Chapter 3
Physical Environment

USFWS

Chapter 3. Physical Environment

3.1 Introduction

3.1.1 Grays Harbor National Wildlife Refuge

Grays Harbor lies midway along the Washington coast about 60 miles west of Olympia and 45 miles north of the mouth of the Columbia River in Washington State (Map 1). Grays Harbor Refuge is located in the northeast corner of Grays Harbor estuary in Grays Harbor County. It encompasses Bowerman Basin and consists of 1,471 acres of estuarine open water, intertidal mudflats, salt marsh, and uplands. The Refuge is bordered by industrial development on the east and south, with State Route 109 and a steep upland slope to the north and open estuary water to the west. Approximately 32 miles inland from the mouth of Grays Harbor, the Chehalis River empties into the estuary. Other major tributaries that empty into Grays Harbor include the Humptulips River in North Bay, the Hoquiam and Wishkah Rivers near Hoquiam and Aberdeen, and the Elk and Johns Rivers in South Bay.

3.1.2 Black River Unit of Billy Frank Jr. Nisqually National Wildlife Refuge

The Black River Unit is located 7 miles southwest of Olympia in Thurston County (Map 1). The Unit boundary begins at the south end of Black Lake at river mile 25. It extends south on either side of the river approximately 7.5 miles to river mile 17.5, just south of 123rd Avenue. The Unit's acquisition boundary is 3,873 acres, and 1,566 acres have been acquired. Much of the Unit lies within the Black Lake, Dempsey Creek, and Black River sub-basin drainages of the Chehalis River. In spite of rapidly growing development nearby, the Unit has retained an isolated and wild character.

3.2 Climate

3.2.1 Grays Harbor National Wildlife Refuge

Grays Harbor has a maritime climate of cool, wet winters and cool, dry summers. Weather patterns are primarily influenced by the Pacific Ocean. Weather parameters representative of the Refuge are measured daily at the Hoquiam/Bowerman Airport adjacent to the Refuge.

The mean annual air temperature between 1953 and 2012 in areas surrounding Grays Harbor was 50.9 °Fahrenheit (°F) (WRCC 2015a). The average temperature difference between day and night is 14 °F during the summer months and 10 °F in the winter. Monthly average air temperatures between 1953 and 2012 can be seen in Table 3-1.

The average annual precipitation for the Hoquiam area from 1953 to 2012 was 69.42 inches and occurred mostly as rain in the winter months (WRCC 2015b). The wettest months are generally November through February. Low temperatures generally range between 20 and 30 °F November through February. During the winter, rainfall is usually of light to moderate intensity and continuous over a long period of time rather than heavy downpours for brief periods. Gray, cloudy days are the norm during the rainy season. Rain can occur any month but is more likely in September and May. The driest months of the year are June, July, and August. Highest temperatures can range in the 90s and can occur from June through September. Two to four weeks may pass with only a few showers

during the summer months. Fog and drizzle may occur year-round, but during the summer months fog often moves in along Washington's coast (GHEMPTF 1987).

Table 3-1. Hoquiam/Bowerman: Air Temperature and Precipitation Summaries, 1953–2012 (WRCC 2015a, 2015b).

Month	Average Temperature (Fahrenheit)	Total Precipitation (Inches)
January	41.9	10.37
February	43.8	7.66
March	45.5	7.56
April	48.5	4.94
May	53.1	3.18
June	57.0	2.21
July	60.1	1.18
August	60.8	1.53
September	59.2	2.97
October	52.8	6.54
November	46.1	10.71
December	42.1	10.59
Annual	50.9	69.42

Storms are unusual in summer, but thunderstorms with occasional hail can occur. Winter storms are common and often generate high winds with large amounts of rain. Snowfall occurs almost yearly with an average of 4.8 inches annually in Hoquiam area. Onshore westerly winds from the Pacific Ocean are predominant year round. The prevailing wind direction in summer is from the northwest; in winter, however, southwesterly winds move air towards the Olympic Mountains, which act as a barrier that affects precipitation and weather conditions. Drier easterly and southeasterly winds are uncommon, but occur periodically each year and are often strong.

Severe storms often hit Washington's coast during the winter, bringing heavy rains, strong winds, and high waves. Storms can generate 70 to 100 inches of rain per year. Coastal storm winds regularly exceed 40 miles per hour (mph). The average annual peak speed of 55 mph can topple chimneys, utility lines, and trees (WDOE 2011).

The larger storms are considered mid-latitude cyclones and can match a Category 3 hurricane in both minimum central pressures and sustained wind speeds (Read 2015). As a strong winter storm system from the southwest approaches the Washington coast, winds created from air pressure differences in the Cascade and Olympic Mountains accelerate as the storm approaches.

A number of severe storms have hit the Pacific Northwest coast in recent years. On March 3, 1999, a coastal storm hit the Grays Harbor area with a storm surge of 4.6 feet and 49.7-mph winds, causing widespread coastal flooding, especially in nearby Ocean Shores on the western edge of Grays Harbor estuary. Wave heights exceeded 29.5 feet for over 5 hours, peaking at 34.8 feet (Read 2015, Sistek 2006). Wind Storm 2006 brought sustained coastal winds of 40 mph which generated high coastal swells augmented by high tides and considerable inland flooding. The Great Coastal Gale of 2007 brought hurricane force winds gusting to 81 mph and heavy rain for 24 hours to the Grays Harbor

area. With every major road out of Aberdeen blocked by fallen trees or mudslides, the storm caused extensive damage throughout the county (Kliem and Holden 2011).

Grays Harbor County has had six declared disasters since 2005 that included severe storms. Usually the storms are county-wide in extent with heavy wind, snow, rain, and ice, and they nearly always coincide with flood events. There is a 40 percent chance that one severe winter storm event with the potential of causing damage will take place every 2 years (Grays Harbor County 2010).

The causes of flooding in Grays Harbor County are a combination of climate, topography, and land use changes in flood-prone areas. Precipitation typically falls as rain, with virtually no snow fall. Rainwater quickly runs down out of the surrounding hills and floods the low-lying lands. River and coastal flooding are the two dominant types of flood events. These types of flooding usually happen simultaneously. For example, rivers in flood stage that flow out into the Grays Harbor estuary experience incoming tidal flooding as well. Both types of flooding can influence each other during natural disaster events. Smaller, more localized flood events in the county result from intense rainfall within a short period, saturated soils, high water tables, and heavy surface runoff. Land use changes, such as excessive historic logging within watersheds, likely affected natural runoff patterns into the estuary (Kliem and Holden 2011). Flooding in the local area has been problematic since record-keeping began in the 1900s and has continued to increase in frequency, duration, and severity. Since 1960 there have been 17 Federal disaster declarations related to flooding.

3.2.2 Black River Unit of Billy Frank Jr. Nisqually National Wildlife Refuge

Oceanic influence from the Pacific Ocean to the west and Puget Sound to the north buffers temperature extremes in the Black River drainage, while the Cascade Mountains to the east protect this watershed from continental air masses. This results in a mild, modified maritime climate with long growing seasons. Prevailing airflow from the ocean greatly modifies the colder winter temperatures and the heat of summer in the area.

Weather parameters representative of the Unit are measured daily at the Olympia Airport, approximately 7 air miles northeast of the Unit. The average annual air temperature between 1948 and 2012 in areas surrounding Olympia was 49.9 °F (WRCC 2015c). Monthly average air temperatures between 1948 and 2012 are identified in Table 3-2. Daily maximum temperatures in nearby Olympia are usually between 70 and 80 °F during summer, while average daily minimum temperatures in winter are near freezing. The July mean high temperature is 77.14 °F and the January mean low temperature is 31.77 °F (WRCC 2015d, 2015e). Area temperatures over 90 °F occur only about 6 days a year and temperatures over 100 °F rarely occur during summer months. Freezing temperatures occur about 83 days/nights a year in the valleys and the average frost-free period is 150 to 210 days. Higher points in the nearby Black Hills have moderately severe winters.

Thurston County has well-defined seasons, and seasonal changes are gradual. The average annual precipitation for the Olympia area from 1953 to 2012 was 50.82 inches and occurred mostly as rain during the winter months (WRCC 2015f). Average annual rainfall of 110 inches along the western county border decreases to 38 inches in the southeastern portion of the county. Olympia averages 52.3 inches per year, but the nearby Black Hills, which drain into Black River, receive considerably higher amounts (CRC 1992). Precipitation is heaviest during late fall (28 percent of yearly average) and winter (46 percent of yearly average) causing many lowlands, including the Black River area, to flood. Approximately 20 percent of the rain falls in spring, and only 6 percent in summer, thus

summers are fairly dry, averaging only 3 inches of rain. The area can expect an average of 73 clear days, 72 partly cloudy days, and 220 cloudy days a year.

Table 3-2. Olympia Area: Air Temperature and Precipitation Summaries, 1948–2012 (WRCC 2015c, 2015f).

Month	Average Temperature (Fahrenheit)	Total Precipitation (Inches)
January	38.2	8.02
February	40.7	5.63
March	43.5	5.24
April	47.7	3.33
May	53.6	2.10
June	58.7	1.57
July	63.3	0.72
August	63.3	1.12
September	58.5	2.02
October	50.1	4.70
November	43.0	8.24
December	38.7	8.12
Annual	49.9	50.82

3.2.3 Climate Cycles in the Pacific Northwest

Two climate cycles have major influences on the climate and hydrologic cycles in the Pacific Northwest: the shorter-term El Niño/La Niña/Southern Oscillation (ENSO) events, and the longer-term Pacific Decadal Oscillation (PDO) epochs (CIG 2012a). In El Niño years, average sea surface temperatures in the central and eastern equatorial Pacific Ocean are warmer than average, with weakened easterly trade winds in the tropical Pacific. La Niña years are characterized by the opposite—cooler than average sea surface temperatures and stronger than average easterly trade winds. These changes in wind and ocean circulation have global impacts on weather events. ENSO influence on Pacific Northwest climate is strongest from October to March. During an El Niño event, the winters tend to be warmer and drier than average. La Niña winters tend to be cooler and wetter than average. Each ENSO phase typically lasts 6–18 months, with phases reoccurring every 2–7 years (CIG 2012a).

Like ENSO, PDO is characterized by changes in sea surface temperature, sea level atmospheric pressure, and wind patterns (CIG 2012a). PDO is described as having two phases: warm and cool. During a warm phase, sea surface temperatures near the equator and along the western coast of North America are warmer, while in the central north Pacific they are cooler. During a cool phase, the patterns are opposite. Within the Pacific Northwest, warm phase PDO winters tend to be warmer and drier than average whereas cool phase PDO winters tend to be cooler and wetter than average. A single warm or cool PDO phase may last 20–30 years.

The potential for temperature and precipitation extremes increases when ENSO and PDO are in the same phases and thereby reinforce each other. When ENSO and PDO are in opposite phases, their

opposing effects on temperature and precipitation can cancel each other out, but not in all cases and not always in the same direction (CIG 2012a).

3.2.4 Climate Change

As guided by DOI Secretarial Order 3226 (Secretary of the Interior 2009) and the Service's Climate Change Strategic Plan (USFWS 2010), the Service considers and analyzes climate change in its decisions, long-range plans, and other activities.

The terms "climate" and "climate change" are defined by the Intergovernmental Panel on Climate Change (IPCC). "Climate" refers to the mean and variability of different types of weather conditions (e.g., temperature, precipitation, wind) over time, with 30 years being a typical period for such measurements, although shorter or longer periods also may be used (IPCC 2007a). The term "climate change" thus refers to a change in the mean or variability of one or more measures of climate (e.g., temperature or precipitation) that persists for an extended period, typically decades or longer, whether the change is due to natural variability, human activity, or both (IPCC 2007a).

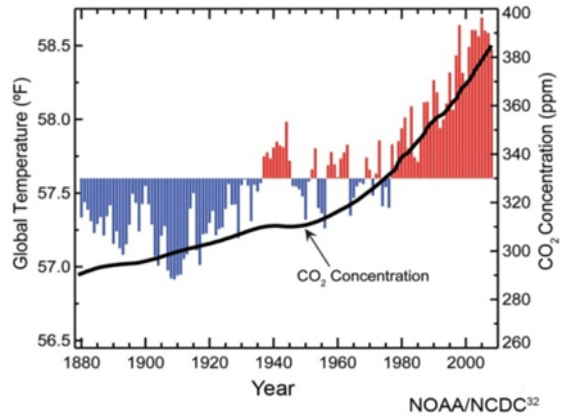
Climate-related concerns are generally focused on potential anthropogenic changes to the atmosphere that have altered Earth's "greenhouse effect" (NOAA 2012a). The greenhouse effect is a natural phenomenon that assists in regulating and warming Earth's temperature. Greenhouse gases (GHG) in the atmosphere—primarily carbon dioxide (CO_2), water vapor, methane, and nitrous oxide —absorb and emit infrared radiation from sunlight, ultimately trapping heat at the Earth's surface. Concentrations of GHGs, especially CO_2, are strongly correlated with global temperatures.

Trends and projections related to climate change are discussed in this section, and potential effects to the Refuge and the Unit are considered in Chapter 6.

Historical Trends in GHGs, Air Temperature, Precipitation, Snowpack, and Streamflow

Empirical evidence indicates that Earth's global climate has been changing rapidly during the 20th and early 21st centuries, with substantial evidence that the magnitude of climate alterations has been amplified by human activities, such as deforestation and the burning of fossil fuels (IPCC 2007, NAS 2008, USGCRP 2009). Well-documented climate variations have occurred throughout Earth's history (NOAA 2012b), but the current warming trend differs from geologically earlier climate shifts in two ways. First, recent climate changes appear to be driven primarily by human activities that have generated greater concentrations of atmospheric GHGs. Second, atmospheric CO_2 (and other GHGs) concentrations are at their greatest levels than at any time during the last 800,000 years and are increasing at unprecedented rates (Lüthi et al. 2008). Prior to the start of the Industrial Revolution around 1750, the amount of CO_2 in the atmosphere was about 280 parts per million (ppm). Current global levels are ~392 ppm and are increasing at a rate of ~2 ppm/yr (Department of Energy 2012, NOAA 2012c).

Empirical climate measurements support an accelerating change in global CO_2 concentrations and temperatures since the 1950s (Figure 3-1). Increased frequencies in extreme regional precipitation and wind events also have occurred (IPCC 2007b, Solomon et al. 2007, USGCRP 2009). These recent changes "very likely" have resulted from human-generated increases in GHGs, especially CO_2 emissions from burning fossil fuels (IPCC 2007c, Solomon et al. 2007). Huber and Knutti (2011) concluded that ~75 percent of global temperature increases since 1950 were caused by human activities.



Global annual average temperature (as measured over both land and oceans). Red bars indicate temperatures above and blue bars indicate temperatures below the average temperature for the period 1901-2000. The black line shows atmospheric carbon dioxide (CO_2) concentration in parts per million (ppm). While there is a clear long-term global warming trend, each individual year does not show a temperature increase relative to the previous year, and some years show greater changes than others.[33] These year-to-year fluctuations in temperature are due to natural processes, such as the effects of El Niños, La Niñas, and the eruption of large volcanoes.

Figure 3-1. Global annual average temperature and CO_2 concentrations, 1880–2008. Source: USGCRP (2009).

In the Pacific Northwest, increased GHGs and warmer temperatures have resulted in a number of physical and chemical impacts. These include changes in snowpack, streamflow timing and volume, flooding, landslides, sea levels, ocean temperatures and acidity, and disturbance regimes such as wildfire, insects, and disease outbreaks (USGCRP 2009:135–138). Climate shifts also may exacerbate the frequency, magnitude, and intensity of extreme weather events, such as winter storms (Dominguez et al. 2012) and ocean wave heights (Ruggiero et al. 2010); both have been reported for the Pacific Northwest since the 1970s and are projected to intensify during the 21st century.

Climate observations have indicated many changes to Pacific Northwest temperature, precipitation, snowpack, and streamflow during the 20th century (CIG 2012c). On average, the region warmed about 1.5 °F; warming was greatest west of the Cascades during winter and spring (Figure 3-2). Trends in precipitation suggest moderate increases west of the Cascades (Figure 3-3); the largest relative increases occurred in eastern Washington and southern British Columbia, mainly during spring. Interestingly, one of the few recording stations where minor precipitation decreases were measured was at Aberdeen, Washington, just east of Grays Harbor Refuge.

Changes in air temperature, especially during winter months, have affected the quantity of mountain snowpack throughout the Pacific Northwest, as well as the timing of spring snowmelt. For the Washington Cascades, Mote et al. (2008) reported that spring snowpack declined 15–35 percent from the mid-20th century to 2006 (also see Figure 3-4); similarly, Casola et al. (2009) reported 8–16 percent declines during 1977–2006. The volume and timing of streamflows throughout the region have also changed; Stewart et al. (2005) reported that spring snowmelt timing was 5–20 days earlier at many Pacific Northwest sites compared with 1948 measurements (Figure 3-4). However, the streams within the coastal Washington region (including the Chehalis River) are primarily rain-dominated, and so are less influenced by snowpack and snowmelt (Mantua et al. 2010). In this area, changes in precipitation would have a greater effect on streamflow and flood timing (Hamlet et al. 2007).

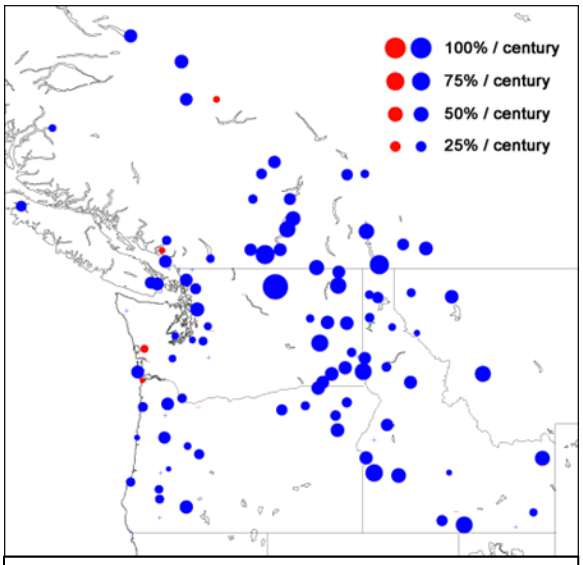


Figure 3-2. Average annual temperature trends (1920–2000) in the Pacific Northwest. Increases (decreases) are indicated with red (blue) dots. The size of the dot corresponds to the magnitude of change (CIG 2012c).

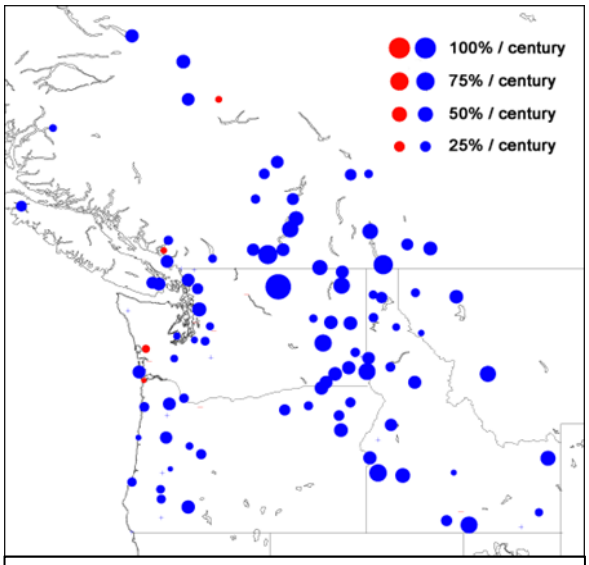
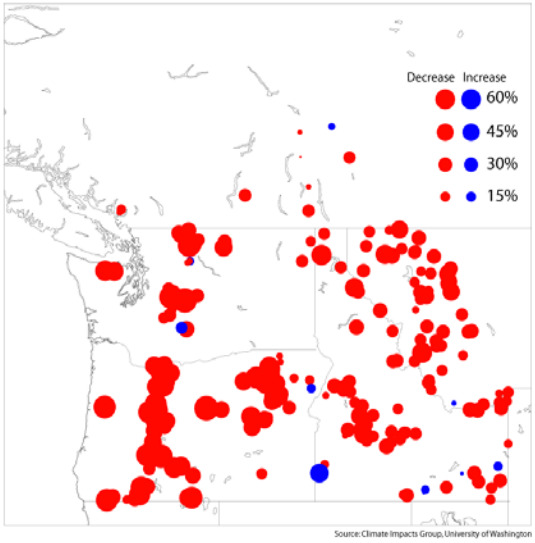


Figure 3-3. Average annual precipitation trends (1920–2000) in the Pacific Northwest. Increases (decreases) are indicated with blue (red) dots. The size of the dot corresponds to the magnitude of change (CIG 2012c)



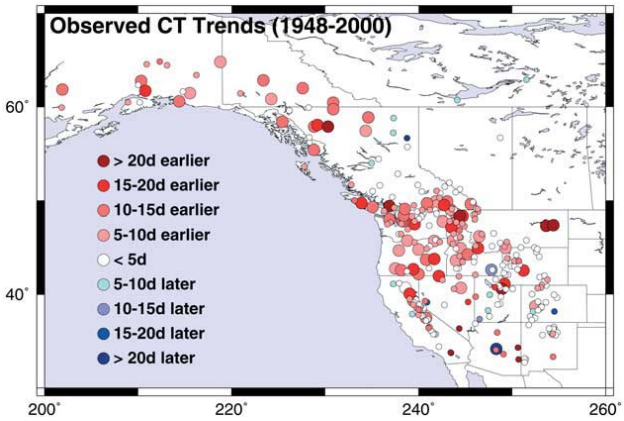


Figure 3-4. Changes in Pacific Northwest snowpack and streamflow runoff timing . (Left) Relative trend in April 1st snowpack (snow water equivalent) during 1950–2000 (CIG 2012c). (Right) Observed changes in timing of snowmelt runoff (center of mass flow) during 1948–2000 (Stewart et al. [2005:Figure 2]).

For the local Grays Harbor area, we assessed temperature and precipitation trends during 1895–2011 and 1981–2011 using Parameter-elevation Regressions on Independent Slopes Model (PRISM; Daly et al. 2002, Daly et al. 2008, PRISM Climate Group 2012) datasets generated by the PRISM Climate Group at Oregon State University. PRISM provides complete, monthly, 1895-to-present temperature and precipitation data at 4-km resolution for any point within the entire conterminous United States. The PRISM method interpolates between point data from thousands of weather stations using a digital elevation model and many other geographic data sets. The gridded estimates account for spatial variations in climate caused by elevation, terrain orientation, effectiveness of terrain as a barrier to flow, coastal proximity, moisture availability, atmospheric inversions, and topographic position (valley, mid-slope, ridge). Missing data from individual weather stations were estimated using a weighted average of values from highly correlated neighboring stations. We calculated annual (January–December) precipitation totals and mean temperatures (maximum, mean, and minimum) from the monthly PRISM data.

Air temperatures tended to increase at Grays Harbor Refuge during 1895–2011 (Figure 3-5). Based on best-fitting linear regressions, overall maximum, mean, and minimum temperatures have increased 1.27, 1.73, and 2.07 °F, respectively, during that 110-year period; the strongest trend was for minimum temperatures. However, the regressions accounted for only 1–25 percent of the variation in temperatures, suggesting that other dynamical factors affect our ability to detect any long-term trends in air temperature at the Refuge. During the most-recent 30-yr period (1981–2011) there were minor decreasing trends in all three temperature metrics (Figure 3-5), but these linear trends again accounted for <12 percent of the annual temperature variations.

Annual precipitation at Grays Harbor Refuge tended to decrease during 1895–2011 (Figure 3-6); regression analysis suggested that total annual precipitation declined 3.8 in (5.2 percent) during that 110-year period. But as with air temperatures, the linear regression model for precipitation fit the annual data poorly ($R^2 = 0.01$). The 1981–2011 precipitation trend was similar to the longer-term results (Figure 3-6).

Air temperatures tended to increase at the Black River Unit during 1895–2011 (Figure 3-7). Based on best-fitting linear regressions, overall maximum, mean, and minimum temperatures have increased 0.70, 1.28, and 1.97 °F, respectively, during that 110-year period; the strongest trend was for minimum temperatures. However, the regressions accounted for only 2–26 percent of the variation in temperatures, suggesting that other dynamical factors affect our ability to detect any long-term trends in air temperature at the Black River Unit. During the most recent 30-year period (1981–2011) there were minor, increasing trends for mean and minimum temperatures, and a minor, decreasing trend for maximum temperatures (Figure 3-7), although these linear trends again accounted for <25 percent of the annual temperature variations.

Annual precipitation at the Black River Unit tended to increase during 1895–2011 (Figure 3-8), although the regression analysis suggested that total annual precipitation increased only 0.93 in/yr (1.8 percent) during that 110-yr period. But as with air temperatures, the linear regression model fit the annual data poorly ($R^2 = 0.00$). The 1981–2011 precipitation trend suggested a minor decrease in annual precipitation, but the regression fit was poor ($R^2 = 0.01$) (Figure 3-8).

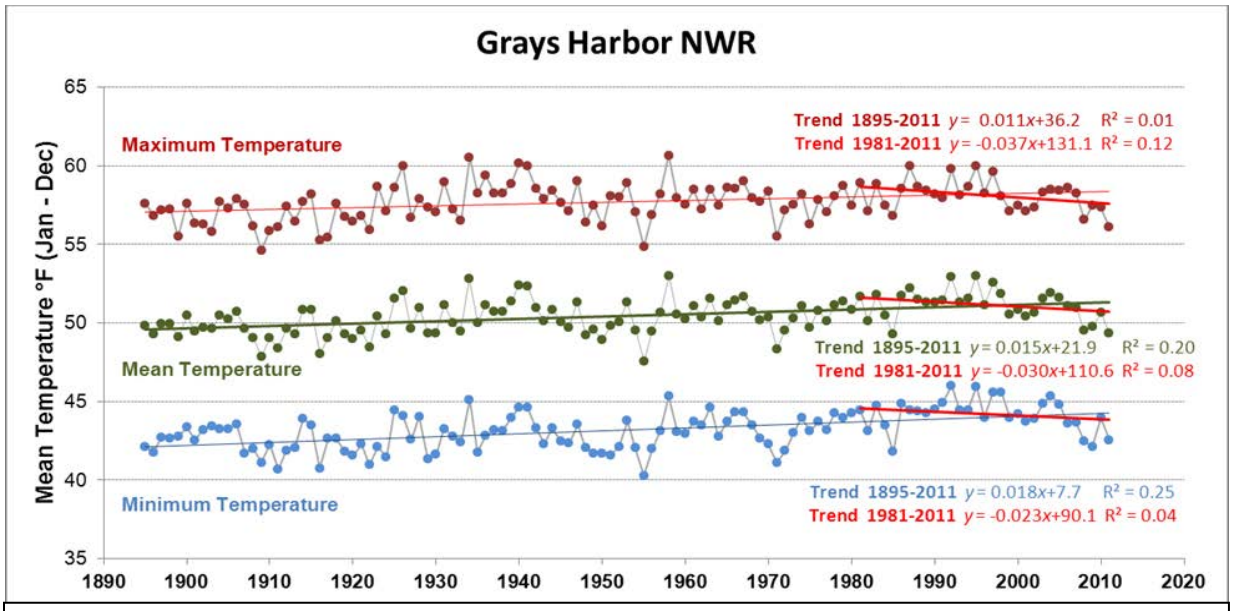


Figure 3-5. Annual mean, minimum, and maximum air temperatures for Grays Harbor NWR during 1895–2011 and 1981–2011 (red regression lines and text). Annual temperatures are the means of the 12 monthly values (January through December). Source of monthly data: PRISM Climate Group (2012).

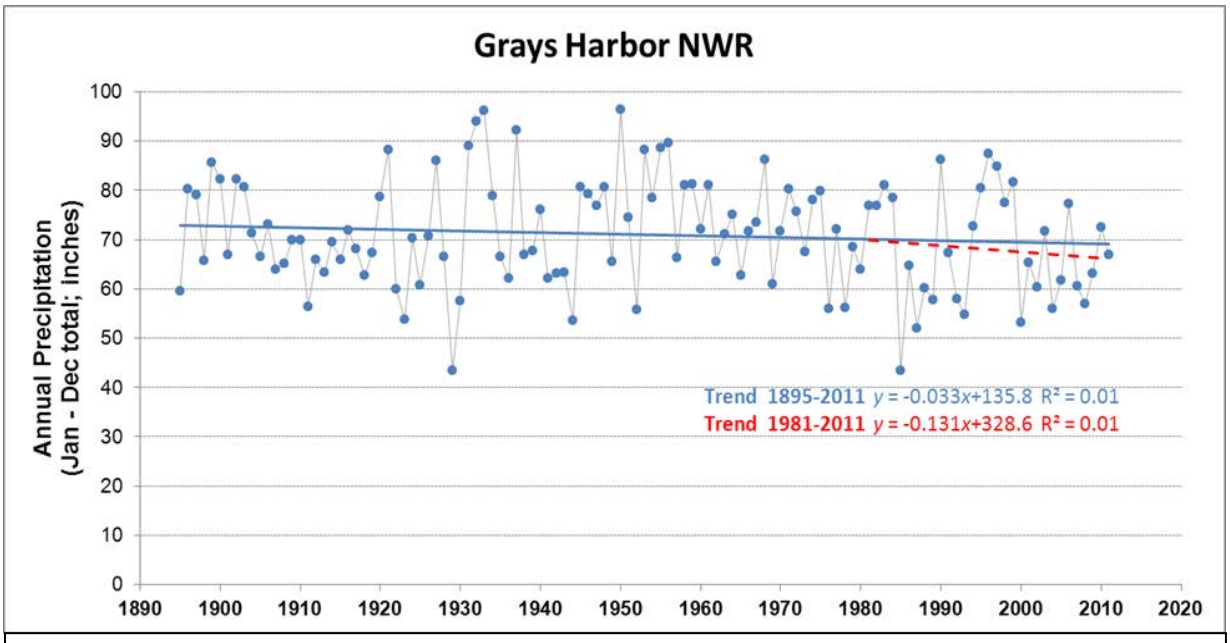


Figure 3-6. Annual precipitation (January through December) totals for Grays Harbor NWR during 1895–2011 and 1981–2011 (red regression line and text). Source of monthly data: PRISM Climate Group (2012).

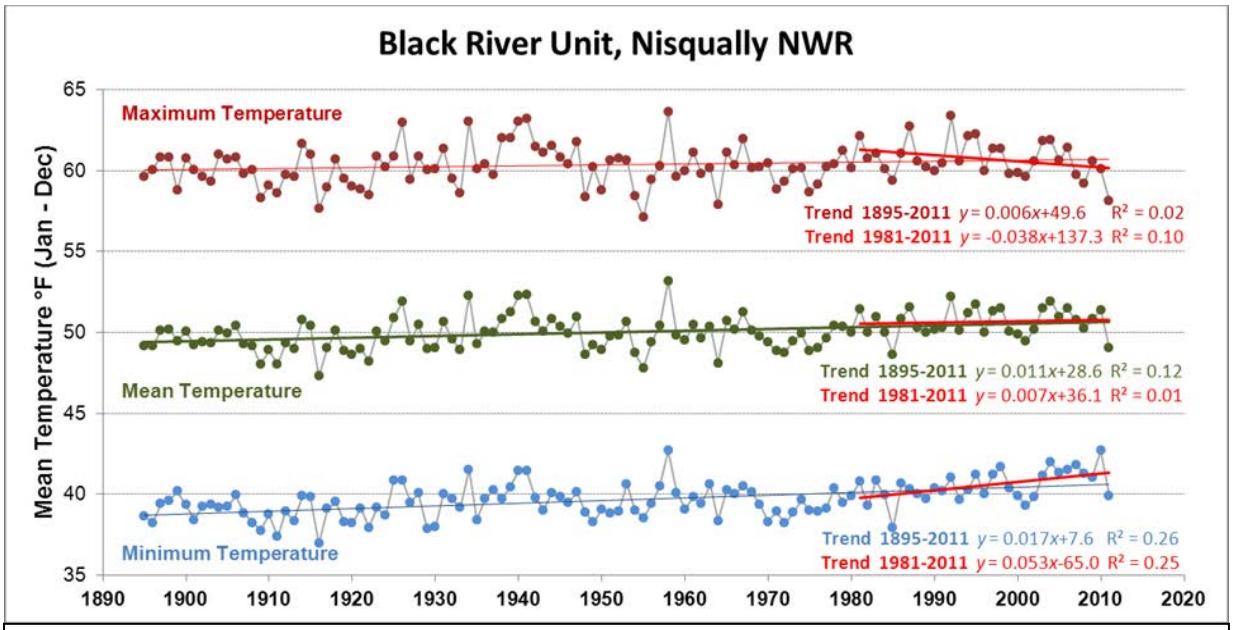


Figure 3-7. Annual mean, minimum, and maximum air temperatures for the Black River Unit, Billy Frank Jr. Nisqually NWR, during 1895–2011 and 1981–2011 (red regression lines and text). Annual temperatures are the means of the 12 monthly values (January through December). Source of monthly data: PRISM Climate Group (2012).

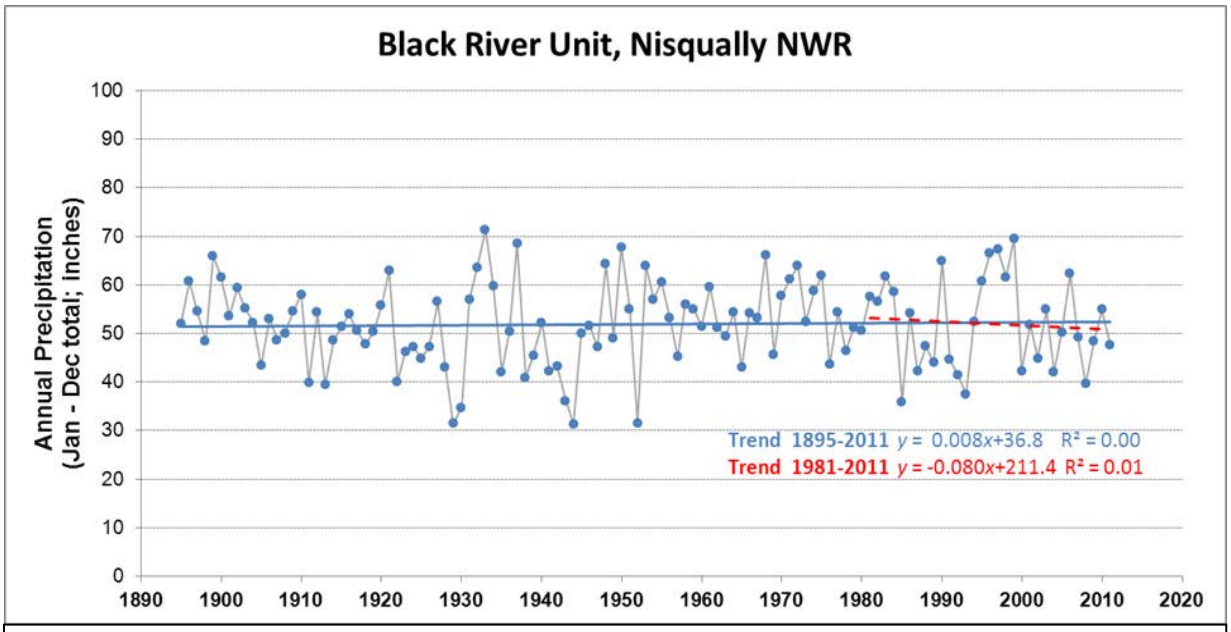


Figure 3-8. Annual precipitation (January through December) totals for the Black River Unit, Nisqually NWR, during 1895–2011 and 1981–2011 (red regression line and text). Source of monthly data: PRISM Climate Group (2012).

Future Climate Projections

Average global surface air temperature is projected to increase 3.2–7.2 °F by 2100 (~0.36 °F/decade), depending on the emissions scenario used (IPCC 2000), i.e., depending on the ultimate concentrations of GHG emissions released into the atmosphere. Interim projections for the six IPCC "marker scenarios" (B1, A1T, B2, A1B, A2, and A1FI) suggest temperature increases of 1.1–1.2 °F by 2030, 2.3–3.1 °F by 2065, and 3.2–5.6 °F by 2100 (IPCC 2007c, and see CIG 2012c:Table 2).

Precipitation projections are less certain, with overall annual precipitation generally expected to remain within the range of natural variability (Solomon et al. 2007); exceptions are for increased precipitation at high latitudes and decreased precipitation in the subtropics. Projected precipitation changes over the next century are small compared to the interannual and decadal variability observed during the 20th century (Meehl et al. 2007).

Regional temperature projections are similar to the global projections. Based on a statistical downscaling of 20 global climate models, Mote and Salathé (2010) projected an overall 0.5 °F/ decade rate of temperature increase through the 2080s. This corresponds to increases of ~2 °F by the 2020s, ~3.2 °F by the 2040s, and ~5.3 °F by the 2080s. All of these increases are greater than the historical 1.5 °F overall increase observed for the Pacific Northwest during the entire 20th century.

Regional precipitation projections suggest only small increases in annual precipitation (~4 percent by the 2080s; Mote and Salathé 2010), although there are large differences among the various model projections. As with the global projections, there is a wide range of natural variability in Pacific Northwest precipitation amounts and timing, making the relatively small climate-change-related changes difficult to distinguish except over long time scales. However, a majority of regional climate models project decreased summer (July–August) precipitation of 6–13 percent, and increased winter (December–February) precipitation of 2–8 percent (Mote and Salathé 2010, Salathé et al. 2010).

Regional snowpack is projected to decrease at accelerated rates compared to those during the 20th century, with shifts to earlier spring snowmelt occurring for snow-dominated and transient basins. Elsner et al. (2010) projected 29 percent, 44 percent, and 65 percent declines in Washington State April 1 snow-water-equivalent by the 2020s, 2040s, and 2080s, respectively (A1B SRES scenario). However, for the rain-dominated basins of coastal Washington, changes in the timing of spring runoff likely will be minimal, although the risk for lower low-flows and greater stream temperatures will increase (Mantua et al. 2010).

For the Grays Harbor area, climate and hydrologic projections were generated for 8-digit Hydrologic Unit Code (HUC4) basins by the Climate Impacts Group's Columbia Basin Climate Change Scenarios Project (Hamlet et al. 2010) and Regional Climate and Hydrologic Change efforts (Littell et al. 2011). We downloaded data via Climate Impacts Group (2012d). We averaged the projections for Grays Harbor (HUC4 17100105) and Lower Chehalis River (HUC4 17100104) basins, in order to include the entire Grays Harbor watershed.

Figure 3-9 presents seasonal summaries of average monthly temperature and total precipitation. Average projections from 10 climate models for time periods ending in the 2020s, 2040s, and 2080s are compared with the empirically based 1915–2006 estimates. Local projections are similar in magnitude to the regional projections. Average temperatures are projected to increase in all seasons (Figure 3-7); precipitation projections indicate increases during fall and winter and decreases during summer (Figure 3-9).

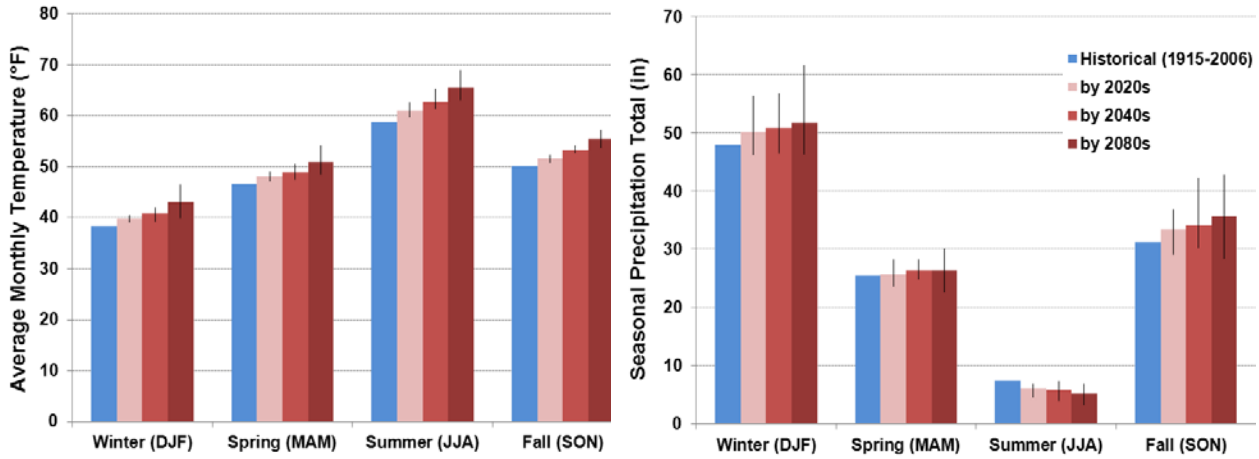


Figure 3-9. Seasonal temperatures (left) and precipitation (right) for the Grays Harbor and Lower Chehalis River HUC4 basins. Projections were for the A1B SRES Scenario. Bars and error bars represent the average and range of 10 climate models (CIG 2012b).

For the Black River area, climate and hydrologic projections were generated for 8-digit HUC4 basins by the Climate Impacts Group's Columbia Basin Climate Change Scenarios Project (Hamlet et al. 2010) and Regional Climate and Hydrologic Change efforts (Littell et al. 2011). We downloaded data via Climate Impacts Group (2012b).

Figure 3-10 presents seasonal summaries of average monthly temperature and total precipitation for the Upper Chehalis River basin (HUC4 17100103), which includes the Black River watershed. Average projections from 10 climate models for time periods ending in the 2020s, 2040s, and 2080s are compared with the empirically based 1915–2006 estimates. Local projections are similar in magnitude to the regional projections. Average temperatures are projected to increase in all seasons (Figure 3-10); precipitation projections indicate increases during fall and winter and decreases during summer (Figure 3-8).

Projections for streamflow and runoff across the Upper Chehalis River basin (Figure 3-11) closely match those for precipitation, with increasing winter flows and decreasing summer flows through the 2080s.

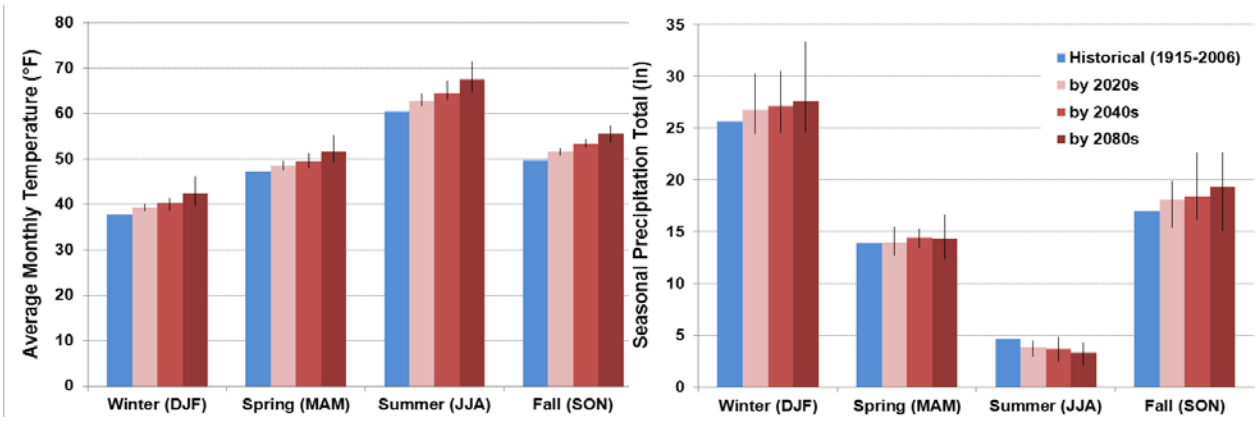


Figure 3-10. Seasonal temperatures (A) and precipitation (B) for the Upper Chehalis River HUC4 basin. Projections were for the A1B SRES Scenario. Bars and error bars represent the average and range of 10 climate models (CIG 2012b).

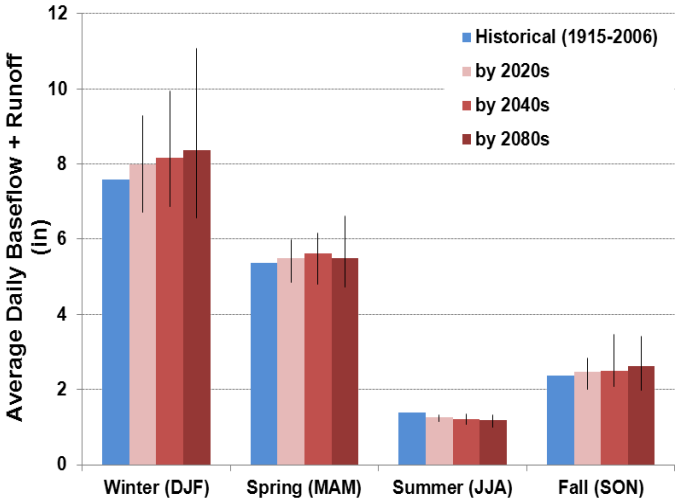


Figure 3-11. Combined average daily flows (baseflow + runoff) for the Upper Chehalis River HUC4 basin. Projections were for the A1B SRES scenario. Bars and error bars represent the average and range of 10 climate models. Runoff represents mean flow across the watershed (not routed through stream channels; Elsner and Hamlet 2010) (CIG 2012b).

Sea Level Rise

Factors Affecting Global and Washington Coast Sea Levels

Rising global sea levels have resulted from the melting of land-based ice within Earth's cyrosphere (especially the Antarctic and Greenland ice sheets, but also glaciers) and thermal expansion of ocean waters as global temperatures increase (IPCC 2007a, McKay et al. 2011). A recent National Research Council (NRC) publication summarized that 68 percent of global sea level rise measured during 1992–2008 resulted from ice mass loss, 35 percent from thermal expansion, and -3 percent from anthropogenic land water storage (Church et al. 2011, NRC 2012). The proportional contribution from ice mass loss has increased since 1993, likely resulting from greater rates of ice melt than during 1961–2003 (IPCC 2007a, Bromirski et al. 2011, Jacob et al. 2012).

In addition to these global factors, sea level heights along the Washington coast are affected by long- and short-term ocean-driven climate patterns (Mote et al. 2008) and vertical land movements (Komar et al. 2011). At longer time scales, Bromirski et al. (2011, 2012) reported that U.S. west coast sea levels are correlated with PDO, with warm-phase PDO epochs associated with suppressed rates of sea level rise. During the most recent warm-phase PDO (ca. 1980–2010), west coast sea levels were nearly static, whereas global sea level rose approximately 3 mm/yr (Bromirski et al. 2011, 2012). At much shorter time scales, ENSO events (El Niño, La Niña) can substantially affect sea levels, e.g., large El Niño events can raise local sea levels by 10–30 cm for several winter months (NRC 2012).

Local, vertical land movements result from tectonic forces and other geologic processes. Tectonic uplift is occurring at various rates along the Pacific coast approximately north of Mendcino, California, as the North American and Juan de Fuca plates collide. Vertical land movements in northern North America also result from continuing glacial isostatic adjustment since the disappearance of the North American ice sheets starting circa 20,000 years ago. Overall uplift estimates for the southern Washington coast range from 1 to 3 mm/yr (Mote et al. 2008, NRC 2012), although short-term GPS-derived information from a Pacific Northwest Geodetic Array station near the southeastern shoreline of Grays Harbor (station P398, lat-lon = 46.926, -123.916) has measured uplift of 0.1 mm/yr (±0.1 mm/yr) since 2006 (Central Washington University 2012). However, longer-term sea level data are sparsely available for much of the southwestern Washington coast, and it is possible that local dynamics may create areas of both uplift and subsidence within this larger geographic expanse (as has been reported for the Oregon coast and Willapa Bay, Washington [Komar et al. 2011]).

At the local scale, the accretion rate of sediments (here referring generically to both mineral and organic-matter sources) is a critical factor affecting the long-term persistence of coastal marshes. Marshes that receive sediment inputs sufficient to raise substrate elevations equal to or greater than the rate of local sea level rise will persist, whereas marshes with lesser sediment accretion eventually will be flooded (Morris et al. 2002, Kirwin et al. 2010). Sediment accretion rates are greater where vegetation is present (Baustian et al. 2012). Thom (1992) reported a mean accretion rate of 3.6 mm/yr (95 percent CI = 2.4 – 4.8) across six Washington and Oregon salt marsh sites; the Elk River marsh site in Grays Harbor had an annual accretion rate of 6.6 mm/yr during 1963–1991. Sediment compaction, however, results in subsidence at local areas within coastal marshes, at least partially counteracting sediment inputs; Mazzotti et al. (2008) measured annual subsidence rates of 1–2 mm in the Frazier River delta lowlands, British Columbia, Canada.

Historical Rates of Sea Level Change

Global mean sea level rose between 1.2 and 2.2 mm/yr during the 20th century (IPCC 2007a, NRC 2012). That rate increased to 3.1 mm/yr during 1993–2003 (Bromirski et al. 2011), and is currently measured at 3.2 mm/yr (NASA 2015).

There are few measuring stations with adequate recording histories to provide specific sea level information for the Grays Harbor area, e.g., the National Oceanic and Atmospheric Administration (NOAA) station at Westport, Washington (approx. 9.5 mi WSW from Grays Harbor Refuge; station ID 9441102), only has water-level data available since 2006 (NOAA 2012d). However, two linear trend analyses of data from the NOAA station in Willapa Bay (Toke Point, station ID 9440910, approximately 19 mi SSW from Grays Harbor NWR) indicated increases in relative sea level ranging from 1.09 mm/yr during 1959–2008 (Tebaldi et al. 2012) to 0.63 mm/yr (95 percent CI = -0.49–1.75) during 1973–2011 (NOAA 2012e).

Future Projections of Sea Level

Global sea levels are projected to rise 13.5 cm (range = 8–23) by 2030, 28.0 cm (range = 18– 8) by 2050, and 82.7 cm (range = 50–140) by 2100 (all relative to 2000 levels; NRC 2012: their Table 5.2). These projected values correspond to average sea level rise rates of 4.5, 5.6, and 8.3 mm/yr during the periods up to 2030, 2050, and 2100, respectively.

Accounting for local dynamical factors, NRC (2012: their Figure S.1 and Table 5.3) projected increased sea levels at the latitude of Seattle, Washington, of 6.6 cm (range = -3.7–22.5) by 2030, 16.6 cm (range = -2.5–47.8) by 2050, and 61.8 cm (range = 10.0–143.0) by 2100 (see Figure 3-12). These projected values correspond to average sea level rise rates of 2.2, 3.3, and 6.2 mm/yr during the periods up to 2030, 2050, and 2100, respectively.

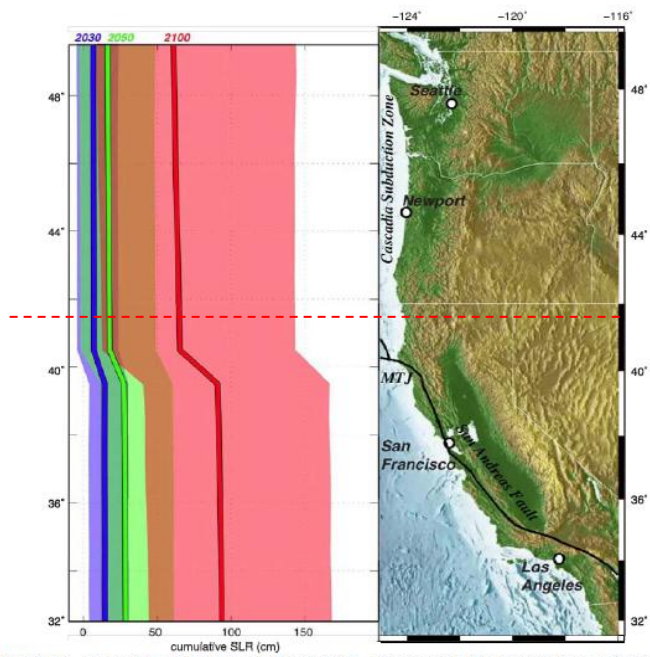


FIGURE S.1 Projected sea-level rise off California, Oregon, and Washington for 2030 (blue), 2050 (green), and 2100 (pink), relative to 2000, as a function of latitude. Solid lines are the projections, and shaded areas are the ranges. Ranges overlap, as indicated by the brown shading (low end of 2100 range and high end of 2050 range) and blue-green shading (low end of 2050 range and high end of 2030 range). MTJ = Mendocino Triple Junction, where the San Andreas Fault meets the Cascadia Subduction Zone.

Figure 3-12. Projected sea level rise for the U.S. Pacific coast for 2030, 2050, and 2100. Red dashed line added to show approximate latitude for Grays Harbor, WA . Source: NRC (2012)

Similar projections of 10-cm and 25-cm increases in sea level at Toke Point, Washington, by 2030 and 2050, respectively, were reported by Tebaldi et al. (2012). However, because these projections started with the year 2008, the corresponding average sea level rise rates by 2030 and 2050 are 4.5 and 6.0 mm/yr, respectively. These projected rates are greater than those in NRC (2012) because they do not incorporate the mitigating "fingerprint" effects of modern land ice melting (e.g., land uplift and reduced gravitational pull on near-ocean waters), which are more pronounced along the Washington coast.

Sea level projections for the entire Grays Harbor estuary were modeled using SLAMM (Sea-level Affecting Marshes Model; Clough and Larson 2010). Those analyses later were subsetted to focus on the Grays Harbor Refuge vicinity (Warren Pinnacle Consulting 2011). The SLAMM model uses input data to assess the dominant processes involved in wetland conversion and shoreline modifications during long-term sea level rise: inundation, erosion, overwash, saturation, and sediment (or vertical land) accretion. Model projections for the year 2100 suggested substantial losses of tidal flats: for a 0.69-m sea level rise, tidal flats declined by 48 percent within Grays Harbor Refuge and 69 percent within the entire Grays Harbor estuary. However, these SLAMM results (especially for tidal flat habitats) should be used with caution, because the only data available for land elevation and habitat types were at very coarse scales, and the modeled acreage of tidal flats is sensitive to even very small changes in elevation. Whenever more-refined elevation, bathymetry, and habitat data are available, future SLAMM analyses would be valuable to project habitat changes both within Grays Harbor Refuge as well as the entire Grays Harbor estuary. The USGS project "Marshes to mudflats: climate change effects along a latitudinal gradient in the Pacific Northwest" in progress at Grays Harbor Refuge and several other sites, measures morphological and ecological characteristics (e.g., elevation, tidal range, vegetation) along transects crossing the habitat continuum of tidal marsh, intertidal mudflat, and subtidal shoals. The project will model vulnerability of these nearshore habitats and dependent avian indicator species to projected sea level rise and storm surge effects (John Takekawa, pers. comm., January 23, 2013, USGS Western Ecological Research Center).

Ocean Chemistry

Ocean water absorbs atmospheric carbon dioxide (CO_2); subsequent reactions with water molecules ultimately produce bicarbonate, carbonate, and hydrogen (H^+) ions (Hönisch et al. 2012). Greater inputs of CO_2 increase concentrations of both H^+ ions (which increases water acidity [= lower pH]) and carbonate ions (which decreases the saturation state of calcium carbonate [$CaCO_3$]) (Orr et al. 2005). $CaCO_3$ is a compound necessary for shell and skeleton development in many marine organisms (Hauri et al. 2009).

Since the beginning of the industrial era, global oceans have absorbed ~560 billion metric tons of CO_2 (Sabine et al. 2004, Doney et al. 2009), including ~50 percent of CO_2 released from the burning of fossil fuels (NOAA 2008). The addition of CO_2 derived from fossil fuels has increased H^+ ion concentrations ~30 percent (NOAA 2008), reducing global mean ocean surface pH by 0.1from ~8.2 to ~8.1 since 1750 (Feely et al. 2008, 2009; Bernie et al. 2010). Along the Pacific Northwest coast, Wootton et al. (2008) reported a recent, short-term (2000–2007) declining trend in ocean pH at Tatoosh Island, although daily and season variability in pH was substantial.

Ocean pH and carbonate ion concentrations vary at different ocean depths (Feely et al. 2004); deeper waters (down to 250 m) have greater acidity and reduced $CaCO_3$ saturation (Byrne et al. 2010). In the California Current System off the U.S. West Coast, Feely et al. (2008) reported that ocean waters

with high acidity and undersaturated carbonate concentrations have risen 50–100 m (164–328 ft) since pre-industrial times, and are now within the density layers that are currently being upwelled onto coasts and into estuaries. Ocean currents that cause upwelling along the Pacific coast are particularly strong in the Pacific Northwest (Hickey and Banas 2003, Feely et al. 2008), and upwelling is a substantial factor in flushing rates within Grays Harbor (Duxbury 1979).

Future Projections

Without strong global emissions mitigation, Bernie et al. (2010) projected that global surface pH will decrease to 7.67–7.81 by 2100. A pH of 7.8 by 2100, which was projected by Feely et al. (2009) using the A2 (nonintervention) IPCC scenario, would result in a 150 percent increase in ocean acidity relative to pre-industrial times.

Regional projections for the North Pacific (Feely et al. 2009) suggest that, by 2100, ocean pH will decrease up to 0.31 units from the 1990–1998 mean of ~8.1, depending on future atmospheric CO_2 levels. Similarly, carbonate ion concentrations will decrease up to 45 percent. Gruber et al. (2012) projects nearshore carbonate saturation will decrease substantially at all depths of the California Current System upwelling areas by 2050, with seafloor habitats (>120 m deep) developing year-long under-saturation within 20–30 years. Within the California Current System, the intensity of acidification may be further enhanced during the 21st century because of large-scale changes in ocean currents and circulation (Feely et al. 2012).

Other Ocean-related Factors

Climate also affects other ocean conditions, such as water temperature, waves, and upwelling currents. Natural variability in these characteristics is large, especially in dynamic ocean regions such as the eastern Pacific Ocean (Hickey and Banas 2003). In general, all of these are projected to change as global and regional climatic conditions change, but the magnitude of these changes is uncertain.

Mote and Salathé (2010) projected sea-surface temperatures to increase 2.2 °F for coastal ocean waters between 46 °N and 49 °N by the 2040s (relative to the 1970–1999 average), but seasonal differences in upwelling events (especially in summer months) cause substantial uncertainty in the magnitude of possible temperature increase; however, little change in the seasonal timing of coastal upwelling is projected (Mote and Salathé 2010). Extreme wave heights, especially during strong winter storms, have increased since the 1970s (Menéndez et al. 2008), and are projected to increase further as warmer global temperatures may cause increased frequency of intense extra-tropical cyclones (Ruggiero et al. 2010). However, these impacts will have greatest impacts to exposed coastal areas; wave effects are greatly muted at estuaries within large bays (e.g., Grays Harbor).

3.3 Hydrology

3.3.1 Grays Harbor National Wildlife Refuge

Grays Harbor is the third largest estuary of the Pacific Northwest Coastal Region. The Refuge makes up less than 2 percent of the entire estuary. Estuaries are most commonly defined as semi-enclosed coastal bodies of water having a free connection with the open sea and within which seawater is diluted measurably by freshwater from land drainage. Research shows Grays Harbor is a drowned river type of estuary (Hickey and Banas 2003, Emmett et al. 2000, GHEMPTF 1987). It is fed by the

2,550-square mile drainage within the Chehalis River Basin and provides nearly 34,000 acres of intertidal mudflats. Tributaries of the estuary include the Chehalis, Hoquiam, Wishkah, Humptulips, Johns, and Elk River basins. The Chehalis River is the major freshwater source, providing approximately 80 percent to the Harbor (GHEMPTF 1987). As a transition zone between fresh water and marine ecosystems, estuaries are highly productive areas that offer habitat of special importance to the early life stages of the many aquatic marine animals, migratory birds, and other animals.

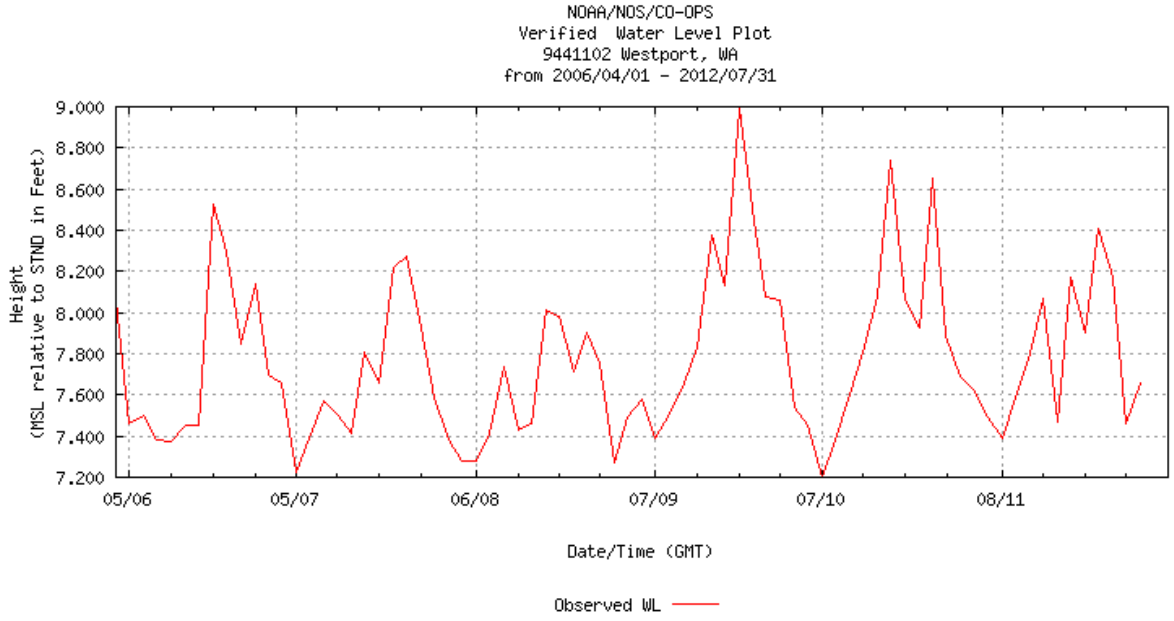
Tides

Tides in the estuary are a major part of the hydrologic influences on Grays Harbor Refuge and its habitats. The depth and width of the harbor mouth influence how much and how fast tidal water flows in and spreads across the estuary and to the Refuge. The tides generally move slowly: peak high tide at Aberdeen is 30 minutes later than the peak at the estuary mouth. The estuary is a shallow basin with depths averaging less than 20 feet. It has multiple tideland-connected channels and wide expanse of mud and sand flats. The tidal flats are important in the movement, mixing, and re-aeration of estuary waters during tidal ebb and flood. More than half of the surface area of this estuary lies in the intertidal zone with the tidal flats averaging about 1 to 2 feet above mean lower-low water (MLLW). Dredged shipping channels are approximately -38 feet MLLW (GHEMPTF 1987, Hickey and Banas 2003).

The mean daily tidal elevation range is 10 feet in the Aberdeen-Hoquiam area. Maximum mean tidal velocities in the upper harbor vary about 3 feet per second (fps) during floodtide to about 4.5 fps during ebb tide (GHEMPTF 1987). The average tidal water levels for Grays Harbor estuary from 2006 to 2012 are represented in Figure 3-13.

The Refuge is sited in what was formerly an open section of the estuary with unrestricted tidal movement. The construction of Bowerman Airfield peninsula in the 1940s restricted tidal flow and changed sediment movement and deposition. Additional uplands created by fill at the east end of the basin may have helped to further restrict tidal action and may be serving to increase the capture of sediments. Currently, Refuge mudflats are some of the last to flood and are among the first to become exposed with the falling tide.

Figure 3-13. Average tidal range recorded at the mouth of Grays Harbor estuary 2006–2012.



Salinity

Mixing of fresh water and salt water varies by season and location. Peak freshwater discharge occurs from streams and rivers in winter, especially during storms, while low freshwater input occurs in the summer months. The ocean, rather than local rivers, is the dominant source of nutrients and biomass along the Pacific Northwest coast and in this estuary (Hickey and Banas 2003). Hickey and Banas report the mid-portion of the estuary (near the Aberdeen-Hoquiam area) ranges from low salinity of 5 parts per thousand during winter to 20 parts per thousand during the summer months. Vertical salinity stratification, with a salt water wedge typical of estuarine systems, occurs only in the south channel (Simenstad and Eggers 1981). The winter salt-water wedge or upstream limit of salt water intrusion stops at the Aberdeen-Hoquiam area, and the summer upstream limit is some 10–12 miles further up the Chehalis River at Montesano (GHEMPTF 1987).

3.3.2 Black River Unit of Billy Frank Jr. Nisqually National Wildlife Refuge

The Black River, a tributary of the Chehalis River, flows southwesterly through the western and southwestern portion of Thurston County. Originating in wetlands at the south end of Black Lake (river mile 25), the Black River begins as an extremely low-gradient river system. The slow descent for most of the river length allows an accumulation of mud, sand, and decomposing organic material that provides for abundant aquatic and semi-aquatic plant and animal life. Beaver dams throughout the northern portion of the river help to create and maintain shallow water swamps and wetlands on the Unit. The Black River features some of the largest natural freshwater wetlands in western Washington (Pickett 1994a, Foster Wheeler 2003, Caldwell et al. 2004, Napier et al. 2008, Easterly and Salstrom 2008, CRC 1992).

Within the Unit acquisition boundary, the river channel varies from 15 feet to 120 feet in width and runs approximately 7 miles in length. Dempsey Creek, Salmon Creek, and Blooms Ditch drain into the river within the current Unit boundary with Waddell Creek bordering the former Weiks Dairy

Unit and entering the river just south of the Unit boundary. There are numerous named and unnamed creeks and streams within the Unit acquisition boundary totaling approximately 23 miles (see Map 4). The acquisition boundary ends north of the town of Littlerock at approximately river mile 17.

There are two major topographic regions which affect the hydrology of the Black River Unit: the western uplands and the eastern lowlands. The Black Hills, a low, mountainous region that includes the Capitol State Forest, forms most of the western watershed. The two largest tributaries of the western watershed are Waddell Creek (10.4 miles long) and Mima Creek (7.15 miles long). There are also smaller tributaries, including Mill, Stony, Baker, Noski, Darlin, and Dempsey creeks, and several smaller unnamed creeks. The eastern lowland region includes forested rolling hills and grasslands. The eastern region of the Black River drainage also includes several lakes and numerous wetlands. Salmon, Blooms Ditch, Beaver, and Allen's Creeks drain from the east into the northern and middle aspects of the River.

The Black River was historically the primary outlet draining Black Lake, but the hydrology of the system has been radically altered through the years. Anecdotal information indicates the river channel may have been dredged or straightened in some areas in the 1800s. Additional changes to the river system began in the early 1900s when water was diverted from the lake to improve drainage north of Black Lake, including digging the Black Lake Ditch in 1922. The ditch continues to divert a large amount of water flow northward to Puget Sound through Percival Creek, instead of south into the Black River. A pipeline was installed in 1965 across the northern portion of the Black River, which appears to have created a low berm across the wetlands. Hydrological studies indicate some impacts on the direction of water flow, although drainage through the Black Lake Ditch is the greatest factor influencing the direction of flow (Foster Wheeler 2003). Many changes throughout the years have affected the natural hydrologic regime of the river system including the issuance of water rights and water withdrawals.

Flooding and Surface Water

The Black River valley is known for its wide, flat lands that rapidly flood with winter and spring season rains. Most flooding along the main stem of the river is inundation flooding with low velocity floodwater because the wetland complex buffers the flow. The main streams draining east of the river are Salmon, Blooms Ditch, Allen, and Beaver Creeks. These are slow-flowing systems that tend to cause inundation flooding with little to no velocity. The east side of the drainage is susceptible to high groundwater flooding when periods of extended rain exist (Thurston County 2012). Within the Unit boundary only Salmon Creek and Blooms Ditch drain into the river from the eastern side. From the west side of the drainage, Dempsey Creek flows into the river, is flashy, rising quickly and spreading out, and then draining rapidly.

The two roads that cross the Black River and associated wetlands within the approved boundary of the Unit act as dikes and increase water levels in wetlands directly upstream. The road dike and bridge situation prevents the channel from naturally changing course at these locations and alters flow through the restricted channel opening. The roadway approaching the 110th Avenue Bridge over the Black River is usually one of the first local roads to close and last to reopen due to surface flooding associated with typical winter rains. The 123rd Avenue roadway itself is sometimes flooded west of the bridge during these periods. All habitats on either side of the river are replenished with sediment and nutrients during periods of surface flooding.

3.4 Topography

3.4.1 Grays Harbor National Wildlife Refuge

The Refuge salt marshes lie at the base of rugged forested hills to the north of the Refuge boundary ascending to a maximum elevation of 2,400 feet. Stream drainages from these hills cut a series of valleys, which lead down to Grays Harbor with habitats transitioning from forested slopes to the lower elevation salt marshes and open water of the Refuge. Along the eastside and continuing to the south side of the Refuge boundary are constructed fill areas which are slightly higher in elevation and support an early successional alder forest. The tidal mudflats and salt marsh habitats are generally flat and become inundated with tides over 8.5 feet.

Overall, Grays Harbor estuary and the Refuge is a shallow basin with depths averaging less than 20 feet (including channel depths). It has multiple connected channels and a wide expanse of mud and sand flats. Ebbing tides and river channels have caused shallow depressions within the estuary and Refuge boundary. Nearly level mudflats and salt marshes border the open water habitat within the Refuge.

3.4.2 Black River Unit of Billy Frank Jr. Nisqually National Wildlife Refuge

The Unit is located within the Puget Sound Trough Ecoregion with the Coastal Range Mountains to the west and the Cascade Range to the east. The Coastal Range Mountains border the western portion of Thurston County, with rolling hills and valleys lying towards the east and south. Foothills of the Cascade Mountain Range and Mount Rainier begin to rise in the southeastern portion of the County. Surrounding elevations in the immediate Black River area range from sea level at Olympia to 2,657 feet in the Black Hills west of the Unit. The Black River valley floor is approximately 200 feet above sea level.

3.5 Geology

3.5.1 Grays Harbor National Wildlife Refuge

Over millions of years, geologic forces such as earthquakes and volcanic eruptions have shaped the land in Washington State. After erosion, deposition, and plate tectonics worked the landscape in Puget Sound for approximately 60 million years, a series of glaciers advanced from what is now British Columbia into the lowlands between the Cascade and Olympic ranges (White 1997). After each advance, the glaciers receded to the north and up the valleys to higher elevations, where they persist today. Between 150,000 and 15,000 years ago, these glaciers formed a glacial drift plain of gravels, sand, silt, clays, and tills that comprise the gently undulating surface of the Puget Sound lowlands (White 1997). In lowland areas around the sound, retreating glaciers left behind a thick mantle of lacustrine and outwash sediments over bedrock as far south as Chehalis, Washington.

The Chehalis River Valley formation was created by debris left by the advance of the Vashon Glacier southward from Puget Sound some 15,000 years ago. Glacial debris can be found east of Grays Harbor and along the banks of the present channel of the Chehalis River, which drained a major portion of Puget Sound during that glacial period. The estuary is a drowned portion of the Chehalis River Valley, and is continually being filled in with river-borne sediments and oceanic materials. The

surrounding uplands are composed of unconsolidated Pleistocene silt, sand, and gravel, which are sedimentary, and volcanic rocks of the Tertiary Age that form low relief hills. The predominant physical feature of the estuary is the vast amount of intertidal mud and sandflats (GHEMPTF 1987).

3.5.2 Black River Unit of Billy Frank Jr. Nisqually National Wildlife Refuge

The Black River is located within and below the maximum southern extent of Pleistocene continental glaciations west of the Cascade Mountains. The north end of the Black River drainage, including Black Lake and the upper reaches of the river, were under ice during the last glacial maxima. During early glacial retreat, meltwater was blocked by ice from flowing northward, and glacial meltwater from much of the entire lobe was channeled southward through a shifting series of outwash channels, including the Black River channel, to the Chehalis drainage, and then out to the Pacific Ocean. Routes of the outwash channels were controlled by the slowly retreating glaciers, the underlying outcrops of Eocene sandstone and basalt in the area, and the overlying topography of moraines and glacial till. Fine-textured sediment deposited during this process blanketed portions of the landscape. Sand was also deposited by overbank deposition during flood surges caused by hydraulic damming associated with the sandstone and basalt bedrock in the channel-ways (Easterly and Salstrom 2008).

The combination of huge volumes of meltwater and blockages by earth and ice caused the water to pond and form a series of temporary lakes, including Lake Russell (Bretz 1913, cited by Easterly and Salstrom 2008), which extended over the southern inlets of what became Puget Sound. Lake Russell had a spillway over a low divide from Budd Inlet to the head of the valley of the Black River. The volume of water that was carried south over the spillway was considerable and became a large erosional force all the way to the mouth of the Chehalis River (WCC 1933). Within flood channels, the flow of meltwater sorted outwash sediments, leaving gravel. The outwash events created, eroded, and reshaped terraces in the massive amount of sediment in the outwash channels. The resulting Black River occupies a channel that is oversized and has a very low gradient (average of 9 inches/mile). Associated with this channel are a series of terraces that are likewise low-gradient, some including perched wetlands on outwash terraces above the Black River channel. Overbank deposition of sand from the outwash events is primarily perched on or above remnant terraces on the edges of the immediate area, as at Olympia Airport and south of Maytown (west of Tilly Road). Mima mounds on both sides of the river appear to be related to/associated with some “middle” terraces of the outwash channels. The oversized drainage basin creates a broad wetland zone along much of the river, especially in the upper reaches. The low-gradient side-slopes produce an overall relatively stable landform, and landslides are rare along the main stem of the river (Smith and Wenger 2001, Easterly and Salstrom 2008).

3.6 Soils

3.6.1 Grays Harbor National Wildlife Refuge

Soil types vary widely within the estuary. Sandy soils dominate the estuary entrance from the Pacific Ocean, while peat-lined, clay-type soils occur near the mouth of the Chehalis River. River drainage areas are primarily of the clay type.

The bed of the estuary is composed of sediments transported into Grays Harbor from the ocean and tributary streams. Most of the sediment in the central and lower third of the estuary is of marine

origin; this area contains less silt and a higher sand content. The North Bay, South Bay, and upper two-thirds of the estuary contain a mixture of marine and river sediments (GHEMPTF 1987).

Tide flats substrates contain silt and clay composition deposited by water flow from storms, river runoff, and dredging. The alluvial soils are deep and poorly drained with no single profile. One commonly observed soil sample is dark olive gray, very fine sand on the surface with gray loamy, very fine sand below the 6-inch depth (GHEMPTF 1987).

In 1987 it was estimated that the Chehalis River transported about two million cubic yards of sediment into the estuary per year. Most of the sediment transport takes place during the winter high-flow months. A similar amount of marine sediments enter the harbor from its mouth per year. The upper portion of the estuary where the Refuge is located contains a mixture of marine and riverine sediments (GHEMPTF 1987).

Bowerman Airfield was constructed by placing dredge spoils within the confines of a bulkhead. After the 1940s, additional unconfined dredged material was placed to connect the airfield to the mainland and to create an east-west lying peninsula. The disposal has covered what later became the Grays Harbor Refuge with a layer of predominately fine-grained materials dredged from the inner harbor channel and over time has converted what was a mix of sand and mudflats to mudflats.

Currently the mudflats are higher in elevation than most others in the greater estuary. The elevation of the Refuge (formerly Bowerman Basin) has been raised because of nearby discharges of unconfined dredged material (GHEMPTF 1987) and tidal action movement of sediments into the basin. The Refuge mudflats are protected from major wave action by the peninsula, and the tides have carried the material back and forth, depositing them at slack tides (GHEMPTF 1987, USFWS 1988). Storm events tend to move sediment into the closed-ended basin and push heavy woody debris into the higher salt marsh areas potentially trapping sediment. Additional fill sites were established and used until 1975. Those areas contain a combination of dredge materials and hillside fill of clay and rock composition (USFWS 1988).

3.6.2 Black River Unit of Billy Frank Jr. Nisqually National Wildlife Refuge

Soils in the Black River drainage range from slightly to strongly acidic at the surface, but become more neutral with depth. Glacial deposits range from porous sands and gravel to till which consists of clay and silt mixed with coarser materials. These deposits are composed chiefly of granite and quartzite. Some soil types were derived from bedrock, valley deposits, lake sediments, and alluvial deposits, while others are highly or purely organic. In the lowlands of this drainage, organic soils are common. They consist of decaying wetland vegetation in various stages of decomposition.

The soil types are diverse and interspersed in an irregular pattern. Using NRCS web soil surveys, over 31 different soil units were identified within the approved acquisition boundary, including 20 hydric and 11 nonhydric units. The floodplain soils are nearly level, very deep, and well drained. They formed in alluvium derived from mixed sources. (USDA 2012, USDA 1990).

Riggs (1958) conducted a detailed soil profile study for peat between the upper reaches of the river to 123rd Avenue. Generally, the quantity of peat decreases from 35 feet deep in the north to 10 feet deep in the south, the river flows over the deepest part of the peat deposit, and fibrous and woody peat form the major part of the deposit. Approximately 1,465 acres of various kinds of peat, including 15

acres of sphagnum, were reported. Sphagnum peat was described as raw and wet, implying little decomposition, and its presence correlates to the presence of bog vegetation. Diatomite shows past diatoms and phosphate presence (Riggs 1958). The soil types, maturity, and depth directly correlate to plant communities found within the Unit boundaries.

3.7 Air Quality

Air quality refers to the cleanliness of the atmosphere. Clean air is vital to human health and is a resource protected by Federal, State, and local regulations because it is a natural resource without boundaries. Pollutants in the air can negatively affect plants, animals, and humans. Air quality is affected by climate, topography, and meteorological conditions.

The Environmental Protection Agency (EPA) has the lead responsibility for air quality in the United States; through the 1990 Clean Air Act, the agency sets limits on the amount of pollutants that can be discharged into the air. According to the EPA, more than 170 million tons of pollution are emitted annually into the air within the United States. The Washington Department of Ecology (WDOE) is responsible for protecting the air quality within the State.

3.7.1 Grays Harbor National Wildlife Refuge

The Olympic Region Clean Air Agency in Aberdeen, Washington, records site-monitoring of ambient air pollutants, meteorological parameters, and other air-related data near the Refuge. Local human activities on and adjacent to the Refuge boundary that can affect air quality include stationary sources, industrial activities, lumber mills, and paper mills. Individuals may also affect air quality through the use of vehicles, motorized boats, equipment, wood stoves and fireplaces, and operation of gas-powered machines. Most Refuge visitors drive their automobiles to participate in wildlife observation and educational activities. Refuge staff may utilize vehicles, heavy equipment, and small gas-powered equipment for various resource management and one-time construction projects.

3.7.2 Black River Unit of Billy Frank Jr. Nisqually National Wildlife Refuge

Air quality at the Unit is susceptible to gravel mining dust, woodstoves, vehicle exhaust, tractors, motorboats (e.g., gasoline-powered engines/equipment), and outdoor burning. Habitat and public use improvement projects, including monitoring activities, may include the use of heavy equipment and the operation of trucks, tractors, or motorboats to access portions of the Unit for management purposes.

3.8 Water Quality and Quantity

3.8.1 Grays Harbor National Wildlife Refuge

The Chehalis River Basin (Basin) drains more than 2,700 square miles of land (Map 1); it is the largest river basin in western Washington. The Basin's land base supports a growing population of more than 141,000 people (U.S. Census 2000). Forest management activities account for approximately 87 percent of the land uses, while only 11 percent are in agriculture, urban, or industrial uses (CBP 1998). Urban centers within the Basin include the cities of Chehalis, Centralia, Aberdeen, and Hoquiam. The Chehalis River is the primary tributary of Grays Harbor estuary and the

largest freshwater source, providing approximately 80 percent of the freshwater to the harbor (GHEMPTF 1987). Other large tributaries of the estuary include the Hoquiam, Wishkah, Humptulips, Johns, and Elk Rivers.

Protecting water quality within the Basin and the ocean remains a priority for many agencies and communities. The cleanliness of the tributary waters discharging into the estuary ultimately affects the quality of the water available for Refuge wildlife resources. Anadromous fish species such as fall Chinook, coho, chum, steelhead and bull trout, Pacific lamprey, eulachon, and green sturgeon are dependent on the estuary for rearing habitat and on the Basin's clean rivers for spawning habitat. Grays Harbor estuary is important to the health of many species of wildlife that need clean water to survive and thrive. Clean water supports prey species which in turn supports shorebirds that feed upon and depend upon invertebrate species during their long migrations.

WDOE is the agency responsible for ensuring that the streams and rivers are within the standards of the Federal Clean Water Act of 1972 (CWA). Over the years, many streams and rivers within the Basin have incurred impaired water quality status due to various levels of point source and nonpoint source pollution.

According to WDOE, the greater Grays Harbor estuary was listed in 1996 under section 303(d) of the CWA as not meeting water quality standards for fecal coliform bacteria (found in human and animal waste) because of inadequate controls of point or nonpoint sources of pollution (WDOE 2010a). Fecal coliform enters the harbor from a variety of sources; contributors were traced to the Chehalis River due to storm water runoff, including the sewage treatment plants in the cities of Aberdeen, Hoquiam, Ocean Shores, and Westport. Identifying, monitoring, and addressing pollution sources containing fecal coliform bacteria within the Basin is a high priority for WDOE. In 1989 WDOE identified eight pulp mills around the harbor including one in Cosmopolis and one in Hoquiam listed as violating water quality standards for the priority pollutant TCDD, a dioxin (WDOE 2010b).

Over the years, a small number of investigations have linked effects of water quality to the health of the estuary and wildlife on the Refuge. A contaminants investigation in 1987 conducted on shorebirds within Grays Harbor estuary found shorebirds contained high tissue burdens of DDE and PCBs. This study included spring migrant and overwintering birds collected within the Refuge boundary. The study noted that shorebirds along the Washington coast were accumulating toxins in their bodies from organochlorine contamination and that shorebirds could be a pathway for organochlorines to accumulate in raptors that feed on shorebirds (Schick et al. 1987). In 1990, the Service's Ecological Services Program conducted an investigation of sediments on the Refuge, which identified high levels of toxins (dioxin and furan) in amphipods. The results of this study have raised concerns because amphipods are an important food source for migrating shorebirds and fish species including salmon (Momot and Mahaffy 2004). WDOE participates in the National Coastal Condition Assessment and Environmental Monitoring and Assessment Program. The 2002 data show samples collected within the Refuge boundary have elevated concentrations of chromium (Partridge, V. 2011, pers. comm.).

State agencies, private groups, and researchers within the Basin, Refuge, and the greater estuary have conducted water quality testing and monitoring. The Chehalis Basin Partnership (Partnership) was formed in 1998 under the State's Watershed Management Act to provide a framework for local citizens, interest groups, and government organizations to work collaboratively to identify and solve water-related issues. Over the years, they have developed a Watershed Management Plan (2004), the

Implementation Plan (2007) and the Progress Report (2011) to address those issues. Refuge staff coordinates with several of the organizations active in the Partnership, participates in outreach efforts, and coordinates with Service staff representing the Service in Partnership issues.

Water quality is a vital component of the local community's health, economy, and the health of the Refuge's wildlife. Refuge managers recognize the need to conduct further research within the Refuge boundary regarding water quality issues (see Objective 2.4.3). They also recognize the need to work with partners in the Chehalis River Basin and throughout Grays Harbor estuary to address issues affecting water quality and to provide education about what can be done to improve it (see Objective 2.3.1 and 2.3.2).

3.8.2 Black River Unit of Billy Frank Jr. Nisqually National Wildlife Refuge

Water quality and pollution is a problem in the Black River and its tributaries (Yake and Bernhardt 1989, Pickett 1991). Nonpoint source pollution is a problem in the Black River basin. Stormwater runoff at commercial, light industrial areas and construction sites can produce potential pollutants, especially in the rapidly growing upper basin. Streets, roads, and highways, including Interstate 5, could discharge pollutants in stormwater or potentially spill into Black River tributaries. Water pollution from adjacent residential septic systems, recreational uses, and agricultural runoff continues to be a problem to be resolved by Federal, State, and local governments. Regional growth in the Black River basin will likely put pressure on the groundwater resource, from both withdrawals and pollutant inputs (Pickett 1994a)**.** The current trend towards increasing numbers of residential developments being serviced by individual septic systems overtaxes the area's capability to naturally treat residential wastes, resulting in ground- and surface water pollution.

Prior to 1989 the Black River had not been studied extensively. The Black River system was poorly understood but appeared to be sensitive to environmental impacts and under pressure from several different land uses and projected regional population growth. In 1989, a large fish-kill in the mid to lower portions of the river indicated poor quality water in the river, which stimulated more in-depth studies. Most studies took place in the 1990s and focused on the middle and lower sections of the river, but some of these established a few sampling points in the northern reaches of the river which are relevant to Unit management.

In 1994, two studies of the Black River were undertaken: one on dissolved oxygen and phosphorus, and one on fecal contamination and nonpoint source pollution. The areas of the river that were sampled (near 110th Avenue, 123rd Avenue, and River Road bridges (upper river)) (Pickett 1994a, 1994b) generally had acceptable temperatures, especially in winter, but late summer temperatures were above the standard of 64 °F (18 °C). The upper river pH levels were generally acceptable, but organic sediments reduce pH near the bottom of the river, while photosynthesis in the submersed vegetation increases pH levels near the water surface. Pickett (1994a, 1994b) suggests the low pH levels near the riverbed appear to be a natural condition, and not a violation of water quality standards.

Dissolved oxygen (DO) levels in Waddell Creek, measured during a significant flow period, were acceptable. However, none of the DO levels in the upper river were high enough to meet the standard of 8.0 mg/L and all samples were below standard saturation levels. Pickett cites Lee et al. (1975), who noted that high organic-matter content in the discharge from marshlands produces low DO levels and high color and that the DO level may be the result of natural processes. Two years of fecal

coliform tests showed no presence at 110th Avenue, but at the River Road site immediately north of Littlerock, testing showed higher concentrations. The likely sources of contamination between 110th Avenue and River Road were thought to be storm water, onsite septic systems, agriculture, and wildlife (Pickett 1994a, 1994b). Since that study was completed, a large dairy farm between 110th Avenue and River Road is no longer operational, reducing the potential for fecal contamination.

Between September 2007 and June 2009, a water quality study had 94 test sites on the Chehalis Rivers and its tributaries. Standard water quality tests included pH, DO, fecal coliform, turbidity, and water temperature. The criteria used to evaluate water quality were based on Washington State standards (173-201A WAC). The rationale for these standards is that water quality meeting the standards provides for the habitat needs of fish and other aquatic life, provides a safe environment for people engaged in water recreation, and provides for the production of healthy and safe seafood (Green et al. 2009).

Two sampling sites from this study are relevant to the Unit: one on the Black River at Black Lake and another at 110th Avenue. All the data collected from the two stations fell within the standard range for pH. The standard for DO is ≥8mg/L and the north-most site showed excellent DO quality with only 1 sample below the standard, but the 110th Avenue site had 16 of the 29 samples (61 percent) below the standard. Again, an explanation for the sub-standard levels could be that the Black River is a relatively low-gradient river that flows through shrub swamp with mostly agricultural lands or forests in nearby uplands, and these lands and fertilizers may create high nutrient inputs into the river. However, this slow-moving river also accumulates organic debris, such as peat soils and rotting leaves that fall from vegetation along the banks.

The river has dense underwater vegetation and algae above the 110th Avenue sample site. The upper reaches of the river contain shrubs rather than taller trees, resulting in full sun exposure. Decomposing algae, aquatic vegetation, and organic debris in water bodies reduce DO in the water due to cellular respiration of the bacteria and fungi that act as decomposers. These natural processes may be contributing to lower DO in the Black River. No fecal coliform was detected in 28 samples in the Black River at the Black Lake site, in 27 samples at 110th Avenue, nor in 28 samples from the Littlerock boat launch site located south of Littlerock. This shows significant improvement from the 1994 study. One sample of 28 and one sample of 27 showed turbidity over the 7 nephelometric turbidity unit standards at the north-most sample site and from the 110th Avenue location, respectively (Green et al. 2009).

Another factor affecting water quality is the growth of macrophytes and periphyton in the Black River. Pickett noted from Hill (1986) that sediments provide much of the nutrient supply for macrophytes, macrophytes transfer large amounts of nutrients back to the sediments, and that macrophytes could release sediment-derived nutrients into the water column. Furthermore, as macrophytes utilize particulate matter and dissolved nutrients from the water column, nutrients are cycled between the living tissue and the sediment, creating a self-sustaining system. Pickett noted that if an effort was made to reduce nutrient levels and phytoplankton in the water column, the plants would have a sediment nutrient source, and macrophyte reduction would occur very slowly, if at all, and the cycle would continue (Pickett 1994a, Green et al. 2009).

In the northern portion of the river, dense growth of submerged plants is currently thought to be primarily native species, although surveys need to be conducted to verify this. Currently submerged plant colonies grow very thick, providing cover and food sources for amphibians and fish. Nonnative reed canarygrass grows densely along the banks and then roots into submersed plants in the

mainstem of the river. This dense plant growth can limit light penetration, causing less oxygen to be generated within the water column. Later, decomposition of the decaying vegetation further depletes oxygen levels to the point of excluding fish, mammals, and invertebrates from those areas with the densest growth. The river's anaerobic bacteria can live in low- to no-oxygen water and produce sulfuric waste products, causing the lake and sediments to release gas and odors (SBLC 2012). Algal mats develop on the river during warm summer temperatures and also when water flow is greatly reduced. Algal growth may be enhanced by artificial nutrient sources, inputs from fertilizers, and leaky septic systems. The algal mats grow on the submersed plants, cover them, and form a thick surface scum layer. This quantity of algae may have detrimental effects on water quality. Although river water quality testing took place in the 1990s, recent information on water quality in the upper reaches of the Black River has not been collected.

Napier et al. (2008) notes concerns in the Black River Management Unit (watershed) that poor water quantity exists naturally due to the river's general character; however, the situation may be exacerbated by loss of water flow resulting from the pipeline crossing along with increasing water withdrawals. General actions to help increase water quantity include reducing water withdrawals from surface sources, determining if water withdrawals are followed according to current water rights, and conducting a study on unregulated/regulated withdrawals. Increasing sediment load in the river mainstem also contributes to poor water quality. Suggestions to reduce sediment loading in the river include reducing road densities (abandon/decommissioned) in upland forests and further identifying sources that are contributing to sediment loading (Napier et al. 2008).

In 2010 and 2012, Black Lake, the headwaters for the river, was temporarily closed to swimming and water sports due to a blue-green algal bloom. Black Lake is infested with nonnative plant species including Eurasian watermilfoil and yellow flag iris. Save Black Lake Coalition is a nonprofit organization formed in 2010 in response to the lake closure. The goal of the coalition is to educate landowners about lake water quality and improve water quality by reducing invasive plants and reducing or eliminating algal blooms.

3.9 Surrounding Land Use

3.9.1 Grays Harbor National Wildlife Refuge

The land use patterns surrounding the Refuge are primarily forestland dedicated to commercial timber production and a mix of urban areas, including the cities of Aberdeen and Hoquiam. To the north of the Refuge boundary is Highway 109 and many rural residential properties. Highway 109 has been designated as a State Scenic Byway. Directly to the east of the Refuge are upland properties, managed by the Port of Grays Harbor as industrial sites, and formerly a log-storage and shipping yard that has been considered for a variety of uses. In 2012 a coal transfer operation was planned but terminated. Currently a crude oil tank farm and transfer operation is being considered for development. South of the Refuge boundary, the City of Hoquiam runs their water treatment facility and the Port operates Bowerman Airport. The Bowerman airfield operates 24 hours a day, providing jet capable access, air cargo, and hangars. Lands currently not acquired within the Refuge acquisition boundary include approximately 309 acres of intertidal mudflat and open water habitat.

3.9.2 Black River Unit of Billy Frank Jr. Nisqually National Wildlife Refuge

Land use in the Black River basin includes undeveloped wetlands, agriculture, and a mixture of residential and commercial development. The uplands are generally commercial timberlands and expanding low- to high-density residential developments. Land use activity in the Black River basin has been transitioning from agriculture to rural residential. A number of dairies in the past have been located in the basin, but most have closed down. Poultry operations, a silviculture nursery, and turf and berry farms have operated in the basin (Pickett 1994a). Timber harvest and management activities currently occur throughout the basin, especially in the Black Hills by WDNR on Capitol Forest lands.

Lands within the Refuge acquisition boundary include approximately 2,293 acres of privately owned tracts, many utilized as residential properties. Two large tracts within the boundary are managed for commercial timber purposes.

Residential housing developments and farms lie outside the Refuge acquisition boundary. A local gravel mining operation lies directly on the northeast side of the Refuge boundary, located both inside and outside of the approved boundary. Interstate 5 is within 5 miles of the boundary and provides access to neighboring cities and communities. Within Thurston County there are a number of recreation areas, parks, and open spaces that benefit wildlife and are open to public access. Some examples are Chehalis Western Trail, Woodard Bay Natural Resources Conservation Area, Capitol State Forest, Mima Mounds Natural Area Preserve, and Glacial Heritage Preserve (see Chapter 5). Thurston County owns the railroad right of way east of the Refuge and is planning the Gate Belmore Trail on the old railroad bed. The State offers approximately 25 areas opened to fishing within the county. The State also offers hunting opportunities throughout the county, which include big game, upland game birds, and waterfowl.

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