SECTION 7

How is Puget Sound's Water Quality Changing?

Puget Sound is projected to experience a continued increase in sea surface temperatures, and continued declines in pH and dissolved oxygen concentrations. These changes, which could affect marine ecosystems and the shellfish industry, will be affected by variations in coastal upwelling and circulation within Puget Sound. While it is currently not known how climate change will affect circulation and upwelling in the region, these processes will continue to fluctuate in response to natural climate variability. Impacts on marine ecosystems and shellfish farming generally point to increasing stress for fish and shellfish populations. Efforts to address Puget Sound's water quality are increasing, particularly in the areas of ocean acidification monitoring and implementation of risk reduction practices in the shellfish industry.

Climate Drivers of Change

DRIVERS ***Wind patterns, natural climate variability, and projected changes in temperature and precipitation can all affect water quality in Puget Sound.[A]***

- *Observations show a clear warming trend, and all scenarios project continued warming during this century*. Most scenarios project that this warming will be outside of the range of historical variations by mid-century (see Section 2).[1,2]
- *Warming.* The salinity of Puget Sound's waters is tightly linked to freshwater inflows from streams. Increasing air temperatures will result in more precipitation falling as rain instead of snow, leading to more freshwater inflows into Puget Sound during winter months, and decreased freshwater inflows during summer. In addition, increasing air temperatures are expected to drive a continued increase in water temperatures, increasing the likelihood of harmful algal blooms (see Section 3).
- *Heavy rain events are projected to become more intense.* Current research is consistent in projecting an increase in the frequency and intensity of heavy rain events.[3] These changes would lead to a further increase in winter streamflow.
- *Most models are consistent in projecting a substantial decline in summer precipitation.* Projected changes in other seasons and for annual precipitation are not consistent

[A] Throughout this report, the term "Puget Sound" is used to describe the marine waters of Puget Sound and the Strait of Juan de Fuca, extending to its outlet near Neah Bay. The term "Puget Sound region" is used to describes the entire watershed, including all land areas that ultimately drain into the waters of Puget Sound (see "How to Read this Report").

among models, and trends are generally much smaller than natural year-to-year variability.[2] The projected decrease in summer precipitation could accentuate the temperature-driven decrease in summer streamflow.

- *Wind patterns are not projected to change*. There are no projected changes for wind speed or the strength of low pressure systems in the region (see Section 2). Wind patterns affect upwelling, mixing, and currents within Puget Sound, all of which have an influence on water quality.

- *Although long-term changes in climate will likely influence currents and mixing in Puget Sound, natural climate variability is also expected to remain an important driver of regional circulation.* Natural variability in both weather patterns and ocean conditions will continue to affect water quality in Puget Sound. It is not known how variability might change with warming.

Circulation and Water Quality in Puget Sound

CIRCULATION **Puget Sound's water quality is strongly affected by changes in coastal upwelling and circulation.** Currents and mixing within Puget Sound, the rate of exchange through the Strait of Juan de Fuca, and the frequency and intensity of upwelling along Washington's coast all affect the water quality of Puget Sound.

- *Seasonal upwelling along the Washington Coast affects water properties within Puget Sound*. Coastal upwelling (see Section 6) brings nutrient-rich (nitrate, phosphate, silicate) water into the Strait of Juan de Fuca and Puget Sound. These nutrients promote phytoplankton blooms and biological productivity. Upwelled waters are also low in oxygen and high in CO_2, which can stress fish and be harmful to calcifying species (e.g., shellfish). Seasonal upwelling is also a major driver of changes in salinity, oxygen, and nutrients in Puget Sound.[4]

- *Seasonal and year-to-year variations in freshwater inflows and air temperature affect Puget Sound water quality.* Freshwater inputs from rivers and local surface air temperatures vary seasonally and from year-to-year. The salinity of Puget Sound's waters is strongly related to surface freshwater inflows from rivers, while the temperature of Puget Sound's surface waters is strongly related to surface air temperatures and regional weather patterns that determine the strength and direction of winds.[5] Variations in river input alter the circulation and the density stratification[B] of Puget Sound (see Section 6). Stratification affects water quality via its impact on mixing between surface and deep water. Greater stratification, for example due to increased freshwater inflows, results in an increased risk of low oxygen in deeper waters ("hypoxia"), and can alter the timing of spring blooms (causing a possible mismatch with the timing needs of larval fish species).[6]

[B] "Stratification" occurs when the water column has varying density levels. Stratified water has less dense water at the surface and the densest water at the bottom. For more on stratification, see Section 6.

- *We do not know how climate change will affect Puget Sound circulation.* Projected changes in upwelling, El Niño/La Niña (or ENSO, the El Niño Southern Oscillation), and the Pacific Decadal Oscillation (PDO) are ambiguous (see Section 2). Although there is high confidence in the projected warming and in the associated shifts in freshwater input (earlier snowmelt, higher winter streamflow, and lower summer streamflow; see Section 3), it is not known how these will compare to other factors affecting circulation (see Section 6).

Warming Water in Puget Sound

WARMING WATER ***Surface and subsurface water temperatures in Puget Sound and the Northeast Pacific Ocean are warming and could alter the marine ecosystem in Puget Sound.*** Puget Sound water temperatures are influenced by regional effects and via inflows from the Northeast Pacific Ocean. Warmer water holds less oxygen than colder water. Increased water temperatures can also increase the likelihood of harmful algal blooms (HABs). Warmer and low-oxygen conditions stress some cold-water fish and shellfish species that are commercially important to the region.

- *Water temperatures are rising in Puget Sound.* Water temperature increases ranged from +0.8 to +1.6 °F from 1950 to 2009 for stations located at Admiralty Inlet, Point Jefferson, and in Hood Canal.[C,7]

- *Water temperatures are rising in the Northeast Pacific Ocean.* Northeast Pacific coastal sea surface temperature has increased by about +0.9 to +1.8°F over the past century (1900-2012)[8] and subsurface temperatures (~300-1300 ft. depth) have increased by +0.45 to +1.1°F from 1956 to 2006.[D,9]

- *Coastal ocean surface temperatures are projected to rise.* Sea surface temperatures in the Northeast Pacific Ocean are projected to warm by about +2.2°F by the 2040s (2030-2059, relative to 1970-1999).[E,F,10] This long-term trend will be obscured by short-term (up to several decades) variability resulting from coastal upwelling and climate variability such as ENSO and PDO.

- *Long-term trends in surface air temperature may be affected by natural variability.* Natural climate variability has a strong influence on trends: one previous study estimated that about half of the observed increase in air temperature in the

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C Trends are statistically significant at the 90% confidence level, based on a seasonal Kendall test.

D Trends are statistically significant at the 95% confidence level, based on a student t-test.

E Projected change in sea surface temperature for model grid points near the coast between 46° and 49°N. Based on an ensemble of 10 global model projections and a moderate (A1B) greenhouse gas scenario.

F Greenhouse gas scenarios were developed by climate modeling centers for use in modeling global and regional climate impacts. These are described in the text as follows: "very low" refers to the RCP 2.6 scenario; "low" refers to RCP 4.5 or SRES B1; "moderate" refers to RCP 6.0 or SRES A1B; and "high" refers to RCP 8.5, SRES A2, or SRES A1FI – descriptors are based on cumulative emissions by 2100 for each scenario. See Section 1 for details.

northern hemisphere (1900-1990) is a result of random natural variability (see Section 2).[11]

Harmful Algal Blooms

HARMFUL ALGAL BLOOMS ***Climate change may increase the magnitude and frequency of Harmful Algal Blooms (HABs).*** Often called "red tides," harmful algal blooms are a public health concern due to the toxins subsequently found in shellfish, and also have negative consequences for ecosystems. The dinoflagellate (a type of microscopic marine organism) *Alexandrium catenella* is often responsible for harmful algal blooms in Puget Sound. *A. catenella* generally blooms in July through November, and blooms are often associated with warm surface water and air temperature, low streamflow, weak winds, and small tidal variability.[12] While there is research on the influence of climate change and other anthropogenic influences on harmful algal blooms throughout the world,[13] and a growing body of research on *A. catenella* within Puget Sound, more research is needed to understand the effects of climate change on other harmful algae species that are found in the region.

- *Climate change may increase growth rates of harmful algal species*. Small increases in growth are projected for *A. catenella* throughout Puget Sound as conditions (e.g., temperature, salinity) become more favorable (Figure 7-1).[G,14]

- *Increasing water temperature is projected to expand the window of opportunity for harmful algal blooms.* By the end of the century (2070-2099, relative to 1970-1999), the number of days with favorable conditions (i.e., the "window of opportunity") for harmful blooms of *A. catenella* in Puget Sound is projected to increase by an average of +13 days, and may begin up to 2 months earlier and persist up to 1 month later compared to present conditions. However, if sea surface temperatures in Puget Sound increase past a threshold that exceeds the temperature range for *A. catenella* blooms, the window of opportunity in Puget Sound may then decline.[H,I,15]

- *Ocean acidification may increase the toxicity of some harmful algal blooms*. The interaction of high carbon dioxide concentration projected under ocean acidification and silicate limitation[J] increases the toxicity of the diatom *Pseudo-nitzschia*

G Climate data from 2 global climate models (CCSM3 and ECHAM5) from CMIP3 under the SRES A1b greenhouse gas scenario for 1969-2069 compared to historical conditions in 1970-1999. Ocean model simulations conducted using Modeling the Salish Sea (MoSSea).

H Based on an ensemble of 20 global climate models and the moderate (A1b) greenhouse gas scenario (from Mote and Salathé 2010) for the 2020s, 2040s, and 2080s representing averages for 2010-2039, 2030-2059, 2070-2099.

I The harmful algal bloom window of opportunity declined at a temperature increase of +2.2°F. Temperature increases between +0.9°F and +2.2°F were not tested.

J Biological productivity is frequently controlled by the availability of the least abundant nutrient. "Silicate limitation" refers to conditions in which productivity is limited by a lack of silicate ($SiO3$), an important nutrient for certain classes of marine organisms.

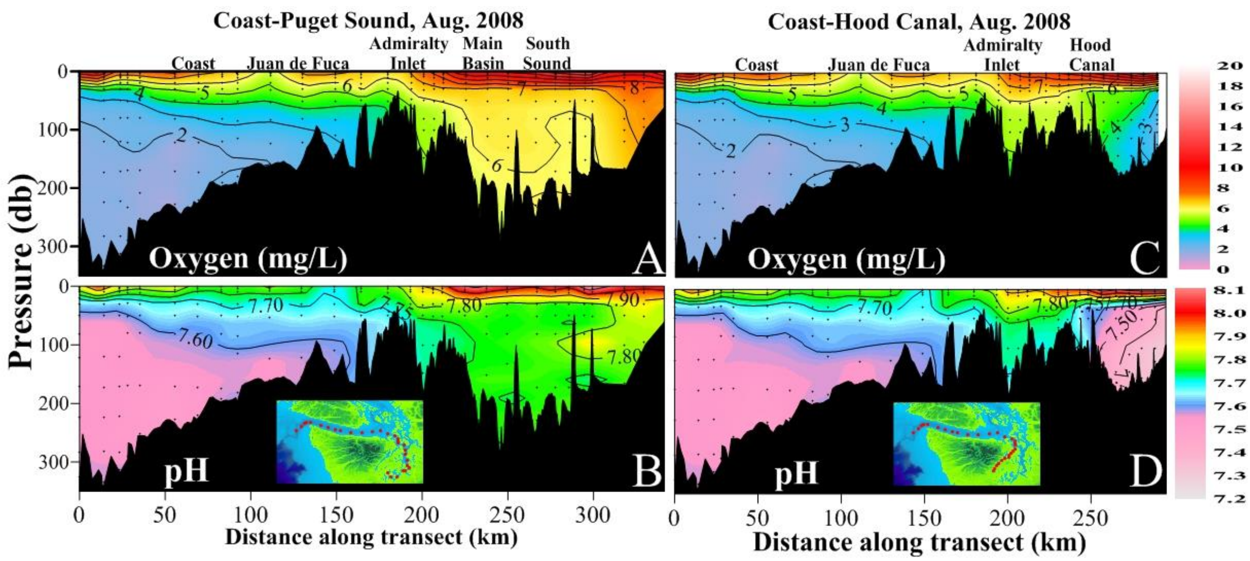

Figure 7-1. Observations from August, 2008: Oxygen and pH are lowest in the deep waters of the Strait of Juan de Fuca and Hood Canal. These figures show the dissolved oxygen concentration (top) and pH (bottom) as a function of depth in the water column (y-axis goes from 0 to 350 m, or about 1150 ft., below the water surface). The inset maps show the paths followed for each transect. The left-hand column shows the results of one transect, which goes from the Pacific Ocean at the entrance to the Straight of Juan de Fuca, to the southern end of Puget Sound. The right-hand column shows the results for a transect that ends in Hood Canal. The height of the sea floor is shown in black, and common landmarks are labeled at the top of the figure (for example, note how shallow the water column is at Admiralty Inlet). Black dots represent measurement locations. *Figure Source: Modified from the original presented in Feely et al. 2010,[24] courtesy of NOAA Pacific Marine Environmental Laboratory.*

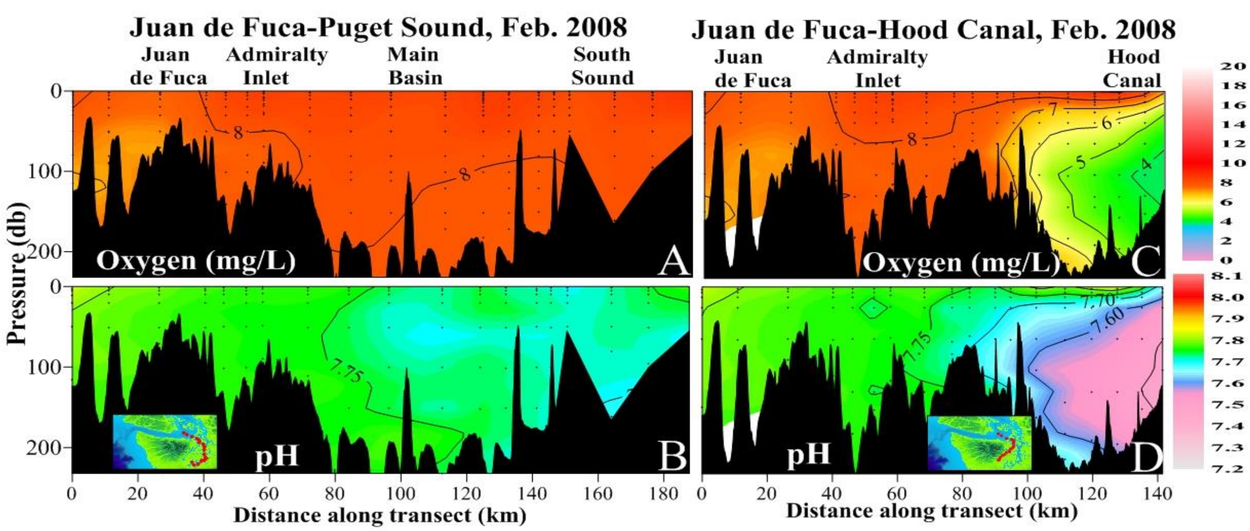

Figure 7-2. Observations from February, 2008: Oxygen and pH fairly uniform, except in the interior of Hood Canal, where there is a zone of low pH and low oxygen. The figure is identical to Figure 7-1, with one exception: the transects do not extend all of the way out to the Pacific Ocean but instead stop at the Strait of Juan de Fuca (see map insets). *Figure Source: Modified from the original presented in Feely et al. 2010,[24] courtesy of NOAA Pacific Marine Environmental Laboratory.*

fraudulenta, which is another harmful algae species in Puget Sound.[K,16] Although silicate is not currently a limiting nutrient in the majority of Puget Sound, observations suggest that it is declining in abundance relative to nitrogen concentrations,[17] and projections indicate increases in Puget Sound nitrogen levels (see below).[18] This suggests that Puget Sound conditions may shift from nitrogen- to silicate-limited conditions in the future. Combined with projected acidification of Puget Sound's waters, this could result in increased toxicity of *Pseudo-nitzschia blooms*.

- *Increases in harmful algal bloom events represent a threat to human and marine health and commercial fisheries.* Shellfish closures and fish deaths damage Washington's shellfish industry, valued at ~$108 million per year.[L,14]

Ocean Acidification

OCEAN ACIDIFICATION ***Ocean acidification is increasing, and is projected to continue to increase, with consequences for Puget Sound's marine ecosystems and shellfish industry.*** The chemistry of the ocean along the Washington coast has changed due to the absorption of excess CO_2 from the atmosphere. Ocean acidification occurs when the pH of the ocean decreases (acidity increases) due to the uptake of CO_2 from the atmosphere.[M] Conditions vary by location and from season to season (Figures 7-1 and 7-2), but appear to have already reached levels that can affect some species (see Section 11).[19]

- *Ocean acidification is increasing.* The pH of the Northeast Pacific Ocean surface waters decreased by −0.1, corresponding to a +26% increase in the hydrogen ion concentration, since the pre-industrial era (since about 1750)[20] and by −0.027 from 1991 to 2006.[21]

- *Ocean acidification will continue to increase.* The pH of Washington's coastal waters is projected to continue to decrease due to increases in global ocean acidity: pH is projected to decline by –0.14 to –0.32 by 2100 (relative to 1986-2005; corresponding to an increase in the hydrogen ion concentration of +38 to +109%).[M,N,22] The patterns of low pH observed in Puget Sound are largely a result of natural processes: mixing, circulation, biology. By the time the atmospheric CO_2

K Determined from laboratory experiments with pCO_2 levels of 200 ppm (preindustrial), 360 ppm (modern day), and 765 ppm (projected for 2100) and silicate levels of 8.4 ppm (pre-industrial), 8.2 ppm (modern day), and 7.9 ppm (projected for 2100).

L Based on 2008 and 2009 data from the Pacific Coast Shellfish Growers Association.

M Although the acidity of the ocean is projected to increase, the ocean itself is not expected to become acidic (i.e., drop below pH 7.0). Average global ocean surface pH has decreased from 8.2 to 8.1 (a 26% increase in hydrogen ion concentration, which is what determines a liquid's acidity) and is projected to fall to 7.8-7.9 by 2100. The term "ocean acidification" refers to this shift in pH towards the acidic end of the pH scale.

N Projections are a particular class of global climate models called "Earth System Models". The 12 models used in this study model the carbon cycle, and can therefore provide estimates of ocean-atmosphere CO_2 fluxes. The numbers give the range among all models and two scenarios: both a low (RCP 4.5) and a high (RCP 8.5) greenhouse gas scenario.

concentration has doubled, ocean acidification could account for 49-82% of the pH decrease in the deep waters of Hood Canal.[23,24] The CO_2 concentration is projected to double by about 2050 for a high greenhouse gas scenario (RCP 8.5), or after 2100 for a low scenario (RCP 4.5, see Section 1). This long-term trend will be modified by short-term variability due to upwelling, nutrient inputs, and other factors.[23,24,25]

- *Other factors influence the pH of marine waters.* For instance, ocean acidification accounts for 24-49% of the total increase in dissolved inorganic carbon[O] in the deep waters of Hood Canal relative to estimated pre-industrial values. The remaining trend is a result of increased biological productivity in response to human or natural nutrient inputs. [24] Natural drivers of acidification include variability in upwelling and river runoff; additional human influences include nutrient runoff (e.g., from fertilizers) and built structures that alter currents.

- *Research on ocean acidification in Puget Sound is limited by a lack of observations*. The lack of high-quality, long-term, carbon time-series measurements in Puget Sound makes it hard to directly determine the increase in anthropogenic CO_2 in the region.[24] Refer to the *"Climate Risk Reduction"* subsection below (page 7-9) for more information about ongoing ocean acidification monitoring efforts in Puget Sound and the Pacific Northwest.

Dissolved Oxygen Concentrations in Puget Sound

DISSOLVED OXYGEN ***Dissolved oxygen levels are declining and are expected to continue to decline due to both climatic and non-climate factors.*** Oxygen concentrations in Puget Sound are affected by warming, changes in the northeast Pacific Ocean, freshwater inflows, and by human and natural sources of nutrients. Low oxygen levels (below 5 mg/L) can stress fish species, and extreme low oxygen events (hypoxia, below 2 mg/L) have caused fish kills in areas of Puget Sound such as Hood Canal.[26]

- *Dissolved oxygen concentrations in the Northeast Pacific are declining.* From 1960 to 2009, May through September dissolved oxygen concentrations have declined by -1.15 ± 0.35 mg/L (a decline of roughly −25%) at a depth of 500-650 ft. off the central Oregon coast.[P,27] Over the period 1956-2006, dissolved oxygen concentrations at Ocean Station Papa (50N, 145W) declined by about −22%, on average, for waters between about 300 and 1300 ft. in depth.[D,9]

- *Dissolved oxygen concentrations are declining in the Strait of Georgia, just north of Puget Sound.* Oxygen concentrations at depth have declined by −0.56 to −1.6 mg/L in May-June from 1971 to 2009 (a decline of roughly −13% to −29%), primarily due

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O Dissolved Inorganic Carbon, or DIC, refers to the concentration of carbon stemming from CO_2 dissolution in water. When CO_2 dissolves in seawater, it forms a buffer solution composed of carbon dioxide (CO_2), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) ions.

P The uncertainty in the trend corresponds to the 95% confidence limits.

to coastal upwelling of water with low dissolved oxygen levels.[Q,28] If this trend continues, parts of the Strait of Georgia could occasionally become hypoxic as early as 2042, though this depends on the strength of mixing between surface and deep waters.

- *Observations of Puget Sound dissolved oxygen concentrations are too short to estimate trends.* Observations of dissolved oxygen concentrations that include measurements extending from the surface to the bottom of Puget Sound date back to 1999. Although the observations show that coastal upwelling has a strong influence on dissolved oxygen concentrations, the record is not sufficiently long to distinguish a long-term trend from natural variability.[4] Combined data sources between 1950 and 2009, however, suggest consistent decreases in dissolved oxygen in the Strait of Juan de Fuca, Admiralty Inlet and Hood Canal, which implies that the change may be driven by North Pacific Ocean waters entering Puget Sound.[7]

- *Observed trends in dissolved oxygen are influenced by natural variability, data availability, and geographic variations within Puget Sound.* Observations from different times and locations reflect a combination of local influences, distinct patterns of natural variability, data availability, and possible measurement biases. These factors can all have an influence on individual trend estimates.

- *Puget Sound oxygen concentrations are projected to decrease as a result of increased air temperatures, declining oxygen concentrations in the Northeast Pacific, and increasing nutrient inputs due to human activities.*[R] Model simulations estimate that nutrient runoff due to human activities (for example, fertilizers) causes over –0.2 mg/L in cumulative dissolved oxygen depletion compared to natural conditions in Puget Sound. Increasing nutrient runoff due to human activities is not a consequence of climate change. Models project that by 2070 (2065-2069, relative to 1999-2008) dissolved oxygen could decrease by more than –1 mg/L in the Strait of Juan de Fuca and dissolved oxygen could decline by more than –0.6 mg/L in Central Puget Sound and Hood Canal.[S,29] It is not known what proportion of this change is due to warming.

Nutrient Concentrations in Puget Sound

NUTRIENTS ***Puget Sound nutrient levels are projected to increase due to non-climatic factors: climate change has not been identified as a dominant factor affecting nutrient concentrations in Puget Sound****.* Increased nutrient levels within Puget Sound enhance biological growth and productivity near the surface and lead to oxygen loss through respiration and decomposition in deeper water. Nutrient inputs are projected to continue to increase with projected population growth. Nitrogen in particular is naturally occurring in rivers and streams, and has also increased as a result of population growth and human activities.[29,30] Although climate could indirectly influence nutrient

[Q] Trends are statistically significant at the 95% confidence level.

concentrations, current studies do not quantify this effect.

- *Although observations of Puget Sound nitrate and phosphate levels show concentrations that are increasing, the records are too short to quantify the effect of warming.*[4,31] Observational records are not of sufficient length to reliably distinguish long-term trends due to climate change from natural variability or other human influences. For example, measurements from 1999-2014 show that the observed increase in nitrate and phosphate concentrations in Puget Sound's surface waters have not been accompanied by a parallel change in silicate concentrations. This suggests that the recent increase is due to a human impact on nutrient fluxes (e.g., changes in land use and development), and is not related to climate change.[17,18]

- *The Northeast Pacific Ocean is the largest source of nutrients for the Strait of Juan de Fuca and Puget Sound.* There are four physical factors governing nutrient concentrations in Puget Sound: the rate of exchange with Pacific Ocean waters, the intensity of upwelling, the magnitude of freshwater inflows, and tidal effects on mixing. Total nitrogen inputs from the Pacific Ocean are ~7-8 times greater than the combined inputs from sewage, runoff, and the atmosphere.[32]

- *Puget Sound nitrogen levels are projected to increase in the future due to projected changes in land use (e.g., development patterns, agriculture, etc.) and are not a consequence of climate change.* Relative to the 2006 baseline, nitrogen concentrations in rivers are projected to increase by +7% by 2020 (2015-2024), +14% by 2040 (2035-2044) and +51% by 2070 (2065-2069).[S,29]

Climate Risk Reduction Efforts

CLIMATE RISK REDUCTION ***Shellfish growers, government agencies, and organizations are preparing for the effects of ocean acidification in Puget Sound.*** These groups are in the initial stages of assessing impacts and developing response plans; some are implementing adaptive responses. For example:

- *The Washington Ocean Acidification Center* works with scientific researchers, policymakers, industry, and other stakeholders to provide a scientific basis for strategies and policies to address the effects of ocean acidification. The Center is hosted at the University of Washington and was established in 2013 by the Washington State Legislature based on a recommendation from the Blue Ribbon Panel on Ocean Acidification. http://environment.uw.edu/research/major-initiatives/ocean-acidification/washington-ocean-acidification-center/

[R] Increased nutrient levels within Puget Sound enhance biological productivity near the surface and lead to oxygen loss through respiration. Respiration is essentially the opposite of photosynthesis: it is the process of breaking down organic material in order to release energy. This is typically accompanied by an intake of oxygen and the release of carbon dioxide (CO_2).

[S] Projection is based on a single global climate model simulation (ECHAM5) and a moderate (A1B) greenhouse gas scenario. The global model projection was dynamically downscaled using a regional climate model.

- *Increased monitoring of ocean acidification in Puget Sound and Washington State's coastal waters.* After confirming a link between acidified waters and the survival of oyster larvae, the Pacific Coast Shellfish Growers Association (PCSGA) established a monitoring network at hatcheries and other locations designed to provide real-time information on the pH of coastal and Puget Sound waters. The effort has now expanded to form the California Current Acidification Network (C-CAN), and involves coordination among partners including individual counties, the U.S. Integrated Ocean Observing System, and others. The C-CAN effort is designed to both directly monitor ocean chemistry and develop predictive and impact models linking low pH events to both the climate drivers and the economic consequences they entail.[33]

- *Changing practices at shellfish hatcheries.* Many hatcheries are now developing water treatment systems that can adjust the chemistry of waters that they draw in to their growing tanks. For example, Taylor Shellfish Hatchery in Puget Sound has installed buffering systems that improve water chemistry issues caused by low carbonate ion concentration. These systems pump carbonate ions, a form of inorganic carbon essential for shell formation, back into the water used to grow shellfish, improving shell development. Since these approaches may not be sufficient to guard against future decreases in pH, shellfish growers are also exploring long-term strategies for adaptation. For example, selective breeding, a practice used to grow shellfish resilient to ocean acidification, is now a common practice in commercial hatcheries. While these stocks were not selected for genetic resistance to ocean acidification, the stocks have been grown in the coastal waters of the Pacific Northwest for several generations and may have formed natural resistance to ocean acidification.[33]

Additional resources for evaluating and addressing the effects of climate change on water quality in Puget Sound.

The following tools and resources are suggested in addition to the reports and papers cited in this document.

- **The Washington Ocean Acidification Center** conducts research, education and outreach on ocean acidification in Washington State. Created in 2013, the Center engages with researchers, policymakers, and industry to advance the scientific understanding of ocean acidification and inform efforts to respond to its effects. http://environment.uw.edu/research/major-initiatives/ocean-acidification/washington-ocean-acidification-center/

- **Northwest Association of Networked Ocean Observing Systems.** NANOOS provides Pacific Northwest ocean observations, model estimates ranging from wave heights to ocean properties, forecasts, and a variety of decision-making tools including visualizations of beach erosion rates, tsunami maps, and information on water properties for use by shellfish growers. http://nvs.nanoos.org/

- **Washington Department of Ecology, Environmental Assessment Program**. Provides monitoring data and assessments of Washington's streams, rivers, lakes, marine waters, sediments and groundwater. http://www.ecy.wa.gov/programs/eap/index.html

- **West Coast Ocean Data Portal.** A project of the West Coast Governors Alliance, the portal is intended to be a hub for ocean and coastal data, and includes information on Puget Sound. http://portal.westcoastoceans.org/

- **NOAA Pacific Marine Environmental Laboratory.** Provides information, research and data relating to Pacific Northwest climate, marine ecosystems and coastal and ocean processes, including ocean acidification. www.pmel.noaa.gov

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