information regarding the approach, see the forthcoming affiliated paper, *The Salish Sea Marine Survival Project: how collaborative ecosystem research addressed a major impediment to salmon recovery* that will be available at www.marinesurvivalproject.com.

In summary, the Salish Sea Marine Survival Project has made a significant contribution to our understanding of Pacific salmon and coalesced an active research and management community in the process. Our findings support the implementation of a number of management actions for the benefit of Chinook and coho salmon and steelhead trout and the other species and for the benefit of Tribes, First Nations, and other people who depend on and value Pacific salmon.

Anemone nestled between rocks on the seafloor
Photo: Kathryn Sobocinski

CASE STUDY:
ORCAS, SOUTHERN RESIDENTS AT RISK

Lynda V. Mapes

The Salish Sea is home to three ecotypes of orcas: the northern and Southern Residents, Bigg's or transient killer whales, and offshores. Of these, the southern resident orcas that visit Puget Sound are at grave risk of extinction. Their small population size and social structure also puts them at risk for a catastrophic event, such as an oil spill that could impact the entire population (National Oceanic and Atmospheric Administration 2016). The southern resident killer whales are struggling for survival and are listed as a Species in the Spotlight by NOAA as one of the ten most endangered animals the agency protects. There are only 74 Southern Residents in the population (Center for Whale Research n.d.). Yet in Canadian waters, the northern resident killer whale population has grown at a mean annual rate of 2.2% since 1973 and in 2019 contained a minimum of 310 individuals (Towers et al. 2020).

The reasons why southern resident killer whales are at risk of extinction are multifold and intertwined with the cumulative effects of environmental harm wrought by 150 years of development since European settlement. Development has profoundly altered and harmed the resources the Southern Residents need to survive, especially abundant, quality salmon that is readily available to them year-round.

The Southern Residents are challenged by at least three main threats: scarce food, pollutants, and marine noise (Lacy et al. 2017). Chinook salmon, the primary food they hunt for today are increasingly scarce. In particular, Chinook salmon are the most sought species by resident killer whales and also are the species most in decline throughout the Southern Residents' foraging range (Hanson et al. 2021). While they eat chum and coho, Chinook salmon are the most sought because of their larger size, year-round presence in coastal waters, and caloric reward for the hunting effort (Ford et al. 2010). Pollutants in the fish they eat are taken up in their bodies and stored in their fat (Mongillo et al. 2016). That means when the orcas are hungry, toxics in their fat are released. These toxics harm their ability to reproduce and to fight disease. Orcas too often also are forced to hunt in a fog of noise (Noren et al. 2009; Williams et al. 2014). Females are the most affected in their foraging by anthropogenic noise, raising further risk for recovery of the species (Holt et al. 2021).

Not a day, and scarcely an hour, goes by when Haro Strait, in the middle of their critical summer habitat, is not busy with bulk cargo carriers, container ships, oil tankers, ferries, fishing vessels, military vessels, and recreational boaters of all kinds including kayakers and commercial whale watch tours (Figure 5.6).

In this clash of maritime cultures, the disturbance and noise caused by boats and vessels masks the natural sounds orcas need to hear in order to hunt using echolocation. Noise and disturbance by boats—even non-motorized vessels, such as kayaks—reduces the areas, and hours in which orcas can hunt effectively to feed their families (Holt 2008; Holt et al. 2019; Williams et al 2019). One of the biggest determinants in vessel noise is speed: the faster a boat, the louder it will be underwater. Additionally, the closer a ship is, the louder it will be. About 85% of vessel noise is created by a ship's propeller (Hildebrand 2009). The rest is created by propulsion machinery including the engine and by water flowing over the ship's hull. Large vessels create lower frequency noise that can travel hundreds of miles underwater in the open waters of the eastern North Pacific (Veirs et al. 2016). Underwater noise from ships and other vessel traffic interferes with the ability of whales to communicate and forage because they overlap with the sound frequencies whales' need to hear (Erbe et al. 2019). This forces orcas to increase the volume (one decibel for each decibel of noise) or length of their calls (Holt et al. 2008). That comes at a cost of energy required for sound production, and increased stress levels.

Scientists have also learned orcas forage less in the presence of vessels (Lusseau et al. 2009). A noisier environment also decreases the distance at which orcas can detect prey, forcing them to work harder to find food (Williams et al. 2014).

When people displace orcas from their primary feeding areas with noise and disturbance, orcas suffer. Where the Southern Residents have, over many thousands of years, learned to use the rock canyon along the west side of San Juan Island, Washington like a fish funnel to hunt Chinook salmon returning to the Fraser River, humans have in just the last century created an echo chamber of industrial noise (Williams et al. 2014). Williams et al. (2014) found that critical habitats for both northern and southern resident killer whales (Robson Bight and Haro Strait, respectively) were the noisiest in the frequency bands that killer whales use for social communication.

These areas are poised to become much noisier given major proposed developments including expanded port facilities at the Fraser River Delta and increased tanker traffic serving increased capacity planned for the Trans Mountain Pipeline at Burnaby, BC. The Canadian National Energy Board found in its reconsideration of the project that it would likely result in significant adverse effects to the southern resident killer whale. While project-related marine vessel traffic would be a small fraction of the total cumulative effects of noise in the Salish Sea, any further increase is damaging (National Energy Board of Canada 2019). The project was subsequently nationalized and is proceeding. It will bring a seven-fold increase in tanker traffic to the inlet, and an attendant risk of oil spills of bitumen oil for shipments overseas.

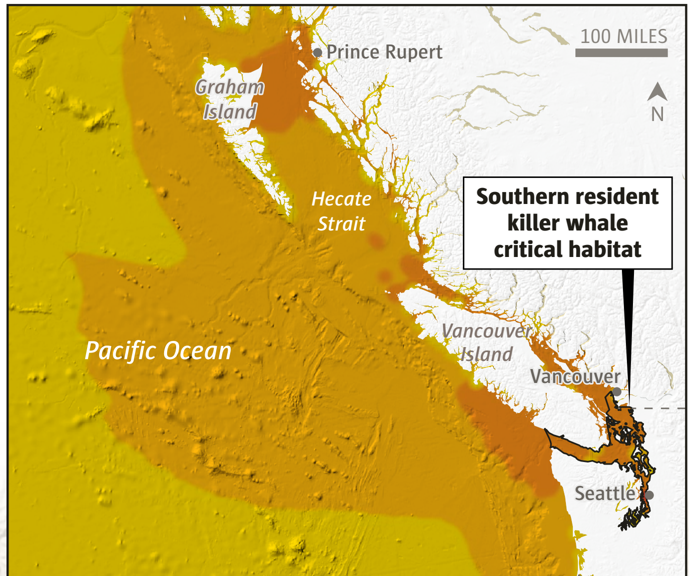
The Southern Residents eat only fish, primarily salmon. Research has confirmed that in winter, as much as half the Southern Residents' diet is coho and chum salmon, steelhead, and some lingcod, skate, or flatfish (Ford & Ellis 2006; O'Neill et al. 2014; Ford et al. 2016; Hanson et al. 2021). What these predators need the most, however, is Chinook salmon. To stay healthy, an adult orca must catch about eighteen to twenty-five salmon every day, or up to 300 pounds, depending on the age and condition of the orca (Lacy et al. 2017). Prey intake for lactating females, an energy expensive activity, is 42% higher, making adequate salmon availability a crucial aspect to southern resident recovery (Williams et al. 2011).

Food specialization in fish, especially chinook salmon, is a culturally-transmitted behavior among resident orcas that is deeply embedded and passed generation to generation. But it has become a risk for the Southern Residents as salmon runs, especially Chinook salmon runs, have declined throughout their foraging range (Ford & Ellis 2014). Of 396 populations of Chinook salmon that used to be available throughout the orcas' foraging range, today 159 are locally extinct, leaving gaps in the calendar year in which the orcas' preferred prey is no longer available. Chum also are depleted, with 23 of 112 populations extirpated and many others reduced in numbers.

THE SOUTHERN RESIDENTS' NOISY HOME

The endangered southern resident orcas that visit Puget Sound confront the noisiest waters in their critical habitat, including the west side of San Juan Island, the Fraser River Delta and the Strait of Juan de Fuca. Noise is caused by vessel traffic, especially commercial shipping.

Their habitat in all of the Salish Sea has underwater noise levels that would be out of compliance with noise-pollution limits that are recommended by the European Union.



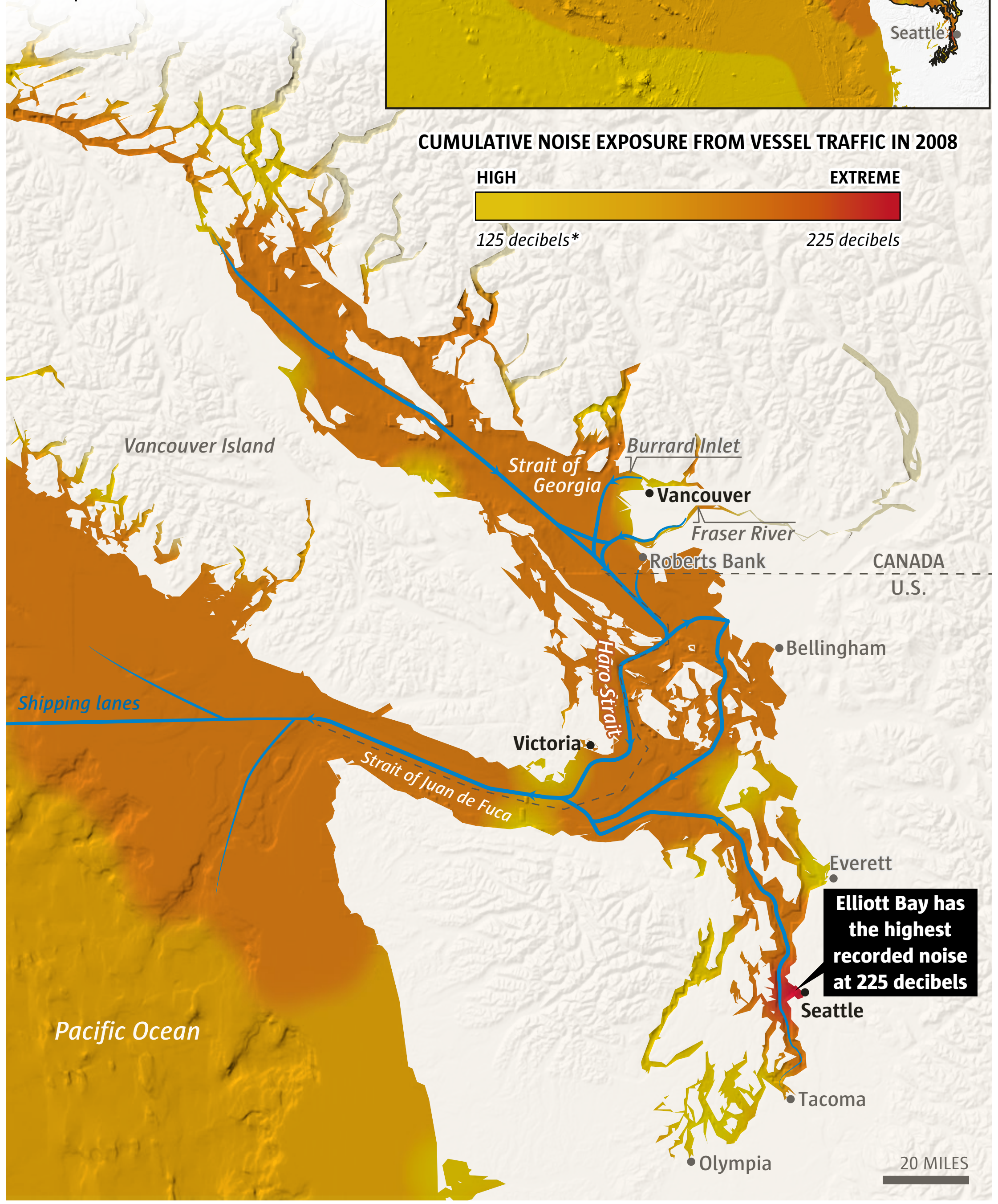
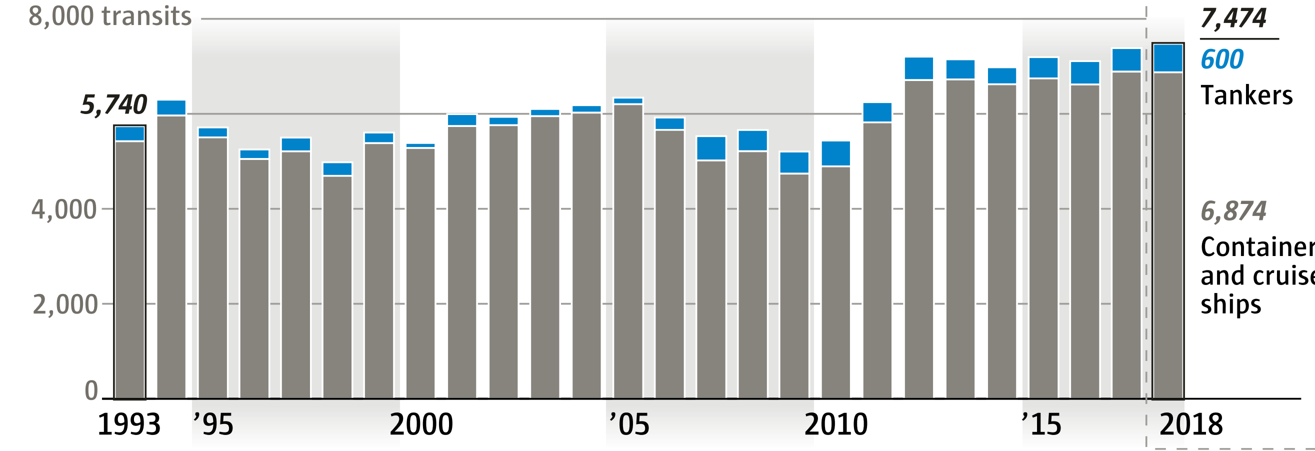


Figure 5.6. (Left and Right) Noise impacts on Southern Resident orcas in the Salish Sea. Source: Emily Eng and the Seattle Times

A BUSIER HARO STRAIT

Busier means noisier: More tankers, container ships and cruise ships bring more noise confronting endangered southern resident orcas in their core summer foraging habitat in Haro Strait.



*Calculated with a reference of one microPascal squared times one second

Sources: Erbe, Christine, et. al, "Mapping cumulative noise from shipping to inform marine spatial planning," The Journal of the Acoustic Society of America, Washington State Department of Ecology

With so much lost diversity and biomass, recovering the southern resident population will be more than a matter of recovering existing salmon stocks. In some cases, reintroduction from captive broods will be necessary, as has been done with winter-run Chinook salmon in tributaries of the Sacramento River (California Department of Fish and Wildlife 2018).

Northern resident killer whales benefit from a wider variety of fish and quieter, cleaner water. They also capture fish targeted by southern resident killer whales when those fish are in the range typically used by the Northern Residents and where the two populations overlap in the Salish Sea (Hanson et al 2021).

Climate change is raising the stakes (Crozier et al. 2019). Across the Northwest, climate change threatens Chinook salmon across their life cycle (Crozier et al. 2021). During the Blob marine heat wave (see discussion in Section 4), temperatures increased as much as 3.9°C (7°F) above average in a mass of warm water that stretched from Alaska to California, and reached to a depth of more than 480 m (1,600 ft). The warm water depleted the ocean food web both in its abundance and nutritional value, killing uncounted millions of animals, from sea birds to marine mammals (Piatt et al. 2020).

Scientists are concerned that downturns in ocean conditions are becoming both more frequent and severe, giving salmon runs little chance to bounce back—another threat to orca survival. The marine heat wave that began in late 2013 reduced salmon returns to the Columbia and Snake Rivers to near record lows. Climate warming is expected to further reduce survival in the ocean because of sea surface warming, making improvements necessary at every life stage. Some salmon, such as Snake River spring and summer Chinook, will be nearly extinct by 2060 without interventions desperately needed to stave off extinction due to cumulative effects of changes in their environment, including warming of sea surface temperatures predicted in the coming decades (Crozier et al. 2021).

From the Salish Sea to California's Central Valley and the Snake River, the Chinook runs scientists have documented as crucial to southern resident killer whales are among the most vulnerable to the effects of climate change, both at sea and in the tributaries to which these salmon return. Sustained temperatures above 20°C (68°F) increase rates of disease and mortality in salmon, a cold-water species. Low marine survival in the Salish Sea also continues to thwart recovery.

Meanwhile, degradation to the freshwater environment has also reduced salmon survival, including dams that have reduced and eliminated spawning habitat; development that has destroyed estuaries, wetlands, and side channel rearing areas; and a steep drop in nutrients in spawning streams to support productivity. Wild Puget Sound Chinook salmon overall have not improved in abundance since they were listed as a threatened species under the United States Endangered Species Act in 1999. Chinook salmon runs in the Columbia, Snake, and Sacramento rivers also remain at risk of extinction. In November 2018, the Committee on the Status of Endangered Wildlife in Canada (2018) determined 12 of 13 Fraser River Chinook stocks were in steep decline, too.

Chinook salmon throughout the Southern Residents' foraging range also have shrunk in size over the past 40 years (Ohlberger et al. 2018). The trend is remarkably widespread, affecting both wild and hatchery fish in the northern Pacific from California to western Alaska. The southern resident orcas are shrinking too, with documented smaller body size in younger whales tracking along with the decline in Chinook abundance (Groskreutz et al. 2019).

Today scientists are concerned about serial failures resulting from cumulative effects, in which orcas throughout their foraging range cannot reliably get enough to eat. That results in poor nutritional status, pregnancy failures, and lost calves. The Southern Residents were listed for protection under the United States Endangered Species Act in 2005 and in Canada under the Species at Risk Act in 2001. With long life spans, low reproductive rates, and only a small number of reproducing orcas in the population, the Southern Residents are even more vulnerable to extinction than their low population would indicate. There were two births to the Southern Residents in 2019 and another two in 2020, bringing the population to 74 animals. That is the second lowest number since counting began in 1974, with 71 Southern Residents. Prior to this time over 50 killer whales were removed from the population and placed in marine parks for exhibition, dramatically reducing the population abundance.

The cumulative impacts of stresses, including noise pollution, poor food supply, and contaminant burden, combined with changing ocean conditions (among other unknown or emerging concerns) continue to threaten southern resident orca whales in the Salish Sea. Population growth today is limited by the nutritional impacts on pregnancy success, with two thirds of pregnancies lost among the Southern Residents because of nutritional stress (Wasser et al. 2017). As we have recognized that capturing whales for captive display is no longer wise for population sustainability, we can make other management decisions favoring their existence. The Southern Residents have long been a symbol of our region, and are considered relatives by many Coast Salish Indigenous peoples. But inhospitable conditions and weak protective regulations will hinder their long-term survival.

PERSISTENT, CONTINUING, AND EMERGING IMPACTS

In assessing cumulative effects, we must consider the decades of ecosystem injury that have previously occurred in our urban ecosystem and the effects of that harm that remain. For example, legacy contaminants remain in the ecosystem, having had deleterious impacts in the past, but also affecting contemporary populations of organisms through continued interaction or accumulation (O'Neill & West 2009; Good et al. 2014; Conn et al. 2020). New stressors, like climate-driven increases in precipitation may bring additional new impacts, such as diseases, into our waterbodies and add to concern (Chhetri et al. 2019). Marine disease is another complex topic, relying on a triad of the pathogen, host, and environment to produce disease conditions. Seastar wasting disease has ravaged the native seastar (*Pycnopodia helianthoides*) from California to British Columbia, with warm temperatures from the marine heatwave implicated as the cause (Harvell et al. 2019). The ecosystem effects of the loss of this predator are as of yet unclear but may not be limited to loss of seastars. As temperatures warm and immune responses in biota are compromised from other insults ("sub-lethal stressors,"; Jeffries et al. 2018; Williams et al. 2019), marine disease may play an increasingly important role in structuring communities in the Salish Sea (Burge and Hershberger 2020). The multiple layers of impacts are not acting in isolation and each new stressor adds additional scope for interactive effects.

While ecosystem impacts are cumulative at one time (multiple stressors), they are also cumulative across time (legacy and contemporary impacts interacting). Additionally, novel conditions brought about by climate change and cumulative local impacts, may further tip the balance, exacerbating the response of organisms to one or more stressors. Ecosystem conditions may ameliorate stressors in some situations, for example, in areas with high flushing where continual replacement of the water mass mitigates low oxygen or high temperature. But in other areas where residence times for water masses are longer, the cumulative stressors of increased temperature, low dissolved oxygen, and nutrient inputs may be more pronounced.

There are numerous other activities not discussed in this report that are occurring within the Salish Sea and that threaten the sustainability and resilience of the ecosystem (see Vignette 18, Bellingham Bay). Some of these activities have been persistent over past decades, while others are emerging concerns. The following table provides a selection of these additional persistent and emerging impacts, organized by the stressor to the Salish Sea ecosystem. Included are references for further reading and an indication if the threat is considered a continuing impact (a recent and ongoing threat) or an emerging impact (new or previously unidentified threat). Legacy impacts (of historical origin but lingering impact) are also of concern, as described in numerous examples in this report.

Additional Emerging and Continuing Stressors in the Salish Sea

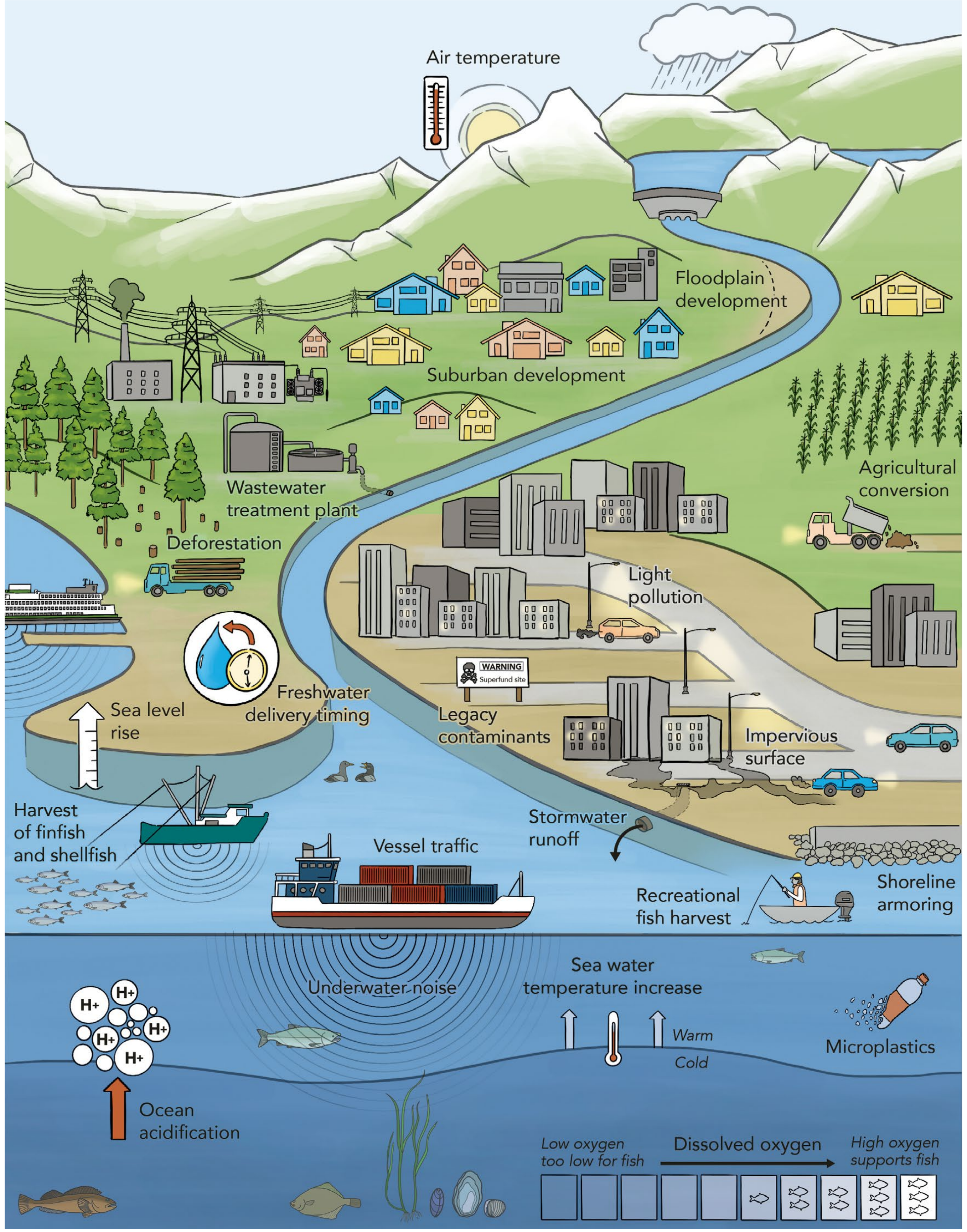
Stressor	Cause(s)	Description	Stressor Status
Disease	Aquaculture (finfish), climate change, cumulative stress	Diseases are gaining attention as ecosystem stressors in the marine environment, beginning with sea star wasting disease in the 2010s along the Pacific coast (see vignette about Eelgrass Wasting Disease and emerging concerns). (Hershberger et al. 2013)	Continuing and Emerging
Acute Trauma to Mammals	Vessel strikes	Marine traffic has resulted in trauma to mammals. (Raverty et al. 2020)	Continuing
Underwater Noise	Vessel traffic, military operations	Noise produced by transiting maritime vessels and airplanes can cause disorientation to marine mammals, birds, and other organisms. Frequently occurring operations may be more disruptive, even if less severe. (Clarke et al. 2009; Rolland et al. 2012; Erbe et al. 2018)	Continuing and Emerging
Light Disruption	Light pollution, light disruption, urbanization	With growing human population, the light regime along shorelines has been dramatically altered with impacts to fishes and birds foraging or seeking refuge from predation. This includes the addition of artificial light at night and the impeding of natural light during the day due to docks and overwater structures. (Nightingale and Simenstad 2001; Ono et al. 2010; Davies et al. 2014; Beauchamp 2018)	Continuing and Emerging
Invasive Species	Ballast water, aquaculture	Invasive species brought into the Salish Sea via ballast water or other aquatic activities have been a concern for some time. A detection and monitoring system is important for identifying problem species. European green crab (Carcinus maenas) is actively being monitored in the United States (see Vignette 19, European Green Crab) and Canada. There are several tunicate species that are invasive in the Salish Sea as well. (Fisheries and Oceans Canada 2018; Strait of Georgia Data Centre 2021; Washington Invasive Species Council 2021)	Continuing and Emerging
Oil Spill Risk	Large spills possible in shipping channels	A spill of nearly any magnitude would cause devastating impact. Removal technologies at very best pick up very small quantities of oil or other contaminants. Heavy fuels like bitumen would sink, with impacts to benthic organisms. (Brace 2018)	Continuing and Emerging

SUMMARY OF CUMULATIVE EFFECTS IN THE SALISH SEA

Identifying cumulative impacts in ecosystems, particularly marine ecosystems, is a challenge in the Anthropocene, where multiple human activities have led to declines in ecosystem condition across prolonged time scales. Assessments can demonstrate the associations among multiple interacting stressors and declining functions of ecosystems (Luoma et al. 2001; Crain et al. 2008; Darling & Côté 2008), but these must be comprehensive investigations and are typically limited to evaluating outcomes on a specific habitat (e.g., eelgrass) or marine species and are rarely on multiple variables simultaneously.

For integrative species, like salmon and seabirds, that rely on multiple connected habitats for their life histories, cumulative effects must be documented beyond the Salish Sea in its strict sense (i.e., the estuarine waters). Moreover, it is in these very integrative species where differences in abundance (Ethier et al. 2020) and survival (Zimmerman et al. 2015; Kendall et al. 2017; Ruff et al. 2017; Sobocinski et al. 2018) within and outside of the Salish Sea occur. These examples both indicate compromised condition and function within the Salish Sea that is having negative effects on biota.

The two primary threats identified in this report—global climate change and the escalation of human impacts to the seascape from local population growth and urbanization—are multifaceted, persistent, and continuing threats to the Salish Sea ecosystem and region. Both could be considered "press perturbations" (i.e., ongoing stressors to an ecosystem; *sensu* Glasby & Underwood 1997). They are chronic and periodically interrupted by additional acute pulses of disturbance from which the ecosystem rebounds (e.g., the Blob event discussed in Section 4). There are multiple interacting and cumulative stressors driven by these overarching threats. Theory and observation suggest an eventual tipping point (Selkoe et al. 2015; Milkoreit et al. 2018). It's unknown if the Salish Sea has the capacity to recover from short-term disruptions while being chronically and increasingly exposed to the ultimate press perturbations discussed in this report.



An illustration of cumulative effects. Source: Emily M. Eng for the Salish Sea Institute.

The "Wicked Problem" of Maintaining Healthy Ecosystems in the Anthropocene

Much of this report was written during the social complexities and uncertainties brought on by the SARS-CoV-2 coronavirus (Covid-19) pandemic of 2020-2021. The challenges associated with solving such a large-scale, constantly evolving public health problem are similar to those faced in environmental management. These problems, often termed complex or "wicked" problems (sensu Rittel & Webber 1973), are policy problems that are difficult to define and typically do not have a single solution. Examples in the literature and in practice include human health, disease prevention and cures, poverty, climate change, urban planning, development of school curricula, and environmental protection.

Discovering and developing solutions to wicked problems, particularly for those involving large seascapes, is challenging due to the multiplicity of actors (landowners, stakeholders) and levels of governance (from municipal to state/provincial to federal), many of them overlapping on the same parts of the seascape (Imperial et al. 2016; Parrot 2017). But the multiplicity of actors is also a benefit, with numerous invested Indigenous groups, agencies, community organizations, and educational outlets already in place. Building a better future will require an ability to anticipate how societies, economies, and ecosystems are linked across scales—and across the international border—and an understanding of how to shift these coupled systems toward more desirable states (Bennett et al. 2019).

The solutions to these wicked problems may be approached from multiple, often competing perspectives, with multiple stakeholders each valuing potential solutions over other potential solutions (e.g., wearing masks versus wiping surfaces to combat the coronavirus until a more complete solution is developed and available in the form of a vaccine). In reality, no solution will be perfect, and some argue wicked problems are in fact relentless and unsolvable by definition, but diverse approaches are necessary for improvement—even if not a perfect solution (e.g., wearing masks and wiping surfaces and social distancing and wide-spread testing and vaccination).

As Ed Yong wrote in his piece America Is Trapped in a Pandemic Spiral (2020), "People forget that controlling the pandemic means doing many things at once." This same observation holds true for maintaining the health and ecological integrity of complex ecosystems like the Salish Sea. Many things will need to be done at once: increasing understanding in the face of a changing ecosystem, limiting further inputs of contaminants that we know cause harm, protecting remaining stretches of shoreline with high function, and enacting policies that move the needle toward resilience and ecosystem health.

18 BELLINGHAM BAY, WASHINGTON: AN EXAMPLE OF LEGACY CONTAMINANTS

Olivia Klein, Salish Sea Institute

This vignette draws information primarily from an interview with Ian Fawley at the Washington State Department of Ecology and the agency's website on Bellingham Bay cleanup.

There are thousands of contaminated sites in the Salish Sea region, causing environmental and economic impacts to people and wildlife. From estuarine deltas to urban shorelines, years of milling, manufacturing, landfilling, and a variety of industrial and municipal activities have contributed to extensive contamination of shorelines and associated waterways.

Bellingham Bay, home to twelve designated hazardous waste cleanup sites, is one example that illustrates the harm of past practices as well as the effectiveness of cleanup efforts. Since 2000, the Bellingham Bay cleanup has focused on the removal of contaminated sediment and soils introduced from a wide variety of sources, including construction and other industrial and municipal activities. Bellingham Bay cleanup is managed by the Washington State Department of Ecology (under the authority of Washington State's Model Toxic Control Act) in coordination with a mult-agency Bellingham Bay Action Team.

Prominent on the waterfront of Bellingham Bay, and often listed as a key contributor of the contaminated sediment and soils in the Bay, are the remains of the Georgia Pacific pulp and paper mill. The factory closed its doors in 2007, leaving behind several pollutants still detected today, including heavy metals, petroleum hydrocarbons, volatile organic compounds, and dioxins/furans. But contamination in the Bay goes well beyond the mill.

Shoreline cleanup and restoration at Bellingham Bay
Photo: Washington State Department of Ecology

Former shipyards with contaminated soil and groundwater account for three of the twelve contamination sites in Bellingham. Other sites include a rock-crushing plant in operation from 1963 to 1992, a frozen food processing company that existed from 1946 to 1959, and a seafood processing plant in operation since 1959 (and still in operation). All are linked to the presence of hazardous substances in Bellingham Bay's marine sediment.

It's not just manufacturing—historic landfill practices contribute additional contaminants to Bellingham Bay. For example, an historic 13-acre landfill near the Old Town district of Bellingham operated in the early 1900s. Property owners filled portions of the site with dredge spoils and other materials to increase usable upland areas, and dumping of municipal waste followed. Landfill disposal practices of the time were vastly different than today, leaving a legacy of contamination.

The collective activities resulted in soil runoff, contaminated groundwater, and particulates like dust and smoke settling from the air, eventually finding its way into Bellingham Bay. Combined with stormwater outfalls carrying surface-born contamination, these pollutants and processes add

Dredging of contaminated sediment
Photo: Washington State Department of Ecology

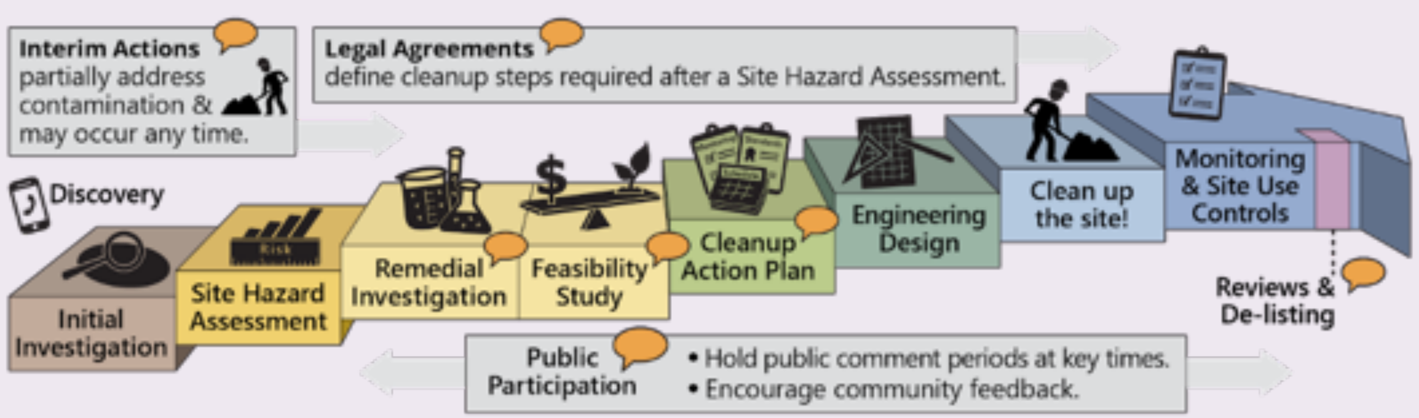
to the collective annual cost of approximately $16 billion in environmental degradation of sediments in the United States, according to the EPA.

Fortunately, restoration efforts are taking place, bringing hope for a cleaner future in the Salish Sea. Bellingham Bay's twelve individual cleanup sites (see chart at right) each have different needs depending on the severity and type of pollution, as well as levels of engineering and management complexity. Management processes for the cleanup sites fall into three categories: the construction of a multi-layered capping system, the treatment of contamination in place, and contamination removal.

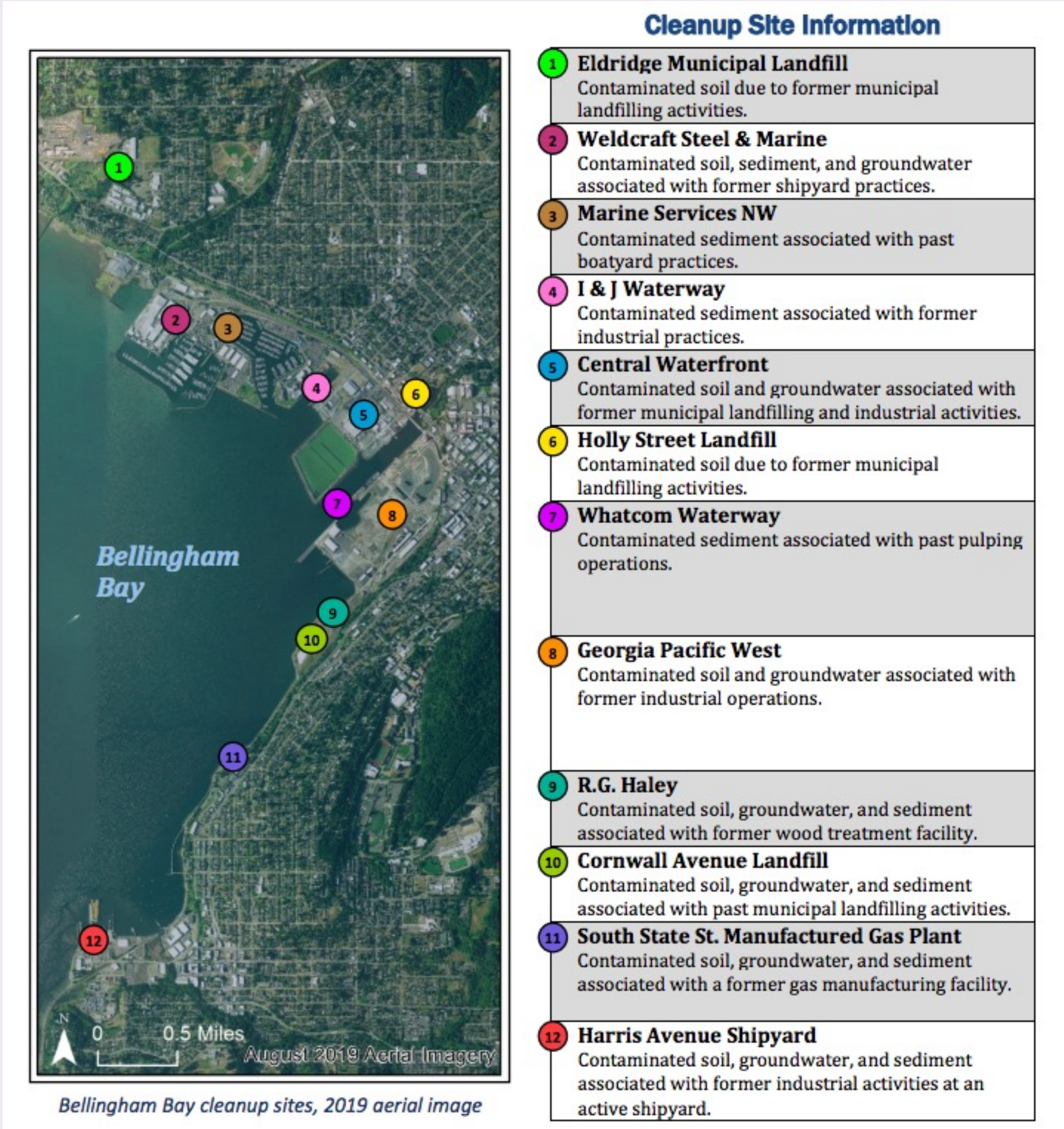
Cleanup is legally and technically complicated, costly, and time consuming. From 2017-18, the Washington State Department of Ecology managed the removal of 14,500 cubic yards of sediment, 3,200 cubic yards of contaminated soil, 36,900 square feet of over-water structures, and 905 creosote-treated pilings. This work was followed more recently by additional planning and cleanup documents to prepare for construction in 2021 and beyond. Supporting work includes legal agreements, a remedial investigation/feasibility study, two cleanup action plans, and two engineering design documents (see process diagram below).

Today, two of the original twelve sites have been completely cleaned up, and most of the other ten are on their way to completion within a few years. Additionally, the removal of legacy contaminants from some of the sites means they will not migrate to the marine waters of the Salish Sea, further protecting biota.

Although Bellingham Bay cleanup is not yet complete, it is significantly cleaner today than 20 years ago and a step closer to regenerative use of Bellingham Bay shorelines and the connected marine waters.



Stages of cleanup of contaminants in Bellingham Bay.
Source: Washington State Department of Ecology



Sites cleanup of contaminants in Bellingham Bay.
Source: Washington State Department of Ecology

19 INVASIVE EUROPEAN GREEN CRAB

Jeff Adams, Washington Sea Grant; Dr. Emily Grason, Washington Sea Grant; Dr. P. Sean McDonald, University of Washington; Allen Pleus, Washington Department of Fish and Wildlife; Dr. Jude Apple, Padilla Bay National Estuarine Research Reserve; Roger Fuller, Padilla Bay National Estuarine Research Reserve; Dr. Lucas Hart, Northwest Straits Commission; and Alexandra Simpson, Northwest Straits Commission

European green crab (*Carcinus maenas*, EGC; Figure 1) pose documented threats to cultured and wild shellfish, eelgrass, and shoreline habitats and ecosystems. EGC diets include clams, oysters, mussels, marine worms, and small crustaceans. Because they can prey on juvenile crabs and shellfish, dense populations of EGC in the Salish Sea region could put fisheries and aquaculture resources in peril. EGC also play a role as ecosystem engineers, disturbing sediments and destroying below-ground tissue of plants while digging for food and burrows, decreasing stability of saltmarsh banks, drastically reducing eelgrass density (up to 75% in Nova Scotia and Newfoundland), and damaging nesting and feeding habitat for shorebirds and nursery grounds for fish and invertebrates.

After Fisheries and Oceans Canada researchers reported an established EGC population in Sooke Basin, BC in 2012, the Washington Department of Fish and Wildlife (WDFW) worked with Washington Sea Grant (WSG) to secure Puget Sound Marine and Nearshore Grant Program funding and establish a volunteer-based early detection and monitoring program (Figure 2). WSG launched Crab Team (wsg.washington.edu/crabteam) in 2015 with seven pilot sites. The program expanded to 26 sites the following year and has monitored more than 50 sites each year since, engaging hundreds of community members and partner staff in monthly monitoring of invertebrates, fish, and habitat in Puget Sound pocket estuaries, lagoons, and tideflats. Concurrent with early detection monitoring, a team led by WDFW developed the Salish Sea Transboundary Action Plan for Invasive European Green Crab, providing a foundation for prevention, early detection, rapid response, research, and coordinated management throughout the Salish Sea.

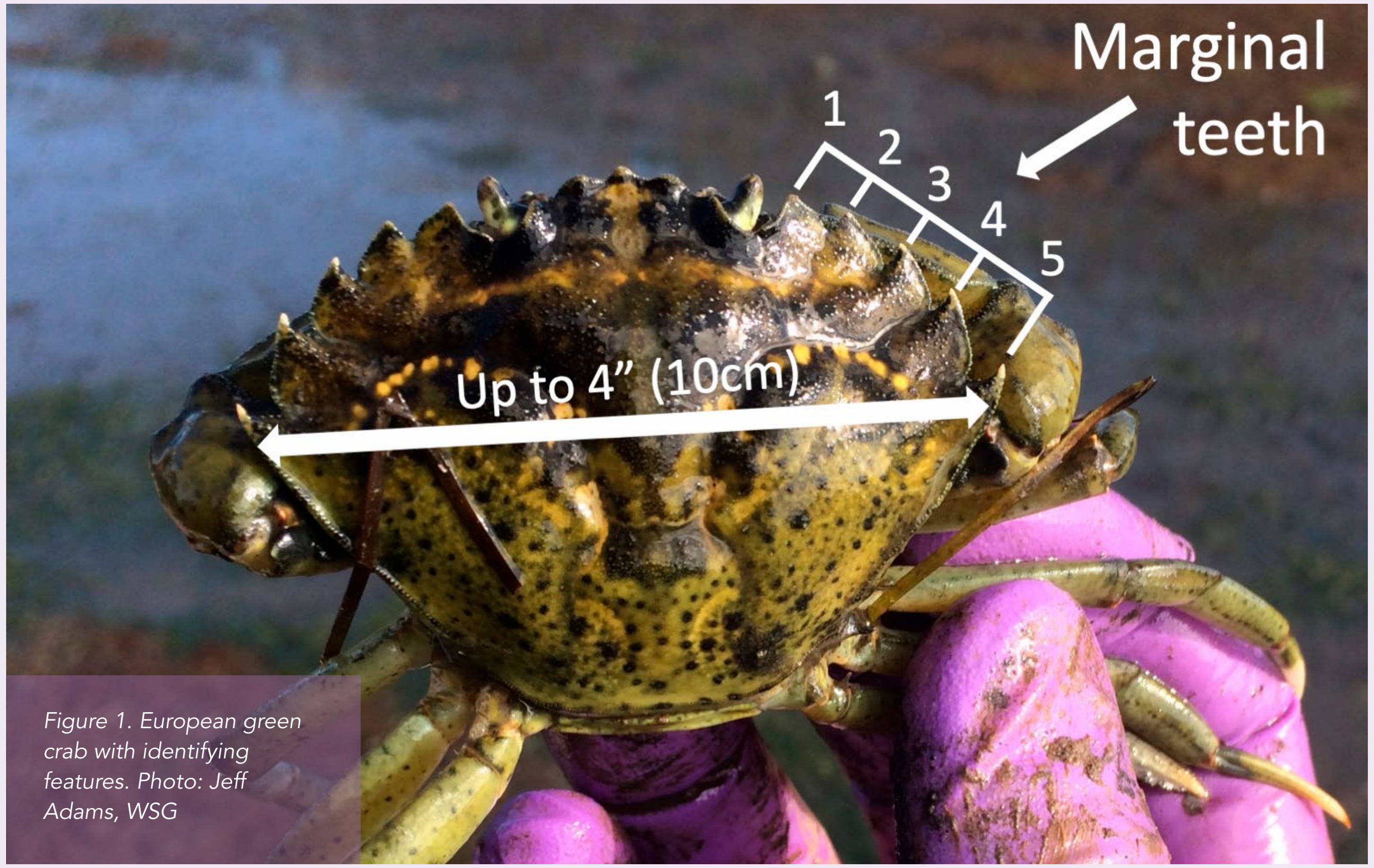


Figure 1. European green crab with identifying features. Photo: Jeff Adams, WSG

The first EGC detections in Puget Sound were made in 2016 by Crab Team volunteers on San Juan Island and by Padilla Bay National Estuary Research Reserve (PBNERR) staff in Padilla Bay (Figure 2). Follow-up rapid assessments detected only a molt on San Juan Island and three additional EGC along the shores of Padilla Bay. In 2017, the first discovery of more than two EGC at a single Puget Sound location occurred at Dungeness National Wildlife Refuge. The response by Refuge staff and volunteers, with support from WDFW, WSG, and other partners, was swift, intense, and sustained. Thousands of trap sets since then have removed over 220 EGC around Dungeness Spit, resulting in a catch per unit effort (CPUE) of 2.44 EGC/100 trap days (2016-2019). These efforts have been largely successful in reducing the abundance of EGC within the refuge; CPUE in 2020 was only 0.2 EGC/100 trap days.

At the same time, detections have increased in other locations. In 2019, EGC were reported across a broad swath of northern Puget Sound. Aquaculture partners in Samish Bay, WDFW staff in Chuckanut Bay, and Crab Team volunteers in Drayton Harbor all recovered evidence of EGC, prompting rapid assessment efforts in 2019 and a sustained response in 2020. Across northern Puget Sound in 2020, CPUE ranged from a low of 0.8 EGC/100 trap days in Padilla Bay to a high of 75.3 EGC/100 trap days in Lummi Bay within the Lummi Sea Pond. Multiple cohorts were observed at many locations, as well as some evidence of local reproduction.

COVID-19 restrictions and precautions slowed and delayed the response in 2020, but the Lummi Nation, WDFW, and Northwest Straits Commission (NWSC) were eventually able to deploy crews for both removal and exploratory trapping. WSG volunteers and PBNERR staff continued long-term monitoring

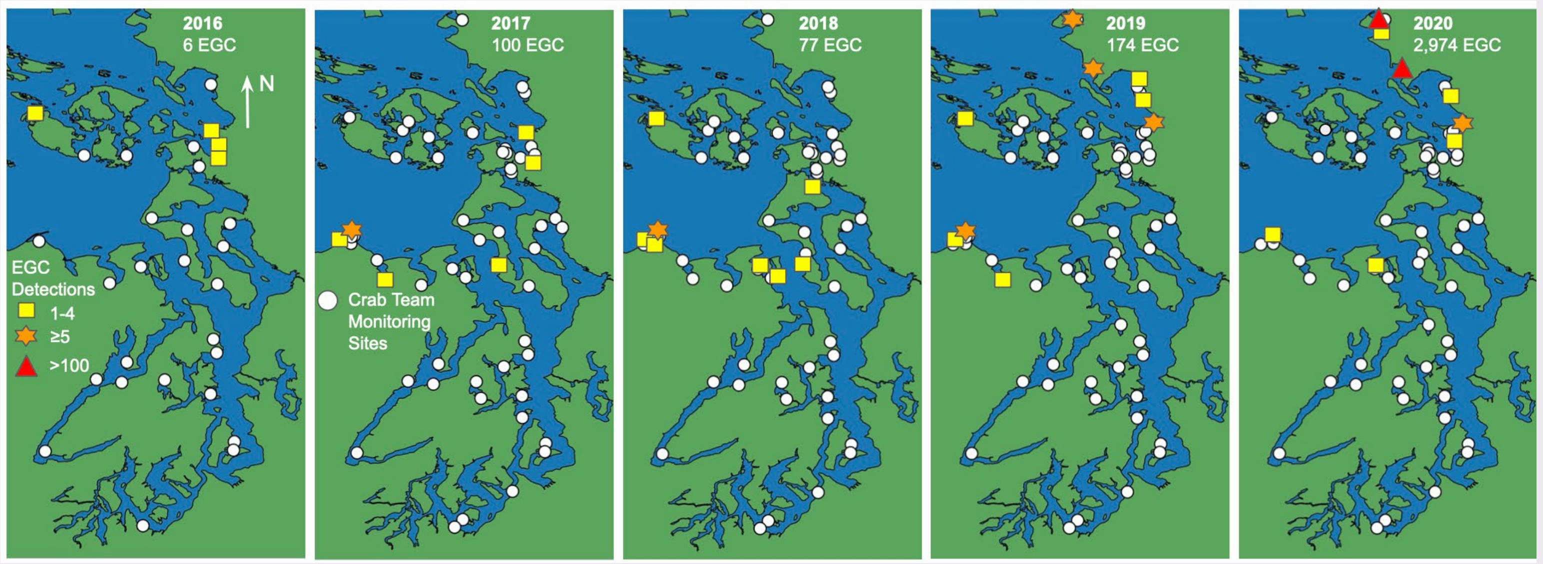


Figure 2. European green crab trapping in Puget Sound by location and year. Yellow squares indicate sites where fewer than five EGC were detected in the year, orange stars indicate sites with 5-99 detections, and red triangles indicates sites with 100 or more detections within the year. Crab Team monthly monitoring network (with the exception of Pysht, west of Port Angeles and beyond the map extent) are identified by white circles. The interactive map is available at tinyurl.com/wagreencrab.

without interruption, and aquaculture partners were able to set traps in Samish Bay. The Lummi Nation continues to devote staff and resources to trapping in Lummi Bay, and the NWSC was able to secure a local coordinator for Drayton Harbor using USEPA National Estuary Program funding for 2019-2020, which continues to present. The Washington State Legislature also provided funding to WFDW to implement an enhanced collaborative response and monitoring effort in Puget Sound as well as assessment efforts on the state's Pacific Coast; these efforts are ongoing. In addition to monitoring and removal, research continues on several fronts, including population genetics, parasite prevalence, and diet composition. This work, as well as lessons from removal trapping at Dungeness Spit, Makah Bay, and elsewhere, will continue to inform detection and control efforts across the Puget Sound region to reduce risk of spread and impact from EGC.

The coordinated response by WDFW and WSG Crab Team, along with tribal, state, and federal partners, and committed volunteers serves as a model for management of invasive species within the Salish Sea. Indeed, efforts to identify and eliminate nascent infestations have proven successful in many locations because of early detection and rapid response. However, as prevalence of EGC increases elsewhere in the northeastern Pacific, it is important to increase capacity to address the threat regionally.

Left and above: As part of the Washington Sea Grant's Crab Team program, volunteers evaluate habitat and monitor for invasive European green crab with baited traps. Source: University of Washington

20 FRASER RIVER ESTUARY IN NEED OF URGENT INTENSIVE CARE

Dr. Laura Kehoe, Oxford University and The Nature Conservancy, and Dr. Tara G. Martin, University of British Columbia

If the Fraser River Estuary were a hospital patient, she would be rushed to the intensive care unit. She would need urgent attention from many different specialists. But if we provide her the care she needs in a timely way, she can heal, and one day thrive. She could once again be bursting with life, bountiful runs of salmon, pods of orcas, and millions of migratory birds.

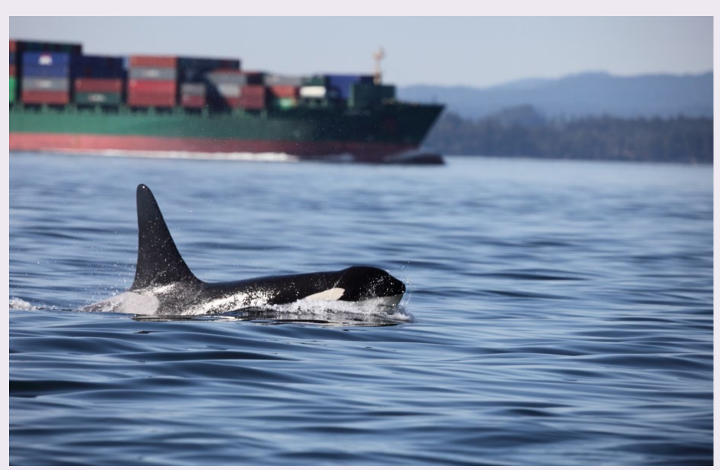
The Fraser River is the lifeline of the Salish Sea, influencing its stratification, circulation, and primary productivity. Historically, the Fraser River was home to the largest salmon runs in the world. These days, an impressive number of fish still frequent this rich ecosystem. Millions of juvenile salmon spend weeks to months in the estuary before embarking on their ocean migration. Above the water, 1.4 million migratory shorebirds stopover in the estuary at peak season. However, everything is not well in the Fraser. Annual salmon returns and bird numbers have been declining for decades and are now at record lows.

Our research finds that within the mighty Fraser River estuary, 102 species are at risk of extinction. Over the past 150 years, multiple and cumulative pressures, including urbanization, agricultural and industrial development, pollution, overexploitation, disease, and climate change, have severely impacted these species. However, we also discovered it's not too late to save them.

The Fraser River estuary isn't just crucial to wildlife, humans rely on this estuary too. Coast Salish First Nations have lived in and found both spiritual and physical nourishment from the Fraser's natural resources for millennia. Today, this resilient and diverse estuary is host to the busiest port in Canada, home to half of British Columbia's rapidly expanding urban population (Vancouver and surrounds), and is particularly vulnerable to sea level rise and continued industrial development.

Audrey Siegl member of Musqueam First Nation, one of over 30 nations who live in and rely on the Fraser River Estuary
Photo: Michael Snyder.

The need for a costed prospectus to deliver long-term ecological resilience to this highly contested region has never been more urgent. Our research delivered exactly that. For the 102 species at risk of extinction in the Fraser River estuary, a suite of conservation strategies, spanning aquatic habitat restoration to better farmland management, is needed to save them from extinction.

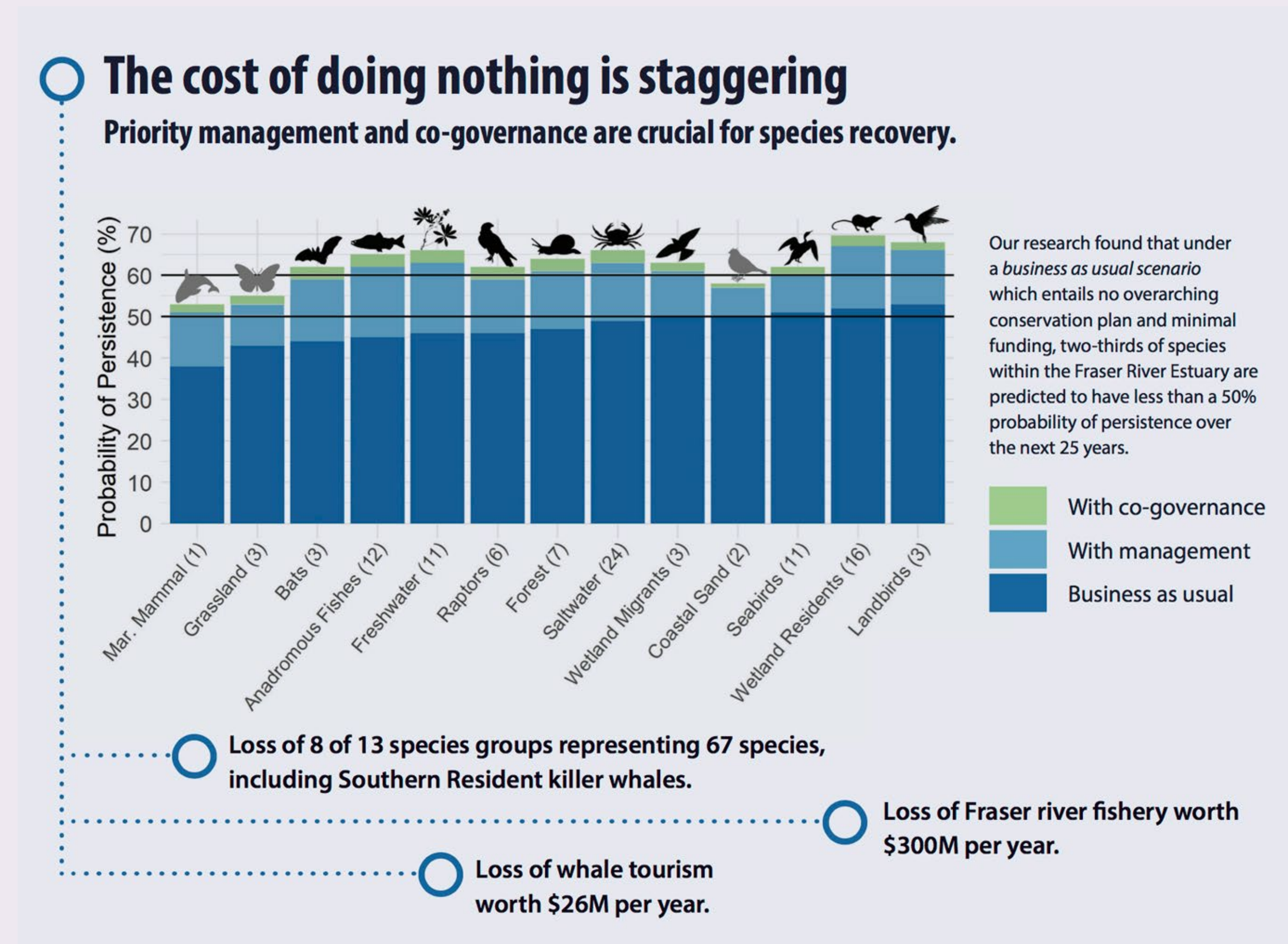


Southern Resident killer whale in the Fraser River Estuary
Photo: Tom Middleton.

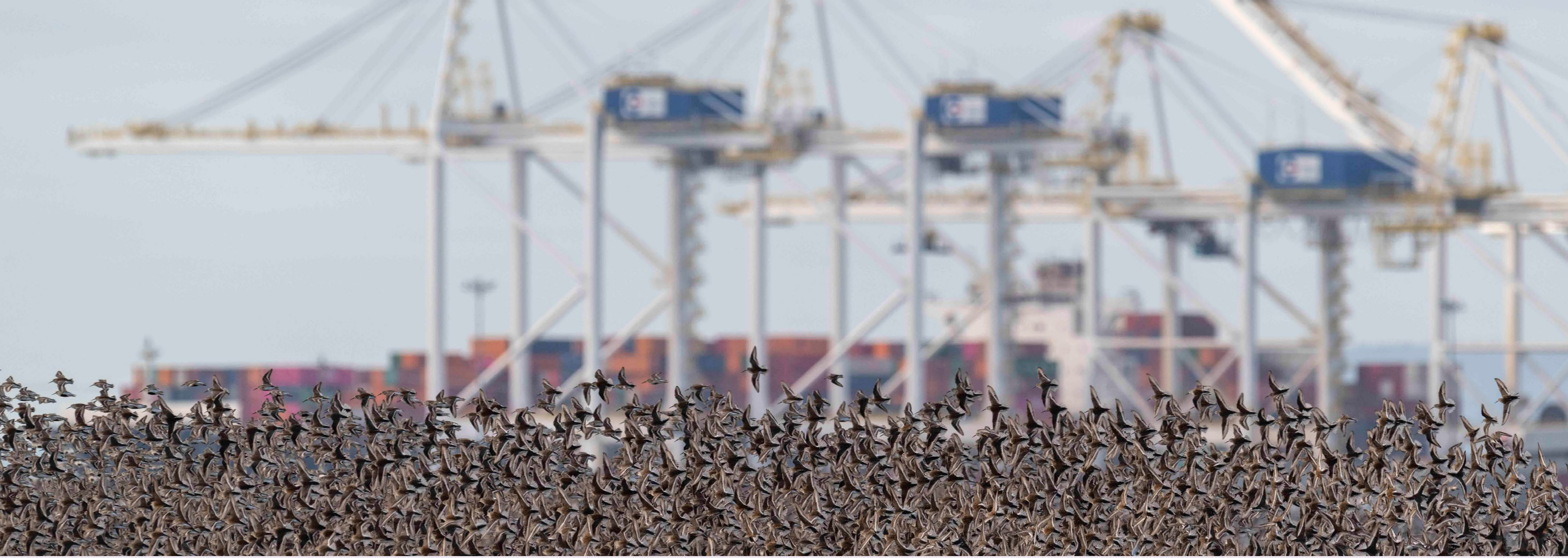
The comprehensive action plan that we developed is estimated to cost $381 million over 25 years, or $15 million a year to implement. This might sound like a lot, but it is only $6 per Vancouverite each year, the cost of one measly beer a year. It's a drop in the ocean compared to the $26 million per year that whale tourism earns in the Salish Sea and the $300 million per year that fisheries in the estuary were estimated to be worth in the 90s. If we all raised a toast to the Fraser, we could save it.

On the other hand, if we don't take strong action to conserve the Fraser River estuary, two-thirds of the species at risk in this region are predicted to have a less than 50% chance of survival. Many of the region's most iconic species could disappear, including the southern resident killer whale, salmon, sturgeon and a raft of internationally recognized migratory birds.

While often overlooked, governance is a key factor influencing the feasibility of conservation management, particularly in regions of high competing interests. Despite this, surprisingly little is known about whether the conservation benefits of building and supporting environmental governance



Probability of persistence for each of 13 species groups under increasing levels of investment over 25 years. Baseline (dark blue) represents species persistence probabilities under no additional management; management (light blue) represents implementing all management strategies; co-governance (green) represents the implementation of an overarching co-governance strategy. Under full management and co-governance, 10 of 13 species groups (black species silhouettes, representing 96 of 102 species) reach a 60% probability of persistence. Species groups are ordered from lowest to highest probability of persistence under baseline scenario. Source: Kehoe et al. (2021).



The Fraser River Estuary is a critical stopover site for western sandpipers. Photo: Jason Puddifoot.

outweigh the costs, especially since effective governance is likely to determine the success or failure of conservation interventions.
Our action plan tested the cost-effectiveness of a co-governance model that sees First Nation, local, provincial, and federal governments working together to implement these cost-effective strategies and ensure their success. We found that co-governance was critical to successful conservation outcomes, as it increased the feasibility and cost-effectiveness of all our conservation actions.

On top of conservation outcomes, we found a wealth of additional benefits of co-governance. These benefits include: better cohesion between partners, stricter adherence to regulations, long-term collaboration on projects, the security of ongoing funding, participatory decision making, a better balance between healthy ecosystems and development opportunities, savings in time and resources, and more public engagement. Our technique is the first to explicitly quantify the cost-effectiveness of co-governance in terms of species conservation and provides a blueprint for future work on assessing the potential for co-governance in imperiled regions.

Co-governance allows for coordinated action to better conserve species under threat—but what about stopping those threats at their source? Multiple large-scale industrial threats face our study region, including (but not limited to): the Trans Mountain Pipeline, a new terminal at Roberts Bank (an ecologically sensitive area), and a new bridge that would allow for more shipping traffic into the estuary.

Alongside prioritizing the most cost-effective management strategies for this imperiled region, we included an assessment of halting future major industrial development. We found that the continuation of industrial development would jeopardize the future of many iconic species such as the southern resident killer whale, anadromous fishes, including salmon and sturgeon, and saltwater species, including the migratory western sandpiper. The gravity of these future threats is underscored with our finding that the benefits from halting future major industrial development are estimated to be greater than nine out of the ten management strategies we assessed. Our research emphasizes that along with restoration action we must prevent further developments that could undermine restoration success.

Our research shows that conservation action combined with environmental governance is a pathway for a brighter future in highly contested regions, such as estuaries, and that the return on investment likely offsets the cost of management. In a world of rapid urban sprawl and ongoing biodiversity declines, our methodology identifies the most cost-effective strategies to conserve nature in areas important to both humans and wildlife. We have the tools to conserve the many wonders of the natural world, but we must employ them while there is still time to act.

Vignette adapted from Kehoe et al. (2021)

SECTION 6

OPPORTUNITIES FOR IMPROVING ASSESSMENT AND UNDERSTANDING OF THE SALISH SEA

Orca whales swimming in Bellingham Bay, WA
Photo: Rhys Logan

SECTION 6

BUILD HABITS AND SUPPORT FOR COLLABORATING ACROSS DISCIPLINES AND BORDER

Establish a Salish Sea Science Panel

Advance Data Collection and Monitoring Using Novel Tools

Use Models as Integrative Tools

Create a Transboundary Salish Sea Data and Information Repository

EMBRACE MULTIPLE WAYS OF KNOWING AND CONNECTING TO THE SALISH SEA

Apply Social-Ecological Systems Science

Recognize Indigenous Knowledge Systems

Build Knowledge, Relationships, and Connection through Place-Based Learning

STRENGTHEN THE SCIENCE-TO-MANAGEMENT BRIDGE

Enable Practitioners to Bridge Science and Community Investment

Use Adaptive Management Tools to Strengthen Planning

Build Sustained and Regenerative Ecosystem Functions to Improve Resilience

VIGNETTES

21: How Ecological Time-Series Inform Response to Stressors

22: Sense of Place

23: Indigenous Management Systems Can Promote More Sustainable Salmon Fisheries in the Salish Sea

Synthesizing key threats and their impacts to an ecosystem like the Salish Sea forms a foundation for action, including but not limited to: science agendas to better understand the impacts of these threats, forecasts to make predictions about future conditions, educational action so municipalities and managers can understand the problems and be responsive with planning and infrastructure, and regulatory action to limit further harm and remediate current ills to result in net ecosystem improvement (Thom et al. 2005; Diaz et al. 2020).

In this section, we highlight several examples of positive actions already underway to better understand the Salish Sea. We also offer several related opportunities for new or enhanced action to meet the needs of science and science-driven management in the Salish Sea. The following table provides a concise overview of those needs and opportunities, organized into three categorical objectives and ten specific actions. The following pages explain and expand upon the proposed objectives and actions.

We do not prescribe scientific collaboration and research as the "fix" for the Salish Sea. Full restoration and protection of the Salish Sea requires a robust suite of enhanced regulatory and management actions, and fundamental shifts in "business as usual" in our bioregion (see Section 7 and Vignette 20, Fraser River Estuary). However, scientific understanding does increase our ability to detect and address environmental changes quickly and at the scale necessary to enable decisive and effective action.

There are significant opportunities to improve science in our region, through early identification of emerging problems and a clearer understanding of the cumulative impacts of legacy, continuing/persistent, and emerging problems. Better science will afford opportunities for better management and a more resilient Salish Sea.

> *"Despite a significant investment of energy and resources from federal, tribal, state, and local governments and non-governmental partners, habitat degradation continues to outpace restoration. While this situation at times seems impossibly bleak, the thousands of passionate people who are devoted to seeing the return of a healthy and resilient Puget Sound give us hope."*
>
> Laura Blackmore, Executive Director, Puget Sound Partnership, from State of the Sound Report 2020

OPPORTUNITIES FOR IMPROVING ASSESSMENT AND UNDERSTANDING OF THE SALISH SEA: OVERVIEW

BUILD HABITS AND SUPPORT FOR COLLABORATING ACROSS DISCIPLINES AND BORDER

Establish a Salish Sea Science Panel

Convene scientists from Indigenous Nations, Washington, and British Columbia to re-prioritize formal collaboration and develop large-scale actionable science needs, priorities, and methods. Maintaining the strength and priority of science in the Salish Sea is essential for identifying emerging concerns and creating actionable solutions.

Advance Data Collection and Monitoring Using Novel Tools

Leverage creative partnerships and new technologies to collect data over long time periods and larger spatial scales to better understand changes from climate change and local human impacts.

Use Models as Integrative Tools

Ongoing modeling work throughout the Salish Sea is bringing together data, computing power, and technical expertise to better understand oceanographic and ecosystem processes. Modeling tools should incorporate the multiple simultaneous and cumulative impacts on the Salish Sea from climate change, urbanization, and more. To become truly powerful and integrative, models must incorporate the transboundary, social-ecological system at multiple levels of spatial and temporal complexity.

Create a Transboundary Salish Sea Data and Information Repository

Develop strategies for integrated data management, including efforts to harmonize data across the border and across disciplines, jurisdictions, and agencies. Long-term collection and curation of Salish Sea-wide data, information, and stories will support shared efforts toward transboundary science, policy, and education.

EMBRACE MULTIPLE WAYS OF KNOWING AND CONNECTING TO THE SALISH SEA

Apply Social-Ecological Systems Science

Invest in initiatives that address human well-being and cultivate a strong sense-of-place within Salish Sea communities. Understanding the complex relationships between people and their environment can stimulate wise management decisions and development actions for ecosystem restoration and protection, as well as economic sustainability.

Recognize Indigenous Knowledge Systems

Recognize traditional ecological knowledge in assessing, managing, and restoring the state of the Salish Sea and its ecosystem functions. Through co-management, creating ethical space for collaboration, and working together as equal partners, we can better ensure the future health and wellness of the Salish Sea.

Build Knowledge, Relationships, and Connection through Place-Based Learning

Invest in more intentional Salish Sea-wide place-based education, including support for Indigenous communities to build capacity for ecological and cultural restoration. Education initiatives can increase appreciation of the Salish Sea, creating stronger ties with the lands and waters around us.

STRENGTHEN THE SCIENCE-TO-MANAGEMENT BRIDGE

Enable Practitioners to Bridge Science and Community Investment

The Salish Sea benefits from many local- and regional-scale organizations that operate at the interface of science and practice, bringing additional participants into actionable science. Foster community science initiatives by promoting local involvement in data collection, restoration, and priority-setting to elevate calls to action within the Salish Sea.

Use Adaptive Management Tools to Strengthen Planning

Use adaptive management strategies to address cumulative impacts associated with climate change and human development in the Salish Sea. The iterative nature of adaptive management allows for simultaneously confronting complexity and uncertainty while also being proactive and responsive at local and regional scales.

Build Sustained and Regenerative Ecosystem Functions to Improve Resilience

Build resilience, especially at the land-sea ecotone where human infrastructure will exacerbate problems associated with rising sea level. Positive, protective, restorative, and regenerative actions are increasingly necessary as the population grows and threats from climate change alter ecosystem processes.

BUILD HABITS AND SUPPORT FOR COLLABORATING ACROSS DISCIPLINES AND BORDERS

Clouds rolling in over Vancouver's English Bay
Photo: iStock

Establish a Salish Sea Science Panel

Convene scientists from Indigenous Nations, Washington, and British Columbia to re-prioritize formal collaboration and develop large-scale actionable science needs, priorities, and methods. Maintaining the strength and priority of science in the Salish Sea is essential for identifying emerging concerns and creating actionable solutions.

There is a need to prioritize ecosystem-scale work, to engage decision-makers at the highest levels in a shared effort to understand emerging and persistent concerns, and to protect and restore the Salish Sea. To increase formal collaboration and provide a groundwork for shared methods and initiatives, a Salish Sea Science Panel with positions for scientists from bioregional universities, agencies, and communities in British Columbia, Washington State, and Coast Salish Nations should be convened to identify and develop large-scale actionable science needs and priorities for the Salish Sea estuarine ecosystem.

There are currently *ad hoc* efforts to integrate science and science policy across the border, driven by researchers with shared interests and methods, as well as large science policy initiatives. In some cases, these efforts are formalized. For example, in Washington, there is the Puget Sound Partnership Science Panel with Canadian scientists represented. The Transboundary Indicators program draws on both United States Environmental Protection Agency and Environment and Climate Change Canada federal agencies to collaborate on the development and communication of indicators. The Salish Sea Marine Survival Project has leadership from both Canada and the United States setting the research agenda for the program. Outside of formal programs, the research community is collaborating through regional professional meetings, shared research interests and joint publications, professional networks, and other forms of cross-border collaboration.

We have world-class universities and invested, collaborative researchers in the region that have garnered support from regional and federal government entities, Tribal and First Nations partners, non-profits, and private citizens. Maintaining the strength and priority of science in the Salish Sea is essential for identifying emerging concerns and creating actionable solutions. A robust Salish Sea Science Panel would bring together scientists and thinkers across disciplines and borders to strengthen and prioritize science in understanding and caring for the shared waters of the Salish Sea.

In many respects the Salish Sea presents a compelling scientific challenge with dynamic, context-dependent mixing, stratification, and biological productivity. The oceanography—from physical to biological—is challenging to resolve on short-term time scales and on small spatial scales. Combined with anthropogenic pressures imposing changes to ecosystem components, there is no shortage of applied science needs and inquiries to develop. A Salish Sea Science Panel would provide structure to identify priorities and shared opportunities for actionable science and solutions.

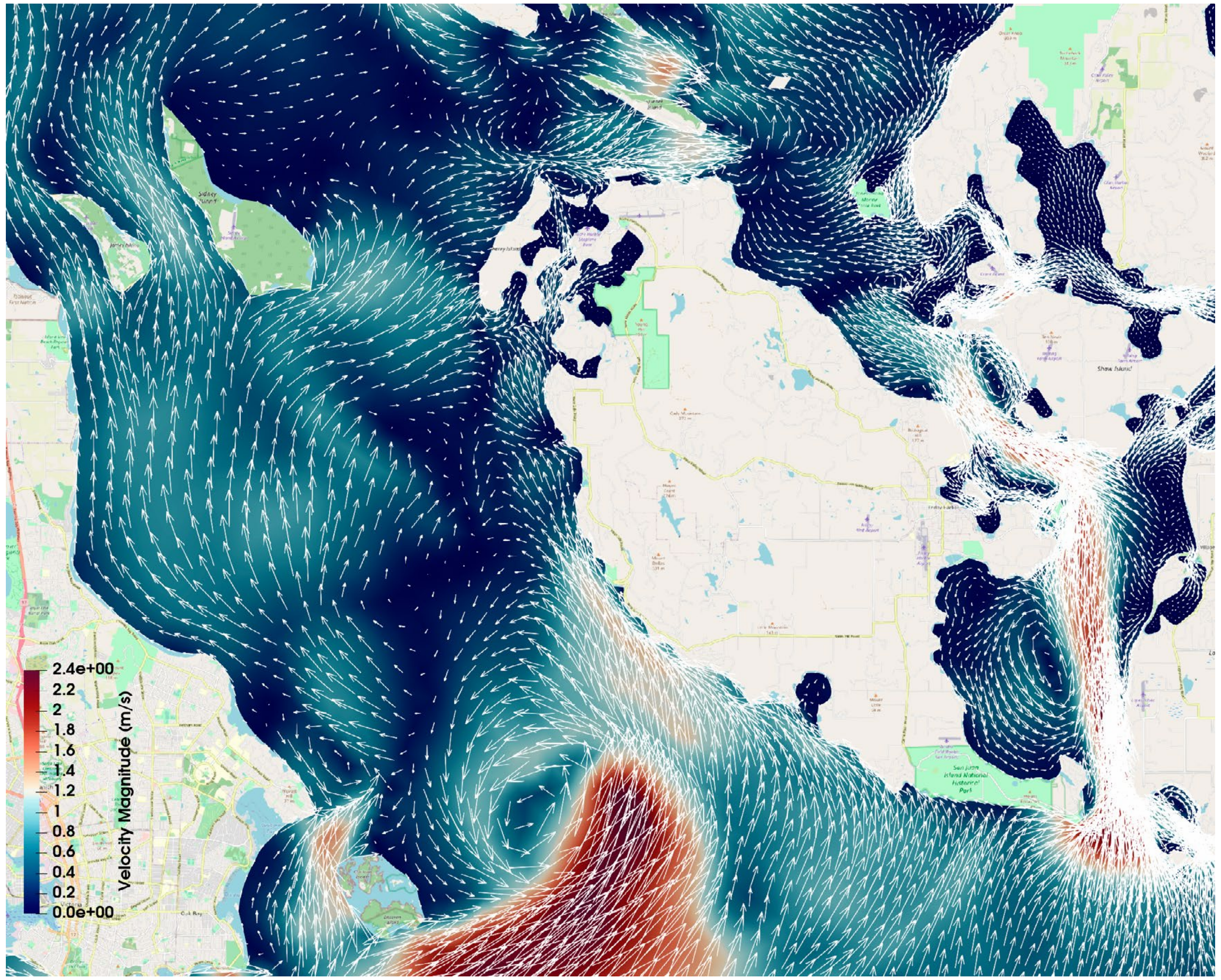
Advance Data Collection and Monitoring Using Novel Tools

Leverage creative partnerships and new technologies to collect data over long time periods and larger spatial scales to better understand changes from climate change and local human impacts.

To truly understand change in our system, time-series on fundamental oceanographic and ecological processes are necessary. The spatial openness of the marine ecosystem where changes hundreds or thousands of kilometers away may influence controlling factors like temperature or ocean chemistry means an immense amount of knowledge must underpin management (Culhane et al. 2018). To understand natural variability in the ecosystem and further detect change, consistent data collection over long time periods is necessary (see Vignette 21, Ecological Time-Series). This need is often unmet due to short funding cycles and the desire for rapid project implementation and completion or action-oriented science on shorter time scales. Targeted studies with specific questions and objectives are no less important for understanding mechanisms of change, but they are enhanced when coupled with long-term understanding to provide context, especially in abnormal or anomalous years, which may portend conditions to come. Decadal-scale data sets are needed, as well as spatial coverage throughout the estuary, to understand the Salish Sea as a system.

New technologies—especially remote sensing—offer the ability to collect vast amounts of data in ways not fully realized 25 years ago. For example, the Spectral Remote Sensing research group at University of Victoria is working towards developing research methods to more effectively use remotely sensed imagery for understanding and monitoring biogeophysical processes in marine waters and has promising projects in the Salish Sea (UVic Spectral 2021). One of the challenges of working with remotely sensed data is that the volume of data collected is often immense. Where a field study may suffer from sample size problems when one jar is accidentally knocked over, remotely sensed data suffers from an overload of information, only some of which may be useful for the question at hand. Processing satellite data or data from sensor arrays requires computational skill and resources. Existing ocean observing platforms like NANOOS (Northwest Association of Networked Ocean Observing Systems) are important assets in understanding Salish Sea oceanography. But an array deployed throughout the Salish Sea with a commitment to funding for maintenance and data stewardship would increase the value of these sensors. In addition to providing a coordinated dataset, a more comprehensive and permanent network will aid in calibration and validation of the many numerical ocean models under development in the region, as well as local-scale studies where continuous data collection may not be feasible. Consistently collected data, as could be obtained by a comprehensive Salish Sea sensor array, would provide an integrated picture of natural variability and emerging trends within the estuary.

Maritime traffic in the Salish Sea can be leveraged for providing data on ocean conditions along regularly traveled routes. For example, Ocean Networks Canada (ONC; Ocean Networks Canada 2021) has put instrumentation on British Columbia ferries to collect weather and oceanographic data along ferry routes. These data are telemetered to ONC when vessels are in port. The ferries collect a variety of data on physical and biological processes, such as



Surface currents in Haro Strait near San Juan Islands showing complex currents eddies
Source: Tarang Khangaonkar

temperature, turbidity, and fluorescence, which enable characterization of the Fraser River plume and the spring phytoplankton bloom. Using vessels of opportunity or other remote platforms, like Saildrones, to collect water quality data may afford a more geographically robust long-term data collection effort.

Few agencies are equipped with the data analytic capacity to process massive transboundary data sets and serve them efficiently to the community. Given that the region is a global center of technological and data analytics development, leveraging local expertise and capacity from the private sector could yield solutions to the problem of data filtering and data management. Creative partnerships may present opportunities to create a robust network of sensors or autonomous platforms that could provide real-time datasets with high spatial and temporal resolution. When integrated with regional models, these datasets may provide increased understanding, and more importantly, an ability to detect change in the ecosystem.

Use Models as Integrative Tools

Ongoing modeling work throughout the Salish Sea is bringing together data, computing power, and technical expertise to better understand oceanographic and ecosystem processes. Modeling tools should incorporate the multiple simultaneous and cumulative impacts on the Salish Sea from climate change, urbanization, and more. To become truly powerful and integrative, models must incorporate the transboundary, social-ecological system at multiple levels of spatial and temporal complexity.

Models have become important tools in ecosystem-based management for integrating many disparate ecosystem components. These models take many forms: hydrodynamic models, elemental models tracking nitrogen or carbon through our ecosystems, stock assessment models, food web models, spill-response models, network models, management strategy evaluation simulations, and others are used in our region by agencies and university researchers. Models rely on high-quality data as inputs, numerical, statistical, and computational know-how, and an understanding of ecosystem and management processes to reap the most benefit. To be reliable, extensive development, testing, and recalibration of models is often necessary. However, ecosystem modeling is progressing in development and presents an opportunity to establish an open-access, community-based approach supported by a suite of truly interdisciplinary efforts (Rose et al. 2010).

Ongoing modeling work throughout the Salish Sea is bringing together data, computing power, and technical expertise to better understand oceanographic and ecosystem processes. The Salish Sea Marine Environmental Observation Prediction and Response Network (Salish Sea MEOPAR 2021), LiveOcean (UW Coastal Modeling Group 2021), and the Salish Sea Model (Pacific Northwest National Laboratory 2021) are just some of the efforts focused on understanding oceanographic processes and the fluxes they drive. Large end-to-end models—models that combine physicochemical oceanographic descriptors and organisms ranging from microbes to higher-trophic-level organisms and humans, in a single modeling framework—are also being developed for the region. These include an Atlantis Ecosystem Model under development by Fisheries Northwest Fisheries Science Center (National Oceanic and Atmospheric Administration 2021), a parallel Atlantis model for the broader Salish Sea (developed by CSIRO Australia), and an Ecopath Food Web Model being developed by researchers at University of British Columbia and the Pacific Salmon Foundation (Global Ocean Modeling 2021).

Several models currently being used in the Salish Sea have the ability to test scenarios by modifying inputs to reflect some defined set of observed or expected conditions. Some of these are simple and are based on conceptual underpinnings (Harvey et al. 2016; Sobocinski et al. 2017) but allow for direct stakeholder input to test cumulative effects or competing hypotheses. In many ways, models allow a glimpse into what a future Salish Sea could look like (see Vignette on the Salish Sea Model) by calibrating the model to existing or past conditions and modifying input parameters to reflect projections for the future. Models allow us to pose questions and make simulations about the ecosystem. But to have the most predictive power they must be calibrated to robust data collected at appropriate spatial and temporal scales. Meanwhile, in the absence of extensive data, simple models that are less data intensive provide insight for a range of possible outcomes.

The demand for a variety of modeling approaches arises from the need for quantitative tools that are capable of handling the multiple simultaneous impacts expected under climate change, continued urbanization and development, and varying management strategies. Most modeling efforts are in direct support of management; for example, we might use a model to identify areas with suitable conditions for eelgrass restoration (Thom et al. 2018) or to identify where oil spilled from a vessel may be transported by currents (Johannessen et al. 2020). Understanding fundamental ecological processes is essential for building robust frameworks, and models both rely on available data and inform where additional data are needed. To become truly powerful and integrative tools for fully understanding and successfully managing the ecosystem in the face of pervasive threats, models must incorporate (and harness) the transboundary, social-ecological system at multiple levels of spatial and temporal complexity.

In order to produce high-quality quantitative models, high resolution data collection, management, and dissemination is key. Leveraging regional capabilities in data analytics could build the data infrastructure needed to move into the next several decades. Our ability to build reasonable forecasts to prepare for what lies ahead is also predicated on robust data collection, identification of key variables, and analytical methods that allow for non-linear responses so common in ecosystems. Forecasting, in general, is an important aspect of modern environmental science, especially given the unprecedented rates of change to ecosystems in the Anthropocene.

There are many aspects of Salish Sea ecology and oceanography that went unmentioned in this report. For example, food web changes as a consequence of human impacts and/or climate change remain unresolved; a comprehensive set of models may provide insight where we lack detailed data. End-to-end models are now feasible because of improvements in the component sub-models (hydrodynamic models, food web models, individual-based models, etc.) and the availability of sufficient computing power to bring extensive datasets and simulations together. In June 2020, The Puget Sound Institute launched the Salish Sea Modeling Center as a host for various modeling efforts (Puget Sound Institute 2021). Strengthening this community of researchers and practitioners and the set of tools available, combined with continued data acquisition is of paramount importance in thinking about the Salish Sea as a complex system.

Create a Transboundary Salish Sea Data and Information Repository

Develop strategies for integrated data management, including efforts to harmonize data across the border and across disciplines, jurisdictions, and agencies. Long-term collection and curation of Salish Sea-wide data, information, and stories will support shared efforts toward transboundary science, policy, and education.

Assembling, harmonizing, sharing, and accessing Salish Sea-wide data and information is a grand challenge for our region. One of the most challenging aspects of a transboundary ecosystem like the Salish Sea is that science and management entities differ from one side of the border to the other, with varying missions, purviews, and systems. The complexity created by an international border is illustrated when researchers or managers attempt to find, share, and/or integrate data representing the bioregion or try to harmonize data from different countries. Leveraging existing data collection efforts and harmonizing data is not an insignificant task, but assembly and integration of ecoregion-wide data needs to be given higher priority to better evaluate status and trends within the Salish Sea as an ecosystem.

Different mapping schemes, units, scales of collection, and other discordant features make assembling comprehensive datasets a challenge. Harmonizing data is rarely a matter of simple calculation to arrive at common units; it can be a much more pervasive problem that makes envisioning and monitoring an ecosystem in its entirety a big challenge.

Cross-border data flows are not a new problem in the data analytics world (World Economic Forum 2020). Regions from the Middle East to Europe have recognized the importance of regional (transboundary) approaches for managing ecosystems, including water resources and air quality. The Salish Sea is no different in terms of political barriers, and harmonizing data in a region-wide initiative will further our ability to integrate across disciplines and agencies to support inferences about impacts in the Salish Sea and potential large-scale solutions.

Programs and systems to harmonize data may not need to be entirely novel. For example, existing programs that monitor fundamental structures and processes like eelgrass beds and water quality (temperature, salinity, dissolved oxygen, and pH) could coalesce to build a regional data management system so that transboundary analysis and evaluation is possible. The Strait of Georgia Data Centre is an excellent example of a data repository with strict metadata standards and cataloging procedures, but currently it is focused on Canadian data (Strait of Georgia Data Centre 2021). There are encouraging examples of data repositories in place and others could be built to accommodate disparate datasets and move toward true harmonization in data collection, storage, sharing, and archiving.

Ongoing projects with long-term data assets will need additional support to move toward an integrated system, but new data collection efforts could integrate across the border by design. New directed projects and long-term monitoring efforts can endeavor to include integrated approaches and move in the direction of "open science," whereby data, code, and products are shared freely and transparently (Hampton et al. 2015).

Mapping is one area where integration would be especially useful. For example, in the 1990s both the Washington and British Columbia governments supported ShoreZone mapping initiatives (ShoreZone 2021). Although used extensively over the last 20 years, the Washington survey has not been updated since it was created. Most of the British Columbia coast was also mapped at that time and has also not been updated. There is an opportunity to revisit the ShoreZone maps and compile new Salish Sea-wide data to take advantage of advances in technology and evaluate changes to the ecosystem in the last 20 years. A comprehensive coastal survey of the Salish Sea is possible given the continued development of the ShoreZone and other mapping protocols, and new technology like drones (capable of carrying sophisticated surveying instruments) could make a transboundary mapping effort less time-consuming and costly.

Funding and infrastructure support for integrated data management is required. Strategies to this end include: 1) data sharing and data curation agreements with funding for the long-term curation of system-wide data, 2) cooperation by scientists on both sides of the border to standardize methods and generate compatible datasets, and 3) funding to support the integration of existing data, quality assurance, data storage, and data upkeep.

Care and consideration will be needed for addressing Indigenous knowledge in data harmonization, integration, and management efforts. Tribal and First Nations communities are distinct with individual jurisdictions, sovereignty, and legal systems. Traditional knowledge and climate-related data are integral to full understanding, but what is collected and observed by one community may not be the same for neighboring Tribes and Nations. Specific research ethics arrangements and cultural protocols will need to shape knowledge and data sharing, with explicit consent and engagement from communities involved in the process.

In addition to collecting and managing data, there is need and opportunity for interpreting, analyzing, and ultimately sharing Salish Sea knowledge and science. Salish Sea science communicators, educators, and storytellers make meaning of what we observe and share it with the community. In addition to compiling and curating Salish Sea data, convenings and digital repositories for sharing information and stories are needed to develop and deepen Salish Sea learning and connection.

The biennial Salish Sea Ecosystem Conference is one of many regional, place-based forums for exchanging ideas, like the State of the Pacific Ocean Meeting, Vine Deloria Jr. Indigenous Studies Symposium, Pacific Estuarine Research Society Annual Meeting, and The Living Breath of wəɬəbʔaltxʷ: Indigenous Foods and Ecological Knowledge Symposium. These forums of exchange build on traditions of bringing people together to share status and trends, knowledge, community impacts of actions, and scientific dialogue and interpretation.

Additionally, the role of the media is also important for sharing information and stories about transboundary environmental topics. While logistics and expenses are barriers to more complete coverage within the bioregion (Moscato 2020), independent publications like Hakai Magazine, blogs like Salish Sea News and Weather, and numerous news and social media outlets are essential for conveying up-to-date information across boundaries.

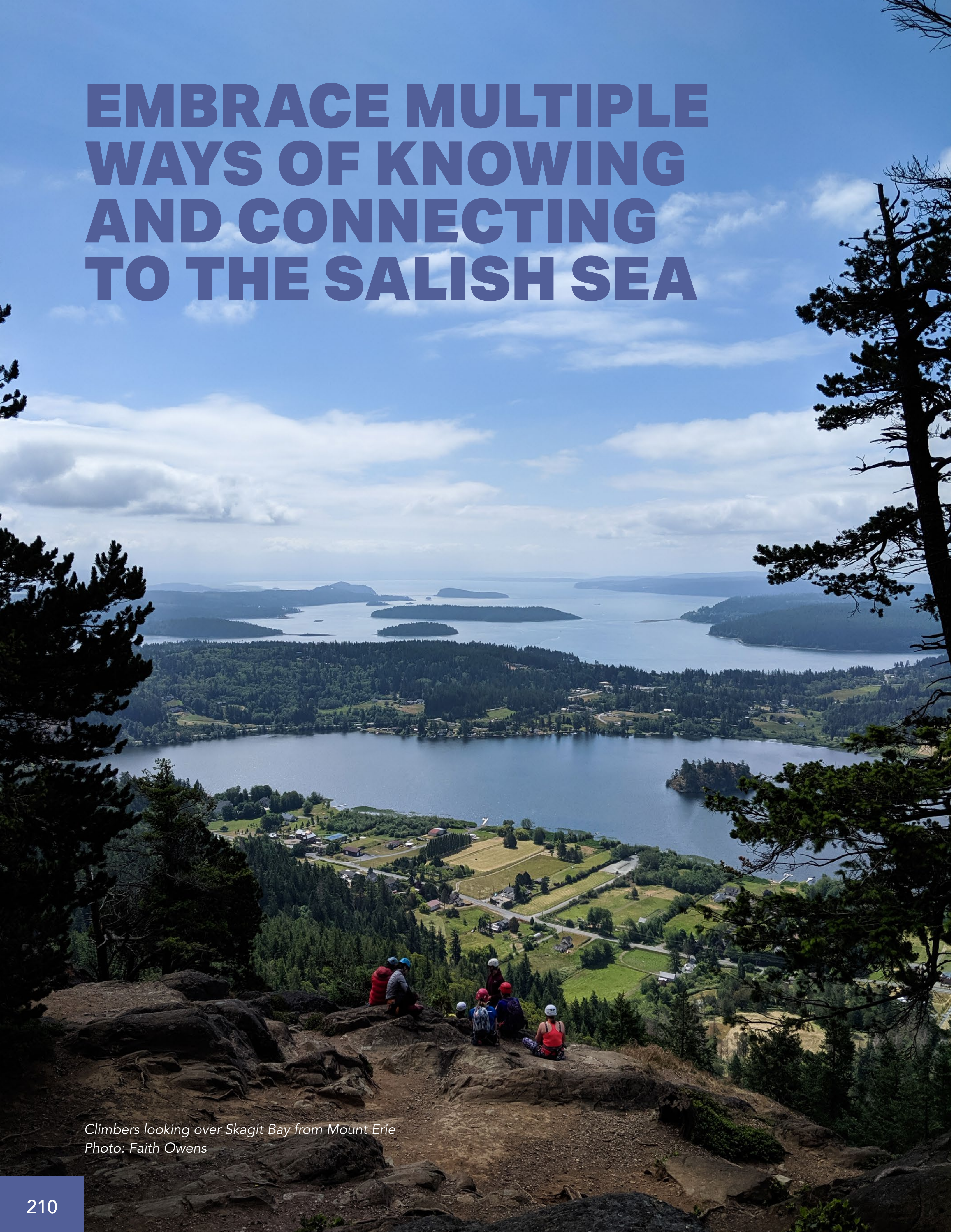
Many of the complexities—and opportunities—identified in this report were part of the rationale for creation of the Salish Sea Institute at Western Washington University in 2017. The Institute shares science, policy, and ecosystem learning across the Salish Sea by administering the Salish Sea Ecosystem Conference, convening transboundary conversations on critical issues, and developing curricula about our shared waters. This report is an expression of the Institute's mission to share Salish Sea science and foster responsible stewardship of the Salish Sea, inspiring and informing its protection for the benefit of current and future generations.

The Salish Sea Ecosystem Conference is a critical place for sharing Salish Sea science, knowledge, and practice. This meeting, previously the Puget Sound/Georgia Basin Research Conference, offers a biennial assembly for scientists, managers, educators, policy makers, leaders, and interested community members from the United States, Canada, and Tribes and First Nations to gather and share the latest scientific research, education, and management approaches relevant to the sustainability of the Salish Sea ecosystem.

This conference is an important forum for building place-based shared knowledge, policies, and practices necessary to guide actions for protecting and restoring the Salish Sea, with presentations archived and available (Salish Sea Ecosystem Conference 2021). The conference presents an excellent opportunity to highlight regional activities that may not be destined for peer-reviewed literature, but which nonetheless strengthen understanding. The conference also aids in relationship building among people and organizations working on behalf of the ecosystem, regardless of the sector they represent.

Aerial view of Seattle, Puget Sound, and the Olympic range
Photo: iStock

EMBRACE MULTIPLE WAYS OF KNOWING AND CONNECTING TO THE SALISH SEA



Climbers looking over Skagit Bay from Mount Erie
Photo: Faith Owens

Apply Social-Ecological Systems Science

Invest in initiatives that address human well-being and cultivate a strong sense-of-place within Salish Sea communities. Understanding the complex relationships between people and their environment can stimulate wise management decisions and development actions for ecosystem restoration and protection, as well as economic sustainability.

The marine social sciences inform and expand an understanding of the benefits of environmental literacy, cultural connections to the ecosystem, human well-being, and social equity (Bennett 2019), all of which are necessary to building resiliency in management within our complex social-ecological system. Efforts to identify and describe human connections within the Salish Sea are essential for a holistic approach to studying and understanding the Salish Sea and supporting future resilience and regeneration (Breslow et al. 2019).

For example, recent research on social-ecological systems from both an ecosystem services and human well-being perspective highlights the importance of well-being in fostering environmental stewardship in coastal regions (Bennett 2019). Combined with leadership by Tribes and First Nations, especially related to timely issues like sea level rise and climate change (e.g., Squaxin Island Tribe 2021; Northwest Indian Fish Commission 2016; Swinomish Indian Tribal Community 2010; Swinomish Climate Change Initiative 2021), efforts to conceptualize the Salish Sea as a social-ecological system will foster greater connectivity among residents across and promote a wider range of solutions.
A recent effort by the "Social Science for the Salish Sea Incubator" at the University of Washington's EarthLab outlined a research agenda for environmental social science that serves the ecosystem recovery needs of the transboundary waters of the Salish Sea (Breslow et al. 2019). Combined with growing knowledge of our biophysical system, understanding the complex relationships between people and their environment can stimulate wise management decisions and development actions for ecosystem restoration and protection, as well as foster human well-being and sense of place (see Vignette 22, Sense of Place).

Humans have made clear and unequivocal impacts to the Salish Sea ecosystem over the past two centuries. But humans have also made positive changes—from centuries of Indigenous management systems and technologies to policy and management efforts in the US and Canada to reverse the course of degradation and ensure cleaner air and water, eliminate or remediate toxic chemicals, improve regulations on harvest, and advance regulatory and restorative actions with broad public support. Understanding the complex and evolving relationship between Salish Sea communities and the ecosystem—the Salish Sea social-ecological system—will continue to present opportunities to change the trajectory of the ecosystem and our relationship with it.

Recognize Indigenous Knowledge Systems

Invest in initiatives that address human well-being and cultivate a strong sense-of-place within Salish Sea communities. Understanding the complex relationships between people and their environment can stimulate wise management decisions and development actions for ecosystem restoration and protection, as well as economic sustainability.

Coast and Straits Salish peoples hold thousands of years of knowledge and practice for managing and conserving the Salish Sea. The strength of this knowledge must be recognized and incorporated in all aspects of assessing, managing, and restoring the state of the Salish Sea and its ecosystem functions. Through co-management, creating ethical space for collaboration initiatives (Ermine 2007), and working together as equal partners, we can better ensure the future health and wellness of the Salish Sea.

Many Indigenous communities in the Salish Sea region are activating Indigenous legal and knowledge systems to fight climate change and protect their homelands and waters from further degradation. Examples include reclaiming traditional fisheries and implementing food sovereignty projects (see Vignette 23, Indigenous Management Systems; Claxton 2015; Curran et al. 2020), contesting industrial projects on traditional homelands (Norman 2017; Allen et al. 2018; Hanson 2018), engaging in archaeology and historical ecology research to inform future land practices, implementing Guardian Watchmen programs (West Coast Environmental Law 2018), developing climate adaptation strategies and plans (e.g., Puyallup Tribe 2016; Pacific Northwest Tribal Climate Change Project 2021), and studying and investing in culturally-grounded community health and environmental justice initiatives (e.g., Indigenous Health Indicators project; Swinomish Indian Tribal Community 2021).

Indigenous laws, languages, and traditional knowledge systems carry integral values, protocols, and understandings, including an understanding of human-environment relationships and roles and responsibilities embedded within. Through past and continued colonial practices, Indigenous communities have faced losses of significant knowledge and degradation of their homelands and waters. It is critical to support Indigenous communities to revitalize and restore cultural identities and ecological knowledge systems, and apply centuries of knowledge of the lands and waters of the Salish Sea to address emerging climate impacts in their communities.

Build Knowledge, Relationships, and Connection through Place-Based Learning

Invest in more intentional Salish Sea-wide place-based education, including support for Indigenous communities to build capacity for ecological and cultural restoration. Education initiatives can increase appreciation of the Salish Sea, creating stronger ties with the lands and waters around us.

Young people around the world are already calling on leaders to address global climate change. Here in our region, school systems from K-12 to higher education can provide students with a bioregional orientation to anchor these global hopes through connection to place and commitment to local change. Land- and water-based pedagogies and place-based education can support students to develop relationships of care and responsibility with their surroundings. SeaDoc's Junior Sea Doctors curriculum, for example, activates curiosity for 5th graders through exploration of the Salish Sea ecosystem. In Sooke, BC, a study of an innovative and place-based cross-cultural marine science program found that students "developed an increased environmental and cultural understanding of their local environment and feel that they have the ability to positively influence future decisions and events" (Ashurt et al. 2018). Place-based awareness of our ecosystems can engage students and their families in local environmental issues (Smith 2002).

Care for the natural environment must be cultivated alongside a deep understanding of our region's histories, cultures, and systems of power (Calderon 2014; Wildcat et al. 2014). The K-12 Since Time Immemorial curriculum in Washington State and curricular changes in British Columbia resulting from the Truth and Reconciliation Commission in Canada offer significant opportunities to shift how we teach and learn on Indigenous lands and waters. In colleges and universities around the Salish Sea, projects and programs are emerging that invite students into critical education about where we live, building on long-standing efforts in tribal colleges and Indigenous education programs. For example, at the University of British Columbia (UBC), the Knowing the Land Beneath Your Feet program is in development to introduce students, faculty, staff, and visitors to the rich place-based histories of the Musqueam Nation and other Indigenous communities on the UBC campus. At Western Washington University and Whatcom Community College, the place-based, experiential, and multidisciplinary Salish Sea Studies curriculum introduces students to the complex human-environment systems of our shared region and is specifically designed to cultivate relationships with the Salish Sea and a sense of place and responsibility.

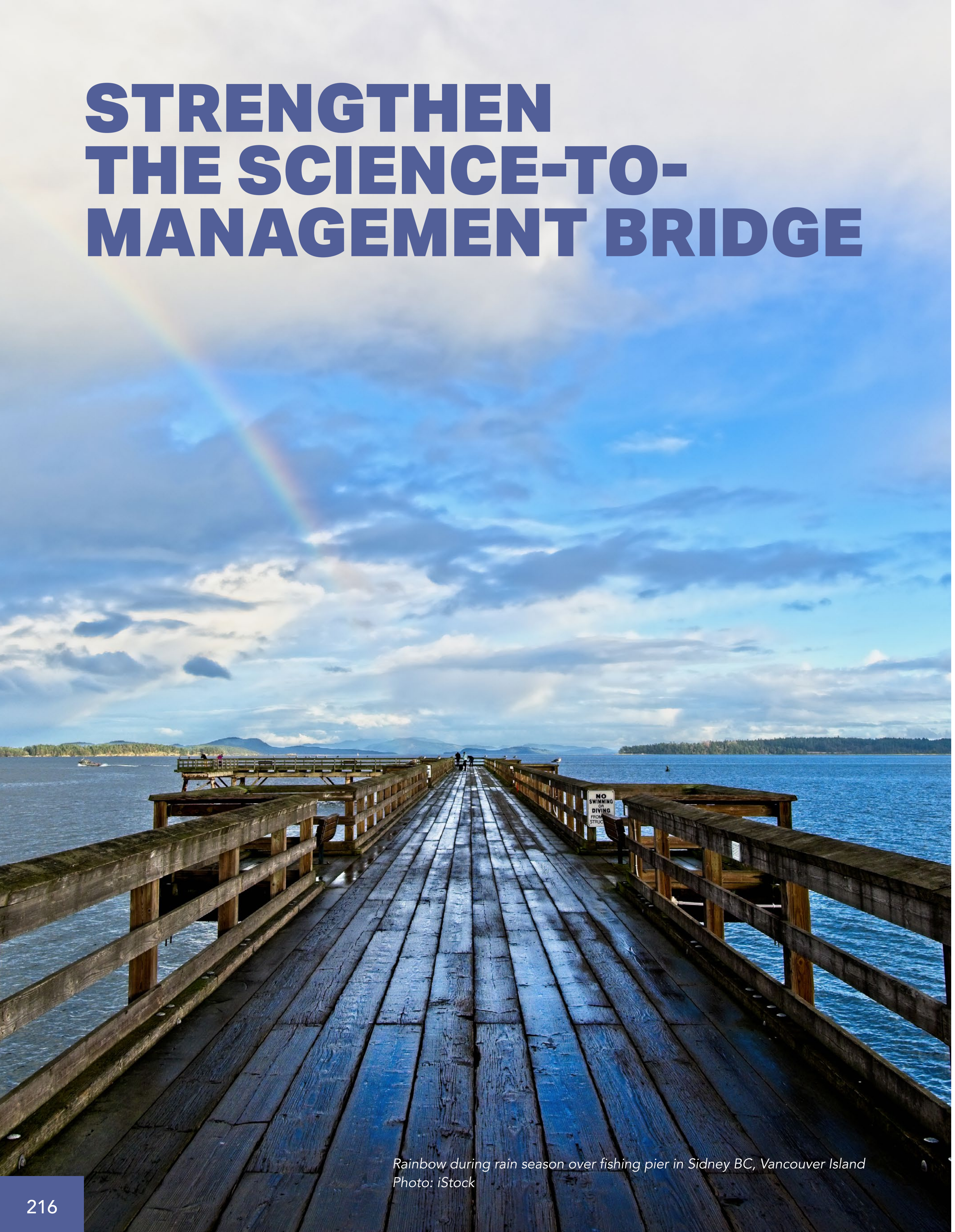
Many other programs exist that help foster appreciation of the Salish Sea, creating stronger ties with the lands and waters around us. These programs, happening at the community level and in formal educational programs, are powerful tools and models that can be supported, adapted, and replicated. Cultivating a sense of place, connection, and relational accountability can translate into attitudes and behaviors that will benefit the Salish Sea, ranging from community science and volunteerism to community organizing, legislative action, and regulatory change.

For example, Salish Sea Stewards, a program of the Skagit County Marine Resource Committee, offers forty hours of training for people interested in learning about the marine environment and volunteer opportunities to make a difference in their community. Hundreds of people have participated in the Biodiversity Galiano project since it launched in 2016 as a community-based effort to document local species around the island. There are many more examples across the Salish Sea. At the same time, there is great need and opportunity for more intentional cross-border place-based education, community science, and community organizing efforts (Säre 2020).

Of primary importance is support for Indigenous communities to build capacity for developing and participating in place-based education that is inclusive of youth and elders and connected to traditional lands, waters, and legal and knowledge systems. It is vitally important that place-based education be accessible and inclusive—reaching people at all income levels, at all ages, and from all backgrounds (Finney 2014).

An aerial look at the Nooksack River delta looking out to the Strait of Juan de Fuca. Photo: Frank James, M.D.

STRENGTHEN THE SCIENCE-TO-MANAGEMENT BRIDGE



Rainbow during rain season over fishing pier in Sidney BC, Vancouver Island
Photo: iStock

Enable Practitioners to Bridge Science and Community Investment

The Salish Sea benefits from many local- and regional-scale organizations that operate at the interface of science and practice, bringing additional participants into actionable science. Foster community science initiatives by promoting local involvement in data collection, restoration, and priority-setting to elevate calls to action within the Salish Sea.

The Salish Sea benefits from many local- and regional-scale organizations supporting science, traditional knowledge, conservation, and restoration. The interface of science and practice affords the opportunity to bring additional participants into actionable science. Fostering community science initiatives, in the vein of the existing Northwest Straits Commission and Ocean Wise, to support local involvement in data collection, restoration, and local priority-setting would elevate the call to action within the Salish Sea by engaging additional groups in larger-scale, but decentralized collaboration.

Innovative efforts in community science have contributed to understanding and action in the Salish Sea in meaningful ways. In British Columbia, a collaboration with Pacific Salmon Foundation, Fisheries and Oceans Canada, and Ocean Networks Canada (ONC) created a "mosquito fleet" of ten fishing vessels to collect oceanographic data during the spring and neap tides at specific locations in coastal waters of the Strait of Georgia (Strait of Georgia Data Centre 2021). The objective of this program is to achieve oceanographic monitoring of the Strait of Georgia at a broader temporal and spatial scale than any one agency could cover on their own, while cooperating with existing vessels. Ocean Networks Canada developed a smart phone application for sample data transfer so that the data can be sent directly from the small boats to ONC. In Washington, the Island County Beach Watchers made measurements along shorelines, documenting taxa, eelgrass coverage, beach slope and more. Using a framework developed collaboratively with professional scientists, the data collected were rigorous and contributed to real understanding of shoreline processes (Toft et al. 2017). This project and others have demonstrated that community scientists should be included not only as participants in data collection, but also as end users with deeper understanding, supporting the idea that a diversity of stakeholders should be included at all stages of program development.

First Nations on the central coast of British Columbia have developed independent assessment and monitoring initiatives, including the creation of "Guardian Watchmen" programs (West Coast Environmental Law 2018). Guardian Watchmen programs facilitate and enhance monitoring, protection, and stewardship of the lands and waters within traditional territories. Guardians, often hired by their Nation, utilize modern science methodologies while incorporating a wealth of local traditional knowledge, legal orders, values, protocols, and worldviews. Guardians gather information, validate predications, develop indicators, and collaborate in developing adaptative capacity. The K'ómoks First Nation has implemented a Guardian Watchmen program, which offers a successful model that could be adapted and adopted by scientists and nations around the Salish Sea.

The examples offered above highlight efforts where creativity and collaborative, participatory approaches yielded successful outcomes and greater investment in regional science. Support for these programs stands to benefit both the community and science-driven management.

Use Adaptive Management Tools to Strengthen Planning

Use adaptive management strategies to address cumulative impacts associated with climate change and human development in the Salish Sea. The iterative nature of adaptive management allows for simultaneously confronting complexity and uncertainty while also being proactive and responsive at local and regional scales.

Adaptive management is a systematic management process of planning, doing, assessing, learning, and adapting by applying what was learned, aimed at continually improving management policies and practices (Holling 1978; Walters 1986). This approach was conceptualized in the Salish Sea region and many of the underlying tenets are critically important for management today. For example, one central tenet asserts that "management involves a continual learning process that cannot conveniently be separated into functions like 'research' and 'ongoing regulatory activities,' and probably never converges" (Walters 1986). Indeed today, many decisions on environmental problems are made in the absence of perfect information and are most likely not perfect solutions.

In designing solutions for the Salish Sea, we know the system is impacted and changing, and any given solution may need to be updated as more understanding is gained. This approach involves adaptively managing: take some action, evaluate that action, and if the solution is imperfect, adapt the solution to improve it (Figure 6.1).

While adaptive management has been widely applied in other estuaries, like Chesapeake Bay (Boesch 2006), and to forest systems (Bormann et al. 2007), wetland restoration (Thom 2000), and fisheries (Walters 2007), there is need and opportunity to more broadly activate these strategies in the Salish Sea estuarine system. While it does not always lead to success due to lack of engagement, weak management experiments, and/or insufficient monitoring, the strength of adaptive management is in the recognition and confrontation of uncertainty (Allen & Gunderson 2011).

Given the uncertainty associated with multiple ecosystem factors (e.g., climate-driven increases in precipitation intensity, sea level rise, widespread impervious surfaces bringing contaminants to the estuary) that are all changing simultaneously and are not yet fully understood, adaptive management would seem not only a viable approach, but necessary. In his book on the subject, Walters states, "Even if managed systems do not keep slipping away and changing under us, there remains the problem of how to use accumulated data" (Walters 1986). Leveraging accumulated data and knowledge in the Salish Sea could help form a strategy to address the cumulative impacts associated with climate change and human development.

In a sense, traditional knowledge and management systems interpret and respond to feedbacks from the environment to guide resource management much as adaptive management approaches do (Berkes et al. 2000). Adaptive management emphasizes flexible decision making and responsive institutions, incorporation of various sources of knowledge, and an iterative learning process (Armatas et al. 2016). Traditional practices include a number of adaptations for the generation, accumulation, and transmission of knowledge and make use of local institutions for regulation (Berkes et al. 2000). And in fact, Tribes and First Nations have been leaders in developing Climate Adaptation Plans (e.g., Puyallup 2016; Jones 2020; Pacific Northwest Tribal Climate Change Project 2021). These plans set the stage for response to climate-driven changes by articulating expected impacts and potential strategies to mitigate or adapt to these impacts. Many Tribal lands are in low-lying areas of the Salish Sea and some communities are already feeling the effects of climate change. Building community health and resilience will necessarily involve environmental resilience and creative and adaptive solutions.

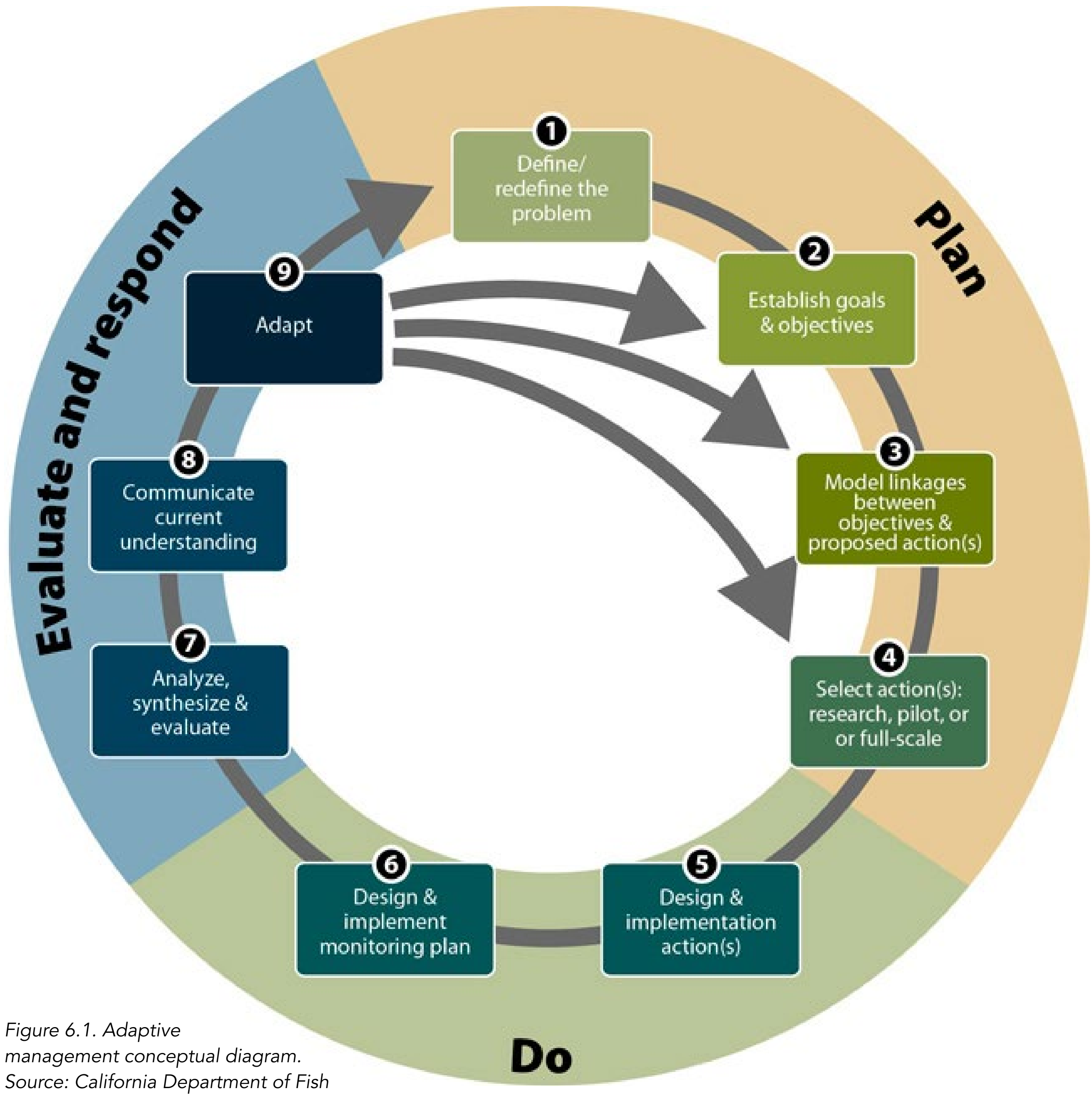


Figure 6.1. Adaptive management conceptual diagram. Source: California Department of Fish and Game 2015

Build Sustained and Regenerative Ecosystem Functions to Improve Resilience

Build resilience, especially at the land-sea ecotone where human infrastructure will exacerbate problems associated with rising sea level. Positive, protective, restorative, and regenerative actions are increasingly necessary as the population grows and threats from climate change alter ecosystem processes.

Given the unrelenting stresses and visible evidence of damages that have been done to the Salish Sea, we must foster both a sustainable and regenerative mindset for the ecosystem. Sustainability implies a steady-state "do no harm" approach, and in some regions of the Salish Sea this focus on sustainability may be sufficient to maintain ecosystem function and provisioning of ecosystem services. But due to the continuing threat of global climate change, we need to build resilience, especially at the land-sea ecotone where human infrastructure will exacerbate problems associated with rising sea level and the landscape's inability to adapt in the face of shoreline armoring and built structures. In order to confer resilience on the system we need to think regeneratively with respect to what we've lost in terms of ecosystem function (Reed 2007).

Cities such as Seattle, WA, Vancouver, BC, and Surrey, BC, are determining the sensitivity of drainage and wastewater systems to extreme precipitation events and planning for climate change mitigation and adaptation. These efforts include amending or implementing new codes and policies to be responsive to climate change, making physical modifications to existing structures, changing the way infrastructure is operated based on current and future conditions, embedding climate information into decision-making tools, and incentivizing changes in behavior. Because much of our built environment is upgraded or replaced on time periods longer than the rate of climate change and ecosystem disruption we are observing, the necessary policy, planning, and adaptive management tools will need to accelerate and continue to innovate to yield enough action and mitigation to keep pace.

We must build a system of responsiveness, based in science but incorporating the interconnected system of humans and environments. Our collective role as stakeholders in the ecosystem is to develop our relationship into one that creates a system of mutually beneficial relationships and the implicit knowledge of these relationships. This will require shifting the thought paradigm from the environment as a resource to be utilized to instead understanding the ecosystem as being part of a complex and integrated relationship with humans. While remediation and restoration have been tools in our ecosystem management kit for some time, regeneration re-envisions restoration to include an entirely new means of ecosystem function, recognizing that the ecosystem is constantly changing and "going back" will not be possible with continued perturbations. Positive, protective, restorative, and regenerative actions are increasingly necessary as the population grows and threats from climate change fundamentally alter ecosystem processes and our human dependencies upon those processes.

Snow geese at Reifel bird sanctuary
Photo: Yuri Choufour

21 HOW ECOLOGICAL TIME-SERIES CAN INFORM ON THE VULNERABILITY OF DIFFERENT MARINE SPECIES TO MAJOR CLIMATE STRESSOR EVENTS

Dr. Jackson W.F. Chu, School of Environmental Studies, University of Victoria

An important part of biodiversity monitoring includes assessing the differences in vulnerability across parts of an ecosystem. Hypoxia is one of the big three climate-related stressors causing biodiversity loss in the oceans. As the ocean warms, its capacity to hold oxygen becomes reduced. At the same time, concurrent shifts in circulation result in changes to how oxygen gets transported from the surface (where oxygen dissolves into the ocean) to the seafloor and from offshore to inshore areas. When a habitat experiences a substantial drop in oxygen, below the point needed to sustain everyday life, animals respond by migrating away, adapting to the new conditions, or dying from suffocation. The key to linking the biodiversity response to the oceanographic change is to simultaneously monitor both because high levels of variability are intrinsic to both sides in the ecology equation.

Since 2006, Ocean Networks Canada (ONC) has continuously collected oceanographic data at their Victoria Experimental Network Under the Sea (VENUS) observatory in Saanich Inlet, British Columbia, Canada (https://www.oceannetworks.ca/). ONC operates several of these permanently powered, cabled seafloor observatories in the Salish Sea. Real-time data are captured every minute and streamed to the internet for free public access. The Saanich Inlet VENUS observatory was the first to go online and has since become the longest continuous time-series among seafloor observatories worldwide. At launch, this new technology captured just how variable the annual oxygen cycle was in the Salish Sea and would eventually reveal the decline in the average oxygen level after 15 years of monitoring (Figure 1). A companion biodiversity time-series was also developed alongside the ONC time-series and used remotely operated vehicles (ROV) equipped with onboard high-definition cameras and oxygen sensors to monitor the benthic fish and invertebrate community living in this habitat. With both

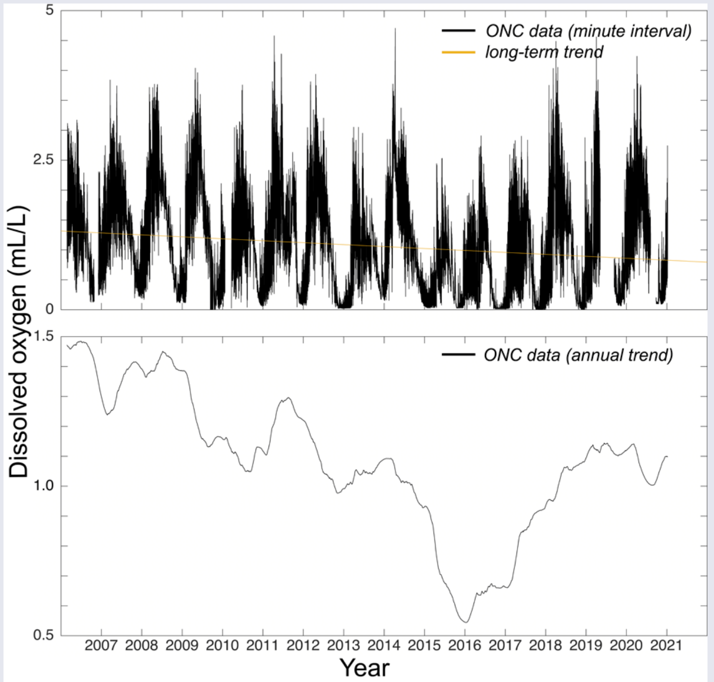


Figure 1. Long-term oxygen time-series from the Ocean Networks Canada cabled, seafloor observatory in Saanich Inlet, British Columbia, Canada. The 2016 severe hypoxia event can be appreciated from looking at the annual trend (one-year running mean) through the raw ONC data and the resulting impacts on the benthic fish and invertebrate community. Source: Open data from http://oceannetworks.ca.

time-series in place, the first eight years established a benchmark period that showed how seasonality in the Salish Sea creates annual cycling of habitat compression and expansion in Saanich Inlet (Chu & Tunnicliffe 2015). In 2016, this ecological monitoring program allowed an unprecedented collapse in the community to be captured and linked back to an extreme marine heatwave in 2016 (i.e., the Blob).

When the extreme marine heatwave occurred in 2016, it had the cascading effect of creating an equally severe hypoxia event in the Salish Sea (Gasbarro et al. 2019). Measuring the impact of this severe hypoxia event was only possible because of the benchmark period and the continued efforts to monitor the fallout for several years after the event had passed. The first sign that the community had reached a tipping point came from the commercially targeted species living in Saanich Inlet. Shrimp such as spot prawn (*Pandalus platyceros*), pink shrimp (*P. jordani*), and humpback shrimp (*P. hypsinotus*) were common in the annual surveys until they disappeared in 2016. Traits of commercially targeted species are often correlated with having a higher sensitivity to hypoxia stress (Chu & Gale 2017). While the shrimp are known to be hypoxia sensitive, they had never entirely disappeared from this site before. Other species, such as those that fishers refer to as "trash species", remained numerous. Populations of squat lobster (*Munida quadrispina*) and slender sole (*Lyopsetta exilis*) remained high and expanded their distributions into the hypoxic areas that usually harboured all the shrimp. All animals need oxygen to survive, but some are physiologically adapted to have higher hypoxia tolerance. Generally, low metabolic demands in squat lobster and slender sole allow them to survive exposure to conditions that are lethal to other species (Chu & Gale 2017; Tunnicliffe et al. 2020). Besides these outliers to the general hypoxia rules, the populations of most other species shrank. The decrease in population density, the absence of shrimp, and the loss of associated species interactions led to a general collapse in the community structure due to the severe hypoxia event (Gasbarro et al. 2019). In 2018, two years after the severe hypoxia event, oxygen conditions returned to normal, and the shrimp returned in abundance. However, the population of what was the most common species at this site, the cold-water coral *Halipteris willeomesi*, continued to decline.
Before 2016, *H. willeomesi* was consistently the most abundant animal observed in Saanich Inlet and had a peak population of approximately 6,000 individuals in 2008. Like the other hypoxia sensitive species, the coral population shrank as a result of the 2016 event. While the shrimp populations recovered by 2018, the coral population continued to decline to approximately 1% of their peak population size, with only 66 individuals observed that year (Figure 2). The 2016 event also introduced a new coral predator to the system. The striped nudibranch *Armina californica* had never been observed in the community before 2016, but a small population has since established itself and fed on the remaining corals in the most recent ROV surveys. The community has yet to recover fully because the coral population remains small, with only 77 individuals observed in the most recent ROV survey performed in 2020. If we exclude the effect of future extreme events, the coral population's recovery to historic numbers will likely take decades, if not centuries, given their low recruitment potential. (Chu et al. 2020).

The story in Saanich Inlet likely reflects what can occur throughout the northeast Pacific Ocean during an extreme climate stressor event. Saanich Inlet's featured species are found throughout the Salish Sea and have distributions throughout the northeast Pacific Ocean. Maintaining these time-series have been challenging but has been made possible through collaboration with Ocean Networks Canada, Fisheries and Oceans Canada, and the University of Victoria. Long-term biodiversity time-series are invaluable to understanding the current state of our rapidly changing oceans, and such data are exceedingly scarce in the deep-sea. This tireless effort has shown that continuous ecological monitoring is needed to establish the empirical connections between climate change and the vulnerability of species to extreme stressor events when they are exposed to conditions that exceed the norm.

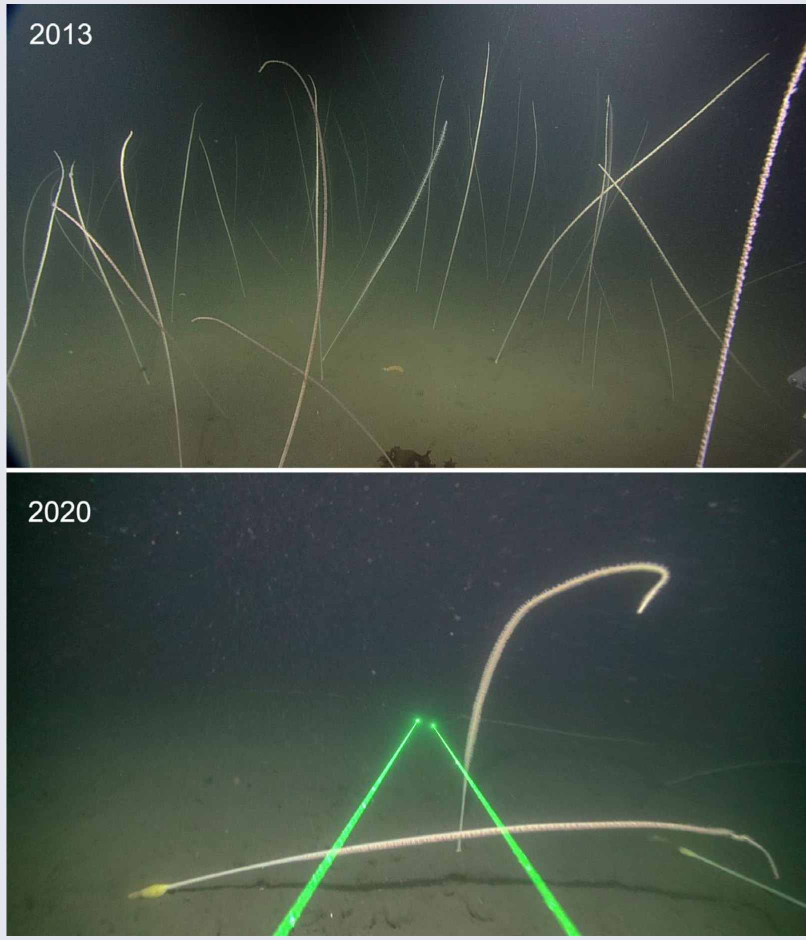


Figure 2. The density of the Halipteris willeomsi coral population before and after the 2016 severe hypoxia event in Saanich Inlet, British Columbia, Canada. Lasers are spaced approximately 10 cm apart in the lower panel.

22 | SENSE OF PLACE IN THE SALISH SEA REGION

Dr. David J. Trimbach, Department of Fisheries and Wildlife, Oregon State University

Sense of place refers to peoples' bonds and meanings associated with place (Masterson et al. 2017). Sense of place tends to include: place attachment (bond or connection to place); place dependence (reliance on place for need or goal achievement); place identity (identification with place); and place meaning (descriptions or imagery that define a place). These dimensions are connected and reflect individual or shared beliefs, emotions, symbols, memories, knowledge, feelings, behaviors, and experiences (Masterson et al. 2017). Sense of place is subjective, yet patterned, providing researchers with the ability to assess shared connections, understandings, meanings, and the potential to predict behaviors or perceptions.

Sense of place is recognized as integral to ecosystem health and recovery. This recognition stems from sense of place's links to: ecosystem services (World Health Organization 2005); human well-being (Biedenweg 2016); health (Donatuto et al. 2016); conflict (Breslow 2014); cultural practices (Poe et al. 2016); responses to place change (Marshall et al. 2019); place names (Trimbach 2019a); and pro-environmental behaviors (Junot et al. 2018). A strong sense of place contributes to human well-being (Biedenweg 2016) and influences pro-environmental attitudes or behaviors, like stewardship or responses to place change (Junot et al. 2018; Marshall et al. 2019). Sense of place can be understood, if not harnessed to address ecosystem challenges and recovery actions. This vignette outlines the status of sense of place in the Salish Sea region based on a non-exhaustive review of regional research.

Since time immemorial, Indigenous communities have developed distinct human-environment relationships. These relationships reflect the centrality of place in Indigenous knowledge and worldviews, and engagements in and through place (Johnson & Larsen 2013). These relationships are demonstrated through cultural keystone places (CKPs), or places with high biocultural diversity that are significant to people's identities and lifeways (Currier et al. 2015). For example, the Lekwungen people consider Tl'eches (an archipelago near Vancouver Island) integral to their community, as this specific place is a source of identities, knowledge, sustenance, and spirituality (Currier et al. 2015). According to Thom (2005), sense of place anchors "Coast Salish people in the world," and "continues to be experienced and thought of in uniquely Coast Salish ways," as reflected in cultural narratives and practices (Thom 2005, p. 4). Practices include activities like traditional shellfish harvesting that link heritage, experiences, and social connections to sense of place (Poe et al. 2016). Regional species like shellfish (Poe et al. 2016), orca (Colby 2013), salmon (Breslow 2014), and gray whales (Deutsch 2017) are also connected to the region's Indigenous communities, reflecting why sense of place is considered an Indigenous community health indicator, as degradation or place change could negatively impact Indigenous communities (Donatuto et al. 2016). Overall, Indigenous peoples have unique senses of place, illustrating the necessity to protect the places that have long been stewarded by these communities and the necessity to integrate Indigenous voices in environmental decision-making.

Place names are powerful symbols that contribute to and reflect sense of place. Place names denote shared or competing identities, attachments, meanings, memories, histories, languages, politics, physiographic features, and cultural narratives. The Salish Sea is a recent official place name (approximately 2009-2010) aimed to acknowledge the Coast Salish people and is not without contention (Tucker & Rose-Redwood 2015). SeaDoc Society, working closely with the author (Trimbach 2019a), co-created a bi-national survey aimed at understanding Salish Sea geographic literacy and place name knowledge. Overall, the region's residents are largely unfamiliar with the Salish Sea as a place name in both descriptive and visual (map) forms, with British Columbia residents having greater familiarity compared to Washington residents. This lack of familiarity or use of inconsistent place names may equate to inconsistent, conflicting, or divergent senses of place among regional residents. These results highlight the power of place names and benefit, if not need, of a shared place name to foster a shared sense of place and responsibility to address shared challenges.

The Puget Sound Partnership's Human Wellbeing Survey (2018-present) and Sense of Place Vital Sign are, to the author's knowledge, the only government-supported effort to explicitly and consistently gauge sense of place of the natural environment in the region (Biedenweg 2016; Puget Sound Partnership 2019). The results reveal that 70% Puget Sound residents have a strong sense of place (index of indicators, including attachment and identity) connected to Puget Sound's environment (Fleming & Biedenweg 2019). The results highlight that residents are attached to, identify with, benefit from, and maintain positive perceptions of the environment. The findings are supported by a complementary 2019 survey (Trimbach 2019b) that shows residents' sense of place of Puget Sound's shorelines, including place meanings that emphasize the importance of natural attributes. While, to the author's knowledge, no paralleled survey has been implemented in British Columbia, Statistics Canada has conducted national surveys, known as the General Social Survey, with a sense of place component. The 2013 results show that 45% of British Columbia residents have a strong regional (British Columbia) sense of place (belonging; Statistics Canada 2015). A 2019 survey showed that British Columbia residents do have a strong regional identity, with 75% stating their province is important for sense of place (identity; Environics Institute for Survey Research 2019). These collective findings reflect that transboundary residents do have a sense of place connected to the region and/or its environment.

Based on this review of regional research, residents appear to share a connection to the Salish Sea region, although those senses of place likely vary. This sense of place could be effectively integrated and applied in environmental planning, management, or governance to better align these efforts with how the region's communities feel, think, experience, and engage the Salish Sea and its environs. More research is also needed to better reflect the full spectrum of sense of place in the region. The author advocates for further sense of place research that better reflects regional and community sense of place diversity.

Photo: David Trimbach

23 INDIGENOUS MANAGEMENT SYSTEMS CAN PROMOTE MORE SUSTAINABLE SALMON FISHERIES IN THE SALISH SEA

Dr. William I. Atlas[1], Dr. Natalie C. Ban[2], Dr. Jonathan W. Moore[3], Adrian M. Tuohy[4], Spencer Greening[5,6], Dr. Andrea J. Reid[7,8], Nicole Morven[8], Elroy White[9], William G. Housty[10], Jess A. Housty[11], Dr, Christina N. Service[12], Larry Greba[12], Sam Harrison[12], Katherine IR Butts[13], Elissa Sweeney-Bergen[14], Donna Macintyre[14], Dr. Matthew R. Sloat[1], Katrina Connors[15]

Introduction and Overview

Indigenous peoples of the Northern Pacific Rim have harvested salmon for more than 10,000 years (Cannon & Yang 2006; Muckle 2007), and Pacific salmon (*Oncorhynchus* spp.) form the foundation of social-ecological systems encompassing communities from California to Kamchatka and Northern Japan (Yoshiyama 1999; Muckle 2007; Tabarev 2011). Through continuous placed-based interdependence with salmon (Campbell & Butler 2010; Cannon et al. 2011; Ritchie & Angelbeck 2020), Indigenous societies formed deliberate and well-honed systems of salmon management (Carpenter et al. 2000; Turner & Berkes 2006; Menzies & Butler 2007). These systems promoted the sustained productivity of salmon fisheries, which likely rivaled early colonial commercial fisheries in their scale (e.g., Craig & Hacker 1940; Glavin 1996; Meengs & Lackey 2005), yet far outperformed them in their resilience and continuity (Campbell & Butler 2010).

In Canada and the United States, Indigenous sovereignty and resource stewardship were forcibly disrupted beginning in the mid-19th century and replaced by colonial government authority. Colonization altered the scales, methods, and locations of salmon harvesting and governance, stripping rights and jurisdiction from Indigenous people, and beginning a struggle for access and authority that continues to this day (Higgs 1982; Harris 2001; Heffernan 2012; Carothers et al. 2021). Commercialization transformed the values and motivations of fishers, as fishing companies and colonial governments sought to develop and extract resources for global markets, and outlawed Indigenous subsistence and trade fisheries (Newell 1993; Yoshiyama 1999; Harris 2001). In the rush to extract wealth from the watersheds of the Pacific Northwest, salmon habitats were damaged, often irreparably, by logging, mining, diking, dam construction, urbanization, and other destructive land uses (Baird 1875; Stone 1892; Miller 2010).

Among the most profound transformations in management brought on by colonization was the shift to mixed-stock ocean fisheries, which gradually replaced Indigenous in-river salmon fisheries as the primary method and scale of harvest (Cobb 1921; Higgs 1982; Morishima & Henry 2000). Many salmon in the Eastern Pacific traverse United States, Canadian, and international waters during their migratory life cycle, and fish are routinely harvested outside their state or country of origin (Malick et al. 2017; Pacific Salmon Commission 2020a). Today, most salmon caught from Southeast Alaska south to California are harvested in marine mixed-stock fisheries, an anomaly in a 12,000+ year history of Pacific salmon fishing.

With a changing climate contributing to declining abundance, and conservation risks posed by modern non-selective mixed-stock fisheries, salmon stocks are struggling to provide sustainable social, economic, and ecological benefits for society. In Canada, long-term and recent declines continue to erode the health and resilience of salmon centered social-ecological systems (COSEWIC 2018; Walters et al. 2019; Steel et al. 2021). Likewise, in Puget Sound, record low sockeye and Chinook returns to the Fraser, and Endangered Species Act-listed Chinook, chum, and steelhead populations limit the cultural, environmental, and livelihood benefits provided by these formerly abundant species (National Marine Fisheries Service 2006; National Marine Fisheries Service 2017; Pacific Salmon Commission 2020b). However, salmon from the Salish Sea are routinely harvested in faraway mixed-stock fisheries, sometimes at unsustainably high rates (National Marine Fisheries Service 2019; Pacific Fisheries Management Council 2020; Pacific Salmon Commission 2020b). The migratory life cycle of salmon thus poses additional challenges to sustainability by creating mismatches between management decisions, fishery opportunities, and the biologically relevant processes that sustain salmon populations (e.g., river disturbance, rainfall and temperature, and ocean climate and productivity; Bottom et al. 2009; Malick et al. 2017).

Despite the destructive impacts of colonization, Indigenous culture and knowledge are resurgent in Canada and the United States. In the face of declining salmon stocks, variable and changing climate conditions, and negative downstream consequences of mixed-stock fisheries, Indigenous fishing technologies and management systems are being documented and reinvigorated (Menzies & Butler 2007; White 2011; Claxton 2015; Atlas et al. 2017). Importantly, many Indigenous fishing technologies enable terminal and selective fishing, reducing mixed-stock fishery risks and creating opportunities to harvest abundant species or hatchery-marked fish. Having supported vibrant salmon-dependent communities for millennia before European settlement, we believe systems of Indigenous salmon management can support long-term opportunities for equitable and sustainable harvest of salmon across western North America.

Indigenous Fishing Technologies and their Application around the Salish Sea

In the Salish Sea, a wide variety of fishing technologies were formerly employed by Indigenous peoples, and the technology, social organization, and governance frameworks of salmon fisheries were tailored to the unique demands of each watershed or fishing location (Figure 1). A more complete discussion of Indigenous fishing technologies can be found in our recent article (Atlas et al. 2021)

Weirs

Around the Salish Sea, one of the most common fishing technologies was weirs—river-spanning fences that channeled salmon into traps or fishways—that were built annually in most river systems (Stewart 1977; Higgs 1982; Harris 2001). In larger rivers around the Salish Sea, there were often multiple weirs (Harris 2001; Ritchie & Angelbeck 2020). Authority over a specific weir location was typically held by hereditary leaders who regulated access in accordance with laws guiding reciprocal relationships with returning salmon and surrounding villages, promoting sustainability, and protecting access for communities that depended upon them (Harris 2001; Trosper 2002; Mathews & Turner 2017). Historical and ethnographic evidence indicates that deliberate conservation measures in the management of weir fisheries allowed returning salmon to pass weirs and reach upriver spawning areas, and strictly enforced rules governed their use (Swezey & Heizer 1977; Higgs 1982; Harris 2001; Ritchie & Angelbeck 2020). Weirs remain a trusted tool for monitoring, in-season management, and selective harvest.

[1] Wild Salmon Center, Portland, OR, USA
[2] School of Environmental Studies, University of Victoria, Victoria, BC, Canada
[3] Earth2Ocean Group, Biological Science, Simon Fraser University, Burnaby, BC, Canada
[4] Wild Fish Conservancy, Duvall, WA, USA
[5] Faculty of Environment, Simon Fraser University, Burnaby, BC, Canada
[6] Gitga'at First Nation, BC, Canada
[7] Centre for Indigenous Fisheries, Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, BC, Canada
[8] Nisga'a Nation, BC, Canada
[9] Central Coast Archaeology, Bella Bella, BC, Canada
[10] Heiltsuk Integrated Resource Management Department, Bella Bella, BC, Canada
[11] QQs Projects Society, Bella Bella, BC, Canada
[12] Kitasoo/Xai'xais First Nations, Klemtu, BC, Canada
[13] Lax Kw'alaams Fisheries, Prince Rupert, BC
[14] Lake Babine Nation Fisheries, Burns Lake, BC
[15] Pacific Salmon Foundation, Vancouver BC, Canada

Fish Traps

Throughout the Salish Sea, intertidal fish traps—built from stone or wood and net fibre—were a common method of harvesting salmon among Indigenous and early-colonial people (Stewart 1977). Archaeological evidence of intertidal fish traps is present in estuaries around the region, living testaments to the utility, durability, and widespread application of this technology (Caldwell et al. 2012; Greene et al. 2015). Intertidal fish traps typically targeted salmon as they staged in estuaries and lower rivers. Ethnographic evidence suggests that traps were often used to selectively harvest salmon, and that traps were dismantled during periods of inactivity to allow salmon to escape unharmed (Menzies & Butler 2007; White 2011).

Fish traps remain a promising tool for low-impact selective fisheries, and a pilot project in the lower Columbia River has demonstrated their potential as a sustainable, economically viable, and less fossil fuel intensive alternative to current mixed-stock fishing technologies like gillnets, seines, and ocean trolling (Tuohy et al. 2019). Fish traps are currently being considered for legalization in the lower Columbia River by the Washington Department of Fish and Wildlife through an Emerging Commercial Fishery Designation (RCW 77.65.400). If successful, a similar legal action could be taken in Puget Sound to legalize fish traps for selective harvest of hatchery fish and release of Endangered Species Act-listed wild salmonids (Tuohy et al. 2020).

Reef Nets

Reef nets are endemic to the Salish Sea, and have long been used by Straits Salish Tribes on both sides of the border to harvest salmon in shallow-water marine approaches to their spawning rivers (Easton 1990; Claxton 2015). The long leads of the reef net are anchored at their ends, tapering back in a funnel shape towards a central net that is fished between two boats (Figure 1). Migrating fish are observed from an upright position, or from a platform in many modern reef net vessels. When salmon have entered the heart of the net the sides are raised into the adjoining boats allowing the fish to be harvested selectively or released.

The construction and use of reef nets was done following Indigenous Straits Salish law and tradition, and was a major source of subsistence, wealth, and cultural stability for Straits Salish people in the pre-colonial era. Reef netting canoes were traditionally captained by individuals who held inherited rights to long-established reef netting locations. The nets were themselves sacred objects imbued with feminine life-giving qualities (Claxton 2015). Despite being protected under treaty agreements, reef nets were outlawed in Canada in the early 1900s (Claxton 2015), and reef net sites used by Indigenous Peoples were appropriated in Washington State to make way for commercial fish traps (Lummi Tribal Archives 1894).

Reef nets continue to be used in commercial fisheries in Washington State. Given the depressed status of many salmon species in Puget Sound, they have recently been highlighted as a selective fishing technology, and efforts are underway in the United States and Canada to reinvigorate reef net fisheries for tribal subsistence and commercial harvesting (e.g., Claxton 2015).

Conclusions

Indigenous fishery systems offer alternatives to contemporary resource management due to differences in cultural values and knowledge systems that motivated their development. Whereas colonial societies have largely emphasized extraction of resources for short-term profit, Indigenous management has tended to emphasize multi-generational sustenance and reciprocity (Trosper 2002; Ban et al. 2019; Curran et al. 2020). Indigenous management also shares several key attributes with contemporary resource management; for example, both are guided by knowledge gained through the continuous observation of natural systems (Carpenter et al. 2000; Turner & Berkes 2006; Lertzman 2009). However, key differences exist in the scale, time horizons, and organizational hierarchies of Indigenous and contemporary resource management systems (Figure 2).

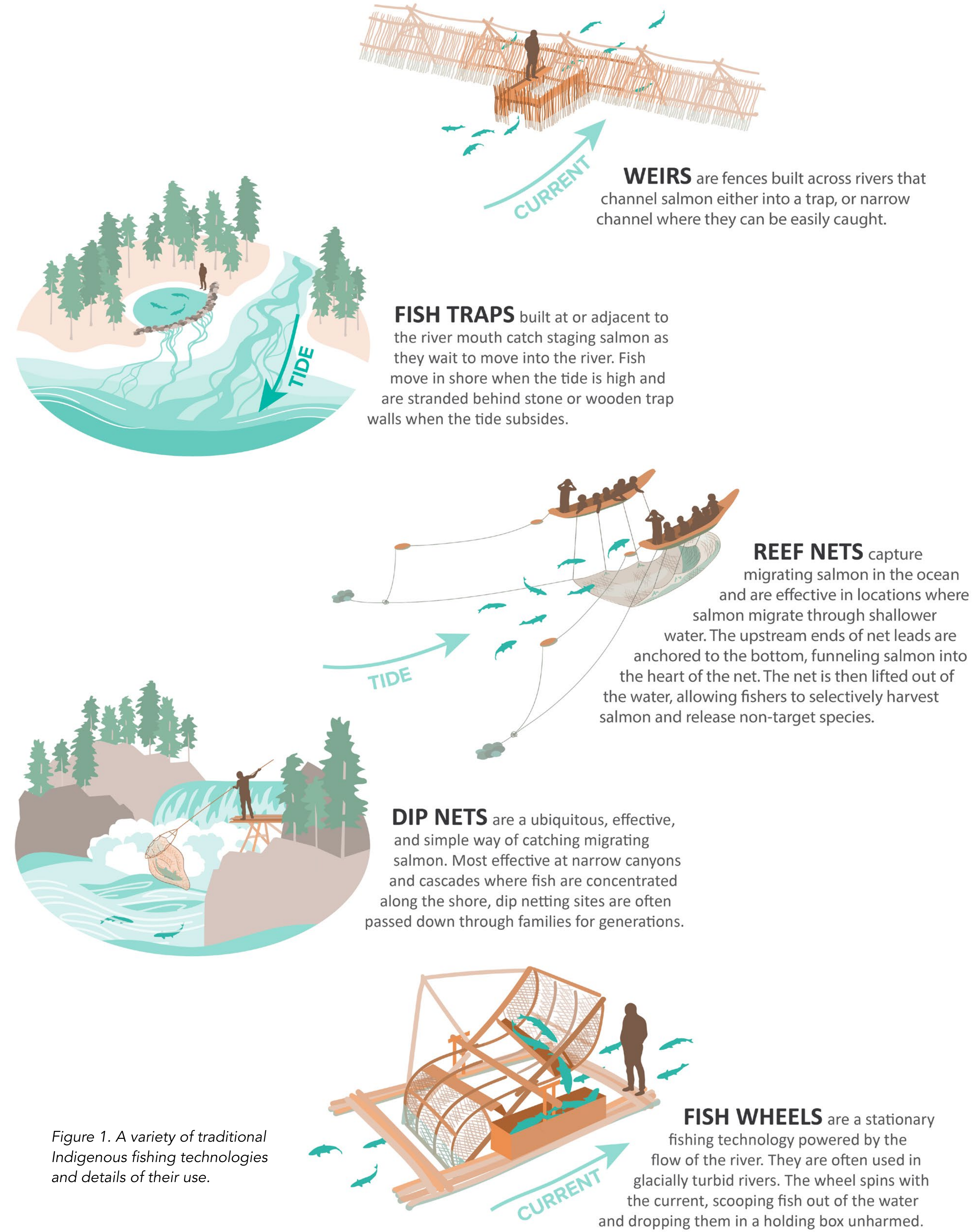


Figure 1. A variety of traditional Indigenous fishing technologies and details of their use.

Fisheries targeting single stocks may be a particularly valuable tool when the status of individual populations is variable and management resources are limited. In cases where circumstances necessitate mixed-stock harvesting, reef nets, seine nets and fish traps—centuries old technologies with deep roots in the Salish Sea—can support selective harvest. By allowing fishers to harvest healthy wild or hatchery-enhanced stocks, and safely release non-target species, these technologies hold the potential for much wider application in selective fisheries. A critical first step is overturning antiquated laws prohibiting fish traps and weirs to enable broader use in fisheries in Washington State and British Columbia.

There is an urgent need to realign the scales of fisheries to reduce conservation risks, create equitable opportunities for sustainable harvest, and support salmon-dependent species and ecosystem processes (Healey 2009; Ward et al. 2009; Gayeski et al. 2018; Walsh et al. 2020). Despite ongoing environmental changes and declining abundance, salmon are resilient and often highly productive, and can support sustainable harvest if fisheries are downscaled to target specific healthy stocks. In the absence of this transformation, salmon managers will continue to face a set of wicked tradeoffs posed by mixed-stock fisheries, where harvesting abundant stocks erodes the biodiversity that underpins future fishing opportunity and resilience (Connors et al. 2020). But more selective and terminal fisheries will produce limited benefits if mixed-stock ocean fisheries continue to intercept a majority of harvestable salmon before they return to their natal watersheds, and terminal fisheries are not immune to overharvesting (Freshwater et al. 2020). For many species, allocation decisions driven by the Pacific Salmon Treaty remain a barrier to recovery and limit the potential for transformation towards more locally managed fisheries. Thus, mixed-stock fisheries will likely need to forgo some opportunity if the social and ecological benefits of terminal and selective fisheries are to be realized (Connors et al. 2020).

Amidst rapid and deep-rooted changes in ecosystems and fisheries, 10,000+ years of Indigenous stewardship knowledge and a growing scientific consensus tell us that revitalizing Indigenous systems of harvest and resource governance should be an urgent priority. Broader application of terminal and selective fishing technologies can help rebuild resilient locally managed fisheries, and in doing so contribute to long-needed shifts in the balance of power, legitimacy, and opportunity. With humility and in a spirit of collaboration, let us work together to bringing the story of salmon fisheries full circle, supporting the revitalization of Indigenous management systems that formerly supported sustainable fisheries for millennia. In doing so, we will move closer to a goal shared by many Pacific Northwesterners: that wild salmon remain at the foundation of North Pacific cultures and ecosystems for generations to come.

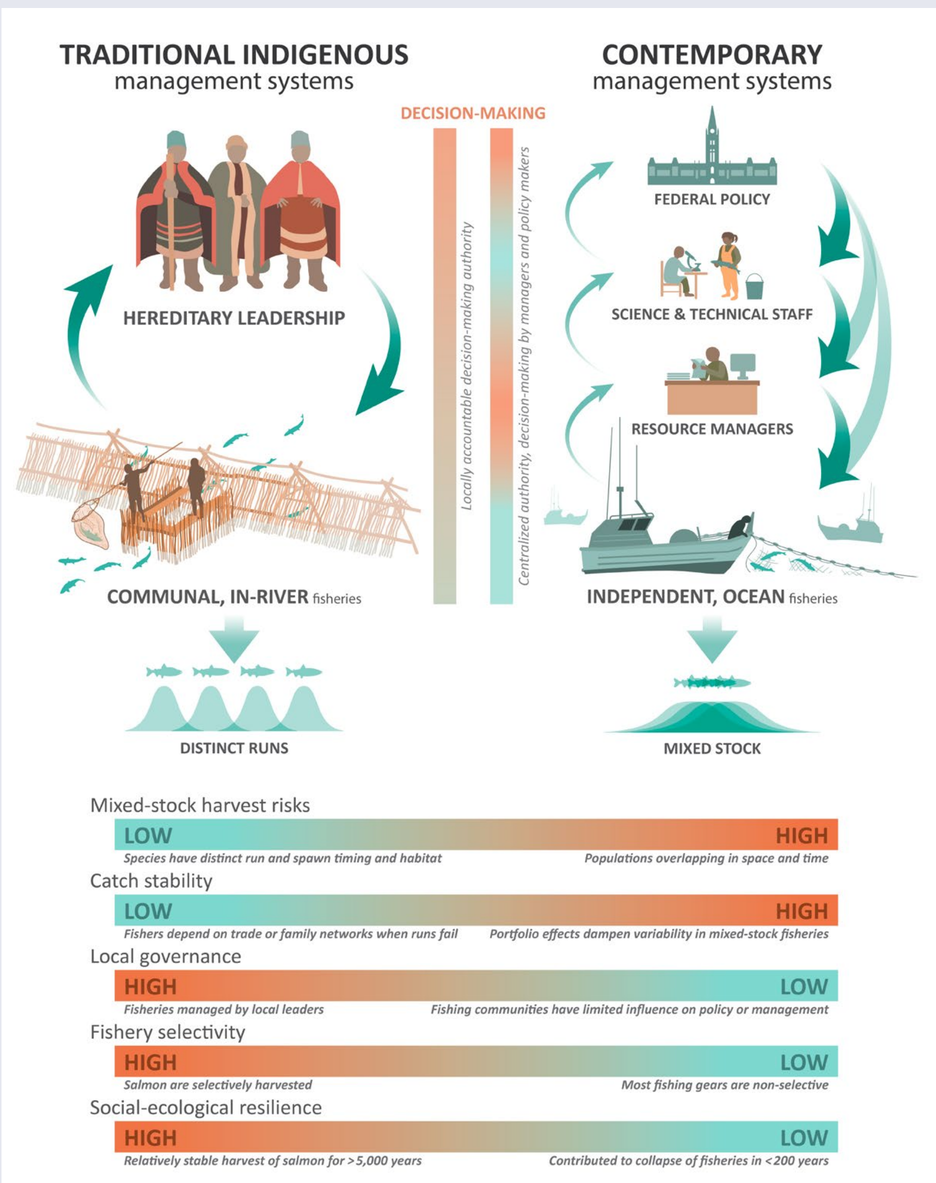


Figure 2: A comparison of Indigenous and contemporary fishery management systems depicting how decision-making authority is distributed within each system, with insights into their social-ecological performance across five key metrics.

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Yelm Jim's fish weir on the Puyallup River, circa 1885. Source: Washington State Archives.

SECTION 7

THE FUTURE OF THE SALISH SEA?

Herring spawn & fishing boats off of Cape Lazo, BC
Photo: Yuri Choufour

A CALL TO ACTION

Ginny Broadhurst, Natalie Baloy, and Kathryn Sobocinski

What is the state of the Salish Sea? As this report documents, the Salish Sea is compromised by the cumulative impacts of global climate change, regional urbanization and a growing population, and intensive human use and abuse across the ecosystem over the last two centuries. While biological response varies throughout this diverse ecosystem —owing to biophysical drivers like geology and oceanography, and gradients of human impacts—caring for our shared waters in more holistic, multi-jurisdictional, and multi-disciplinary ways is sorely needed to be responsive to current and emerging threats.

Over time, government agencies and others around the Salish Sea have implemented numerous management programs, policies, and regulations to protect the ecosystem. Transboundary governance agreements have been signed and initiatives launched. Yet, as the Coast Salish Gathering Treatise asks, "Would the Salish Sea be in the state [it's] in if, in fact, these agreements were doing what they intended to do?" (2010:6).

Ecosystem decline has outpaced restoration and protection (Treaty Indian Tribes of Western Washington 2011; State of the Sound 2019). Layers of laws, treaties, regulations, and jurisdictions make for a complicated and even fragmented approach to Salish Sea governance (Clauson & Trautman 2015), exacerbating challenges from global climate change to local lack of enforcement and funding. The cost of business as usual is high—staggering—especially as we anticipate further declines and unknown repercussions for the region (Kehoe et al. 2021).

It is clear that structural changes are needed if we are to be truly effective in supporting a thriving ecosystem. Righting the course to a more functional and sustainable Salish Sea requires strategic planning, systemic changes in governance, large-scale investment, and significant shifts in our economic systems, collective values, and relationships to lands and waters (Treaty Rights at Risk 2011; Poe et al. 2016; Caillon et al. 2017; Kehoe et al. 2021).

> *"In the past 150 years, since the nation states of Canada and U.S. made their claims to our territory, we have seen the thriving Salish Sea of our Ancestors impacted by pollution, development and environmental mismanagement."*
>
> Coast Salish Gathering Treatise 2010

It is unlikely that we will fully reverse the legacies of urbanization and industrial impacts to the Salish Sea, but it is possible to improve conditions from what they are today. Much can be achieved through well-coordinated restoration, mitigation, and protection measures to restore ecosystem function and create greater resilience to the future impacts we know are coming. In some cases, the ecosystem will rebound on its own once harms are removed, but action is imperative.

We end this report with a series of questions to invite dialogue and ignite action. While the science documented in this report is sound, science alone is not a solution. Enhanced collaboration is needed but is also not the only answer. Many voices beyond our own will be needed to respond meaningfully to the challenges presented in this report. Our questions acknowledge the limitations of this project, and invite dynamic and diverse responses across disciplines, sectors, communities, cultures, and borders. We ask readers to consider your roles, responsibilities, and opportunities for caring for our shared waters in the days, years, and generations ahead. We encourage you to add your own questions and answers to this list for debate and action in organizations, institutions, and communities across the Salish Sea.

> Can we create and commit to shared goals to recover the Salish Sea? Can agencies, people, and organizations acknowledge the Salish Sea as a shared ecosystem to shape their work ahead?
>
> Can we liberate ourselves from a pollution-based economy in support of a healthy Salish Sea and connected watersheds for all beings who call this place home?
>
> How will we collectively prioritize restoration and stronger protection of the Salish Sea through shared governance, shared ingenuity, and shared responsibility to act?
>
> How will we recognize Indigenous sovereignty and laws, and support Coast Salish involvement and representation at all decision-making tables?
>
> How and when will we fully apply science, Indigenous knowledge, and multiple ways of knowing in making critical policy decisions?
>
> How can we sustain and deepen existing practices while also building new habits and systems to connect people with each other and to the Salish Sea?

As a convenor of many voices in the Salish Sea, the Salish Sea Institute recognizes the need to gather and promote diverse ideas to build solutions collectively and collaboratively. Through curriculum, collaborations, and convenings, we look forward to stimulating dialogue, connection, and collective action for restoring and protecting the Salish Sea.

This report synthesized science to help us all better understand the Salish Sea as an interconnected and shared ecosystem facing many unrelenting threats. In light of this realization, how will we collectively move forward together?

Our hope is that the science presented here serves to inform, illuminate, and ultimately ignite deep discussion and meaningful action, from grassroots efforts to large-scale collective and governmental investments. Addressing centuries of degradation, swelling human population, and global climate change requires vision and solutions for the future that are innovative, adapt easily to local needs, and spark change in our collective values and relationships with the Salish Sea.

Regeneration of the Salish Sea will require multi-faceted and collaborative approaches that support greater understanding through education and science, plus sufficient political will, public support, and systemic changes. Fundamental alteration of human–environment relationships, coupled with new and ambitious goals, are needed to change the arc of anthropogenic impacts (Diaz et al. 2020). Will we choose to work together to make these commitments and investments toward a future of resilience and connection across the Salish Sea?

> *"Science gives us knowing, but caring comes from someplace else."*
>
> **Robin Wall Kimmerer**

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Nisqually National Wildlife Refuge near Olympia, WA
Photo: iStock

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