FTA RESEARCH

Sound Transit
Climate Risk Reduction Project

SEPTEMBER 2013

FTA Report No. 0075
Federal Transit Administration

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liter	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

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ABSTRACT

The Climate Risk Reduction Project assessed how climate change may affect Sound Transit commuter rail, light rail, and express bus services. The project identified potential climate change impacts on agency operations, assets, and long-term planning; options for strengthening the agency's resilience to these impacts; and opportunities for integrating climate change considerations into agency decision making processes. The project concluded that many climate change impacts will likely be minor to moderate, although potentially significant impacts are possible with higher rates of sea-level rise and mudslide activity.

EXECUTIVE SUMMARY

Sound Transit's Climate Risk Reduction Project assesses how the agency can build resilience to the potential impacts of climate change. The Federal Transit Administration (FTA) funded the 18-month project as part of its Transit Climate Change Adaptation Assessment pilot program, which made awards to seven transit agencies nationwide. Sound Transit's project was undertaken as a partnership with the University of Washington Climate Impacts Group and the Washington Department of Transportation (WSDOT).

The central goal of the project was to identify potential:

- climate change impacts on Sound Transit operations, assets, and long-term planning
- options for strengthening the agency's resilience to these impacts
- opportunities for integrating climate change considerations into agency decision making processes

As one of seven national FTA-funded pilots, the project also aimed to:

- create a process and a model for assessing and planning for climate change impacts that is transferable to transit agencies across the United States
- provide a state-to-local testing ground for WSDOT's pilot use of the Federal Highway Administration's (FHWA) climate change vulnerability assessment methodology

Meeting Federal Climate Adaptation and Resilience Goals

Sound Transit's project was selected by FTA to advance the state of practice for adapting transit systems to the projected impacts of climate change. In 2011, FTA issued a policy statement on climate change adaptation[1] to ensure proper stewardship of federal investment in public transportation systems, public safety for the traveling public, continued mobility, and maintenance of a state of good repair.

According to FTA, climate-related changes are already being observed in the United States and will increase in the future, as projected by the federal government's Global Change Research Program. Expected impacts from climate change for the Pacific Northwest (PNW) include rising temperature and sea level, as well as increases in both extreme downpours and drought. Reducing greenhouse gas (GHG) emissions will lower the severity of these impacts over the long term. However, even with immediate aggressive action to reduce emissions going forward, past emissions will continue to cause climate change impacts for many decades.

[1] Available at http://www.fta.dot.gov/documents/Final_FTA_Policy_Statement_signed_5_31_11.pdf.

Defining Climate Adaptation and Mitigation

FTA's policy statement noted that an effective response to climate change must include both mitigation and adaptation. The following terms—as defined by FTA[2]—are integral to how Sound Transit approached this project.

- *Mitigation*: An intervention to reduce the causes of changes in climate, such as through reducing emissions of GHGs to the atmosphere.
- *Adaptation*: Adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects.
- *Resilience*: A capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment.
- *Vulnerability*: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes.

Why Climate Change Matters to Sound Transit

Sound Transit plays a key role in facilitating mobility for approximately 28 million riders annually in Washington State's central Puget Sound region. Sound Transit's transportation network is a multimodal system combining commuter rail (Sounder), light rail (Central Link and Tacoma Link), and express bus service (ST Express) (Figure ES-1). The agency's service area encompasses 1,100 square miles in a diverse urban landscape that includes three counties (King, Pierce, and Snohomish) with a population of about 3 million. By serving these counties, the agency provides service to the most congested urban areas in the Puget Sound region, including the Everett, Seattle, and Tacoma metropolitan areas.

[2] See http://www.fta.dot.gov/12347_12128.html.

Figure ES-1

Current Sound Transit service map, inclusive of Link extensions under construction or in planning as part of the ST2 ballot measure approved by voters in 2008

Source: Sound Transit

Defining the Phrase "Sound Transit Services"

The term "service" is used in this report to collectively refer to Sound Transit's three transit modes (Sounder, Link, ST Express), its customer facilities, and environmental mitigation activities. Customer facilities were discussed as a separate service given that facilities can be used by multiple modes.

Sound Transit is committed to examining the potential impacts of climate change because:

- *The agency operates in a diverse natural landscape sensitive to climate change.* Sound Transit services currently operate in areas prone to mudslides, flooding, poor drainage, and storm surge. These events already contribute to service disruptions and increase maintenance and operating costs.
- *Projected changes in regional climate are likely to affect Sound Transit services.* A substantial body of peer-reviewed international, national, and regional research shows that climate change could have potentially significant impacts on the PNW, Washington State, and the Puget Sound region. These impacts could affect many aspects of Sound Transit's operations, asset management objectives, and long-term system development.
- *Sound Transit has an unprecedented "window of opportunity" to address potential climate change impacts in a rapidly expanding system.* Sound Transit is currently implementing ST2, a 2008 voter-approved regional transit expansion plan to better connect the region's busiest population and job centers. The ST2 Plan will grow regional express bus service by 17 percent and commuter rail service capacity by 65 percent while building more than 30 additional miles of light rail and enhancing station access to form a regional light rail system over 50 miles long. Many aspects of this expansion are currently in the planning and design stages, providing a unique window of time to integrate information on potential climate change impacts into long-term planning and asset management decisions.

Major Project Phases

The Sound Transit Climate Risk Reduction Project drew on the expertise of Sound Transit staff, regional climate change science and adaptation experts, and published literature on climate change impacts. The project's major phases, summarized below, were structured to reflect this expert-based approach.

- *Preparation of technical materials.* The Climate Impacts Group developed a white paper summarizing relevant climate change projections for the region to provide a technical foundation for the project. The Climate Impacts Group also worked with Sound Transit GIS staff to develop maps showing rail alignments[3] and bus routes relative to current flood zones and projected sea-level rise inundation zones. Finally, the project team conducted an anonymous survey of Sound Transit staff to establish a baseline understanding of staff knowledge and opinions about how current and future climate conditions could affect infrastructure, operations, and planning at Sound Transit. Information from the survey was used to help plan the vulnerability assessment workshops.

- *Vulnerability assessment, adaptation, and integration workshops and meetings.* A series of workshops, organized by service, was held with more than 50 technical staff and senior managers. The workshops primarily focused on current services and approved expansions funded for design and construction under the ST2 expansion plan. In a few cases, expansions in the earliest stages of development were evaluated for potential climate impacts. These projects were included in the analysis to allow for early discussion of potential climate issues. Inclusion of potential projects in this report does not indicate Board commitment to these projects.

  Staff identified and qualitatively rated how today's extreme events (e.g., extreme heat, precipitation events, or high tide events) affect Sound Transit services, and how projected changes in those events could affect operations and planning. Staff also discussed adaptation options and approaches to integrating climate change considerations into agency processes.

- *Synthesis and assessment.* Results from the project's workshops were summarized in detail by service and analyzed to assess how climate change may affect Sound Transit. The analysis included a relative ranking of climate change impacts across services as well as a relative ranking of services based on impacts. Both approaches can inform decisions about if, when, and where adaptation measures may be warranted.

Climate Change Impacts Evaluated

Potential changes in climate relevant to Sound Transit include increasing summer temperature, increasing winter precipitation, more extreme heat and precipitation events, and sea-level rise (Table ES-1). The project focused on a range of impacts resulting from these changes (Table ES-2).

[3] The term "alignment" refers to the route upon which a train travels and the track is constructed (AREMA 2003).

Table ES-1

Projected Changes in PNW Climate

A substantial body of research shows that rising GHG emissions are inducing fundamental changes in global and regional climate that could affect Sound Transit. Projected changes in PNW climate relevant to Sound Transit services include the following. More details are available in Section 2 and Appendix A.

- Increased average annual temperature of 2.0°F (range: 1.1–3.3°F) by the 2020s, 3.2°F (1.5–5.2°F) by the 2040s, and 5.3°F (2.8–9.7°F) by the 2080s, relative to 1970–1999.[4]
- More frequent and longer extreme heat events.[5]
- Increases in winter precipitation and extreme precipitation events.[6]
- Decreased summer precipitation.[7]
- Increased slope instability and sediment loading in rivers and streams.[8]
- Increased winter flooding in many PNW rivers, including the Green, White, Puyallup, and Duwamish.[9]
- Sea-level rise of 4–56 inches for Seattle.[10]

These projections are based on assumptions about future GHG emissions and global climate models that are updated over time and therefore subject to change. Past experience shows that these updates often produce slightly different numeric values but do not alter the anticipated direction of change.

Will Snow and Ice Events Still Occur in a Changing Climate?

Climate change does not eliminate the potential for lowland snow and ice events in the Puget Sound region — we will continue to see years and seasons that are warmer or cooler than average even as the average around which temperatures vary increases. Potential changes in snow and ice events were not discussed in the project given the current lack of information regarding how these types of events may change. Over time, however, the frequency of snow and ice events may decrease.

[4] Mote and Salathé, 2010.
[5] Mote and Salathé, 2010; Jackson et al., 2010.
[6] Salathé et al., 2010; Rosenberg et al., 2010.
[7] Mote and Salathé, 2010.
[8] Hamlet, 2011.
[9] Elsner et al., 2010; Mantua et al., 2010.
[10] NRC 2012.

Table ES-2

Potential Climate Change Impacts Evaluated, Grouped by Principal Climate Cause

Related to Temperature *Increased potential for…*	Related to Precipitation *Increased potential for…*	Related to Sea level Rise *Increased potential for…*
• Rail buckling[11] • Heat stress on electrical and safety equipment • Heat stress on overhead catenary system • Heat stress on pavement, structures • Heat stress on landscaping and environmental mitigation sites	• Mudslides and slope instability • Larger and/or more frequent river and stream flooding • Increased localized flooding due to more stormwater runoff or poor drainage • Seepage due to higher groundwater tables • Summer drought	• Temporary flooding of low-lying areas • Permanent inundation of low-lying areas • Higher tidal and storm surge reach • Erosion • Drainage problems • Corrosion from more frequent or prolonged exposure to saltwater

Summary of Key Findings and Considerations

1. Climate change exacerbates many existing issues already facing Sound Transit.

- Many of the climate change impacts evaluated for the Sound Transit Climate Risk Reduction project are already possible in today's climate and are not unique to climate change. For example, impacts on infrastructure and operations from extreme precipitation events, heat stress, mudslides, and major river flooding can occur even without climate change. Although Sound Transit already accounts for these issues in current infrastructure design and operations, climate change may alter the frequency, intensity, location, or duration of these impacts.

2. The probability, timing, and degree to which climate change may affect Sound Transit are dependent on many factors.

- *The rate and magnitude of climate change*. Past, current, and future GHG emissions are a key determinant to how much climate changes and how quickly it changes. The amount and rate of change, in turn, can affect both the magnitude (or size) of impacts and the ability to adapt; it can be more difficult to adapt to large impacts or rapid rates of change. This report is based on current projections about the rate and magnitude of climate change; these projections may be altered as new scientific data and analysis is performed.
- *Assumptions about climate conditions*. Climate change impacts on infrastructure and operations will be shaped, in part, by assumptions made about current and future climate conditions. The larger the mismatch between observed climate and the climate assumptions embedded in design, construction, and operation standards, the greater potential for climate impacts. Embedded assumptions

[11] A rail buckle is an unwanted bend or kink in steel rail that occurs when rail temperatures are high enough to cause steel rail to expand beyond the holding capacity of the rain anchors, forcing the rail out of alignment.

may include assumptions about minimum and maximum temperature, the amount of rain falling in a 25-year, 24-hour storm event, groundwater seepage rates, and the size of flooding associated with the 100-year flood event.

- *Changes external to the agency.* Actions taken by partner agencies and jurisdictions can affect how climate change affects services. For example, changes in development may alter stormwater runoff patterns, reducing or increasing the potential for increased localized flooding during extreme precipitation events. Similarly, adaptive actions taken by partners and jurisdictions to address sea-level rise could reduce the probability of many sea-level rise impacts.
- *Natural variability.* Natural climate variability will continue to have an important influence on PNW climate and how we experience climate change. Natural variability is expected to remain an important feature of PNW climate, at times amplifying or counteracting the long-term trends caused by rising GHG emissions.

3. Many climate change impacts on Sound Transit services will likely be minor to moderate, although more significant impacts are possible if higher rates of sea-level rise and mudslide activity occur.

- *Ranking the relative significance of climate change impacts.* Climate change impacts were ranked as potentially minor, moderate, or significant.
  - This ranking was primarily based on how each climate change impact could affect service delivery. The geographic distribution of the impact, potential cost issues related to managing or responding to an impact, and other factors were also considered. The estimated probability of an impact occurring was not a determining factor for ranking impacts. However, information on probability was noted to help inform decision making.
  - The prioritization results rate impacts and services relative to each other, not against an external benchmark. Any designations as "significant" or "high" must be considered in context of the project's overall conclusion that many climate change impacts on Sound Transit services will likely be minor to moderate.
- Ranking results are based on system characteristics (e.g. where and how services operate, equipment types, etc.) and climate change projections during the project period (February 2012-August 2013). Updates to regional climate change projections and changes in system design could alter these findings.
  - As noted previously, the degree to which climate change impacts affect Sound Transit can vary depending on how large the climate change impact is (e.g., 22 inches versus 50 inches of sea-level rise), system design, and other factors. This report's prioritization of climate change impacts assumes the size of the projected impact is at the high end of what would be expected. Table ES-3 illustrates how different magnitudes of a climate change impact can have different probabilities and impact implications for Sound Transit.

Table ES-3

*Projected Climate Change Impacts by Degree of Potential Impact and Estimated Probability **

Estimated Impact on Operations and Infrastructure	Low	Medium	High
Significant	• **Inundation** of Mukilteo and Edmonds Sounder facilities (possible only with sea-level rise of 50 inches or more, which is currently at high end of projections for 2100)	• **Increased mudslide activity** causing more than 70 train cancellations in a season (Sounder)	
Moderate	• **Increased major flooding** in both rain-dominant and rain/snow mix rivers • **Potential for rail buckling**	• **Increased mudslide activity** causing 33–70 train cancellations in a season (Sounder) • **Increased localized flooding** due to more stormwater runoff or poor drainage (in previously unaffected areas) • **Increased storm surge reach, higher high tides, and more temporary flooding** related to moderate amounts of sea-level rise (e.g., in range of 22 inches, near the mean value for 2100)	• **Increased localized flooding** due to more stormwater runoff or poor drainage (where already an issue) • **Increased storm surge reach, higher high tides, and more temporary flooding** related to lower amounts of sea-level rise (less than 22 inches)
Minor	• **Heat stress** on: - auto-tension overhead catenary system (OCS) (Link) - air-conditioned electrical equipment - environmental mitigation projects (established wetland sites)	• **Heat stress** on: - facility landscaping (established sites) - environmental mitigation projects (pre-established wetland sites) • **Increased minor to moderate flooding** in rain-dominant rivers and streams • **Increased groundwater seepage into tunnels**	• **Heat stress** on: - facility structures - non-tunnel fixed termination OCS (Link) - natural ventilated electrical equipment - facility landscaping (during establishment) • **Increased minor to moderate flooding** in rain/snow mix rivers • **Increased mudslide activity** causing less than 33 train cancellations in a season (Sounder)
	Estimated Probability of Climate Change Impacts		

*If, when, and where these impacts affect services will vary. Some impacts have the potential to affect limited areas or services while others may apply more broadly.

- **Potentially significant impacts** are those that could cause frequent extended (e.g., multi-day) or permanent service cancellations, require expensive infrastructure repairs or adjustments, and/or reduce customer confidence. Potentially significant climate change impacts for Sound Transit are increased mudslide activity and sea-level rise.
  - *Increased mudslide activity.* Mudslide risk is already an issue for the North rail alignment used by Sounder and other services (e.g. Amtrak, freight rail service). Increased mudslide activity could lead to more train cancellations, increased use of "bus bridges" in lieu of cancelled trains, and reduced customer confidence, particularly if the number of train cancellations exceeds 70 per season on a more consistent basis. The potential for damage to trains and derailment also increases with more mudslide activity. Ongoing efforts by Burlington Northern Santa Fe (BNSF), WSDOT, Amtrak, and Sound Transit to mitigate slide risk along the North rail alignment[12] are likely to help reduce the frequency of mudslides in some of the highest problem areas in the corridor. However, other areas may still be vulnerable to slides or become vulnerable as a result of projected increases in precipitation.
  - *Sea-level rise*. Sea-level rise has the potential to affect most of the North rail alignment as well as the Edmonds and Mukilteo facilities. Permanent inundation of rail track and facilities is the most significant impact and is possible in the vicinity of Edmonds and Mukilteo if sea-level rises 50 inches or more (currently near the high end of projections for 2100). Lower levels of sea-level rise would not permanently inundate the track or facilities but would still expose the length of the North rail alignment to more extreme high tides, temporary flooding, saltwater corrosion, and storm surge impacts.

- **Potentially moderate impacts** are those that could cause occasional (e.g., occurring every few years or longer) multi-day service cancellations, frequent moderate-length service delays (e.g., in the range of hours) and cancellations, increased maintenance, moderate structural repairs, and customer service issues. Potentially moderate climate change impacts for Sound Transit are increased river flooding, increased localized flooding due to more stormwater runoff or poor drainage, and rail buckling.
  - *Increased river flooding.* The potential for increased flooding is most relevant to the South rail alignment used by Sounder and the Kent and Tukwila Sounder stations. River and creek flooding could affect other parts of the Sound Transit system as well. The South rail alignment and facilities are located in the Green and White river valleys. Both rivers already have the potential for damaging floods even with fully operational dams and levees. Increased river flooding, particularly large-scale flooding, could result in

[12] See, for example, "Project aimed to stop landslides on rail tracks north of Seattle," Seattle Times, September 5, 2013, http://seattletimes.com/html/localnews/2021764571_railroadmudslidesxml.html.

widespread inundation that damages Sound Transit facilities (primarily parking areas and ground-level infrastructure) and limits customer access to services.

- *Increased localized flooding*. Increased localized flooding due to more stormwater runoff or poor drainage can occur anywhere in the Sound Transit service area. Stormwater is managed on Sound Transit properties through a variety of approaches, including Low Impact Development (LID). The robustness of LID system design relative to the size of current extreme rainfall projections is unknown at this time. Additionally, high volumes of stormwater runoff and drainage problems beyond Sound Transit's properties can affect agency operations and infrastructure. Potential impacts can include minor infrastructure damage, increased maintenance and stormwater management costs, service disruptions, and short-term impacts on customer access to services.
- *Rail buckling*. The potential for rail buckling exists in any at-grade or aboveground portion of Link and for all of Sounder but is more likely in areas where wood tie-and-ballast track is used, in inland areas away from Puget Sound, and in areas with high sun exposure. The potential is also slightly higher for Central Link, relative to the current and planned Link extensions, because of differences in the rail neutral temperature[13] used for installing Central Link track versus new track. Potential impacts may include service delays, interruptions, heat-related track repairs, and track retrofits.

- **Potentially minor impacts** are those that could cause frequent short-term (e.g., less than an hour) service delays and cancellations, increased minor maintenance, minor structural repairs, and minor (if any) customer service issues. Potentially minor climate change impacts for Sound Transit are heat-related impacts on electrical equipment, the overhead catenary system, facility structures and landscaping, and environmental mitigation activities. Increased groundwater seepage into tunnels is also a possibility. Potential impacts associated with heat stress may include minor service delays, service cancellations, additional maintenance requirements, infrastructure repairs or retrofits, and increased irrigation needs. These impacts are considered minor primarily because of their limited impact on infrastructure and operations.

4. Several services are likely to become priority areas for adaptive action.

- *Services with potential to become a higher adaptation priority*: North Sounder and the Edmonds and Mukilteo stations. Adaptive actions may be needed to address the potential for increased mudslide activity and sea-level rise impacts on the Edmonds and Mukilteo facilities. These measures would be high priority actions given their role in securing the safety of passengers and agency infrastructure.
- *Services with potential to become a medium adaptation priority*: South Sounder, the Tukwila and Kent Sounder stations, and at-grade or aboveground Link

alignments. Key issues for South Sounder and the Tukwila and Kent Sounder stations are potential impacts from increased flooding and higher summer temperatures. Key issues for at-grade or aboveground Link alignments are potential impacts from increasing temperature and precipitation as well as potential financial exposure for addressing impacts to Link, which is solely owned and operated by Sound Transit. adaptive actions to address these issues would have the benefit of reducing the potential for service interruptions in the heavily used South Sounder and Link services, reducing the need for potentially costly retrofits, and ensuring continued safety of passengers and agency infrastructure.

- *Services with potential to become a lower adaptation priority*: ST Express, Environmental Mitigation, other customer facilities, and underground Link alignments. Addressing climate impacts for these services is likely to be a lower priority relative to other services because the climate impacts potentially affecting these services have generally minor impacts on infrastructure and operations. However, as with other services, there may be cost savings associated with integrating adaptive actions for these services into routine asset management even if considered a lower priority area.

5. There are many options for action when Sound Transit determines that adaptation efforts are warranted.

- The Climate Change Risk Reduction Project identified more than 70 options for adapting to the climate change impacts listed in Table ES-2. In general, adaptation options fell into one or more of the following categories: adjustments to infrastructure, adjustments to operations and maintenance, design changes, and decision support and capacity-building activities (e.g., implementing new tools to gather additional information, using partnerships to address impacts).
- Implementing actions to address climate change impacts can strengthen Sound Transit's resilience to climate change and help ensure the agency is able to achieve its goals in a changing climate. Taking adaptive action can also protect agency investments, reduce risks to the current system associated with climate variability, and help the agency avoid creating new risks as future plans are developed.

6. Sound Transit's financial exposure to climate change impacts and adaptation vary by service.

- *Sounder*. Because Sound Transit does not own most of the rail infrastructure used for Sounder service, Sound Transit's financial exposure for adapting Sounder services is somewhat limited. Assuming current agreements

[13] Temperature-induced rail expansion and contraction is mitigated by heating or mechanically stretching the steel to "Rail Neutral Temperature" (RNT) during installation and maintenance. RNT is the temperature at which point the rail is neither expanding nor contracting in response to temperature.

continue, BNSF would be responsible for adapting (if needed) the North and South rail alignments used by Sounder. Sound Transit would be responsible for any required repairs and potential adaptive actions for the 8-mile Tacoma-to-Lakewood rail segment, Sounder facilities, Sounder locomotives, and Sound Transit-owned trackside infrastructure.

- *Link*. Sound Transit is sole owner and operator of the Link system. This enables Sound Transit full control over decisions about climate adaptation. However, this also means that any costs associated with adapting Link infrastructure will be Sound Transit's responsibility. This financial exposure will continue to grow along with the system.
- *ST Express*. Sound Transit's financial exposure for ST Express includes the coaches, transit centers, and bus shelters. Sound Transit is not responsible for any adaptation decisions or costs related to the highway infrastructure used by ST Express buses.

7. Integrating climate considerations into decision-making processes will help ensure that Sound Transit can meet agency goals and objectives in a changing climate.

- Sound Transit makes decisions on a daily basis that influence current and future resilience to climate change. Integrating consideration of climate change impacts and adaptation into agency processes helps ensure that decisions related to strategic planning, system design, and operations and maintenance (among others) are robust to a changing climate. All of these decisions both influence, and are influenced by, the need to adapt to climate change.
- Potential opportunities for integrating climate change considerations into agency processes include the following activities: policy setting, participation in regional transportation planning efforts and inter-governmental relations, environmental review, strategic and system planning, preliminary engineering and final design, construction, operations and maintenance, asset management, and Environmental Management System Administration, among others.

8. Sound Transit already possesses some degree of climate resilience and capacity to address climate impacts, both of which will be further enhanced by integrating climate considerations into decision making.

- The Sound Transit system is young relative to most major urban transit agencies and generally reflects current design and construction standards. Because of this, the agency has relatively few long-term legacy issues influencing its overall vulnerability to climate change.
- Sound Transit services are designed to accommodate a range of conditions and periodic service interruptions. This potentially allows for some amount of climate change to occur before impacts begin to exceed design tolerances in ways that may require adaptation. The point at which design or performance

tolerances are exceeded will vary, and some systems may benefit from adaptive measures taken during planning, design, and construction rather than waiting to retrofit after impacts occur.

- Sound Transit has institutionalized review of system performance and design standards as the system undergoes expansion. Annual updates to design criteria and value engineering programs help provide for an adaptive learning framework with opportunities for adjustment and integrating adaptation strategies into decision making.
- Sound Transit is an organization already comfortable with defining risk and managing uncertainty. Although climate change brings new considerations into risk management activities, the agency's experience with risk management may reduce some of the challenges associated with making decisions about if, when, and how to adapt.

9. Effective adaptation requires an ongoing effort.

- The long-term nature of climate change means that adapting to climate change is not a one-time activity. Vulnerability and resilience to climate change impacts will shift over time as scientific understanding about specific impacts advances, as climate changes, and as the Sound Transit system and the communities it serves grow.
- It will be necessary to periodically determine whether past assumptions about climate change impacts remain valid and whether adaptive action, or modification to existing actions, is warranted.

Next Steps

The Sound Transit Climate Risk Reduction Project found that in most cases climate change is likely to have minor to moderate impacts on Sound Transit services. It is critical to note that this does not mean that the agency is not vulnerable to climate change impacts. Some impacts identified through this project may be significant and will require potentially large amounts of time and resources to address. Furthermore, vulnerabilities to climate change and the ability to be resilient to climate impacts will change over time.

Ensuring that climate impacts remain minor to moderate will require that Sound Transit continually address climate adaptation opportunities. It will require monitoring relevant developments in PNW climate change science and considering how those developments could affect the agency. Sound Transit will need to regularly evaluate:

- "How does climate change affect agency goals?"
- "Does the agency need to do anything different as a result?"

These questions are particularly important when making decisions about long-lived infrastructure that is likely to be more difficult to adapt at a later date.

The following are recommended "next steps" for beginning to build adaptive capacity within Sound Transit and integrating climate change considerations into decision making at the agency:

- *Disseminate project findings*. In order to help build awareness of the project's results within the agency and maximize its value as a template for use by transit agencies nationally, the project team will:
  - Provide project materials to the public via the FTA's Transit Climate Adaptation Pilot web page.
  - Brief Sound Transit leadership and staff, as well as peer agency leadership, regarding the project's main findings.
  - Develop periodic briefings for agency technical staff regarding climate science and potential climate impacts for the region.
  - Share project findings with national peer groups, such as the Public Transportation Association (APTA) Sustainability Committee, Climate Preparedness Learning & Adaptation Network (CPLAN) and other similar outlets.

- *Prioritize next steps to address the report's major findings*. In order to ensure that the project's findings remain relevant to Sound Transit's planning, design, construction and operations activities, the project team will work with staff to develop a formal set of recommendations outlining steps the agency should take to address the report's major findings. These next steps may include, but are not limited to:
- *Continue working with service partners and partner jurisdiction*s to monitor climate change impacts as related to Sound Transit services.
- *Continue working with regional partners to identify further areas of research* to better understand climate impacts affecting Sound Transit.
  - Identify the climate adaptation considerations that could be integrated into agency processes in the near -term.
  - Provide guidance on when Sound Transit might consider developing a Climate Adaptation Plan and what the scope of such a plan should include.

- In pursuing these near term actions, Sound Transit will begin to formally address adaptation and integration opportunities to strengthen the agency's resilience to climate change.

SECTION 1

Introduction

Sound Transit's Climate Risk Reduction Project assesses how climate change may affect agency infrastructure, operations, and planning and identifies approaches for strengthening the agency's resilience to these impacts.

The Federal Transit Administration (FTA) funded the 18-month project as part of its Transit Climate Change Adaptation Assessment pilot program, which made awards to seven transit agencies nationwide. Sound Transit's project was undertaken as a partnership with the University of Washington Climate Impacts Group and the Washington Department of Transportation (WSDOT). The project emphasized process and expert elicitation, rather than climate modeling and engineering analyses, to provide an easily transferable approach that can be used by transit agencies interested in planning for climate change.

This report includes:

- the project's goal and approach and an overview of Sound Transit services
- a summary of projected climate change impacts for the region
- a discussion of the climate change impacts that matter most to Sound Transit and which services may become higher priorities for adaptation action in the future
- potential adaptation options and opportunities for integrating climate change considerations into agency processes

Why the Sound Transit Climate Risk Reduction Project?

Meeting Federal Climate Adaptation and Resilience Goals

Sound Transit's project was selected by FTA to advance the state of practice for adapting transit systems to the projected impacts of climate change. In 2011, FTA issued a policy statement on climate change adaptation[14] to ensure proper stewardship of federal investment in public transportation systems, public safety for the traveling public, continued mobility, and maintenance of a state of good repair.

[14] Available at http://www.fta.dot.gov/documents/Final_FTA_Policy_Statement_signed_5_31_11.pdf.

According to FTA, climate-related changes are already being observed in the United States and will increase in the future, as projected by the federal government's Global Change Research Program. Expected impacts from climate change for the Pacific Northwest (PNW) include rising temperature and sea levels, as well as increases in both extreme downpours and droughts. Reducing GHG emissions will lower the severity of these impacts over the long term. However, even with immediate aggressive action to reduce emissions going forward, past emissions will continue to cause climate change impacts for many decades.

FTA's policy statement noted that an effective response to climate change must therefore include both mitigation and adaptation. The following terms— as defined by FTA[15]—are integral to how Sound Transit approached this project.

- *Mitigation*: An intervention to reduce the causes of changes in climate, such as through reducing emissions of greenhouse gases(GHGs) to the atmosphere.
- *Adaptation*: Adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects.
- *Resilience*: A capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment.
- *Vulnerability*: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes.

Defining the Phrase "Sound Transit Services"

The term "service" is used in this report to collectively refer to Sound Transit's three transit modes (Sounder, Link, ST Express), its customer facilities, and environmental mitigation activities. Customer facilities were discussed as a separate service given that facilities can be used by multiple modes.

[15] See http://www.fta.dot.gov/12347_12128.html.

Climate Change Matters to Sound Transit

Sound Transit is committed to examining the potential impacts of climate change because:

- *The agency operates in a diverse natural landscape sensitive to climate change.* Sound Transit services currently operate in areas prone to mudslides, flooding, poor drainage, and storm surge. These events already contribute to service disruptions and increase maintenance and operating costs.
- *Projected changes in regional climate are likely to affect Sound Transit services.* A substantial body of peer-reviewed international, national, and regional research shows that climate change could have potentially significant impacts on the PNW, Washington State, and the Puget Sound region. These impacts could affect many aspects of Sound Transit's operations, asset management objectives, and long-term system development.
- *Sound Transit has an unprecedented "window of opportunity" to address potential climate change impacts in a rapidly expanding system.* Sound Transit is currently implementing ST2, a 2008 voter-approved regional transit expansion plan to better connect the region's busiest population and job centers. The ST2 Plan grows regional express bus service by 17 percent and commuter rail service capacity by 65 percent while building more than 30 additional miles of light rail and enhancing station access to form a regional light rail system over 50 miles long. Many aspects of this expansion are currently in planning and design stages, providing a unique window of time to integrate information on potential climate change impacts into long-term planning and asset and risk management decisions.

Project Goals

The central goals of the Sound Transit Climate Risk Reduction Project were to identify potential:

- climate change impacts on Sound Transit operations, assets, and long-term planning
- options for strengthening the agency's resilience to these impacts
- opportunities for integrating climate change considerations into agency decision making processes

As one of seven national FTA funded pilots, the project also aimed to:

- create a process and a model for assessing and planning for climate change impacts that can be transferable to transit agencies across the United States
- provide a state-to-local testing ground for WSDOT's pilot use of the Federal Highway Administration's (FHWA) climate change vulnerability assessment methodology

Major Project Phases

The Sound Transit Climate Risk Reduction Project drew heavily on the expertise of Sound Transit staff, regional climate change science and adaptation experts, and published literature on climate change impacts. The project's major phases, summarized below, were structured to reflect this approach. More information on the project's methodology is included in Appendix B.

- *Preparation of technical materials*. The Climate Impacts Group developed a white paper summarizing relevant climate change projections for the region to provide a technical foundation for the project (Appendix A). The Climate Impacts Group also worked with Sound Transit GIS staff to develop maps showing rail alignments[16] and bus routes relative to current flood zones and projected sea-level rise inundation zones. Finally, the project team conducted an anonymous survey of Sound Transit staff to establish a baseline understanding of staff knowledge and opinions about how current and future climate conditions could affect infrastructure, operations, and planning at Sound Transit. Information from the survey was used to help plan the vulnerability assessment workshops.
- *Vulnerability assessment, adaptation, and integration workshops and meetings*. A series of workshops, organized by service, were held with more than 50 technical staff and senior managers. The workshops primarily focused on current services and approved expansions funded for design and construction under the ST2 expansion plan. Several potential expansions evaluated, such as the Federal Way Transit extension, are currently unfunded and will need funding and approval from the Sound Transit Board. This potential expansion was included in the analysis to allow for early discussion of potential climate issues. Inclusion in this report does not indicate Board commitment to those projects.

  Staff identified and qualitatively rated how today's extreme events (e.g., extreme heat, precipitation events, or high tide events) affect Sound Transit services, and how projected changes in those events could affect operations and planning. Staff also discussed adaptation options and approaches to integrating climate change considerations into agency processes.

- *Synthesis and assessment*. Results from the project's workshops were summarized in detail by service (Appendix C) and analyzed to assess how climate change may affect Sound Transit. The analysis included a relative ranking of climate change impacts across services as well as a relative ranking of services based on impacts. Prioritizing impacts across services shows the relative significance of individual climate change impacts in shaping the agency's vulnerability to climate change and insight into which impacts

[16] The term "alignment" refers to the route upon which a train travels and the track is constructed (AREMA 2003).

may become higher priorities for monitoring and adaptation. Prioritizing services by impacts identifies which services may become a higher or lower adaptation priority based on how climate change may affect a service. Both approaches can inform decisions about if, when, and where adaptation measures may be warranted.

Climate Change Impacts Evaluated

The climate change impacts evaluated for Sound Transit services are listed in Table 1-1. Potential changes in Puget Sound lowland snow and ice events and potential changes in high wind speeds (identified as a potential issue for the planned East Link crossing over Lake Washington) were not discussed given the current lack of information on how these types of events may change.[17]

Many of these impacts are already possible in today's climate and therefore not unique to climate change. However, climate change may alter the frequency, intensity, location, or duration of these impacts by affecting the underlying climate drivers (e.g., temperature, precipitation, sea level) that cause an impact. In other cases, climate change introduces new challenges or brings existing challenges to new areas.

Table 1-1

Potential Climate Change Impacts Evaluated, Grouped by Principal Climate Cause

Related to Temperature *Increased potential for…*	**Related to Precipitation** *Increased potential for…*	**Related to Sea level Rise** *Increased potential for…*
• Rail buckling[18] • Heat stress on electrical and safety equipment • Heat stress on overhead catenary system • Heat stress on pavement, structures • Heat stress on landscaping and environmental mitigation sites	• Mudslides and slope instability • Larger and/or more frequent river and stream flooding • Increased localized flooding due to more stormwater runoff or poor drainage • Seepage due to higher groundwater tables • Summer drought	• Temporary flooding of low-lying areas • Permanent inundation of low-lying areas • Higher tidal and storm surge reach • Erosion • Drainage problems • Corrosion from more frequent or prolonged exposure to saltwater

[17] Puget Sound lowland snow and ice events occur when cold air outbreaks combine with moist air masses over the area. These occurrences have more to do with short-term (e.g., hours to days) weather patterns, rather than seasonal climate conditions, and are therefore not well simulated in current climate change projections.

[18] A rail buckle is an unwanted bend or kink in steel rail that occurs when rail temperatures are high enough to cause steel rail to expand beyond the holding capacity of the rain anchors, forcing the rail out of alignment.

Key Considerations Related to Project Results

The results presented here should be considered a preliminary assessment meant to guide further internal discussion and evaluation within the agency for the following reasons:

- *The project's scale required making generalizations—and, thus, the project results are preliminary.* The Sound Transit Climate Risk Reduction project covered a wide range of agency services and activities. While the project provided an opportunity to explore how climate change could affect issues specific to individual services and locations, the scale of the project still necessitated some amount of generalization about potential impacts.
- *The project was developed to provide a baseline scenario for the agency based on present day design and operations.* To develop a baseline scenario for the agency, the project's results assume that no adaptive actions are taken on the part of Sound Transit, its partner agencies, or the communities it serves. Although some measures of adaptive actions are expected to occur over time, this assessment provides an opportunity to see—in advance—where those adjustments may be most needed.
- *The project's prioritization approach ranks services only relative to each other.* The prioritization results presented in Section 3 rate impacts and services relative to each other, not against an external benchmark. Any designations as "high" priority must be considered in context of the project's overall conclusion that many climate change impacts on Sound Transit services will likely be minor to moderate.
- *The project's results are based on today's climate change projections.* The project's results are based on climate change projections available at the time of this analysis. Future updates to climate change projections for the region may influence these conclusions, as would changes in system design or other factors. Potential impacts, and the probability of those impacts, should be periodically reassessed as climate change scenarios are updated and/or as system changes are made.

About Sound Transit Services

Sound Transit designs, plans, and constructs its transit services and operates them via contractual partnerships with King County Metro, Pierce Transit, Community Transit, Amtrak, and Burlington Northern Santa Fe (BNSF). Brief information on each of these modes is provided here.

All three transit modes were addressed in this project as well as customer facilities, which can service multiple modes, and environmental mitigation. These five focal points are collectively referred to as services for the purposes of this report. A system map is shown in Figure 1-1.

Figure 1-1

Current Sound Transit service map, inclusive of Link extensions under construction or in planning as part of the ST2 ballot measure approved by voters in 2008

Source: Sound Transit

Sounder Commuter Rail

- *Service area*. Sounder commuter rail is Sound Transit's heavy rail commuter line connecting north and south central Puget Sound communities between Everett and Lakewood. South Sounder operations began in 2000 with service running from Seattle to Tacoma (40 miles). Subsequent alignments extended service north from Seattle to Everett (34 miles, 2003) and south from Tacoma to Lakewood (8.2 miles, 2012). There are 12 Sounder stations in total.
- *Ridership*. Total annual ridership in 2012 was more than 2.8 million boardings, with the heaviest ridership on the South Sounder line. Sounder service is limited primarily to weekday mornings and afternoons. Weekend runs are limited to major events such as Seattle Mariners and Seahawks games.
- *Sounder track and rail car management*. The only Sounder track owned and maintained by Sound Transit is the 8.2-mile segment between Lakewood and Tacoma. All other track used for Sounder service is owned and maintained by BNSF. Permanent (for the North alignment) and 40-year (for the South alignment) passage rights were purchased from BNSF for Sounder service; Sound Transit also has cost-share obligations to BNSF for costs related to technology and infrastructure improvements required by law. Freight transport and Amtrak passenger rail service also runs on the North and South rail alignments. Fuel service and maintenance of Sounder locomotives and rail cars are provided via contract with Amtrak at the Holgate Yard, located near the King Street Station in downtown Seattle.

Link Light Rail

- *Current service area*. Link light rail is Sound Transit's newest transit service and its most active in terms of system planning and expansion. The Link network currently consists of two independently run systems: Central Link and Tacoma Link.
  - *Central Link*. Central Link is a 15.6-mile segment servicing 13 stations between SeaTac Airport and downtown Seattle. The system opened in July 2009 and consists primarily of aboveground or at-grade track. A relatively small portion of the system runs through two sets of tunnels: the nearly 1-mile long twin tunnels that comprise the Beacon Hill Tunnel and the 1.3-mile Downtown Seattle Transit Tunnel.
  - *Tacoma Link*. Tacoma Link is a 1.6-mile at-grade segment servicing 6 stations between the Tacoma Dome and the Theater District. Tacoma Link was Washington State's first light rail service when it began operations in August 2003. A potential 2.3-mile expansion of the Tacoma Link system is currently under review and was not addressed in this study.
  - *System expansions*. Several extensions are funded as part of the ST2 expansion plan and are either currently under construction (University Link, Northgate Link, South 200th Link Extension) or in various planning stages (Lynnwood Link, East Link, Federal Way). the extensions will bring the system's total size to more than 50 miles of rail once completed (between 2016 and 2023).

- *Ridership*. Central Link boardings averaged more than 8.6 million boardings in 2012. Tacoma Link had 1.02 million boardings in that same period. The current expansions will add an estimated 125,000 daily boardings to the system by 2030 (71,000 for the north extensions, 50,000 for the East Link extension, and 5,400 for the South 200th Link Extension).
- *Link track and train management*. Sound Transit owns, maintains, and operates the Link system and trains. Trains are stored and maintained at the Operations and Maintenance facility in south downtown Seattle (the SODO area).

ST Express

ST Express buses service major urban centers in King, Snohomish, and Pierce counties via 25 limited-stop routes that predominantly operate in peak travel directions. ST Express is Sound Transit's oldest service, starting in 1999. ST Express coaches primarily service park-and-rides, transit centers, and stops in other high-volume locations (e.g., downtown Seattle). Annual boardings were 15.4 million in 2012. ST Express's 277 coaches are operated and maintained via contract with regional partner transit agencies: Community Transit, King County Metro, and Pierce Transit.

Customer Facilities

Sound Transit's customer facilities currently include 12 Sounder stations, 21 Link Light Rail stations, and 10 major and 5 minor parking facilities located both aboveground and underground throughout the Sound Transit service area. Each facility is unique with respect to its size, design, and access, and many facilities serve multiple modes and/or transit agencies (e.g., Amtrak, King County Metro, Community Transit, Pierce Transit). More than 19 new facilities are currently under construction or planned as part of system expansion funded under the 2008 ST2 ballot measure. (For the purposes of this analysis, the term "facility" applies to current and future stations or parking facilities unless specified otherwise.)

SECTION 2

Overview of Projected Climate Change Impacts

Rising global GHG emissions are inducing fundamental changes in the Earth's climate system and are expected to affect the PNW climate in potentially significant ways. This chapter provides a general overview of projected changes in the key drivers of climate change that are relevant to Sound Transit operations and planning. These include changes in temperature, precipitation, streamflows, and sea-level rise.

More detailed information on projected impacts is available in Appendix A. Note that these projections are based on assumptions about future GHG emissions and global climate models that are updated over time. The next major update of the global climate scenarios used for projecting changes in regional climate is scheduled for release in Fall 2013. Past experience shows that climate change scenario updates often produce slightly different numeric values but do not alter the anticipated direction of change.

Projected Changes in PNW Temperature

- *Average annual and seasonal temperatures.* Average annual and seasonal temperatures in the PNW are projected to increase through the 21st century for both moderate (A1B) and low (B1) GHG emissions scenarios (see box and Table 2-1).[19] Warming is projected to occur in all seasons with the largest increases occurring during the summer months.
- *Extreme heat events.* The average number and duration of heat waves (days above 92°F) are projected to rise in the Puget Sound region. Heat waves could last as long as 18 days by 2045 compared to a maximum duration of 6 days for the period 1980–2006.[20]
- *Scientific confidence in projected temperature changes.* There is high confidence that the PNW will warm as a result of GHG emissions. All global climate models project warming under high, medium, and low GHG scenarios. Confidence in the amount of change projected through mid-century is higher than later in the century because of uncertainty over future rates of GHG emissions; the amount of change projected before mid-century is a function of past GHG emissions and therefore more certain. Scientific confidence in the exact projections for extreme heat events is lower due to the limited number of scenarios used to evaluate changes in extreme heat events.

[19] Mote and Salathé, 2010.

[20] Jackson et al., 2010.

Modeling Projected Changes in Climate

Projecting changes in 21st century climate requires the use of global climate models and scenarios of future GHG emissions. These models incorporate assumptions about future changes in global population, technological advances, and other factors to project the amount of carbon dioxide and other GHGs emitted into the atmosphere as a result of human activities.

The research summarized here is based on a subset of GHG emission scenarios used by researchers globally to evaluate future climate and climate change impacts. This includes a moderate GHG emissions scenario (the A1B scenario) and a low GHG emissions scenario (the B1 scenario). Sea-level rise scenarios produced by the National Research Council in 2012 (NRC 2012) include a high GHG emissions scenario (the A1FI scenario).

Scenarios based on a range of GHG emissions result in a range of projected changes in temperature, precipitation, and other climate-related variables important for the PNW. Which scenario is most likely is unknown, although current GHG emissions trends are making the low scenario increasingly unlikely.

Table 2-1

*Projected Changes in Average Annual and Seasonal PNW Temperature and Precipitation (with Range)**

Temperature			
Period	Annual	June August	December February
2020s	+2°F (1.1° to 3.4°F)	+2.7°F (1.0 to 5.3°F)	+2.1°F (0.7 to 3.6°F)
2040s	+3.2°F (1.6° to 5.2°F)	+4.1°F (1.5 to 7.9°F)	+3.2°F (1.0 to 5.1°F)
2080s	+5.3°F (2.8° to 9.7°F)	+6.8°F (2.6 to 12.5°F)	+5.4°F (1.3 to 9.1°F)

Precipitation			
Period	Annual	June August	December February
2020s	+1% (-9 to 12%)	-6% (-30% to +12%)	+2% (-14% to +23%)
2040s	+2% (-11 to +12%)	-8% (-30% to +17%)	+3% (-13% to +27%)
2080s	+4% (-10 to +20%)	-13% (-38% to +14%)	+8% (-11% to +42%)

*All changes are relative to 1970-1999. The range of projections is derived from different global climate models run with two GHG emission scenarios (the A1B and B1 scenarios).[21]

[21] Mote and Salathé, 2010.

Will Snow and Ice Events Still Occur in a Changing Climate?

Climate change does not eliminate the potential for lowland snow and ice events in the Puget Sound region — we will continue to see years and seasons that are warmer or cooler than average even as the average around which temperatures vary increases. Potential changes in snow and ice events were not discussed in the project given the current lack of information regarding how these types of events may change. Over time, however, the frequency of snow and ice events may decrease.

Projected Changes in PNW Precipitation

- *Average annual and seasonal precipitation.* Average annual precipitation is projected to change only modestly in the 21st century when averaged across scenarios in Table 2-1.[22] Seasonal changes are likely to be greater, with half or more of the models projecting increases in winter (December–February) precipitation. Most global climate models project decreases in summer (June–August) precipitation.
- *Extreme precipitation.* Regional climate models generally agree that the amount of rainfall during extreme events is expected to increase for western Washington in winter.[23] Many instances of extreme precipitation events and winter flooding in the PNW have been linked to a weather phenomenon known as "atmospheric rivers," often referred to as "pineapple expresses."[24] Warming associated with climate change could lengthen the pineapple express season and increase the intensity of extreme precipitation events associated with these weather events given that higher temperatures increase the atmosphere's capacity to hold more water.[25]
- *Scientific confidence in projected precipitation changes.* There is good scientific confidence that winter precipitation will increase and that we will see more extreme precipitation in the region, particularly after mid-century. However, there is low confidence in specifically how much wetter winters may become and how much larger extreme precipitation events may be. The uncertainty in future precipitation changes is large, given the wide range of natural variability in PNW precipitation, and uncertainties in how dominant modes

[22] Mote and Salathé, 2010.
[23] Salathé et al., 2010; Rosenberg et al., 2010.
[24] Neiman et al., 2008; Ralph et al., 2006.
[25] Trenberth, 2011; Dettinger, 2011; Leung and Qian, 2009.

of natural variability influencing precipitation may be affected by climate change. Additional uncertainties are derived from the challenges of modeling precipitation globally.

Projected Changes in Puget Sound Hydrology

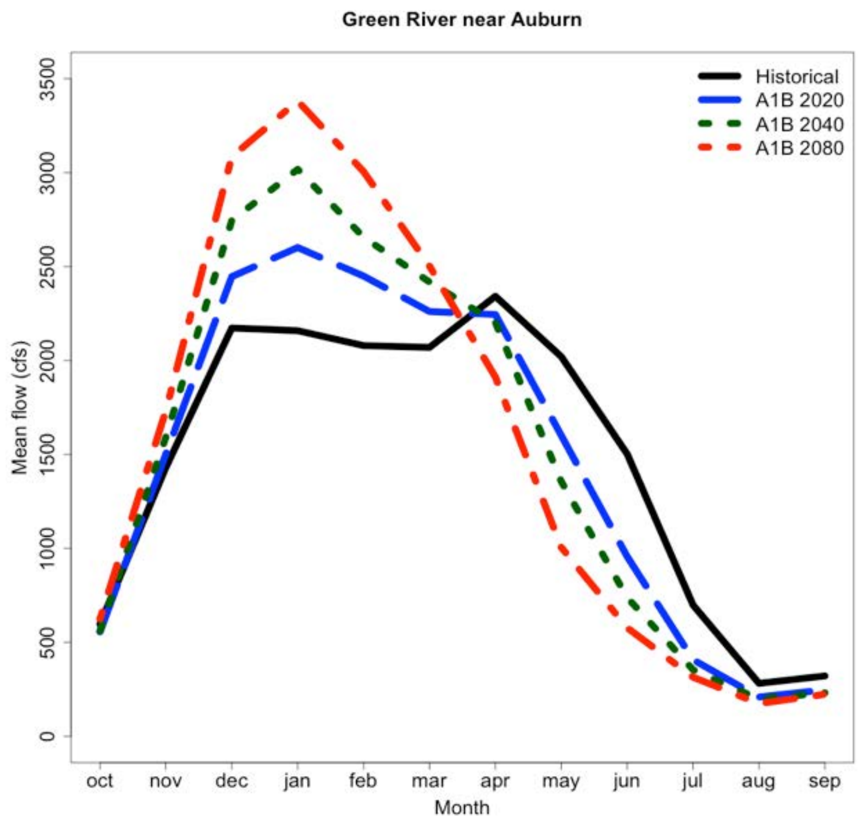
Higher winter temperatures and increasing winter precipitation are expected to increase flood risk in the Puget Sound region. The relative size of the increase varies with river type, however. Flood risk in two river types found in the Sound Transit service area is discussed below.

- *Flood risk in rain/snow mix (transient) watersheds.* Flood risk is projected to increase most in mid-elevation rain/snow mix watersheds such as the Green and White rivers, where warmer temperatures cause more winter precipitation to fall as rain rather than snow over a larger portion of the basin. This produces instantaneous streamflow rather than delayed runoff stored in the form of snow.[26] These changes become more pronounced with time; by the 2080s, peak streamflows in the Green River (for example) shift from April to January (Figure 2-1). Increasing winter precipitation, including more intense atmospheric rivers, would further increase flood risk in these basins.

[26] Hamlet et al., 2007; Mantua et al., 2010; Hamlet et al., 2010.

Figure 2-1

*Projected changes in average monthly unregulated flows (in cubic feet per second) for the Green River near Auburn**



* Projected changes in average monthly unregulated streamflows (simulated) for the Green River near Auburn under the A1B GHG emissions scenario for three time periods: the decades of the 2020s (blue line), the 2040s (green line), and the 2080s (red line). All changes are relative to historical average flows (1916–2006; black line). Peak runoff shifts from April to January as a result of increasing winter temperatures, which cause more winter precipitation to fall as rain. This change becomes more pronounced as the amount of warming increases. Unregulated streamflows are naturalized flows, meaning they do not take the effects of dams into account.

- *Flood risk in rain dominant systems*. Flood risk in low-elevation rain dominant rivers and creeks such as the Sammamish River is driven primarily by individual rain events. Projected changes in these systems are more modest compared to rain/snow mix watersheds and are more sensitive to uncertainties about the size of projected changes in precipitation.
- *Scientific confidence in projected increases in flooding.* There is high confidence that flood risk will increase in rain/snow mix watersheds given the high confidence in projections for warmer winter temperatures and impacts on snowpack. There is less confidence in specifically how much larger flood flows could become, however. Confidence in projections for more frequent flooding in rain-dominant rivers is good given projections for increasing winter precipitation. However, there is low confidence in specifically how much larger flooding could be in these systems given uncertainties about the size of projected changes in precipitation.

Projected Sea-level Rise

- *Factors influencing sea-level rise.* Key contributing factors to rising sea levels globally are (1) melting of land-based ice sheets and glaciers, which add freshwater to the ocean, and (2) thermal expansion of seawater as it warms, which increases the ocean's volume. Local factors influencing sea-level rise include seasonal wind patterns and subsidence or uplift of land surfaces as a result of plate tectonics. Each of these factors has its own range of projections, contributing to the wide range of projections for global and regional sea-level rise.
- *Projections for Central Puget Sound.* Sea-level rise projections for Seattle are provided in Table 2-2.[27] The current range of projections for the region has been fairly consistent between studies[28] but the range remains large. This is due to uncertainty about the rate of future ice losses in Greenland and Antarctica, long-term changes in vertical land movement in Washington State, and other components used to calculate sea-level rise at specific locations. Note that Sea-level rise will not necessarily occur in a consistent, linear fashion. Episodes of faster and slower rise are likely, as well as periods of no rise.

Table 2-2

Sea-level Rise Projections for Seattle Compared to 2000 Levels

Time Period	Average Increase (in.)	Range from B1 (low) to A1FI (high) (in.)
2030	2.6 ± 2.2	-1.5–8.8
2050	6.5 ± 4.1	-1–18.8
2100	24.3 ±11.5	3.9–56.3

Range based on estimates from highest and lowest emissions scenarios.[29]

- *Sea-level rise values used in this project.* Two values of sea-level rise were used for this project: 22 inches and 50 inches. These values are both within the range of projections for the latter half of the century and were selected to be consistent with the approach used by WSDOT for its climate change vulnerability assessment.[30] In addition to inundating low-lying areas, higher sea level amplifies the inland reach and impacts of waves and storm surge. Higher sea level also increases the likelihood for more frequent and/or more extensive coastal flooding.
- *Scientific confidence in sea-level rise.* There is high scientific confidence that sea-level rise will occur, although confidence levels for specific projections vary. Confidence in the values projected for 2030 and possibly 2050 for the U.S. West Coast is higher[31] than values after mid-century given uncertainties about the amount of change expected in some of the factors contributing to sea-level rise. Of the two levels of sea-level rise mapped for this project, 22 inches of sea-level rise is considered more probable than 50 inches of sea-level rise. Sea-level rise of less than 22 inches is considered a high probability.

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[27] NRC, 2012.
[28] E.g., Mote et al., 2008; NRC, 2012.
[29] NRC, 2012.
[30] WSDOT. 2011.
[31] NRC, 2012, p.6.

Closing Considerations: Natural Variability

While the focus of the Sound Transit Climate Risk Reduction project is on climate change, it is important to remember that natural climate variability will continue to have an important influence on PNW climate and how we experience climate change over shorter time scales. Key modes of natural variability such as the El Niño/Southern Oscillation and the Pacific Decadal Oscillation can tilt the odds for warmer and drier or cooler and wetter than average years or decades depending on which phase these modes are in and how long those phases persist. Natural variability is expected to continue, at times amplifying or counteracting long-term trends caused by rising GHG emissions.

SECTION 3

Prioritizing Climate Change Impacts and Services

Sound Transit is a large multimodal system potentially affected by a range of climate change impacts. Prioritizing impacts and services can help focus agency adaptation efforts. This section provides a relative ranking of climate change impacts and services based on Sound Transit expertise and scientific understanding of projected regional climate change. The results presented here should be considered preliminary and are meant to guide further internal discussion within the agency.

Prioritization Approach

Prioritization is approached in two ways:

- *Prioritization of potential climate change impacts.* The first approach identifies which climate change impacts matter more across all services. Prioritizing impacts across services shows the relative significance of individual climate change impacts in shaping Sound Transit's overall vulnerability to climate change. The approach also provides insight into which impacts may become higher priorities for monitoring and adaptation and for what reasons.
- *Prioritization of services.* The second approach identifies which services may become a higher or lower priority for adaptation based on how a range of climate change impacts may affect the service. Both approaches can inform decisions about if, when, and where adaptation may be warranted.

Note that neither prioritization approach is based on the probability of the impact, although information on general probability is provided as an additional input for decision making. Probability will shift over time and should be periodically re-evaluated in light of the number of factors influencing if, when, and where an impact occurs and the degree to which the impact affects Sound Transit. These factors include:

- how quickly climate changes
- how much climate changes
- how operations and design standards change over time
- how actions taken by partner services and jurisdictions with whom Sound Transit works affect potential climate change impacts. For example, changes in development may alter stormwater runoff patterns, reducing or increasing

the potential for increased localized flooding during extreme precipitation events. Similarly, adaptive actions taken by communities to address sea-level rise could reduce the probability of sea-level rise impacts.

It is also important to note that probability and the degree of impact can vary by location even within the same service. For example, the potential for localized flooding may be a moderate impact overall, but could be significant at one location while being a non-issue at another location.

Prioritizing Projected Climate Change Impacts: Which Impacts Matter More?

A relative ranking of climate change impacts across services was performed based on the nature of the expected and possible impacts associated with a specific climate change impact. Impacts were rated as having a potentially significant, moderate, or minor impact on Sound Transit services based on the characteristics identified in Table 3-1. A key consideration in this assessment was how the impact might affect service delivery. Other considerations included the geographic distribution of the impact (i.e., did it have the potential to affect all parts or limited parts of the system?) and the potential cost of managing or responding to the impact. No attempt was made to quantitatively or qualitatively document those potential costs, however.

Table 3-1

Characteristics of Potentially Significant, Moderate, and Minor Climate Change Impacts

Potentially Significant Impacts *could result in….*	**Potentially Moderate Impacts** *could result in….*	**Potentially Minor Impacts** *could result in….*
• Permanent service cancellations, • Frequent (e.g., multiple times within a year or season) multi-day service cancellations, • Expensive infrastructure repairs or adjustments, and/or • Reduced customer confidence	• Occasional (e.g., occurring every few years or longer) multi-day service cancellations, • Frequent moderate-length (e.g., in the range of hours) service delays cancellations, • Moderate structural repairs, • Increased maintenance, and/or • Customer service issues	• Frequent short-term (e.g., less than an hour) service delays and cancellations, • Minor structural repairs, • Increased minor maintenance, and/or • Minor (if any) customer service issues

Results for this prioritization approach are summarized in Table 3-2 and discussed in the following sections. The degree to which the climate change impacts listed in Table 3-2 affect Sound Transit can vary depending on how large the climate change impact is (e.g., 22 inches versus 50 inches of sea-level rise), system design, and other factors. The prioritization of climate change impacts presented in this section assumes the size of projected impact is at the high end of what would be expected.

Table 3-2

Projected Climate Change Impacts Evaluated, Sorted by Potential Significance

Potentially Significant Impacts	Potentially Moderate Impacts	Potentially Minor Impacts
• Increased mudslide activity • Sea-level rise and related impacts	• Larger and/or more frequent river and stream flooding • Increased localized flooding due to more stormwater runoff or poor drainage • Potential for rail buckling	• Increased heat stress on electrical equipment • Increased heat stress on the overhead catenary system • Increased heat stress on facility structures and landscaping • Increased heat stress on environmental mitigation sites • Increased tunnel seepage

Recognizing Climate Change as a Spectrum of Change and Probabilities

Although probability was not a central factor in determining which impacts are more or less important to Sound Transit, qualitative estimates of probability are provided to help inform decision making. Estimated probability was primarily based on scientific confidence in the underlying climate changes affecting a potential impact. Known design features and other factors potentially influencing probability are noted to the extent possible.

Estimated probability is used in Table 3-3 to provide a more detailed sorting of impacts that reflects the fact that some impacts (e.g., sea-level rise) can have different levels of probability depending on the amount of change that occurs and the frequency or scale of impacts that result. New information on projected changes in climate, changes in design standards, decisions about where to locate services, and other factors can shift the distribution of impacts within this table over time. For example, updated climate change scenarios may shift the probability of some impacts higher or lower. Similarly, efforts taken to address climate change impacts could reduce the probability and/or the potential magnitude of an impact.

Table 3-3

*Distribution of Projected Climate Change Impacts by Degree of Potential Impact and Estimated Probability of Impacts**

Estimated Impact on Operations and Infrastructure	Estimated Probability of Climate Change Impacts: Low	Estimated Probability of Climate Change Impacts: Medium	Estimated Probability of Climate Change Impacts: High
Significant	• **Inundation** of Mukilteo and Edmonds Sounder facilities (possible only with sea-level rise of 50 inches or more, which is currently at high end of projections for 2100)	• **Increased mudslide activity** causing more than 70 train cancellations in a season (Sounder)	
Moderate	• **Increased major flooding** in both rain-dominant and rain/snow mix rivers • **Potential for rail buckling**	• **Increased mudslide activity** causing 33–70 train cancellations in a season (Sounder) • **Increased localized flooding** due to more stormwater runoff or poor drainage (in previously unaffected areas) • **Increased storm surge reach, higher high tides, and more temporary flooding** related to moderate amounts of sea-level rise (e.g., in range of 22 inches, near the mean value for 2100)	• **Increased localized flooding** due to more stormwater runoff or poor drainage (where already an issue) • **Increased storm surge reach, higher high tides, and more temporary flooding** related to lower amounts of sea-level rise (less than 22 inches)
Minor	• **Heat stress** on: - auto-tension overhead catenary system (OCS) (Link) - air-conditioned electrical equipment - environmental mitigation projects (established wetland sites)	• **Heat stress** on: - facility landscaping (established sites) - environmental mitigation projects (pre-established wetland sites) • **Increased minor to moderate flooding** in rain-dominant rivers and streams • **Increased groundwater seepage into tunnels**	• **Heat stress** on: - facility structures - non-tunnel fixed termination OCS (Link) - natural ventilated electrical equipment - facility landscaping (during establishment) • **Increased minor to moderate flooding** in rain/snow mix rivers • **Increased mudslide activity** causing less than 33 train cancellations in a season (Sounder)

*If, when, and where these impacts affect services will vary. Some impacts have the potential to affect limited areas or services while others may apply more broadly.

Potentially Significant Climate Change Impacts

Increased Mudslide Activity

- *Potentially affected service(s)*: Sounder, Link (minor relevance)
- *Basis for rating*. The potential for more frequent or larger mudslides is considered a potentially significant climate change impact due to:
  - the agency's existing history with mudslides
  - the amount of track exposed to mudslides
  - implications for service delivery and safety, particularly if more frequent or larger slides cause frequent train cancellations (e.g., greater than 70 per season, as identified by staff) on a consistent basis

  The high cost of reducing mudslide occurrence on the Sounder line is also a factor even though the cost is incurred by BNSF.

Differentiating the Range of Potential Outcomes Associated with Climate Change Impacts

The following terms are used to differentiate potential outcomes of projected climate change impacts:

- "Expected" impacts are impacts that would be expected to occur even at the low end of climate change projections.
- "Possible" impacts are impacts that may occur in limited cases and/or only at higher amounts of climate change.

- *Potential impacts*. The potential for increased mudslide activity may result in the following issues for infrastructure and operations:
  - Expected issues:
    - more train cancellations due to required wait periods and/or track repairs, when needed
    - loss of ridership due to unreliability of service as a result of mudslides
  - Possible issues:
    - damage to track infrastructure
    - potential for damage to trains and/or derailment, although the probability is reduced given the existing and expected acquisition of additional safety measures and tools that predict the probability of slides

  The estimated duration of service impacts is several hours to a week or more per slide depending on the frequency of mudslides and extent of track clean-up and right-of-way repair required.

- *Probability of increased mudslide activity.* The probability of increased mudslide activity is high given projected increases in average and extreme precipitation, particularly after mid-century. The specific magnitude of change is not known, however, given uncertainties about how much wetter winters may become and how other non-climate factors influencing mudslides may change. The probability of mudslides causing more than 70 train cancellations per season is assumed to be lower than the probability of mudslides causing less than 70 train cancellations per season.

  Ongoing efforts by BNSF, WSDOT, Amtrak, and Sound Transit to mitigate slide risk along the North rail alignment[32] is likely to help reduce the frequency of mudslides in some of the highest problem areas in the corridor. However, other factors unrelated to weather may still contribute to slide activity in areas targeted by BNSF and WSDOT, and other areas may still be vulnerable to slides or become vulnerable as a result of projected increases in precipitation.

Sea-level Rise and Related Coastal Impacts

- *Potentially affected service(s)*: Sounder, Customer Facilities (specifically Edmonds and Mukilteo), Link (minor relevance)
- *Basis for rating.* Sea-level rise is considered a potentially significant climate change impact because of:
  - the amount and types of infrastructure exposed to sea-level rise impacts
  - the long-term implications for service delivery (particularly at the Edmonds and Mukilteo stations)
  - the probable high costs for addressing sea-level rise impacts

  Sea-level rise has the potential to affect most of the North rail alignment as well as the Edmonds and Mukilteo facilities. Permanent inundation of rail track and facilities is possible in the vicinity of Edmonds and Mukilteo if sea-level rises 50 inches or more (currently near the high end of projections for 2100). Sea-level rise under this amount would not permanently inundate the track or facilities, but would still expose the length of the North rail alignment to more extreme high tides, temporary flooding, saltwater corrosion, and storm surge impacts. Drainage issues at the facilities would also likely still be an issue.

  Other areas possibly affected by the highest projections for sea-level rise include a small portion of the South rail alignment in the Tacoma-Fife area, which could experience inundation and/or increased temporary flooding, and the facilities and alignments used by Link and Sounder in the south

[32] See, for example, "Project aimed to stop landslides on rail tracks north of Seattle," Seattle Times, September 5, 2013, http://seattletimes.com/html/localnews/2021764571_railroadmudslidesxml.html

downtown Seattle area, where sea-level rise increases the potential for drainage and groundwater seepage issues.[33] Sea-level rise may also compound flood risk in the tidally-influenced reaches of the Duwamish and Puyallup rivers.

- *Potential impacts.* If, when, and where sea-level rise impacts occur is highly dependent on how much sea-level rises and how quickly it rises. In general, sea-level rise may result in the following issues for infrastructure and operations:
  - Expected issues:
    - more frequent service interruptions due to higher high tides, increased wave reach, and storm surge when these events coincide with operating times
    - increased maintenance needs and costs related to managing on-site drainage issues at the Edmonds, Mukilteo, Stadium, and SODO facilities
    - damage to infrastructure in localized areas from increased flooding, higher storm surge reach, and/or saltwater corrosion
    - temporary reduction in customer access to the Edmonds and Mukilteo facilities due to more frequent and/or extensive localized flooding of key access routes or facility parking areas
  - Possible issues:
    - permanent loss of track in localized areas, key access routes, and/or facilities due to permanent inundation of low-lying areas

  The estimated duration of service impacts is in the range of minutes to hours (e.g., for tidally-influenced delays) to permanent (in the case of permanent inundation).

- *Probability of sea-level rise and related coastal impacts.* The probability that sea level will rise in the central Puget Sound region is high, although there is low confidence in specifically how much rise will occur, especially after mid-century. As a result, the probability of sea-level rise impacts in general is high, although the probability of the most significant impact (permanent inundation of the Mukilteo and Edmonds facilities) is low given current projections.

  Public and private sector responses to address sea-level rise impacts will also affect if, when, and where these impacts occur. There will be a strong incentive on the part of the cities of Edmonds and Mukilteo, as well as the WSDOT, BNSF, and Amtrak, to ensure the long-term viability of areas potentially affected by sea-level rise given the importance of locally and state-

[33] Neither of the mapped sea-level rise scenarios (22 inches or 50 inches) showed marine waters reaching Link or Sounder facilities in the International District or SODO area, including the Downtown Seattle Transit Tunnel.

owned infrastructure (including two Washington state ferry terminals) near the Edmond and Mukilteo stations. Adaptation decisions related to the track will be made by BNSF.

Moderate Climate Change Impacts

Increased River Flooding

- *Potentially affected service(s)*: Sounder, ST Express, Link, Customer Facilities (specifically the Kent, Tukwila, and Sumner Sounder Stations)
- *Basis for rating*. Expectations for larger and/or more frequent river and stream flooding is considered a moderate climate change impact because of the minor to moderate implications for service delivery at locations affected by flooding and potential costs for repairing damaged infrastructure. Areas with the greatest potential for flood impacts include:
  - Portions of the South rail alignment and ST Express bus routes running near or through existing 100 year flood zones for the Green, White, and Puyallup rivers
  - Kent, Tukwila (current and future), and Sumner Sounder stations
  - Link's crossing of the Duwamish River
  - Link's traction power substation at South 133rd Street and at 112th Street and East Marginal Way (potentially affected by flooding in the Duwamish and Green rivers)

  Creek-based flooding could also affect a portion of the Lynnwood Transit Center parking, although the impacts would be minor. Changes in flood risk are also relevant to East Link's potential alignment in Redmond.

- *Potential impacts*. Flooding can impact Sound Transit in ways that vary depending on the location, size, and duration of flooding. Increased flooding may result in the following issues for infrastructure and operations:
  - Expected issues:
    - service delays, cancellations, or re-routes due to more frequent slow orders and/or flood impacts on track infrastructure, roads, or facilities
    - need for Increased visual monitoring of infrastructure near river banks
  - Possible issues:
    - increased erosion around infrastructure located on or near river banks
    - raising or relocating sensitive ground-level or below ground equipment vulnerable to flooding
    - LImits on train capacity if and when tracks are exposed to saturation or inundation;
    - flood damage to facility structures, equipment, and parking areas

- temporary closure of facilities due to flood damage
- reduced or blocked customer access to facilities due to flooding

The estimated duration of service impacts from river flooding is minutes to hours (e.g., for tidally-influenced flooding or minor flooding) to a week or more depending on the extent of infrastructure damage and needed repairs.

- *Probability of increased river flooding.* The probability of larger and/or more frequent river and stream flooding ranges from low to high depending on river type and the magnitude of flooding being considered. In general:
  - The probability of more frequent minor to moderate river flooding in rain/snow mix rivers like the Green and White rivers is considered high given projected increases in winter temperatures, which cause less snow and more rain to fall in the mountains. Increasing precipitation would also contribute to higher flood risk although specifically how more winter precipitation we are likely to see in the region is uncertain (the range of projected change is large).
  - The probability of more frequent minor to moderate river flooding in low elevation rain-dominant rivers and streams like Bear Creek, Scriber Creek, and the Sammamish River is solely dependent (from a climate standpoint) on how much winter precipitation changes. The probability of more minor to moderate flooding in these systems is considered medium given projected increases in winter precipitation. Uncertainty about exactly how much wetter winter becomes, and how extreme precipitation events change, matter more to this river type than snow-melt fed rivers.
  - The probability of major flooding (i.e., flooding that causes extensive damage) in either river type is still considered low but could increase depending on how rapidly temperatures increase and if changes in the duration or intensity of precipitation fall near the high end of projected changes (or as a result of other changes in watershed/floodplain development patterns).

  The probability of flood impacts also increases in river systems with flood control dams and levees. Flood risk in the Green and White Rivers is managed by the U.S. Army Corps of Engineers (USACE) and local communities via dams and levees. Increases in flooding that remain at or below design limits for the dams and levees are less likely to result in downstream flood impacts. Flood damage is more likely if and when peak flows exceed design limits for the dams and levees.

Increased Localized Flooding Due to More Stormwater Runoff or Poor Drainage

- *Potentially affected service(s)*: Sounder, Link, ST Express, and Customer Facilities (various locations)

- *Basis for rating.* The potential for increased localized flooding due to more stormwater runoff or poor drainage is considered a moderate climate change impact because of:
  - existing problems with these issues
  - their potential to occur anywhere in the system
  - potential high costs of managing these problems

  Little impact on customer service is expected, however. Stormwater is managed on Sound Transit properties through a variety of approaches, including Low Impact Development (LID). The robustness of LID system design relative to the size of current extreme rainfall projections is unknown at this time. Additionally, Sound Transit operations and infrastructure can be affected by high volumes of stormwater runoff and drainage problems beyond Sound Transit's properties. Periodic issues with localized flooding, drainage problems, and stormwater management already exist in areas near the Edmonds and Tukwila Sounder stations, Commerce Street in Tacoma, and south of downtown Seattle (e.g., near the SODO station). Staff also identified Central Link's alignment along Martin Luther King Jr. Way S. in the Rainier Valley as an area that requires active monitoring during extreme precipitation events.

- *Potential impacts.* The potential for increased localized flooding may result in the following issues for infrastructure and operations:
  - Expected issues:
    - increased inspection and monitoring of infrastructure during and after heavy precipitation events
    - more difficulties draining water from low-lying areas
    - more frequent flooding of underground equipment
    - more maintenance of ground-level and underground equipment affected by localized flooding and drainage problems
  - Possible issues:
    - reduced customer access to facilities affected by these issues during periods of heavy precipitation
    - increased temporary use of bus services ("bus bridges") if customers are not able to access rail facilities
    - increased track ballast maintenance due to saturation
    - changes in the grounding properties of electrical systems
    - increased wear-and-tear on existing pump systems
    - need to use temporary or permanent pumps to manage problem flooding
    - need to resize stormwater vaults

- need to raise, relocate, and/or retrofit sensitive ground level or underground equipment

Service impacts are assumed only for flooding that affects customer access. The estimated duration is hours to a day depending on how quickly localized flooding drains.

- *Probability of increased localized flooding and drainage/stormwater management issues.* The probability of increased localized flooding and stormwater management issues is considered high in areas already dealing with these problems and medium for all other areas. The duration and intensity of precipitation events, stormwater drainage capacity, topography, runoff patterns from surrounding areas, and soil type are all factors that influence if, where, and for how long localized flooding and soil saturation occurs. As noted previously, there is good scientific confidence that winters will be wetter and that we will see more extreme precipitation but low confidence in specifically how much wetter winters may become given the wide range of projected changes.

  There is also high scientific confidence that sea level will rise this century, which could exacerbate localized flooding, drainage, and stormwater management issues at facilities and alignments located near the coast. Sea-level rise may raise groundwater levels in coastal areas and limit the ability of stormwater systems to quickly drain stormwater runoff. As a result, even moderate precipitation events may result in larger localized flooding and drainage issues.

Potential for Rail Buckling

- *Potentially affected service(s)*: Sounder, Link
- *Basis for rating.* Rail buckling can occur when rail temperatures are high enough to cause steel rail to expand beyond the holding capacity of rail anchors and shift laterally, forcing the rail out of alignment and causing the rail to bend or kink. The potential for rail buckling is a considered a moderate climate change impact overall for Sound Transit because of:
  - the agency's extensive use of rail types that are less prone to buckling
  - the high cost of retrofitting Sound Transit-owned rail to higher temperatures, if needed
  - the implications for service delivery and safety if a rail buckle occurs

  The potential for rail buckling exists in any at-grade or aboveground portion of Link and for all of Sounder but is more likely in areas where wood tie-and-ballast track is used, in inland areas away from Puget Sound, and in areas with high sun exposure. Extensive paving around track can also elevate temperatures locally when exposed to sun (i.e., the heat island effect). Areas matching one or more of these conditions include much of the South rail alignment used by Sounder and the Central Link alignment in the Rainier Valley. The Federal Way, East Link, and Lynnwood Link Extensions are also likely to have areas of high sun exposure and paving.

- *Potential impacts*. The potential for increased rail buckling may result in the following issues for infrastructure and operations:
  - Expected issues:
    - service delays due to more heat-induced slow orders
    - increased visual monitoring of track
  - Possible issues:
    - heat-related track repairs
    - retrofitting of temperature-sensitive structures, such as rail expansion joints, rail anchors, and special trackwork areas
    - potential for train damage or train derailment, although the probability is extremely low even in a changing climate given existing safety measures

  The estimated duration of service impacts is several minutes (for slow orders) to a week or more depending on the extent of track repair, if required.

- *Probability of rail buckling*. The probability of more frequently exceeding temperature thresholds that trigger slow orders and increased monitoring for Sounder and Link is high given scientific confidence in projections for increasing average and extreme summer temperatures. The amount of change required to cause a rail buckle is unknown, however.

  The probability of a rail buckle actually occurring is low for both Link and Sounder, although not equally low. Several factors differentiate how rail buckling could impact Sounder versus Link. These include track type, design standards, the timing of operations, and track ownership. In general:

  - Although low for both services, the potential for buckling and any resulting service interruptions is slightly higher for Sounder than Link because of the type of track used by Sounder. The North and South rail alignments are wood tie-and-ballast, which is more sensitive to heat than other track types. The potential for heat-related track repairs is also higher for wood tie-and-ballast track. However, repair costs would only be incurred by Sound Transit if repairs were required on the 8.4 miles of Sound Transit-owned track running between Tacoma and Lakewood. Repair costs in other areas are the responsibility of BNSF.
  - Link is less likely to experience a rail buckle relative to Sounder because Link track is almost entirely (at this time)[34] concrete tie-and-ballast,

[34] Small sections of wood tie-and-ballast track are used in Link for "special trackwork" but will be replaced with concrete ties as part of routine maintenance over the next 10–20 years.

direct fixation, and embedded track. Each of these listed track types is progressively less sensitive to heat. Within the Link system, the potential for buckling is slightly higher for Central Link (relative to the current and planned Link extensions) because of differences in the rail neutral temperature used for installing Central Link track versus new track.

- The potential for minor service delays due to preventative measures such as slow orders is equally likely for Link and Sounder. Slow orders are based on exceeding general temperature thresholds, rather than track type. However, more Link trains would be affected since Link service runs through the afternoon and evening; Sounder service is typically limited to early weekday mornings and late afternoons. Heat-related slow orders would only be expected in the afternoons and early evening.
- The potential for heat-related track repairs for Link is lower than Sounder, particularly in the near term, because of Link's track types and the high rail neutral temperature used for newer track installation. Financial exposure for heat-related track repairs and prevention is higher for Link, however, given the amount of current and planned Link track (over 50 miles pending build-out of the ST2 service extensions) and Sound Transit ownership of that track.

Minor Climate Change Impacts

Increased Heat Stress on Electrical Equipment

- *Potentially affected service(s)*: Sounder, Link, ST Express, Customer Facilities (various locations)
- *Basis for rating.* The potential for increased heat stress on stationary and vehicle electrical equipment is a minor climate change impact because of:
  - minor implications for service and maintenance
  - relatively low cost of adapting equipment to warmer temperatures, although some structural retrofits (if needed) could be challenging depending on the equipment and location

Heat stress is most likely in equipment that is naturally ventilated, produces heat while operating, and/or located in areas with prolonged exposure to sun. Equipment discussed with Sound Transit staff included Sounder locomotive head-end power (HEP) units, signal bungalows, small signal boxes, traction power substations (TPSS), and uninterruptible power supply (UPS) batteries and ticket vending machines (TVMs). Heat stress has already affected some Central Link TPSS, which were installed with natural ventilation. Those units are currently being retrofitted with air conditioning and design standards now require air conditioning for any TPSS installed after 2012.

- *Potential impacts*. The potential for increased heat stress on electrical equipment may result in the following issues for infrastructure and operations:
  - Expected issues:
    - less effective use of natural ventilation to maintain preferred temperatures
    - increased cooling demand on air conditioning units
    - increased operating and maintenance costs for air conditioning
    - increased maintenance of HEP units on Sounder locomotives
    - lost revenue from heat stressed TVMs
  - Possible issues:
    - trip cancellations if HEP units fail
    - minor train delays due to slow orders and line-of-sight operations where heat stress causes small signal boxes to shut down
    - need to increase air conditioning capacity
    - need to increase ventilation in small signal boxes
    - more frequent replacement of UPS battery systems
    - retrofits to heat-sensitive equipment rooms (e.g., UPS rooms) to allow for installation of, or upgrading of, air conditioning

  The estimated duration of service impacts is minutes for slow orders to less than one day for train cancellations.

- *Probability of heat stress on electrical equipment*. The probability of increased heat stress on naturally-ventilated electrical equipment is considered high given scientific confidence in projections for warmer summer temperatures. The amount of warming required to cause heat stress is unknown but will vary by equipment type. The probability of heat stress on air conditioned equipment is low.

Increased Heat Stress on the Overhead Catenary System

- *Potentially affected service(s)*: Link
- *Basis for rating*. Increased heat stress on the overhead catenary system (OCS) is considered a minor climate change impact because of:
  - relatively minor impacts on service and maintenance from heat-induced OCS line sag
  - minor adjustments (and costs) required to adapt the OCS for warmer temperatures
- Sound Transit uses two types of OCS: auto-tension, which is used in non-tunnel areas, and fixed termination, which is used in tunnels, by Tacoma Link, and in the maintenance yard. Heat stress is possible for both types of OCS; however, sensitivity to temperature variations and changes in average and

extreme temperatures differ between the types. Overall, the non-tunnel portions of the fixed termination OCS are more sensitive to changes in average and extreme temperatures because of the system's inability to auto-adjust to changing temperatures. Heat sensitivity of the auto-tension OCS is mostly limited to changes in maximum temperatures.

- *Potential impacts*. The potential for increased heat stress on the OCS may result in the following issues for infrastructure and operations:
  - Expected issues:
    - need for more frequent visual monitoring for both OCS types
  - Possible issues:
    - more slow orders or short-term train cancellations if line sag exceeds auto-tension tolerance
    - adjustments to OCS set points based on changes in average temperature
    - installation of longer guide bars and related structural adjustments for auto-tension OCS

  The estimated duration of service impacts is minutes for slow orders to several hours if re-tensioning or repairs are required.

- *Probability of increased heat stress on the OCS*. The probability of increased heat stress on the OCS is considered high for non-tunneled fixed termination OCS and low for the auto-tension OCS given the differential sensitivity of the two systems to increasing average and extreme temperatures.

Increased Heat Stress on Facility Structures and Landscaping

- Potentially affected service(s): Customer Facilities
- Basis for rating. Increased heat stress on facility structures and landscaping is considered a minor climate change impact because of:
  - minor impact on customer service
  - limited impact on maintenance and operations
  - existing requirements for using native and/or drought tolerant species for landscaping
  - relatively minor costs associated with heat stress on facility structures and landscaping (although some structural retrofits, if needed, could be costly depending on scale)

  Any aboveground facility, as well any aboveground structures servicing underground stations, is potentially affected by heat stress. Heat stress has already had minor impacts on some facilities, although changes in design standards have addressed most issues experienced to date.

- *Potential impacts*. The potential for increased heat stress on facility structures and landscaping may result in the following issues for infrastructure and operations:
  - Expected issues:
    - increased maintenance and repairs of infrastructure affected by heat
    - increased need for irrigation and higher irrigation costs, even for native species
  - Possible issues:
    - more frequent replacement of infrastructure affected by heat
    - increased susceptibility of plants to disease and higher mortality
    - reduced facility aesthetics
    - temporary minor inconveniences to customers during maintenance and repair activities

  The estimate duration of service impacts, if they occur, will depend on the nature of the maintenance and repair activities.

- *Probability of heat stress on facility structures and landscaping.* The probability of heat impacts on facility structures is high given scientific confidence in projections for increasing average and extreme summer temperatures. The probability of heat impacts on facility landscaping is also high (even with irrigation), particularly during the establishment period for landscaping. The probability of heat stress drops to medium once the plants are established. Heat stress on landscaping may be compounded by projected decreases in summer precipitation. Which facilities and landscaping are likely to be affected, how they could specifically be affected, and at what point increasing temperatures start to cause problems are uncertain. Facility age may increase the probability of heat stress moving forward in time.

Increased Heat Stress on Environmental Mitigation Activities

- *Potentially affected service(s)*: Environmental Management
- *Basis for rating.* Increased heat stress on environmental mitigation sites is considered a minor climate change impact because of:
  - existing site connectivity to wetlands, which can reduce the potential for drought stress on sites
  - the relatively short time period for which Sound Transit is responsible for sites
  - the separation of impacts on mitigation sites from service provision (i.e., failure of a mitigation site does not affect customer service)

  Sound Transit is required to maintain environmental mitigation sites for 5–10 years. The projects are typically small, in the range of ¼–3 acres and mostly involve wetlands restoration. Sites are often located on public property such as parks to maximize environmental benefits, public enjoyment of the projects, and continued long-term maintenance of the sites. Native species are used on the sites and are irrigated until established.

- *Potential impacts*. The potential for increased heat stress on environmental mitigation sites may result in the following issues:
  - Expected issues:
    - increased need for irrigation, longer periods of irrigation, and higher irrigation costs during establishment period
  - Possible issues:
    - increased susceptibility of new and establishment plants to disease and higher mortality during periods of prolonged heat, although any potential obligation to replace lost vegetation would only be during the 5–10 years Sound Transit is maintaining the site.
- *Probability of increased heat stress on environmental mitigation sites*. The probability of increased heat stress on newly-planted environmental mitigation sites is medium, given that most sites are connected to wetlands and are irrigated during site establishment. Irrigation costs may be higher or required for longer periods of time however, as noted above. Once established, the probability of heat stress drops to low. However, even established native plants can be affected by extreme heat and/or summer drought if no irrigation is provided.

Increased Groundwater Seepage into Tunnels

- *Potentially affected service(s)*: Link (various tunnels), Customer Facilities (Downtown Seattle Transit Tunnel stations and Beacon Hill Station), ST Express (Downtown Seattle Transit Tunnel only)
- *Basis for rating*. Increased tunnel seepage is considered a minor climate change impact because of:
  - limited impact on customer service and operations
  - current ability to accommodate increases in seepage rates
  - changes in design standards that have addressed the potential for seepage issues in new tunnels

  Existing odor issues are currently being treated. However, Increases in the frequency, duration, and intensity of minor odor issues associated with sulfur-reducing bacteria in the Beacon Hill Tunnel are possible and would potentially require additional action. At this point in time, it is assumed that odor problems are only an issue for the Beacon Hill Tunnel and station while increased seepage rates could occur in any current and future tunnel and underground station.

- *Potential impacts*. The potential for increased seepage may result in the following issues for infrastructure and operations:
  - Expected issues:
    - increased maintenance of pumps and drains used to manage seepage
  - Possible issues:
    - additional odor control efforts if odor issues become more intense or persistent (Beacon Hill)
    - reduced customer service quality where odor issues become more intense or persistent
    - increased seepage into below-ground tunnel infrastructure (e.g., elevator pits)

  The estimated duration of service impacts associated with odor issues is minutes to hours depending on the intensity of the odor. No service impacts are expected from increased seepage rates.

- *Probability of increased tunnel seepage*. The probability of increased tunnel seepage is considered medium. There is good scientific confidence that winter precipitation will increase and that the region will see more extreme precipitation, but low confidence in specifically how much wetter and how much more extreme winters could be. Any resulting changes in groundwater flows are also uncertain.

Which Services May Become Priority Areas for Adaptation?

Climate change impacts will vary by service and location. As a result, some services may become a higher priority for adaptation than others. This section provides a relative ranking, organized by Sound Transit service, of potential adaptation priorities. The ranking was based on:

- types of climate change impacts potentially affecting a service
- range of potential issues associated with a climate change impact
- geographic extent of the impacts
- how easily those impacts can be adapted to

Results are summarized in Table 3-4 and discussed below.

Table 3-4 *Potential Priority Areas for Taking Adaptive Action, by Service**

Rating	Service	Primary Issues *(potential for…)*	Other Issues *(potential for…)*
Potential high adaptation priority services	North Sounder; Edmonds and Mukilteo Stations	• More mudslide activity and slope instability • Impacts related to sea-level rise: - More frequent temporary flooding of low-lying track and facilities - Permanent inundation of low-lying track and facilities - Higher tidal and storm surge reach - Increased erosion - More drainage problems - Corrosion from more frequent exposure to saltwater • Minor to significant financial exposure for impacts-related repairs and adaptation (principally for the Edmonds and Mukilteo facilities)	• Increased localized flooding due to more stormwater runoff or poor drainage (even with small amounts of sea-level rise) • Increased seepage due to higher groundwater tables (exacerbated by sea-level rise) • Impacts related to temperature (but moderated by proximity to Puget Sound): - Rail buckling - More heat stress on electrical and safety equipment - More heat stress on facility structures and landscaping
Potential medium adaptation priority services	South Sounder; Tukwila and Kent Sounder stations	• Larger and/or more frequent river flooding of the Green and White Rivers (also affecting flooding in the Duwamish and Puyallup Rivers) • Impacts related to temperature: - Rail buckling - More heat stress on electrical and safety equipment - More heat stress on facility structures and landscaping - Extra vegetation removal, cleaning, and fire protection; and - Heat-related track repairs and/or retrofits	• Increased localized flooding due to more stormwater runoff or poor drainage • Increased seepage due to higher groundwater tables • Permanent inundation of low-lying track (limited to small area in Tacoma) • Ridership volume on the South Sounder line • Minor financial exposure for impacts-related repairs and adaptation for the Tukwila and Kent Sounder stations
	At-grade or aboveground Link alignments	• Impacts related to temperature: - Rail buckling - More heat stress on electrical and safety equipment - More heat stress on overhead catenary system • Impacts related to precipitation: - Increased localized flooding due to more stormwater runoff or poor drainage - Increased seepage due to higher groundwater tables (also compounded by sea-level rise in SODO area) • Minor to significant financial exposure for impacts-related repairs and adaptation	• Larger and/or more frequent river flooding of Duwamish River, Bear Creek, and creeks near current and planned Link alignments

Table 3-4 (cont'd.) *Potential Priority Areas for Taking Adaptive Action, by Service**

Rating	Service	Primary Issues *(potential for…)*	Other Issues *(potential for…)*
Potential low adaptation priority services	ST Express	• Larger and/or more frequent river flooding of the Green and White Rivers (also affecting flooding in the Duwamish and Puyallup Rivers)	• More heat stress on electrical and safety equipment (specifically carriage air conditioning) • Minor financial exposure for impacts-related repairs and adaptation
	Environmental mitigation	• More summer drought stress on landscaping (also compounded by decreasing summer precipitation)	• Minor financial exposure for impacts-related repairs and adaptation
	Other customer facilities	• Impacts related to temperature: - More heat stress on electrical and safety equipment - More heat stress on facility structures and landscaping • Impacts related to precipitation: - Increased localized flooding due to more stormwater runoff or poor drainage - Increased seepage due to higher groundwater tables	• Minor financial exposure for impacts-related repairs and adaptation
	Underground Link segments	• Increased seepage due to higher groundwater tables	• Minor financial exposure for impacts-related repairs and adaptation

* "Primary issues" are climate change impacts and other factors that provided the primary basis for the rating.
"Other issues" are climate change impacts and other factors that are also relevant to the rating.

The potential adaptation priority ratings for service areas are:

- *High*: North rail alignment used by Sounder and others and the Edmonds and Mukilteo Sounder stations
- *Medium*: South rail alignment used by Sounder, the Tukwila and Kent Sounder stations, and aboveground and at-grade segments of Link
- *Low*: ST Express, Environmental Mitigation, all other customer facilities, and underground segments of Link

As with the prioritization of impacts in the previous section, conclusions about which services may become higher or lower adaptation priorities should be considered initial findings. These ratings will likely change over time based on changes in the services, infrastructure replacement and upgrades made as part of routine asset management, and evolving data on climate projections. Note also that climate change impacts on individual services, facilities and/or specific alignment segments may result in a different potential adaptation priority rating than the overall rating assigned to that service.

Services That May Become a Higher Priority for Adaptation

North Sounder Rail Alignment, Edmonds and Mukilteo Sounder Stations

The North rail alignment used by Sounder and the Edmonds and Mukilteo Sounder stations could be affected by a number of climate change impacts, including sea-level rise, mudslides, and drainage issues. Heat impacts are also possible but less likely to affect the north rail alignment and Edmonds and Mukilteo Sounder stations given the alignment's proximity to Puget Sound, which moderates air temperature.

Potential challenges for Sounder North and its stations, and the primary basis for rating these services as a potential high priority for adaptation, are:

- the alignment's exposure to sea-level rise and mudslide risk
- potential inundation of the Edmonds and Mukilteo facilities if sea level rises 50 inches or more (currently near the upper end of projections for 2100)
- the additional costs Sound Transit could incur to address sea-level rise impacts at the Edmonds and Mukilteo facilities

Sea-level rise below 50 inches would not inundate the Edmonds and Mukilteo facilities but could still result in more frequent service interruptions due to higher tides and storm surge, increased drainage problems, increased localized flooding in the vicinity of the Edmonds and Mukilteo facilities, and other impacts.

Services That May Become a Medium Priority for Adaptation

South Sounder Rail Alignment, Kent and Tukwila Sounder Stations

The South rail alignment used by Sounder and the Kent and Tukwila Sounder stations have the potential to become a medium adaptation priority because of the projected impacts associated with major flooding and heat stress. Other notable factors contributing to this rating are the potential for localized flooding and sea-level rise impacts, ridership volume, and financial exposure.

- *River flooding*. The South rail alignment and facilities are located in river valleys that already have the potential for damaging floods, even with fully operational dams and levees. Climate change increases the probability of these damaging floods, potentially shifting today's 0.2 percent flood event to a 1 percent flood event as early as the 2020s in some scenarios. Projected inundation mapping by the USACE for today's 0.2 percent flood event puts as much as 6–10 feet of water in the vicinity of the current, and to a lesser degree the future, Tukwila Station and portions of the south rail alignment for several days as it runs through the Green River Valley. The overall impact of major flooding on South Sounder would likely be moderate since damage to the Tukwila and Kent facilities would likely be limited to the parking areas and access roads (e.g., Long Acres Way and Strander Boulevard). Flood damage to tracks or bridge infrastructure in other parts of the south rail alignment could also have implications for service delivery depending on the extent of damage.
- *Heat stress*. Heat-related impacts are more likely for South Sounder given the system's extensive use of wood tie-and-ballast track, which is more sensitive to heat than other track types (e.g., concrete tie-and ballast). Heat stress is also more likely along this line given that most of the South line is located inland and in open areas with little shading. Air temperatures tend to be slightly higher in the South Sounder service area because of this.
- *Localized flooding and sea-level rise*. Poor drainage along Long Acres Way and Strander Boulevard (near the current and future Tukwila Station) already produces localized flooding that is likely to be exacerbated by projected increases in precipitation. Sea-level rise could inundate a small portion of Sounder track in Tacoma near Bay Street between mile posts 38X-39X if sea level increases 50 inches or more, which is currently near the high end of projections for 2100. This potential also assumes no adaptive action is taken by the City of Tacoma to prevent inundation (considered unlikely).
- *Ridership and financial exposure*. Any impacts on South Sounder that result in delays or cancellations have a larger impact on Sounder service overall because of the high ridership volume on the South. This makes it more difficult to run bus bridges in the event of service interruptions. Financial

exposure for repairs and/or adaptation measures is a relevant issue but is somewhat constrained given that Sound Transit does not own the majority of track used by Sounder. Sound Transit would be responsible for impacts-related repairs and adaptation costs for Sounder facilities, the 8-mile Tacoma to Lakewood segment, and any Sound Transit-owned trackside infrastructure.

Aboveground and At-grade Segments of Link

Aboveground and at-grade segments of Link may become a medium adaptation priority given the amount of current and future infrastructure exposed to heat and precipitation-related impacts. Sound Transit's financial exposure for managing impacts on Link is also an important issue. Sound Transit is sole owner and operator of the Link system. This allows full control over decisions about adapting the Link system to climate change. Additionally, Sound Transit has more flexibility (to a point) to choose alignment routes that avoid areas potentially affected by increased river flooding and sea-level rise. However, this also means that any costs associated with adapting the system will be the responsibility of Sound Transit. This financial exposure will continue to grow along with the system.

- *Heat stress*. Heat impacts have the potential to affect any aboveground and at-grade portion of Link. Heat stress has been an issue in the past with Link TPSS and signal bungalows because of past reliance on natural ventilation. Ongoing retrofitting of Central Link units with air conditioning and changes in design criteria requiring air conditioning in new units are remedying the problem. However, some heat sensitive equipment, such as small signal boxes, cannot be air conditioned and therefore may be more frequently affected by heat over time (although with minor impact to the system).

  The need to raise rail neutral temperature (RNT), which is used to reduce the potential for rail buckling, is not expected, at least in the next few decades, but cannot be ruled out without further technical analysis of projected rail heat tolerance. Link rail recently (summer 2013) raised its RNT to 95°F–105°F and makes extensive use of rail types that are less prone to buckle relative to wood tie-and-ballast track. However, retrofitting existing rail—including Central Link, which was installed with a lower RNT—to a higher RNT would be both expensive and difficult to do if required.

- *Localized flooding*. Increased localized flooding due to more stormwater runoff and poor drainage is another impact that could affect aboveground or at-grade portions of the Link system. Stormwater runoff is already a costly issue to manage and resizing stormwater vaults or resizing outfalls can be expensive and/or difficult to implement. Higher groundwater tables could also be difficult to manage, particularly in low-lying areas like the south downtown Seattle industrial area. the potential for increased flooding in the Duwamish River, Bear Creek, and other small creeks could have minor impacts on track infrastructure.

Services That May Become a Lower Priority for Adaptation

ST Express, Environmental Mitigation, Other Customer Facilities, Underground Link Segments

ST Express, environmental Mitigation, customer facilities other than Edmonds, Mukilteo, Tukwila, and Kent, and underground Link segments are likely to become a lower adaptation priority. This rating was given because of the limited number of climate change impacts potentially affecting these services (relative to other services) and/or the limited number of ways those impacts could affect the services specifically. Note that a potential low adaptation priority rating does not mean that the service would be unaffected by climate change. Some adaptive actions may be required. The costs of these actions will vary but Sound Transit will be responsible, at least in part, for these costs depending on the service.

Conclusions Regarding Prioritization

Prioritizing impacts and services reveals several key concluding points about how climate change may affect Sound Transit.

- Many of the climate change impacts evaluated are likely to have minor to moderate impacts on Sound Transit services based on current climate projections. These include all heat-related impacts, most precipitation-related impacts, and lower levels of sea-level rise (in the range of 22 inches or less, which is currently near the average projected for 2100). The estimated probability of these minor to moderate impacts varies from low to high across impacts.
- Potentially significant impacts are associated with increases in mudslide activity causing more than 70 train cancellations in a season, which can occur at any point in the future, and sea-level rise of 50 inches or more, which is currently near the upper range of projections for 2100. The estimated probability of mudslide activity causing more than 70 train cancellations in a season is considered medium, primarily because of the agency's experience to date with frequent mudslides. The estimated probability of 50 inches of sea-level rise and potential inundation of the Edmonds and Mukilteo facilities is low. The potential for these impacts along the North rail alignment used by Sounder were important factors in rating Sounder North and the Edmonds and Mukilteo facilities as services that could become higher adaptation priorities relative to other services.
- Sound Transit services are designed to accommodate a range of conditions and periodic service interruptions. As a result, a good amount of resilience is already built into the system based on current climate change projections. This potentially allows for some amount of climate change to occur before

impacts begin to exceed design tolerances in ways that may require adaptation. The point at which design or performance tolerances are exceeded will vary, and some systems may benefit from adaptive measures taken during planning, design, and construction rather than waiting to retrofit after impacts occur.

SECTION 4

Strengthening Resilience through Adaptation

The Sound Transit Climate Risk Reduction project identified numerous ways that climate change might affect service delivery and other important agency objectives. The project also showed that the system already has some degree of resilience to current climate change projections as a result of how the system is designed and operated. This resilience could be reduced, however, depending on the size and rate of climate change, decisions made by Sound Transit, its partners, or the communities it operates in, and other factors noted in this section.

Implementing actions to address climate change impacts—in other words, adapting to climate change—can strengthen Sound Transit's existing resilience to climate change and help the agency:

- achieve its goals in a changing climate
- protect investments
- reduce risks associated with climate change
- avoid creating new risks as it plans for the future

This section discusses why adaptation is important and identifies adaptation options for Sound Transit.

Adapting to Climate Change

Activities intended to reduce the harmful impacts of climate change are generally classified as either mitigation or adaptation activities. Mitigation activities are focused on slowing (and ultimately stopping) the rate of climate change by reducing human-caused emissions of GHGs such as carbon dioxide, methane, and nitrous oxide. Reducing GHG emissions is a long-standing priority for Sound Transit that was formalized in 2007 with release of the agency's Sustainability Initiative.[35] Sound Transit's climate change mitigation efforts include calls to develop "measurable targets related to fuels, vehicles, and emissions; ecosystem protection; green procurement; recycling and waste prevention; energy and water conservation; sustainable design and building; and education and awareness."[36]

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[35] See http://www.soundtransit.org/Documents/pdf/about/environment/ExecutiveOrderNo1_Sustainability.pdf.

[36] http://www.soundtransit.org/About-Sound-Transit/News-and-events/News-releases/News-release-archive/ISO14001; see also Sound Transit's 2012 Sustainability Progress Report (released April 2013), http://www.soundtransit.org/Documents/pdf/about/environment/2012%20Sustainability%20Progress%20Report.pdf.

While efforts to reduce GHG emissions are critical, the slow pace of mitigation and recognition that climate is already changing based on past GHG emissions have led to increased focus on the need to adapt to climate change impacts in addition to reducing GHG emissions. Broadly speaking, adaptation is "a continuous set of activities, actions, decisions, and attitudes undertaken by individuals, groups, and governments" intended to reduce the negative consequences of climate change, strengthen resilience to climate change impacts, and, where relevant, take advantage of new opportunities. Actions may focus on building adaptive capacity within an organization as well as delivering adaptive actions (Table 4-1) and can be both proactive (i.e., in anticipation of projected impacts) and reactive (i.e., in response to impacts).

Table 4-1

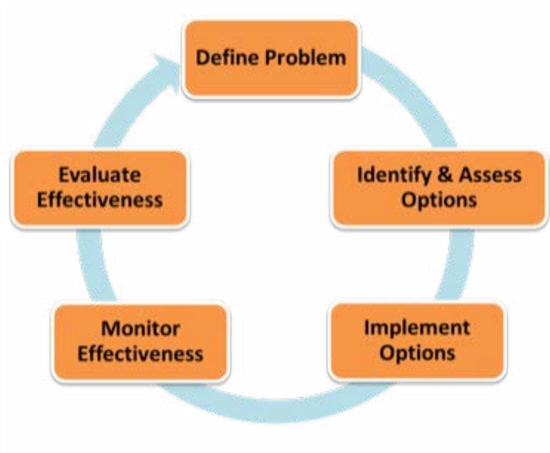
Purpose, Sensitivity to Climate Uncertainty, and Examples of Actions that Build Adaptive Capacity and Deliver Adaptive Action

Building Adaptive Capacity	Delivering Adaptive Action
Purpose: Actions intended to reduce institutional, legal, cultural, technical, fiscal and other barriers that can limit adaptation.	*Purpose*: Actions intended to reduce specific climate vulnerabilities.
Sensitivity to uncertainties in climate projections: Activities can be taken independent of specific climate projections.	*Sensitivity to uncertainties in climate projections*: The choice and timing of some actions may depend on the specifics of the climate projections (e.g., whether sea-level rises 6 or 16 inches, and by when).
Examples: • Develop (and update) a strategy to guide adaptation activities • Increase stakeholder outreach and education • Increase staff training and access to technologies that support adaptation needs • Increase partnerships with organizations that can support adaptation needs • Identify and address regulatory, institutional, and other barriers to adaptation planning	*Examples*: • Raise rail neutral temperature • Increase design thresholds for storms • Plant tree species known to have a broad range of climatic tolerances • Improve the use of early warning systems for extreme heat events • Raise or relocate sensitive electrical equipment located in 100 -year and 500 -year flood zones

In all cases, adaptation is a continual process where decisions and actions evolve to reflect changes in the systems being managed, the effectiveness of adaptation efforts over time, and understanding of climate change impacts. This concept of continual evaluation and adjustment is underscored by the general stages of adaptation, which establish (at least in principle) an adapting learning framework (Figure 4-1). Finally, while adaptation and mitigation actions are typically considered distinct activities, some actions, such as green infrastructure and water and energy conservation measures, provide both mitigation and adaptation benefits (see Figure 4-2). This nexus between adaptation and mitigation can create unique opportunities to further both objectives through the same effort.

Figure 4-1

General stages of adaptation



Source: University of Washington Climate Impacts Group

Figure 4-2

Adaptation-mitigation nexus

Source: Center for Clean Air Policy, http://ccap.org/what-does-climate-resilience-look-like

Some activities provide both adaptation and mitigation benefits, as indicated by the activities listed in the center of the Venn diagram.

Why Consider Adaptation Now?

Climate change projections are inherently uncertain to some degree, as are any projections about the future, such as population projections or economic forecasts. This begs the question: Why not wait and see how climate changes before adapting?

As noted previously, some amount of adaptation will be reactive given the inability to precisely predict how climate will change. However, relying exclusively on reactive adaptation can be problematic for the following reasons:

1. *Decisions made today can shape tomorrow's vulnerabilities*. For example, decisions about where to place infrastructure and the conditions under which that infrastructure must be able to operate will influence infrastructure resilience to a changing climate.
2. *Significant time may be required to develop adaptive capacity and to implement changes*. Some barriers to adaptation can be easily addressed while others may take longer. Similarly, the time, tools, and resources required to implement adaptation actions will vary. The ability to effectively implement certain actions may become more limited over time, while other options may become closed off entirely due to other decisions.
3. *Retrofitting for climate resilience may cost more than building for it in the first place*. Fixed infrastructure can be difficult and/or costly to retrofit in response to climate impacts. In some cases, it may be more cost effective to integrate adaptation into alignment selection, infrastructure design, monitoring programs, and other areas as decisions are being made.

Proactive adaptation provides for a more measured and deliberate approach to adaptation. For example, proactive adaptation gives organizations the opportunity to:

- identify ways of tracking change impacts in asset management systems, maintenance logs, and operations
- integrate implementation of adaptation measures into maintenance and infrastructure replacement cycles
- develop a long term -strategy for addressing more complicated adaptation needs

Deciding when, where, and how to adapt will ultimately depend on the nature of the climate change impacts and vulnerabilities that need to be addressed, how quickly climate changes, individual and institutional risk tolerance, available resources, and other factors. Any adaptive actions taken by the communities and partners with whom Sound Transit works are also likely to affect Sound Transit's adaptation choices. For example, decisions about how to manage the potential for inundation near the Edmonds and Mukilteo waterfront will be made by the cities of Edmonds and Mukilteo. In each case, the decisions made by these parties can affect how climate change impacts affect the Sound Transit system and which adaptation options the agency may want to pursue.

Adaptation Options for Sound Transit Services

Options for adapting to the impacts of climate change are presented in the following sections. The adaptation options provided here are not intended to be an exhaustive list of all possible approaches nor are they all required for the agency to adapt to climate change. This section provides an initial menu of options relevant to Sound Transit services that can be implemented if and when it is determined that adaptation is warranted.

The options are presented collectively for all services by climate change impact and generally fall into one or more of the following categories:

- Adjustments to Infrastructure – retrofitting, replacing, or relocating infrastructure
- Adjustments to Operations and Maintenance – changes in maintenance frequency or standard operations
- Design Changes – changes in design criteria (specifications) for new and existing infrastructure
- Decision Support and Capacity-building Activities – implementing new tools to gather additional information related to climate impacts on the system, using partnerships to address impacts

Because the adaptation options are aggregated across modes, listed options may not apply to all of the services potentially affected by a specific impact. See Appendix C for adaptation options specific to each service.

As noted previously, climate change exacerbates many existing issues. As a result, some of the identified adaptation options are activities that would be pursued regardless of any knowledge about projected climate change impacts or desire to pursue pre-emptive adaptation. However, climate change may accelerate the need for these adaptation options and/or require implementation at a scale larger than would normally be expected. In other cases, climate change may raise the need for new approaches or require reprioritizing activities.

In all cases, the listed actions should be considered optional and "if needed." decisions about which adaptation options to employ, and when, will depend on a variety of factors, including how rapidly climate change occurs and the cost of implementing the adaptation option(s). Additionally, these costs will vary with the specifics of the adaptation option, the scale of deployment, and how readily the option can be integrated into routine asset maintenance and replacement cycles. Further discussion and analysis of these issues is required before these or other adaptation options not included here can become implementation-ready recommendations.

Adapting to Heat Impacts

Potential for Rail Buckling

- *Relevant infrastructure*: Sound Transit-owned rail
- *Relevant service(s)*: Sounder, Link

Adaptation options for addressing rail buckling for Link and Sounder rail can be grouped into two categories. The first category of actions directly reduces the potential for buckling via structural changes and maintenance adjustments to Sound Transit-owned track and track beds. Options include any combination of the following (with relevant mode noted):

- If technically possible, evaluate how much change in temperature would be needed to warrant raising rail neutral temperature (Link and Sounder).
- Raise rail neutral temperature (Link and Sounder).
- Re-install expansion joints in areas prone to buckling (Central Link).
- Increase ballast maintenance to improve stability/rail support (Sounder).
- Replace stone ballast with concrete slab where increasing ballast maintenance becomes cost prohibitive or is difficult to do (Sounder).
- Replace wood ties with concrete crossties, which are better able to resist movement but may require more frequent replacement on track used by heavy freight trains (Sounder).
- Employ new technologies that allow movement of rails to accommodate expansion (Central Link and Sounder).

The second category helps manage the risk of rail buckling by informing decisions about when and where to issue slow orders (capacity-building and decision support). Information gathered through these approaches may also help inform decisions about the potential structural changes listed in the first category of adaptation options. Options include any combination of the following:

- Evaluate temperature variations in urban areas (the "urban heat island effect") and how those variations may affect the potential for rail buckling.
- Directly monitor actual rail temperature through the use of thermocouples.
- Use models to predict rail temperatures based on real time weather forecast data, e.g., the Federal Railroad Administration model tested on Amtrak's Northeast Corridor.[37]
- Evaluate and update metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

[37] See Zhang and Al-Nazer (2010) for more details.

Increased Heat Stress on Electrical Equipment

Heat-sensitive stationary and vehicle electrical equipment discussed by staff in this project were Head-end Power (HEP) units on Sounder locomotives, Traction Power Substations (TPSS), signal bungalows and small signal boxes, Uninterruptable Power Supply (UPS) systems, and Ticket Vending Machines (TVMs). Adaptation options for each are provided here. These options could also be relevant to other heat-sensitive equipment not discussed as part of this project.

Head-end Power (HEP) Units

- *Relevant infrastructure*: Sounder locomotives
- *Relevant service(s)*: Sounder

HEP units are naturally ventilated systems providing electricity for lighting, electrical, air conditioning, and other non-motive power uses needed by Sounder trains. HEP units are powered by a separate smaller diesel engine that is more difficult to cool than the main locomotive engine. Adaptation options could include any combination of the following capacity-building activities and adjustments:.

- Increase the frequency of routine testing, maintenance, and replacement of HEP units as temperatures increase.
- Upgrade HEP units to accommodate warmer temperatures.
- Evaluate and update metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

Traction Power Substations (TPSS), Signal Bungalows, and Small Signal Boxes

- *Relevant infrastructure*: Sound Transit-owned TPSS equipment/structures and signal bungalow equipment/structures
- *Relevant service(s)*: Link, Sounder

All new Link TPSS and signal bungalows will be air conditioned in accordance with changes made in 2012 to the Design Criteria Manual; all current Central Link TPSS and signal bungalows will be air-conditioned by summer 2014. Small signal boxes used to control the loop detectors along Martin Luther King Jr. Way S. (for Central Link) cannot be air-conditioned and therefore rely on natural ventilation.

Adaptation options for TPSS, signal bungalows, and small signal boxes could include any combination of the following capacity-building activities and infrastructure and design adjustments:

- Where possible, use more reflective roof coating or increase shading around TPSS, signal bungalows, and small signal boxes to maximize passive cooling or to reduce demands on air conditioning systems.
- Increase ventilation to small signal boxes.
- Provide structural flexibility to increase air conditioning or fan capacity at a later date if needed by providing adequate space and opportunity to upgrade power feeds.
- Add new (for Tacoma Link TPSS) or increase existing air conditioning capacity where heat stress becomes or continues to be an issue.
- Evaluate, and where relevant update, metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

Uninterruptable Power Supply (UPS) Systems

- *Relevant infrastructure*: UPS batteries and rooms
- *Relevant service(s)*: Customer facilities

The UPS battery system provides 90 minutes of emergency and standby power for critical systems (e.g., signaling, fire and safety) in the event of power loss. UPS battery systems are designed for a minimum 20 year life when operating at 74°F. Warmer temperatures can halve this life span, requiring more frequent replacement of the battery systems. Adaptation options for UPS systems include any combination of the following capacity-building activities and design and infrastructure adjustments:

- Evaluate the remaining non-air conditioned UPS rooms to determine which units may require air conditioning in the future as a result of warming temperatures (e.g. those with potential for high sun exposure).
- Increase battery heat tolerance (i.e., average temperature batteries are designed to).
- Add new or upgrade existing air conditioning capacity where heat stress becomes or continues to be an issue.
- Evaluate and update metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

Ticket Vending Machines (TVMs)

- *Relevant infrastructure*: TVM units
- *Relevant service(s)*: Customer facilities

TVMs collect revenue at Sound Transit facilities and are sensitive to prolonged sun exposure and heat. TVMs cannot be air conditioned and therefore rely on natural ventilation. Adaptation options for TVMs may be limited but could include any combination of the following structural and design adjustments:

- Where possible, increase shading around TVMS to maximize passive cooling.
- Increase the specified heat tolerance for TVM units and/or evaluate options for more heat-tolerant TVMs.
- Evaluate and update metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

Increased Heat Stress on the Overhead Catenary System (OCS)

- *Relevant infrastructure*: OCS wires, guide poles, cantilevers, and related equipment
- *Relevant service(s)*: Link

OCS heat sensitivity and adaptation options vary with OCS type. Adaptation options for heat stress on the OCS could include any combination of the following capacity-building activities and adjustments to maintenance and operations, infrastructure, and design criteria:

- If technically possible, evaluate how much change in average and extreme temperature may be needed to require changes in auto tension guide rod lengths and the fixed-termination nominal tension temperature set point.
- Adjust auto tension and fixed-termination set points to a higher average temperature.
- Install longer guide rods on auto-tension poles during installation to provide a longer travel range for auto-tension weights.
- Install taller poles for auto-tension systems during installation to provide a longer travel range for auto-tension weights.
- Evaluate and update metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

Increased Heat Stress on Facility Structures, Landscaping, and Environmental Mitigation Activities

- *Relevant infrastructure*: Building structures, paved areas, and other constructed facility features; facility trees and plants; mitigation landscaping
- *Relevant service(s)*: Customer facilities, Environmental mitigation

Heat stress can occur any time temperatures cause building materials to expand beyond design specifications. Building features that may be impacted include expansion joints, concrete, building facades, and metalwork. Facility landscaping and environmental mitigation projects can also be stressed by high summer temperatures, requiring more frequent irrigation or replacement of plants.

Adaptation options for heat stress on facility structures, landscaping, and environmental mitigation could include any combination of the following capacity-building activities and adjustments to maintenance and operations, infrastructure, and design specifications:

- Increase visual monitoring for premature wear related to heat stress on structures.
- Periodically evaluate assumed design temperature tolerances and temperature benchmarks (e.g., Uniform Temperature and Temperature Gradient benchmarks set for 64°F) in relation to projected changes in climate. If potentially inadequate, evaluate the cost and benefits of changing the standards to increase robustness of the designs.
- Increase the use of shading around structures and more reflective roof coating to reduce exposure to sun and potential for heat stress on structures.
- Reduce the use of small planter areas (e.g., narrow planting strips) that may be more prone to heat stress because of irrigation challenges, reflected pavement heat, or other factors.
- Extend (in duration or by location) the option to use irrigation during and after the establishment period.[38]
- Evaluate and update metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

Adapting to Precipitation Impacts

Increased Mudslide Activity

- *Relevant infrastructure*: rail, trackside equipment, trains
- *Relevant service(s)*: Sounder

Efforts to address mudslide risk at priority locations along the north rail alignment used by Sounder are ongoing as a result of the dramatic rise in mudslides affecting rail transport between Seattle and Everett in 2012–13. Additional options for adapting to increasing mudslide frequency or severity include any combination of the following adjustments to operations and maintenance and capacity-building and decision support activities. Sound Transit currently implements many of the activities mentioned below, however their frequency or duration of use may be affect by projected increases in mudslide activity.

[38] Current Sound Transit landscaping standards already require the use of native species, drought-tolerant species, and "sustainable alternative approaches" to stormwater management that provide benefit to landscaping.

- Plan for increased use of bus bridges.
- Work with rail partners (BNSF, Amtrak, and WSDOT) to model the frequency and location of future mudslide risk based on projected changes in precipitation. The results can be used to inform decisions about slide intervention activities (e.g., slope stabilization, maintenance, community outreach).
- Work with rail partners to expand slide intervention activities to additional priority areas.
- Implement and continue refining predictive models for slides, including installation of additional rain gauges and other monitoring devices that can help improve the accuracy of the models over time.
- Evaluate and update metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

Increased River Flooding

- *Relevant infrastructure*: rail and/or support infrastructure, ground level and underground electrical equipment, stations, parking facilities, access roads
- *Relevant service(s)*: Sounder, ST Express, Link, Customer Facilities

The potential for increased river flooding in the Sound Transit service area is a regional issue that will be managed by a number of entities, including the USACE, the Federal Emergency Management Agency (FEMA), the State of Washington, and floodplain communities. BNSF will also play a key role in adapting track, if needed, as owner of the rail infrastructure used by Sounder and others. Actions taken by these groups are likely to influence if and how Sound Transit adapts its facilities and operations to increasing flood risk.

Adaptation options for addressing increased river flooding include any combination of the following capacity-building activities and adjustments to operations and maintenance, infrastructure, and design standards:

- Update emergency planning procedures and relevant design standards for longer-lived or hard-to-upgrade infrastructure to reflect a wider range of projected flood risks;
- Modify design standards to provide higher level of flood protection for infrastructure that must be located in or near flood hazard zones (e.g., raising minimum top-of-rail height based on 100-year flood elevations or extending this design preference out to the 500-year flood zone);
- Extend design standards required for the 100-year flood zone out to the 500-year flood zone for flood-sensitive equipment, facilities, and other infrastructure.
- Increase visual monitoring of river banks where Sound Transit-owned rail infrastructure crosses to check for signs of erosion or other changes that could affect bridge supports.

- Raise or relocate sensitive underground or ground-level infrastructure to reduce or eliminate potential for flooding.
- Work with the USACE and floodplain communities to help ensure that Sound Transit's current and projected flood management needs are considered in flood management and hazard mitigation decisions.
- Work with BNSF to raise track elevations in areas with recurrent flooding.
- If and when relevant, work with the City of Tukwila on any future efforts to address flood and erosion risks at Link's Duwamish crossing and the City of Tukwila's adjoining E. Marginal Way crossing.
- Evaluate and, where relevant, update metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

Increased Localized Flooding Due to More Stormwater Runoff or Poor Drainage

- *Relevant infrastructure*: rail and/or support infrastructure, ground level and underground electrical equipment, stations, parking facilities, access roads
- *Relevant service(s)*: Sounder, ST Express, Link, Customer Facilities

Increased localized flooding can occur anywhere extreme precipitation overwhelms the drainage capacity of soils or stormwater infrastructure, even when properly maintained. Increasing sea level and high groundwater tables can exacerbate this issue. Adaptation options for managing and reducing the impacts of increased localized flooding include any combination of the following capacity-building activities and adjustments to operations and maintenance, infrastructure, and design standards:

- Increase visual and/or electronic monitoring in areas with drainage problems.
- Raise or relocate sensitive ground-level infrastructure to reduce or eliminate potential for localized flooding.
- Change ballast, or if necessary track bed, where poor drainage affects track performance or maintenance costs are escalating.
- Modify design standards to provide higher level of flood protection for equipment that must be located in areas where drainage could be an issue.
- Design for more intense and/or longer duration rain events (i.e., planning for amounts higher than the 24-hour, 25-year storm event).
- Expand used of Low Impact Development, bioswales and other green stormwater management to add design robustness to hard infrastructure.
- Modify drainage patterns to re-direct surface flows and improve drainage.
- Partner with Seattle Public Utilities and other community utility programs to target problem drains/drainages.

- Evaluate and, where relevant, update metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

Increased Groundwater Seepage into Tunnels

- *Relevant infrastructure*: tunnel infrastructure, pumps, and stations
- *Relevant service(s)*: Link

The potential for increased seepage in the Beacon Hill Tunnel and in new tunnels could require minor maintenance adjustments. Increased seepage could also require additional treatment of minor odor issues associated with sulfur-reducing bacteria in the Beacon Hill Tunnel if the seepage causes odors to become more intense or persistent.

Adaptation options for managing increased tunnel seepage and odor issues include any combination of the following capacity-building measures and adjustments to operations and maintenance and operations:

- Increase maintenance frequency of pumps and drains used to manage seepage.
- Explore alternate approaches to reducing or redirecting groundwater flows away from Beacon Hill Tunnel or reducing the growth of sulfur-reducing bacteria in the Beacon Hill Tunnel.
- Evaluate, and where relevant update, metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

Adapting to Sea-level Rise

Sea-level rise may result in a range of impacts depending on how quickly sea-level rises and the amount of rise that occurs. As with river flooding, decisions made by coastal communities, the State of Washington, BNSF, and others to address sea-level rise impacts are likely to influence any potential adjustments made on the part of Sound Transit.

Adaptation options for sea-level rise include any combination of the following capacity-building activities and adjustments to operations and maintenance, infrastructure, and design criteria. Most options are focused on potential ways to adapt the Edmonds and Mukilteo facilities. Decisions about adapting the north rail alignment used by Sounder will be made by BNSF, assuming current agreements are carried forward.

- Update service interruption plans to accommodate more service interruptions from higher tides and storm surges.

- Increase visual and/or electronic monitoring in areas with drainage problems.
- Raise or relocate sensitive ground-level infrastructure to reduce or eliminate potential for flooding.
- Modify design standards to provide higher level of protection for infrastructure that must be located in or near coastal flood zones, sea-level rise zones, or areas with poor drainage.
- Design for more intense and/or longer duration rain events (i.e., planning for amounts higher than the 24-hour, 25-year storm event).
- Install (or work with partner communities to install, where relevant) tide flaps or other controls that will prevent high tides from flooding parking lots and facilities via backflow into stormwater drains.
- Modify drainage patterns to re-direct surface flows away from flood-prone areas and improve drainage.
- Partner with community utility programs to target problem drains/drainages.
- Work with Mukilteo, Edmonds, the State of Washington, and others to help ensure that Sound Transit's current and projected needs related to sea-level rise are considered in decisions about adapting the area to sea-level rise.
- Work with BNSF on improvements to and upgrading of the sea wall where needed.
- Work with BNSF to raise track elevation and relevant overheard clearances.
- Evaluate, and where relevant update, metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

SECTION

5

Integrating Adaptation into Agency Processes

Integrating adaptive thinking into Sound Transit agency processes helps ensure that decisions related to strategic planning, system design, and operations and maintenance (among others) are robust to a changing climate. This section discusses the role of integrating climate change considerations into agency processes and finding opportunities for integration.

The long-term nature of climate change means that evaluating climate impacts and adaptation needs is not a one-time activity. Scientific understanding about specific impacts will continue to evolve over time as will the Sound Transit system and the communities it serves. Effective adaptation efforts will require making sure that past assumptions about climate change impacts remain valid and determining whether adaptive action, or modification to existing actions, is warranted on the basis of any changes in climate impacts science, Sound Transit services, or other relevant factors.

Note that integrating climate adaptation considerations into agency processes does not commit the agency to acting on adaptation. As noted in Section 4, decisions about when, where, and how to adapt to climate change will vary. Incorporating climate change considerations into the decision making process simply creates the opportunity to discuss how climate change may affect the decision being made and whether adjustments are needed to increase resilience. Asking these and other related questions can help Sound Transit:

- reduce any existing vulnerabilities
- optimize adaptation investments by identifying of "windows of opportunity" for planned implementation
- avoid building—both literally and figuratively—new vulnerabilities into the system
- continue to meet agency goals and objectives in a changing climate

Examples of possible questions relevant to specific program areas are provided in Table 5-1. Suggestions of how climate change adaptation could be integrated into Sound Transit's Environmental and Sustainability Management System and information on WSDOT's current approach to integration are provided in Appendix D.

It is important to recognize that integrating climate adaptation considerations into agency processes does not commit the agency to acting on adaptation. As noted in Section 4, decisions about when, where, and how to adapt to climate change will vary. Integrating climate change considerations into the decision process simply creates the opportunity for that decision to be made in the context of existing agency processes and decision milestones.

Table 5-1 *Sound Transit Climate Change Integration Matrix*

This matrix provides examples of how climate change relates to the range of activities at Sound Transit, the kinds of questions about climate change that could be posed, and a menu of potential adaptive actions that could be integrated into Sound Transit processes. The actions below solely represent potential options for action, and should not be perceived as an agency-endorsed work plan or agenda. Additionally, the information below is an initial analysis and should not be considered all-inclusive.

Transit Planning Objective and Process	Relevance to Climate Change	Agency Processes Related to Objective	Questions to Ensure that Climate Change is Considered in Objective	Potential Actions to Integrate Adaptive Thinking into Agency Process
1. Policy – set agency vision and priorities	Articulating a vision and associated priorities establishes planning for climate change as an integral component of agency processes.	• Board and administrative policies	• What are the agency's goals, objectives, and priorities for adapting to climate change? • How can the agency ensure that climate change risks and opportunities are being considered in agency processes? • How can the agency support staff needs related to climate adaptation? (e.g., provide/ ensure access to current information on climate impacts, training opportunities, etc.) • Do agency budgeting priorities and processes reflect agency priorities for climate adaptation?	• Create agency climate adaptation policy through an Executive Order or Board Resolution. • Develop an agency climate adaptation plan identifying how and where resilience will be strengthened. • Develop a set of climate adaptation planning and design guidelines that specify the climate change projections and decision parameters for evaluating climate impact risks and adaptation options (e.g., select low/medium/high values for sea-level rise, temperature, precipitation intensity, etc. to be used in risk assessment and planning). Establish required frequency of guidance updates and Determine how to best distribute guidelines to appropriate program areas and staff.

Table 5-1 (cont'd.) *Sound Transit Climate Change Integration Matrix*

Transit Planning Objective and Process	Relevance to Climate Change	Agency Processes Related to Objective	Questions to Ensure that Climate Change is Considered in Objective	Potential Actions to Integrate Adaptive Thinking into Agency Process
1. Participation in regional transportation planning efforts; Inter-governmental relations	Climate change impacts in the region will affect transportation-related decisions made by ST partner jurisdictions, partner agencies, and federal, state, and local government agencies. These decisions may directly impact ST and/or affect the environment in which ST operates.	• Partner service agreements • Strategic plan incorporation of Puget Sound Regional Council planning requirements • State and federal funding and grant agreements • ST planning requirements for partner jurisdictions • State and federal legislative advocacy • General engagement with Board of Directors • General engagement with local governments and the public	• Are partner agencies and jurisdictions: - Considering climate change impacts on their own communities or organizations? - Taking any adaptation actions? - Embedding considerations of adaptation actions into agreements with ST? • Are staff aware of available technical resources and/or approved adaptation strategies from partners? • What are the key messages about ST's actions on climate adaptation that the agency wants to communicate to the public, partner agencies, and others? • How and where does ST want to communicate these priorities and objectives?	• Add relevant questions/criteria regarding climate adaptation to appropriate planning processes (Environmental Impact Statements, Alternatives Analysis evaluations, interlocal agreements, etc). • Survey partner agencies regarding current climate adaptation priorities and activities. • Develop messages to communicate ST actions on climate adaptation. • Contribute to regional policies related to preparing for climate change. • Where relevant, help stimulate regional action that raises awareness, develops regional policies related to adaptation, and leverages resources among partners to address larger climate change adaptation policy/information needs. • Brief government relations staff about the agency's potential climate vulnerabilities.
1. Environmental Review	Climate impacts may affect the range of environmental and public health issues ST is required to assess when completing Environmental Assessment and Environmental Impact Statements.	• Environmental Assessments • Environmental Impact Statements • Environmental review for retrofit/small works projects	• Is evaluation of climate change impacts included in the scope of relevant environmental analyses conducted by staff and consultants? • What climate impacts are relevant to environmental evaluations?	• Develop guidelines and questions for how and when to include assessment of climate change impacts in internal and externally-contracted Sound Transit environmental reviews. • Develop guidelines and questions for assessing climate change impacts in specific chapters of National and State Environmental Policy Act (NEPA/SEPA) analyses. • Brief environmental review staff about the agency's potential climate vulnerabilities.

Table 5-1 (cont'd.) *Sound Transit Climate Change Integration Matrix*

Transit Planning Objective and Process	Relevance to Climate Change	Agency Processes Related to Objective	Questions to Ensure that Climate Change is Considered in Objective	Potential Actions to Integrate Adaptive Thinking into Agency Process
I. Strategic Planning	Larger-scale climate change impacts such as flooding and sea-level rise could influence choices about which regional centers to connect, or raise additional issues that would need to be addressed if service is extended to affected areas.	• Long Range Plan (Update in 2014/15) objectives and evaluation metrics	• Do any of Sound Transit's existing objectives or evaluation metrics specifically address climate resilience? • Are Long-Range Plan objectives or evaluation metrics consistent with ensuring system resilience to climate change impacts? • Are any of the regional centers identified for connection particularly vulnerable to specific climate change impacts? • Do any of the regional centers have plans to address climate change impacts that could influence long-range plan objectives or that should be considered in developing objectives?	• Integrate climate adaptation considerations into Long-Range Plan objectives and evaluation metrics. • Brief planning and project development staff about the agency's potential climate vulnerabilities.
I. System Planning (subset of Long Range Planning)	Climate change impacts could affect how the agency identifies travel corridors for high capacity transit (route and technology alternatives) and other facility, maintenance and access needs.	• System/corridor studies	• How do potential climate impacts affect: - The proposed corridor? - The areas in a corridor that will be served? - The type of transportation technology chosen for a particular corridor? - The selection criteria used to evaluate alternatives? - The combination of routes and technologies included in the alternatives analysis? - The selection criteria used to evaluate alternatives?	• Ensure that project scoping evaluates climate change impacts. • Develop selection criteria that minimize or reduce system exposure to climate change impacts to the extent possible. • Brief planning and project development staff about the agency's potential climate vulnerabilities.

Table 5-1 (cont'd.) *Sound Transit Climate Change Integration Matrix*

Transit Planning Objective and Process	Relevance to Climate Change	Agency Processes Related to Objective	Questions to Ensure that Climate Change is Considered in Objective	Potential Actions to Integrate Adaptive Thinking into Agency Process
I. Preliminary Engineering and Final Design	Climate change impacts could influence a myriad of choices from structure orientation and design to materials and mechanical/ electrical/plumbing systems' selection.	• Value Engineering and risk workshops in conceptual engineering and preliminary engineering for alignment • Final design for stations and alignment	• What design choices are affected by climate impacts? Relevant climate impacts may include temperature, precipitation, flood risk, tidal and storm surge reach, and seepage rates. • Are the current design criteria for a specific component of the system adequate given projected changes in climate and the expected lifespan of the component? • Which adaptive options might be appropriate now (where warranted) or in the future for specific components of the system? For components that may need to be adapted in the future: - Do the current design choices provide flexibility to adapt the component in the future to expected climate change impacts? - If not, can additional flexibility be integrated into current design choices to allow for adaptive action in the future? • At what point do design criteria need to be altered to accommodate climate impacts?	• Identify potential climate impacts for discussion during design reviews, where applicable. • Identify design criteria and technical specifications that should be evaluated periodically to determine whether modifications are necessary to strengthen climate resilience. • Track design criteria modifications at other public agencies for climate resilience. Evaluate whether any of these changes should apply to ST criteria. • Brief engineering staff about the agency's potential climate vulnerabilities.
I. Construction	Climate change impacts could affect how project construction is approached at particular sites.	• Construction	• How could climate change impacts such as more extreme temperature and precipitation, increasing flood risk, higher tidal and storm surge reach, and higher seepage rates affect construction activities? These activities may include: - Demolition - Excavation - Stormwater management - Equipment storage during construction • Do current construction practices adequately address identified impacts? - If no, what additional changes are needed to reduce climate change impacts affecting construction activities?	• Identify which aspects of construction are potentially affected by climate change. • Where relevant, identify best management practices and other approaches to reducing climate change impacts that affect construction activities. • Where relevant, integrate those practices into construction specifications for contractor bids. • Brief construction staff about the agency's potential climate vulnerabilities.

Table 5-1 (cont'd.) *Sound Transit Climate Change Integration Matrix*

Transit Planning Objective and Process	Relevance to Climate Change	Agency Processes Related to Objective	Questions to Ensure that Climate Change is Considered in Objective	Potential Actions to Integrate Adaptive Thinking into Agency Process
I. Operations & Maintenance	Climate change could affect performance, safety, or reliability of the system. Factoring climate change into O&M can help ensure service objectives are being met.	• Standard Operating Procedures • Maintenance Implementation Plans • Procurement plans	• What climate impacts are relevant to different aspects of operations and maintenance? • Do those impacts require any changes in how operations and maintenance are *currently* conducted? - If yes, what are the necessary changes and where do those changes need to be documented for implementation? - If no, what steps are required to ensure that the need for changes is assessed on a periodic basis? • Are climate change projections included in the relevant operating procedures and plans? • Are there appropriate metrics for tracking climate impacts on operations and maintenance?	• Identify those aspects of O&M for modes, facilities, and other areas that may be affected by climate change. • Integrate appropriate metrics for tracking weather and climate impacts into reporting related to operations and maintenance. • Brief operations and maintenance staff about the agency's potential climate vulnerabilities.
I. Asset Management	Climate change could affect risk evaluations and capital improvements planning, including prioritization of activities. Asset management provides opportunity to monitor and track trends in climate impacts.	• 360 System (current) • Asset Works Asset Management System (Future) • Maintenance Management System (Future)	• Do asset surveys/catalogues monitor or note weather/climate related impacts? • How Can asset management planning cycles include consideration of the vulnerability and resilience of the transportation system to affected assets?	• Track weather related impacts to assets via 360/ Asset Works (add this as a field). • Periodically review climate impacts to determine if these have any impact on planned asset management planning cycles. • Brief asset management staff about the agency's potential climate vulnerabilities.

Table 5-1 (cont'd.) *Sound Transit Climate Change Integration Matrix*

Transit Planning Objective and Process	Relevance to Climate Change	Agency Processes Related to Objective	Questions to Ensure that Climate Change is Considered in Objective	Potential Actions to Integrate Adaptive Thinking into Agency Process
1. Environmental and Sustainability Management System (ESMS) Administration	Including climate change adaptation considerations in the ESMS would ensure that this is a criterion in determining agency priorities.	• Aspects Analysis (determining priorities) • Control Procedures – detailed procedures for how climate adaptation considerations are applied	• What are the agency's environmental impacts, regulatory requirements or other commitments related to climate change? How are we mitigating or meeting them and achieving continual improvement? • How are we communicating to and training staff on appropriate climate-related procedures and emergency response protocols? • How are we monitoring the agency's performance related to agency-adopted climate adaptation policies, goals and/or measures? • What are we doing to ensure continual improvement and establish corrective and preventive actions for potential deviations from agency climate-related commitments?	• Integrate climate change considerations into the ISO 14001 model of "Plan, Do, Check and Act" used by Sound Transit (see Appendix D for details). • Brief environmental program staff about the agency's potential climate vulnerabilities.
1. Real Estate Acquisition and Relinquishment of Assets	Climate change impacts may affect decision about which properties and assets to acquire or relinquish.	• Development agreements • Real estate acquisitions or assessments • Property valuation • Real estate disposition	• Were climate change impacts considered prior to investment decisions? • Do projected climate change impacts affect any decision to relinquish property? Could that property provide a needed adaptive capacity buffer?	• Educate staff regarding climate vulnerabilities and the types of impacts that could affect property acquisition and disposition. • Update real estate property disposition policy to include consideration of climate change impacts in decisions related to disposition of property.
1. Emergency Preparedness, Response, and Recovery	Climate change may affect the frequency, intensity, location, or duration of events included in emergency planning activities.	• Safety guidelines for the Design Criteria Manual • Inclement weather plans • Disaster preparedness • Annual safety drills	• Are there any design related safety issues that need periodic updating in the Design Criteria Manual? • Are there any other weather or climate related issues that should be considered for future inclement weather related plans?	• Brief emergency management staff about the agency's potential climate vulnerabilities. • Update emergency management plans to recognize the potential for climate change to affect the frequency, intensity, location, or duration of events.

SECTION 6

Conclusion and Next Steps

The Sound Transit Climate Risk Reduction Project involved a systematic evaluation of potential:

- climate change impacts on Sound Transit operations, assets, and long-term planning
- options for strengthening the agency's climate resilience
- opportunities for integrating climate change considerations into agency decision making processes

The project identified a variety of ways that climate change may affect Sound Transit services. Overall, climate change is likely to have minor to moderate impacts on many Sound Transit services. More significant impacts are possible if higher rates of sea-level rise and mudslide activity occur.

Sound Transit has many things working in its favor as the agency plans, constructs, and delivers transit services in a changing climate.

- The Sound Transit system is young relative to most major urban transit agencies. Current services began between 1999 and 2009 depending on the service, with several planned expansions scheduled to open between 2016 and 2023. As a result, the system generally reflects the latest in design and construction standards and has few long-term legacy issues.
- Sound Transit has some degree of buffer against specific climate change impacts built into some infrastructure decisions, at least in the near term. For example, the agency's OCS wire temperature thresholds are high for this region and extensive use of auto-tension OCS allows for above average temperatures to affect the OCS wires without interrupting service or requiring manual adjustment.
- Sound Transit has institutionalized review of system performance and adequacy of design standards as the system undergoes expansion. Annual updates to design criteria and value engineering programs help provide an adaptive learning framework with opportunities for adjustment and integration of adaptation strategies into decision making.
- Sound Transit is an organization already comfortable with defining risk and managing uncertainty. Although climate change brings new considerations into risk management activities, the agency's experience with risk management may reduce some of the challenges associated with making decisions about if, when, and how to adapt.

- Sound Transit has systems in place for regular dialogue with transit partners and local communities. These create opportunities for sharing information on climate change impacts and adaptation.

Ultimately, this report provides guidance on the climate change adaptation issues Sound Transit may want to address in the future. The following are recommended "next steps" for beginning to build adaptive capacity within Sound Transit and integrating climate change considerations into decision making at the agency:

- *Disseminate Project Findings*. To help build awareness of the project's results within the agency and maximize its value as a template for use by transit agencies nationally, the project team will:
  - Provide project materials to the public via the FTA's Transit Climate Adaptation Pilot web page.
  - Brief Sound Transit leadership and staff, as well as peer agency leadership, regarding the project's main findings.
  - Develop periodic briefings for agency technical staff regarding climate science and potential climate impacts for the region.
  - Share project findings with national peer groups, such as the Public Transportation Association (APTA) Sustainability Committee, Climate Preparedness Learning & Adaptation Network (CPLAN) and other similar outlets.
- *Prioritize next steps to address the report's major findings*. To ensure that the project's findings remain relevant to Sound Transit's planning, design, construction and operations activities, the project team will work with staff to develop a formal set of recommendations outlining steps the agency should take to address the report's major findings. These next steps may include, but are not limited to:
  - Continue working with service partners and partner jurisdictions to monitor climate change impacts as related to Sound Transit services.
  - Continue working with regional partners to identify further areas of research to better understand climate impacts affecting Sound Transit.
  - Identify the climate adaptation considerations that could be integrated into agency processes in the near -term.
  - Provide guidance on when Sound Transit might consider developing a Climate Adaptation Plan and what the scope of such a plan should include.

In pursuing these near-term actions, Sound Transit will begin to formally address adaptation and integration opportunities to strengthen the agency's resilience to climate change.

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APPENDICES

The following appendices include more information on specific aspects of the Sound Transit Climate Risk Reduction Project. Appendices are listed in order of relevance to report sections.

APPENDIX

A

Projected Changes in Key Drivers of Climate Change Impacts in Puget Sound: An Overview

White paper prepared for Sound Transit by the University of Washington Climate Impacts Group

Projected Changes in Key Drivers of Climate Change Impacts in Puget Sound: *An Overview*

White Paper Prepared for Sound Transit for the Sound Transit Climate Risk Reduction Project

August 23, 2013

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About This Paper

This white paper was produced by the Climate Impacts Group at the University of Washington to support vulnerability assessment and adaptation planning workshops held as part of the Sound Transit Climate Risk Reduction Project. The purpose of this document is to provide a general overview of changes in key drivers of climate impacts in the Puget Sound region that are relevant to Sound Transit operations and planning. The document should not be considered a complete synthesis of regional climate impacts. For more on climate change impacts, contact the Climate Impacts Group (www.cses.washington.edu/cig).

1. Introduction

Climate impacts on transit systems are widespread and can lead to potentially significant service disruptions and damage to physical infrastructure. Nationally and regionally documented climate impacts on transportation systems include flooding of low-lying roads and damage to bridge supports, closure of subway tunnels due to localized flooding from extreme precipitation events, landslides onto rail lines and roads utilized by transit agencies, higher electricity prices for power during droughts, overheated electrical equipment, lengthening of catenary wires, rail and pavement buckling due to extreme heat, increased maintenance needs for air conditioning, impacts on construction schedules associated with extreme heat events, and reduced rider access to facilities and services.[1] Projected changes in 21st century climate suggest that these impacts may become more common and/or more severe absent efforts to prepare for a changing climate.

In February 2012, Sound Transit launched an 18-month project funded by the Federal Transit Administration aimed at identifying climate change risks to operations and planning, and options for reducing those risks. This paper was developed for use by Sound Transit and partner agency staff participating in the project. The paper begins with a description of major modes of natural variability that influence Pacific Northwest (PNW) climate on seasonal to annual time scales. The remainder of the paper provides an overview of projected changes in key drivers of climate change impacts in the Puget Sound region. These include changes in:

- temperature,
- precipitation,
- streamflows (including extreme high and low flows), and
- sea level rise.

The potential impacts associated with changes in these key drivers were evaluated by Sound Transit during project workshops.

Note that these projections are based on assumptions about future GHG emissions and global climate models that are updated over time.[2] The next major update of the global climate scenarios used for projecting changes in regional climate is scheduled for release in Fall 2013. Past experience shows that climate change scenario updates often produce slightly different numeric values but do not alter the anticipated direction of change.

2. Climate Variability

PNW climate varies from year to year and decade to decade, with some years (decades) having warmer and drier than average winters, and some years (decades) having cooler and wetter than average winters. This natural variability is likely to persist into the future, affecting the PNW along with the long-term global warming trend.

Climate variability in the PNW is largely governed by two large-scale oceanic and atmospheric patterns that occur in and over the Pacific Ocean. The first pattern is the El Niño Southern

[1] Hodges et al. 2011, Hamlet 2011, TRB 2008
[2] More specifically, the projections described in this paper are based on a subset of up to 20 CMIP3 global climate models used to produce global climate change scenarios and data sets as part of the Intergovernmental Panel on Climate Change's 4th Assessment Report, released in 2007 (http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml)

Oscillation (ENSO), which refers to a recurring pattern of sea surface temperatures in the equatorial Pacific that affects global climate on an annual basis. Warm phases of the ENSO cycle are called El Niño and cool phases of ENSO are known as La Niña. Each ENSO phase lasts for a few months to a year (Figure 1, top), typically peaking between December and April.

The second major pattern of natural variability affecting PNW climate is the Pacific Decadal Oscillation (PDO). The PDO is also characterized by warm and cool phases, but unlike ENSO, the PDO is based in the North Pacific and the cool/warm phases tend to persist for 10 to 30 years (Figure 1, bottom). Table 1 provides a breakdown of individual years by ENSO and PDO since 1990.

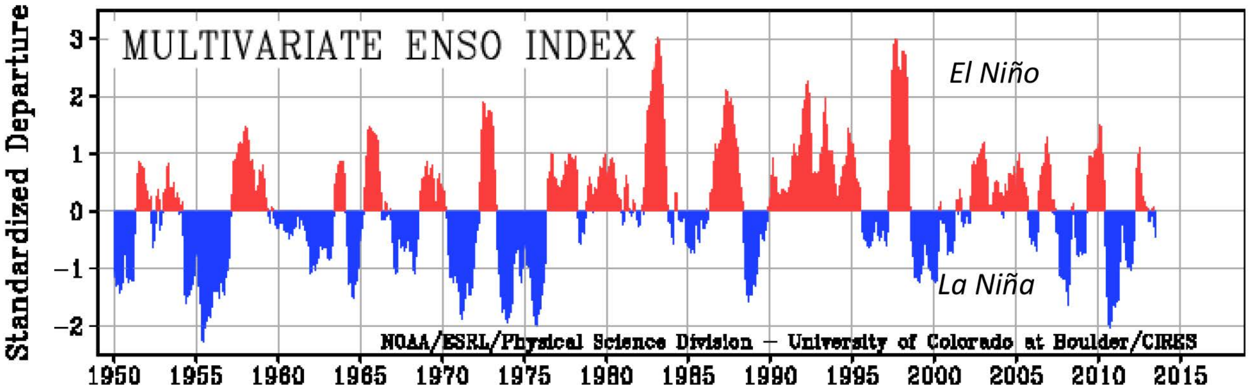
El Niño and warm phase PDO increase the odds for (but do not guarantee) above average annual temperatures and drier winters in the PNW. La Niña and cool phase PDO increase the odds for below average annual temperatures and wetter winters. When ENSO and PDO are in the same phase (i.e., during a year that is both El Niño *and* warm phase PDO or La Niña *and* cool phase PDO), the impact on PNW climate is typically larger. If the ENSO and PDO patterns are in opposite phases, their effects on temperature and precipitation may offset each other to some degree.

How (and whether) ENSO and PDO will change in the future as a result of climate change remain open questions. Some studies suggest that climate change may cause a persistence of El Niño conditions in the equatorial Pacific, although the reasons remain uncertain.[3] Despite this uncertainty, we expect ENSO and PDO to continue influencing PNW climate in the coming decades. For example, if PDO were to persist in its cool phase for another decade or so, the long-term global warming trend could be masked in the PNW, leading to smaller near-term changes and the possibility of more sudden, significant, or "surprising" changes when it returns to warm phase conditions.

Table 1. ENSO/PDO conditions since 1990. A complete listing of years dating back to 1900 is available at http://cses.washington.edu/cig/pnwc/compensopdo.shtml.

		Cool phase (negative) PDO: 1900-1924, 1947-1976, 1999-2002, 2006-present	**Warm phase (positive) PDO:** 1925-1946, 1977-1998, 2003-2005
ENSO Phase	La Niña (cool)	1999, 2000, 2008, 2011, 2012	*(no La Niña/warm phase PDO events between 1990-2012)*
	ENSO Neutral	1990, 2002, 2006, 2009	1994, 1996, 1997, 2001
	El Niño (warm)	1991, 1995, 2007	1992, 1993, 1998, 2003, 2004, 2005, 2010

[3] Collins 2005, Trenberth and Hoar 1997



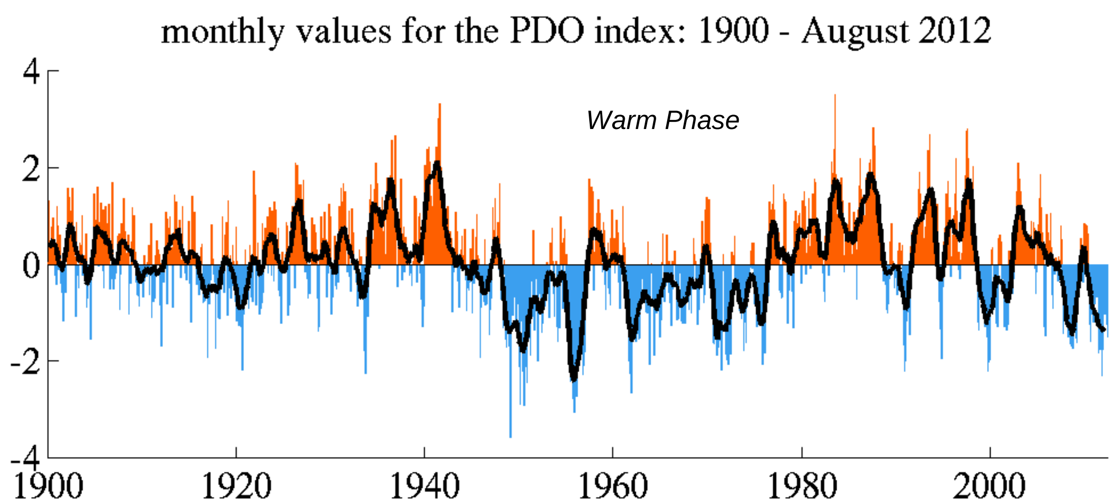


Figure 1. The ENSO Index (Top) from 1950–August 2013 and the PDO Monthly Index (Bottom) from 1900–Aug 2012. The positive (red) index values represent warm events (i.e., El Niño and warm phase PDO) and the negative (blue) indices represent cool events (i.e., La Niña and cool phase PDO). *Figure sources: NOAA[4], Climate Impacts Group[5].*

4 http://www.esrl.noaa.gov/psd/enso/mei/
5 http://cses.washington.edu/cig/pnwc/aboutpdo.shtml

3. Climate Change

Observed global warming since the mid-20th century is very likely due to human activities. PNW climate has changed in ways that are consistent with longer term global warming trends, i.e., increasing temperatures, decreasing snowpack and earlier peak streamflow. In the short-term, these changes have been obscured or even reversed by natural climate variability.

Naturally occurring greenhouse gases, including carbon dioxide, methane, and nitrous oxide, play a large role in moderating the Earth's climate by trapping outgoing energy and heating the atmosphere. Since the start of the Industrial Revolution (c. 1750), the concentration of greenhouse gases in the atmosphere has risen sharply due to rapid increases in fossil fuel combustion and other greenhouse gas-emitting activities. These emissions also contributed to the rise in average global temperature observed since the late 1800s (Figure 2). Most of the observed warming in globally averaged temperatures since the mid-20th century has been attributed[6] to human-caused increases in atmospheric greenhouse gas concentrations.[7]

Climate in the PNW has also changed, producing impacts that are consistent with warming and observed changes in other parts of the world. For example, PNW average annual temperature rose 1.5°F between 1920 and 2000, annual snowpack accumulation declined in the last half of the 20th century, and the timing of peak streamflow – which is closely linked to snowmelt – shifted earlier in the year. [8]

Although natural variability has played a role in these trends, the trends cannot be fully explained by ENSO and PDO. Natural variability has strongly influenced PNW climate on shorter timescales, causing shorter term *decreases* in temperature and *increases* in snowpack during various times during the last century. Long-term warming associated with climate change is likely to have played a role in 20th century PNW climate trends, although quantifying specifically how much so is not possible at this point.[9]

[6] With more than 90% likelihood.
[7] IPCC 2007
[8] Mote 2003, Hamlet et al. 2007, Barnett et al. 2008, Bonfils et al. 2008, Casola et al. 2009, Hidalgo et al. 2009, Pierce et al. 2008, Stewart et al. 2005
[9] Quantifying (or "attributing") the influence of human-caused climate change on trends in temperature and other climate-sensitive indicators is easier to do over large geographic areas than small areas. The contribution of human activities has been quantified for observed changes at the global scale, continental scale, and scales as "small" as the western United States. In the western U.S., research has quantified the contribution of human-caused climate change to observed increases in temperature, decreases in snowpack, and shifts toward earlier peak streamflows (Bonfils et al. 2008, Hidalgo et al. 2009, Pierce et al. 2008).

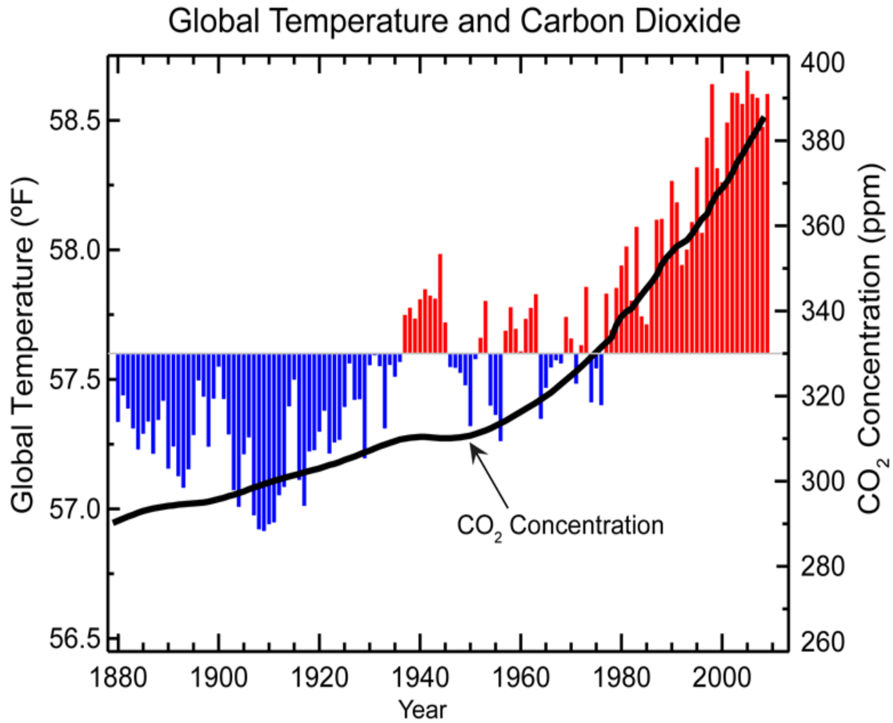


Figure 2. Global Average Temperature and Atmospheric Carbon Dioxide (CO_2) Concentrations, 1880-2010. Average annual temperatures globally have increased by 1.3°F since 1906 (IPCC 2007) and the past decade has been the warmest on record. Red (blue) bars indicate temperatures above (below) the 1901-2000 average temperature. The black line shows atmospheric CO_2 concentration in parts per million. *Figure source: NOAA – NCDC.*[10]

3.1. Projecting Future Climate

Estimates of future changes in global climate rely on assumptions, or scenarios, of future human activities and their associated greenhouse gas emissions. Global temperatures are projected to increase under all scenarios of future emissions.

Projecting changes in 21st century climate requires the use of global climate models and scenarios of future greenhouse gas emissions, which incorporate assumptions about future changes in global population, technological advances, and other factors that influence the amount of carbon dioxide and other greenhouse gases emitted into the atmosphere as a result of human activities. The research summarized in this paper is based on a subset of greenhouse gas emissions scenarios used by researchers globally to evaluate future climate and climate change impacts (Table 2).

[10] http://www.ncdc.noaa.gov/indicators/

Table 2. Description of Greenhouse Gas Emissions Scenarios Used in Studies Summarized in This Report. The emissions scenarios were developed in 2000 by the Intergovernmental Panel on Climate Change. The qualitative (e.g., "moderate", "high") descriptions are based on projected greenhouse gas emission levels in 2100; scenario ranking will vary through the century. Table adapted from IPCC 2007.[11]

Scenario	Description
B1	*Low greenhouse gas emissions scenario:* Global population peaks mid-21st century at 9 million then declines. Economic growth favors a service and information economy with reductions in material consumption and resource-efficient technologies.
A1B	*Moderate greenhouse gas emissions scenario:* Assumes rapid economic growth. Global population peaks in mid-21st century at 9 million then declines. Rapid introduction of more efficient energy technologies after 2050. Although a moderate scenario by end of century, A1B has the highest emissions through 2050.
A2	*High greenhouse gas emissions scenario:* Regionally distinct development worldwide, with slow continuous population growth. Economic growth and technological change is slow and fragmented.
A1FI	*Highest greenhouse gas emissions scenario:* Same assumptions as the A1B scenario but assumes continued reliance on fossil fuel intensive energy technologies.

The question of which scenario is most likely remains unanswered – the creators of the greenhouse gas emissions scenarios did not assign probabilities to the various scenarios. However, the B1 scenario is increasingly unlikely based on current trends in greenhouse emissions, which are within the range of the highest emission scenarios for the early 21st century, and lack of progress towards meaningful reduction in global greenhouse gas emissions.

Scenarios with a range of greenhouse gas emissions result in a range of projected changes in global temperature, precipitation, and other climate-related variables important for the PNW. Average annual global temperature is currently projected to increase 3.2°F-7.2°F by 2100 compared to the average for 1980-1999 (Figure 3).[12] Even if all human-related greenhouse gas emissions were completely halted today, the Earth would continue to warm by about 1.1°F through the 21st century due to the long-lived nature of carbon dioxide and many other greenhouse gases.[13]

[11] http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf
[12] IPCC 2007.
[13] *Idem*

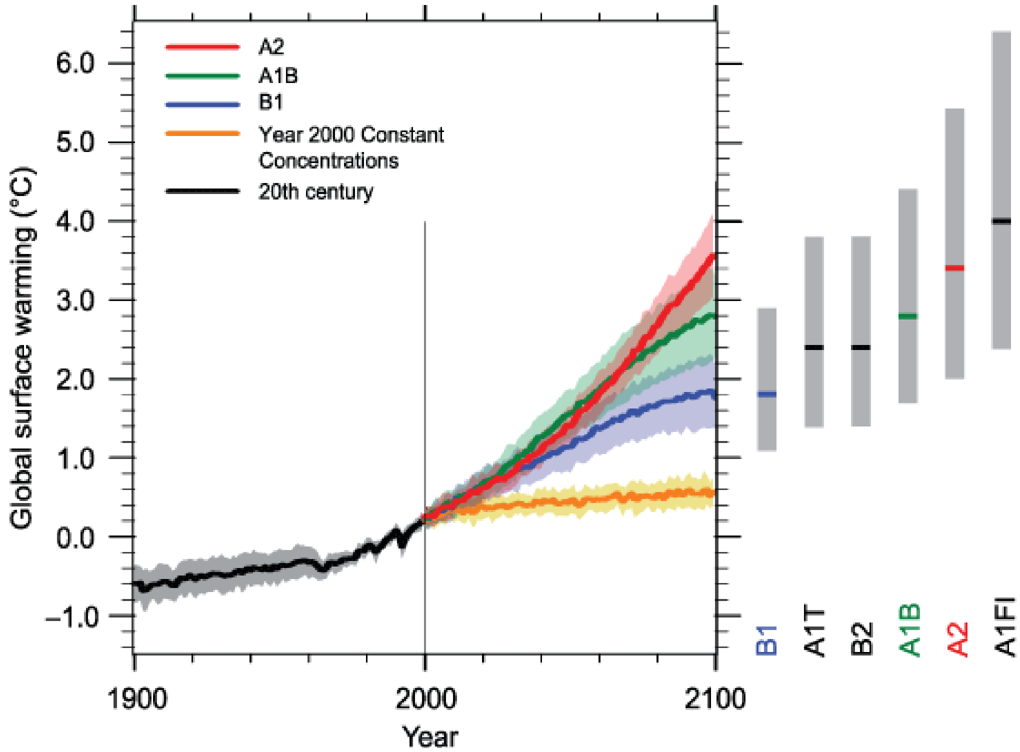


Figure 3. Average Increases in Global Temperature Projections for Different Greenhouse Gas (GHG) Emissions Scenarios. Solid colored lines represent multi-model averages of warming (compared to 1980-1999 baseline). The orange line is for the experiment where atmospheric GHG concentrations were held constant at year 2000 values. Colored shading indicates the range of ±1 standard deviation of individual global climate model annual averages. Gray bars to the right of the plot represent the best estimates for each GHG scenario (colored line), with the likely (>66% chance) range shown by the bars. *Figure source: IPCC 2007.*

3.2. Projected Increases in PNW Temperature

The PNW is projected to warm under all emissions scenarios, both on an annual average basis and in all seasons. The Puget Sound region is expected to experience more frequent and intense extreme heat events in the future.

3.2.1. Average Annual and Seasonal Temperatures

The PNW is projected to warm under all 39 scenarios evaluated in Mote and Salathé 2010. Average annual and seasonal temperatures in the PNW are projected to increase through the 21st century for both the moderate (A1B) and low (B1) greenhouse gas emissions scenarios (Table 3, Figure 4).[14] Warming is projected to occur in all seasons with the greatest increases occurring during the summer months. By the mid-21st century, projected increases in average annual temperature are expected to exceed the 20th century's range of natural variability attributable, in part, to ENSO and PDO.

[14] Mote and Salathé 2010

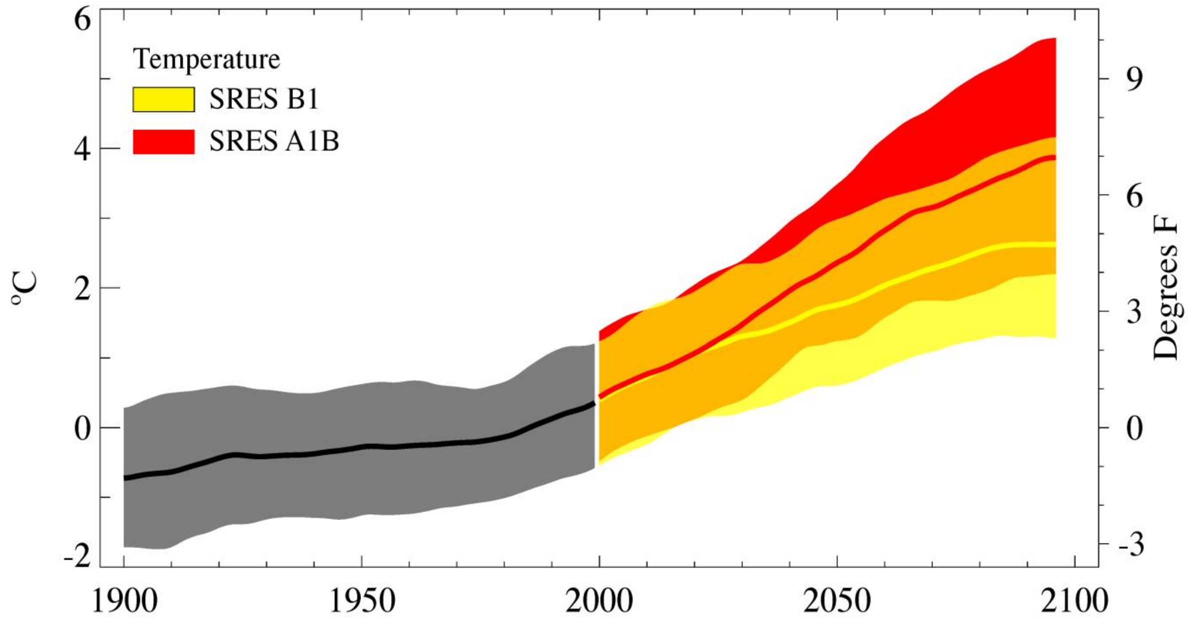


Figure 4. Projected 21st Century PNW Annual Temperature Increases Compared to the Historical Baseline (1970-1999). Solid lines represent the mean projections from 20 global climate models for the historical (black), the B1 (yellow) and A1B (red) future emissions scenarios (39 model scenarios total). Colored swathes around the means show the range of temperature projections, represented by the 5th to 95th percentiles. F*igure source: Mote and Salathé 2010.*

Table 3. Projected Changes in Average Annual and Seasonal PNW Temperature (with Range), in Degrees Fahrenheit. All changes are relative to 1970-1999. *Source: Mote and Salathé 2010.*

Period	Annual	June-August	December-February
2020s	+2°F (1.1° to 3.4° F)	+2.7°F (1.0 to 5.3°F)	+2.1°F (0.7 to 3.6°F)
2040s	+3.2°F (1.6° to 5.2° F)	+4.1°F (1.5 to 7.9°F)	+3.2°F (1.0 to 5.1°F)
2080s	+5.3°F (2.8° to 9.7° F)	+6.8°F (2.6 to 12.5°F)	+5.4°F (1.3 to 9.1°F)

Although we do not yet know how ENSO and PDO will change as a result of climate change, natural variability will continue to influence PNW climate in the 21st century. Consequently, the region will continue to see both years and seasons that are warmer or cooler than average. Because of climate change, however, the long-term average around which annual and seasonal temperatures vary will increase, even to the point at which even both below average temperatures are warmer than those typically experienced in the 20th century.

3.2.2. Extreme Heat

Regional climate models indicate that the Puget Sound region is expected to experience more frequent and intense extreme heat events in the future (Jackson et al 2010, Salathé et al. 2010). Under both low (B1) and moderate (A1B) emissions scenarios, the frequency of extreme heat events in the Seattle metropolitan area—that is, days warmer than 99% of days in the historical period[15]—is projected to increase through the 21st century compared to the 1980-2006 historical baseline (Figure 5). The average and maximum durations of these events are also projected to increase. Some of the changes could be substantial: under the high warming scenario the maximum number of consecutive days in the Seattle metropolitan area above the extreme heat event threshold of 92.5°F increased from six days historically to 57 days in the 2080s.[16]

3.3. Projected Changes in PNW Precipitation

Little change in average annual precipitation is expected, although changes in seasonal precipitation could be more significant. More extreme precipitation is expected. However, challenges in modeling extreme precipitation make it difficult to know if the projected changes are statistically significant from past variability.

3.3.1. Average Annual and Seasonal Precipitation

Modest changes in average annual precipitation are projected in the 21st century when averaged across scenarios (Figure 6; Table 4), although individual scenarios produce larger changes.[17] Average annual precipitation is projected to increase 1-2% by mid-century and 4% by the 2080s.

Seasonal changes are likely to be greater. The majority of global climate models (50-80% depending on the decade and emissions scenario) project increases in winter (December-February) precipitation. Some increases are as large as +42% by the 2080s. Model agreement is even greater for changes in summer precipitation; 68-90% of the global climate models, depending on the decade and emissions scenario, project decreases in summer (June-August) precipitation.[18]

The range of projected changes for PNW precipitation is greater than those associated with projected temperature due to the wide range of natural variability in regional precipitation. This makes it more difficult to "see" with statistical certainty when climate change pushes

[15] In this study an "extreme heat event" was defined as the 99th percentile daily maximum May-September temperature over the period 1980 to 2006. For Seattle, this threshold is 92.5°F. The 99th percentile daily maximum temperature is the average daily maximum temperature that is warmer than 99% of average daily maximum temperatures for a defined period.
[16] Jackson et al. 2010
[17] Mote and Salathé 2010
[18] *Idem*

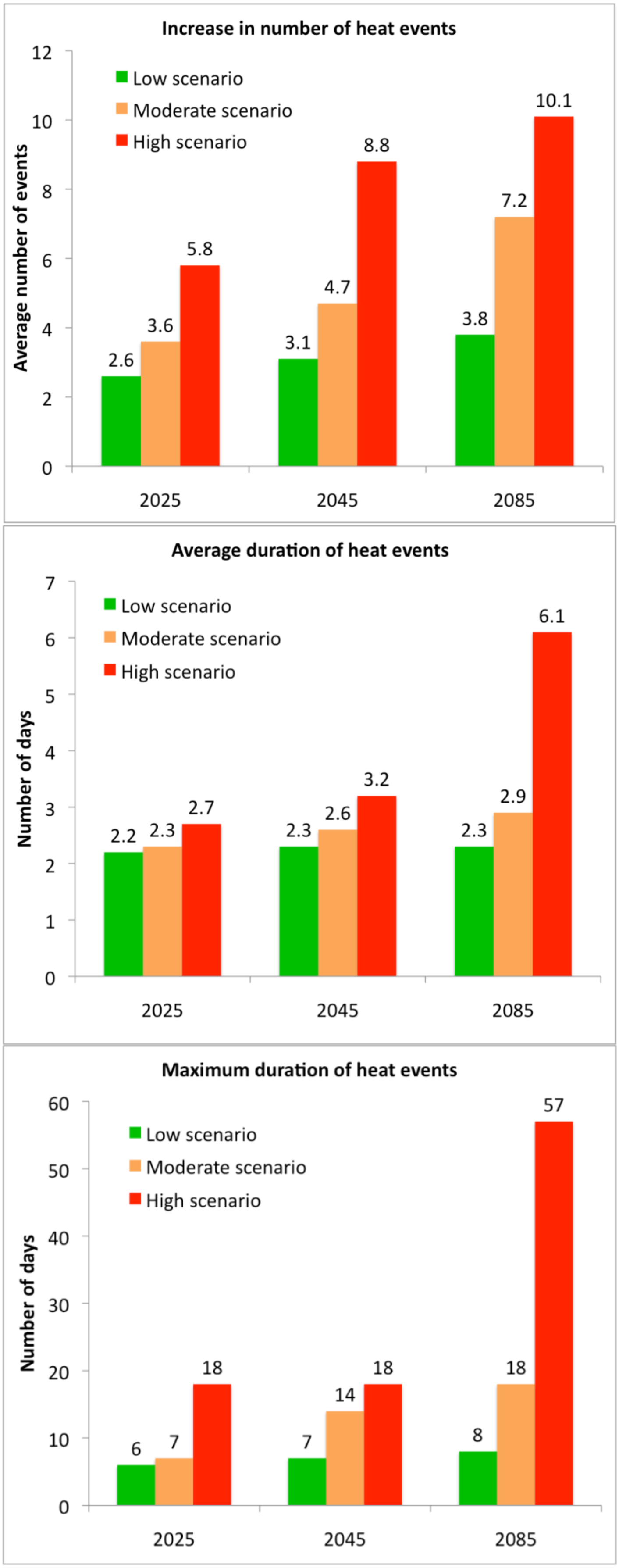


Figure 5. Projected Increase in the Frequency (Top), Average Duration (Middle), and Maximum Duration (Bottom) of Extreme Heat Events in the Seattle Area for Three Future Time Periods. Projections relative to the historical baseline (1980-2006) for the average frequency (1.7 events), average duration (2.2 days) and maximum duration (6 days) of heat events (temperatures above 92.5°F). *Figure source: Climate Impacts Group, based on Jackson et al. 2010.*

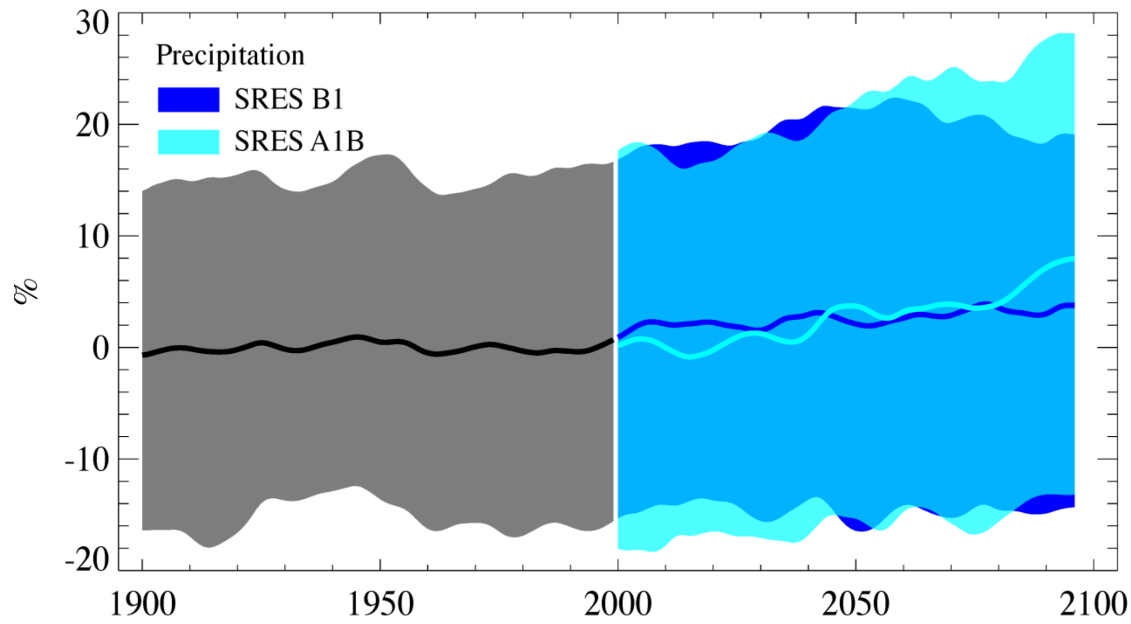


Figure 6. **Projections of Percent Change In Precipitation for the 21st Century Compared to Historical Conditions (1970 – 1999).** Solid lines represent the percent change in the mean of downscaled projections averaged over 20 global climate models (GCMs) for the historical (black), the B1 (light blue) and A1B (dark blue) future emissions scenarios. Colored swathes show the range of GCM projections, represented by the 5th to 95th percentiles. *Figure source: Mote and Salathé 2010.*

Table 4. Projected Changes in Average PNW Precipitation (with Range), in Percent. All changes are relative to 1970-1999. *Source: Mote and Salathé 2010.*

Period	Annual	June-August	December-February
2020s	+1% (-9 to 12%)	-6% (-30% to +12%)	+2% (-14% to +23%)
2040s	+2% (-11 to +12%)	-8% (-30% to +17%)	+3% (-13% to +27%)
2080s	+4% (-10 to +20%)	-13% (-38% to +14%)	+8% (-11% to +42%)

precipitation beyond what we would expect from natural variability. An additional challenge is determining how dominant modes of natural variability may be affected by climate change. Despite these challenges, it is certain that the region will continue to see both very wet years and very dry years in the future due to natural variability.

3.3.1. Extreme Precipitation

Historical records of Puget Sound precipitation indicate that the amount of rainfall associated with extreme precipitation events has increased over time[19], although proving statistical significance is difficult given the small sample size for historical extreme precipitation events.

The 24-hour duration of an extreme precipitation event with a 50-year return interval (i.e., a 24-hour rainfall event with a 1-in-50, or 2%, chance of occurring in any given year) as measured at SeaTac Airport was six times more likely in 1981-2005 than in 1956-1980.[20] This represents a shift in the 1-in-50 year (2% probability) event to a 1-in-8.4 year (12% probability) event. All of the return periods for the 1-hour and 24-hour precipitation events analyzed for SeaTac in Rosenberg et al. 2010 (i.e., the 2, 5, 10, 25, and 50 year return periods) decreased, although none of the changes were found to be statistically significant at the scientifically rigorous 95% confidence interval. This makes it difficult to conclude if the shift in probability is a real shift in the record or the result of sampling.

Projections for the amount of precipitation associated with heavy events and the specific location of such events in Washington State vary depending on the choice of global climate model simulations and emissions scenarios. Nonetheless, regional climate models generally agree that the amount of rainfall during extreme events is expected to increase for western Washington in winter.[21] The magnitude of the 24-hour and 2-day precipitation events shows a statistically significant increase for 2020-2050 compared to 1970-2000 in two regional climate models run with moderate (A1B) and high (A2) greenhouse emissions scenarios (Table 5).[22] Both models runs also projected increases in the 5- and 10-day storm events but not at a statistically significant level.

Table 5. Projected Increase in Extreme Precipitation Events at SeaTac Airport, 2020-2050, Relative to 1970-2000. *Data source: Rosenberg et al. 2010.*

Extreme precipitation event	*CCSM model/ A2 scenario*	*ECHAM5 model/ A1B scenario*
24-hour	+28.7%	+14.1%
2-day	+24%	+14.1%

[19] Kunkel et al. 2003, Rosenberg et al. 2010, Mass et al. 2011
[20] Rosenberg et al. 2010
[21] Salathé et al. 2010, Rosenberg et al. 2010
[22] Rosenberg et al. 2010, Table 10

Many instances of extreme precipitation events and winter flooding in the PNW have been linked to a weather phenomenon known as "atmospheric rivers", often referred to as "pineapple expresses."[23] Atmospheric rivers are narrow bands of enhanced water vapor content in the atmosphere that originate in warmer latitudes over the Pacific Ocean and stretch towards the U.S. west coast (Figure 7).[24] Warming associated with climate change could lengthen the atmospheric river season and increase the intensity of extreme precipitation events associated with atmospheric rivers due to the fact that higher temperatures increase the capacity for the atmosphere to retain more water.[25]

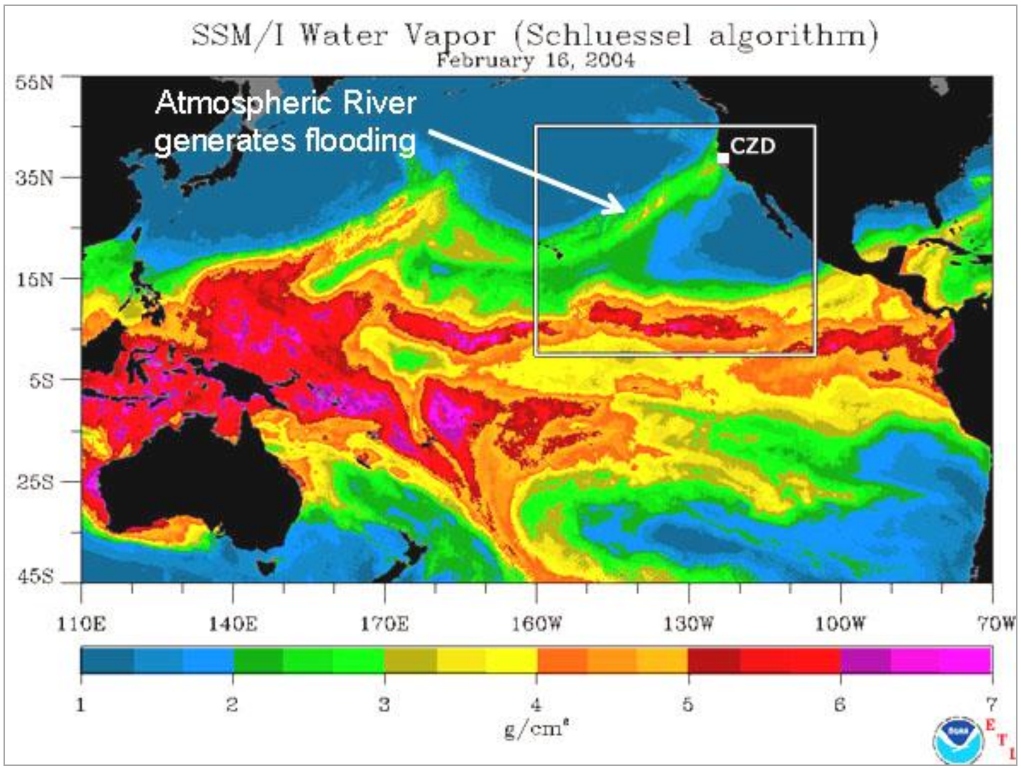


Figure 7. Visual Image of an Atmospheric River. *Figure source: NOAA* [26]

The projected changes in extreme events presented here should be considered good indicators of the likely direction and general magnitude of changes in extreme precipitation, rather than specific predictors of change, for the following reasons:

- These analyses of historical and projected extreme precipitation events are not synonymous with storm events. An analysis that includes storminess would have to factor in precipitation intensity as well as concurrent wind speed and direction, which are not yet well resolved by climate models.

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[23] Neiman et al. 2008, Ralph et al. 2006
[24] Ralph et al. 2004
[25] Trenberth 2011, Dettinger 2011, Leung and Qian 2009
[26] http://www.noaanews.noaa.gov/stories2005/s2529.htm

- Projecting changes in extreme precipitation is a challenge given that most extreme events tend to be concentrated on very small spatial scales, which are not well represented in global climate models.
- Demands on the computational capacity required to run multiple greenhouse gas emission scenarios through fine-scale regional climate models are very high.[27]

Ongoing regional climate modeling work at the Climate Impacts Group and elsewhere in the region is aimed at improving projections of these important events.

3.4. Projected Changes in Puget Sound Hydrology

Climate change will alter the amount and timing of streamflow in many Puget Sound watersheds, increasing the risk of flooding in the winter and lengthening the low-flow summer period.

Increases in temperature and precipitation associated with climate change are projected to shift both the magnitude and timing of streamflow in many Puget Sound watersheds. The specifics of those changes will vary by watershed type and river. The two dominant types of watersheds in the central Puget Sound region are rain dominant and transient (rain/snow mix) basins. A third hydrologic basin type, snow-dominant basins, is found outside the Sound Transit service area in colder, high elevation basins like the Skagit and North Cascade watersheds. Snow-dominant basins are not discussed in this paper.

Rain Dominant Basins
Rain dominant basins are low elevation basins where average winter temperatures typically remain above freezing and little if any snow accumulates in the basin. Because most precipitation falls as rain in these basins, the highest streamflows occur during the fall and winter, when 70% of the region's annual precipitation falls. Streamflows gradually diminish during the spring and are lowest during the summer dry season. Examples of major rain dominant basins include the Chehalis and Nisqually basins; other smaller low elevation rivers (e.g., the Sammamish River) and creeks are also considered rain dominant.

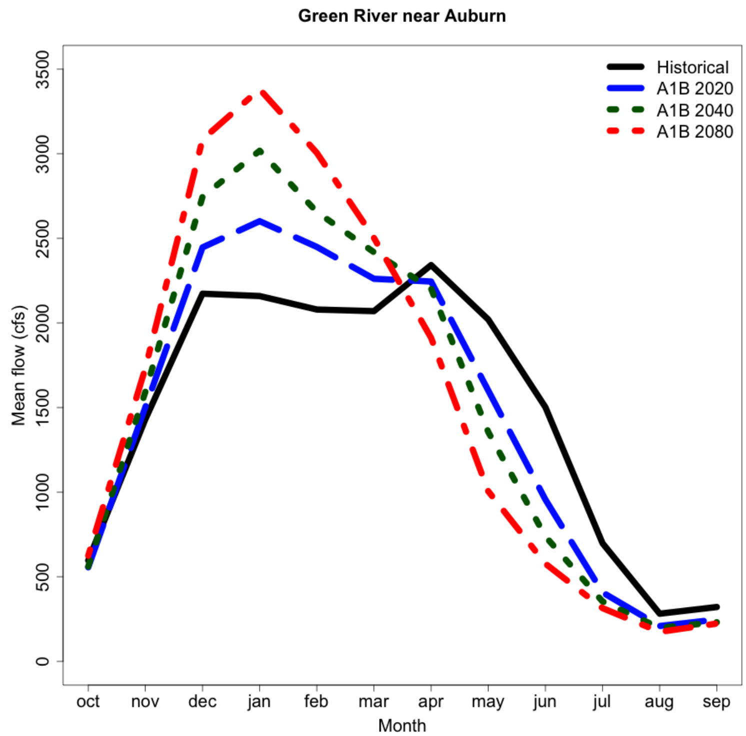
The impacts of projected warming on rain dominant basins are likely to be modest. Winter streamflow is likely to increase given projected increases in winter precipitation; the size of the increase depends in part on how much wetter PNW winters become. Summer streamflows are projected to decrease due to increased evaporative loss from warmer temperatures.

Transient Basins
Transient basins, also known as rain/snow mix basins, are mid-elevation watersheds where average winter temperatures are typically just below freezing. Transient basins have two periods of relatively high streamflows (see black lines in Figure 8). The first period is during late fall/early winter when temperatures are still warm enough for most precipitation to fall as rain. By mid-winter, upper basin temperatures are typically low enough for precipitation to fall predominantly as snow. As a result, winter streamflows drop. Peak streamflows occur during spring when warmer temperatures melt the snow stored in the cooler upper reaches of the basin. Examples of transient basins in the Central Puget Sound region include the Green, White, Cedar, and Snohomish River basins.

[27] Rosenberg et al. 2010

Climate impacts on streamflows are most evident in transient basins, which are highly sensitive to even small increases in winter and spring temperature. Warmer temperatures cause more winter precipitation to fall as rain rather than snow. They also accelerate spring melt. Warming therefore increases early winter streamflows and lowers winter snowpack, resulting in lower and earlier spring runoff.

These changes become more pronounced as projected temperatures rise. For example, peak streamflows in the Green River shift from April-May to November-December by the 2080s (Figure 8, top), effectively changing the Green River from a transient to a rain-dominant basin. The White River, a tributary to the Puyallup River, is similarly impacted (Figure 8, bottom). It is important to note that the simulated streamflows shown for these two basins represent unregulated flows and do not account for the dam operations that help control flood flows on these rivers.



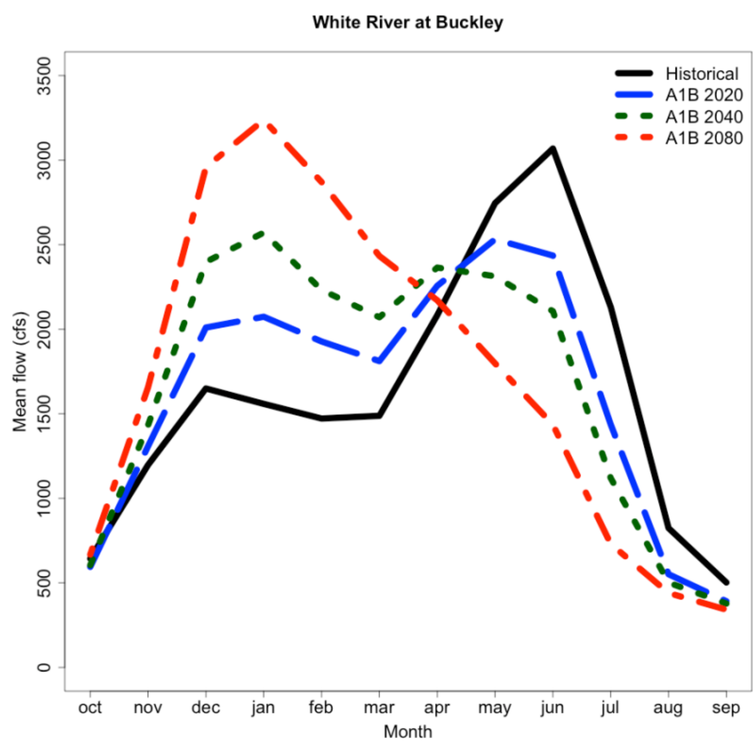


Figure 8. Projected Changes in Average Monthly Streamflows (in Cubic Feet Per Second) for the Green River Near Auburn (Top) and the White River at Buckley (Bottom). Changes are shown for three time periods: the 2020s (blue line), the 2040s (green line), and the 2080s (red line) for the A1B emissions scenario. All changes are relative to average historical flows (1916–2006; black line). Streamflows are naturalized flows, meaning they do not take the effects of dams into account. *Figure source: Climate Impacts Group, based on data from Hamlet et al. 2010.*[28]

[28] Hydrologic Climate Change Scenarios for the Pacific Northwest Columbia River Basin and Coastal Drainages data set, available at http://warm.atmos.washington.edu/2860/.

3.4.1. Increasing Flood Risk

Projected increases in winter precipitation and streamflow described in the previous section are expected to increase winter flood risk in the Puget Sound region. The increase in flood risk is most significant in transient basins, where the shift to more winter precipitation falling as rain rather than snow produces instantaneous streamflow rather than delayed runoff stored in the form of snow.[29] Winter flood risk is further increased by projections for more winter precipitation overall. Flood risk also increases in rain dominant basins, although the risk in these basins is driven exclusively by projected increases in winter precipitation, which are less certain than increases in temperature.

One way to examine future changes in flood risk is to compare the size of flood events estimated under projected future and past climatic conditions. For example, the volume of flow associated with the 100-year (1% annual probability) flood event for the Green River near Auburn is projected to increase 15-76% by the end of the 21st century under the moderate (A1B) emissions scenario (Figure 9, left panel).[30] Flooding in the Green River is also affected by atmospheric rivers, which are not included in these scenarios but which may become more frequent or intense under a warmer climate, as noted previously. Projections for the White River at Buckley show that the 100-year flood magnitude could increase 40-145% by the end of the 21st century under the same scenarios (Figure 9, right panel).[31]

3.4.2. Decreasing Summer Streamflows

Streamflow is projected to decrease during the historically low-flow summer period in the Puget Sound region. These changes are most evident in transient basins, where lower winter snowpack and earlier spring snowmelt combine to produce earlier spring runoff and lower summer streamflows. Warmer summer temperatures also reduce summer streamflows by increasing evaporative losses and water uptake by vegetation.

Reduced summer streamflows in rain-dominant basins are driven primarily by evaporative losses, and therefore less pronounced than in transient basins. In both basin types, contributions from groundwater could help offset summer losses but these contributions are highly variable by location and have not been quantified. Both basin types are also likely to be affected to some degree by projected decreases in summer precipitation.

By the 2080s under the A1B scenario, summertime low flow levels, defined as the 7-day consecutive lowest flows with a 10-year return interval, are projected to decline -7 to -16% for the Green River near Auburn and -12 to -50% for the White River at Buckley (Figure 10).[32]

[29] Hamlet et al. 2007, Mantua et al. 2010, Hamlet et al. 2010
[30] Based on data available from the Hydrologic Climate Change Scenarios for the Pacific Northwest Columbia River Basin and Coastal Drainages data set (http://warm.atmos.washington.edu/2860/).
[31] *Idem*
[32] *Idem*

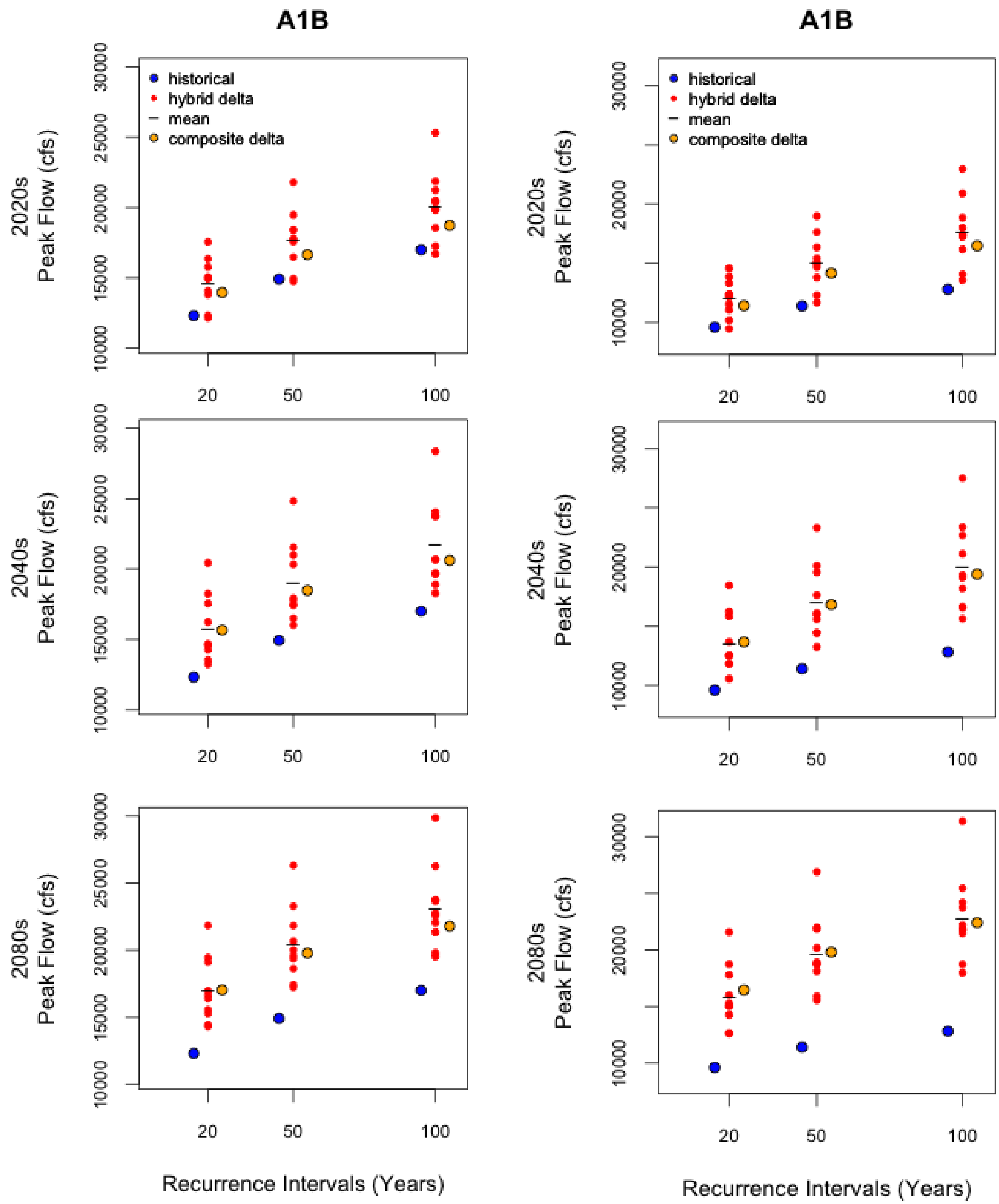


Figure 9. Historical and Future Flood Magnitudes (in Cubic Feet per Second) Associated with 20-, 50-, 100-year Return Intervals for the Green River at Auburn (left) and the White River at Buckley (right) for the 2020s (Top), 2040s (Middle) and 2080s (Bottom). Flow magnitudes are shown for the 1915-2006 historical period (blue), 10 global climate models (GCMs) (red; average indicated by black dash), and an average change from 10 GCMs (yellow) under the moderate (A1B) emissions scenario. *Figure source: Hamlet et al. 2010.*

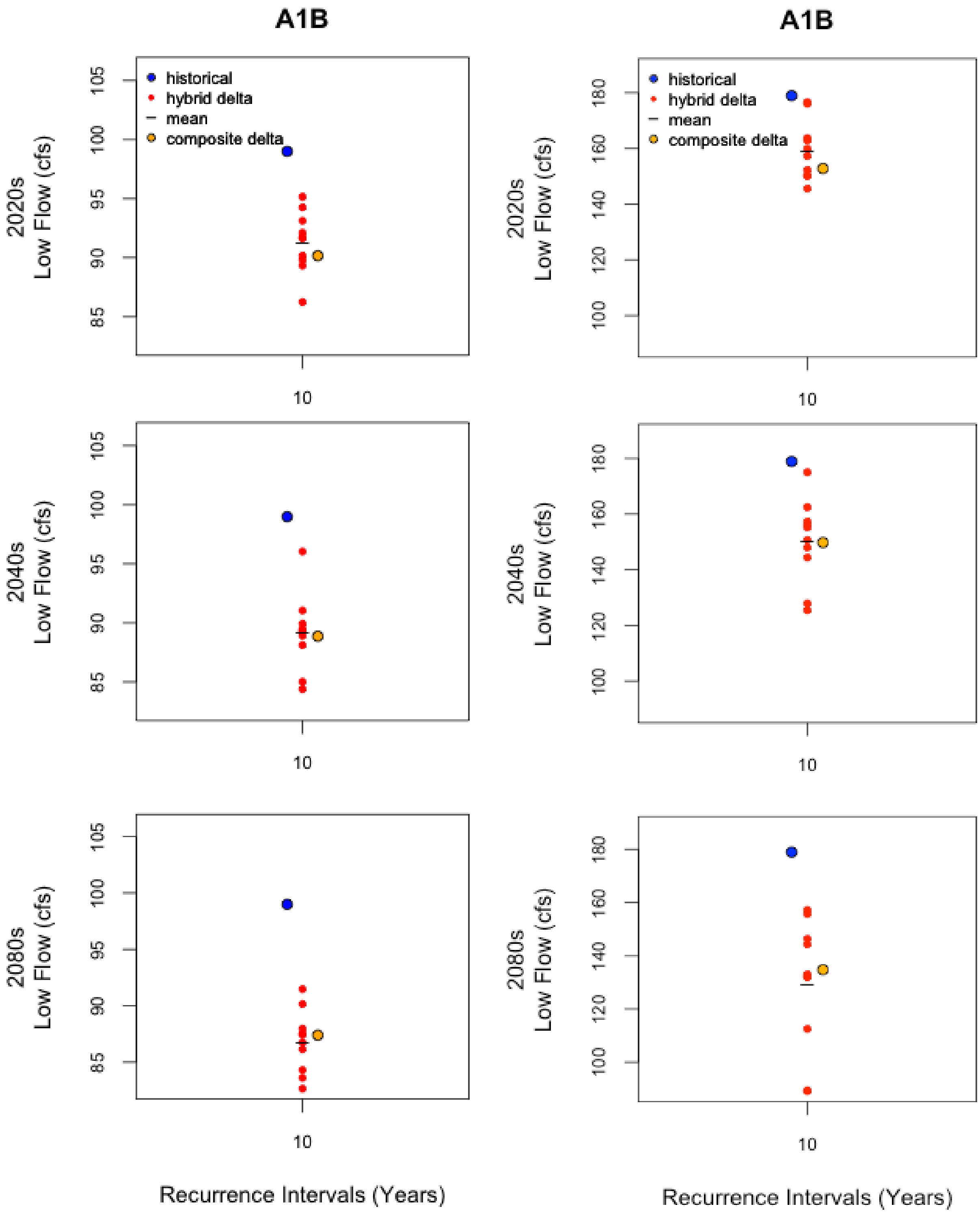


Figure 10. Comparisons of the Estimated Historical and Future Low Flow Magnitudes (in Cubic Feet Per Second) for the Green River at Auburn (Left Panel) and the White River at Buckley (Right Panel) for the 2020s (Top), 2040s (Middle), and 2080s (Bottom). Flow magnitudes are shown for the 1915-2006 historical period (blue), 10 global climate models (GCMs) (red – average indicated by black dash), and an average change from 10 GCMs (yellow) under the moderate (A1B) emissions scenario. *Figure source: Hamlet et al. 2010.*

3.5. Projected Sea Level Rise

Sea level rise is virtually certain. The amount of sea level rise at a given location in the Puget Sound region will vary depending on local changes in vertical land elevation, regional changes in wind patterns, and global-scale changes in average sea level, among other factors.

Sea level rise is an unequivocal consequence of rising global temperatures. Key contributing factors to rising sea levels globally are

(1) melting of land-based ice sheets and glaciers, which add freshwater to the ocean, and
(2) thermal expansion of seawater as it warms, which increases the ocean's volume.

Recent estimates of global sea level rise indicate that sea level will increase globally on average 3-9 inches by 2030, 7-19 inches by 2050, and 20-55 inches by 2100 (NRC 2012).

Global sea level rise projections form the basis for regional estimates, which must also take into account local factors that can enhance or suppress sea level rise at a given location. For the west coast of the U.S., these additional factors include seasonal wind patterns (which can cause wind-driven wave "pile-up" and higher sea levels, especially during El Niño years) and plate tectonics (which can cause subsidence or uplift of land surfaces depending on location).

Sea level rise projections for Seattle by mid- and end-of-century are provided in Table 4 (NRC 2012).The current range of projections for the region has been fairly consistent between studies[33] but the range is large (+3.9 inches to +56.3 inches for 2100) due to uncertainty in the rate of future ice losses and other components used to calculate sea level rise at specific locations through the 21st century. Note also that sea level rise will not necessarily occur in a consistent, linear fashion. Episodes of faster and slower rise are likely, as well as periods of no rise.

Table 4. Average (+/- 1 standard deviation) and range of sea level rise projections, in inches, for Seattle. *Source: NRC 2012*

Timeframe	Average increase (A1B emissions scenario)	Range, low (B1) to highest (A1F1) emissions scenario
2030	2.6 (± 2.2)	-1.5 to +8.8
2050	6.5 (± 4.1)	-2.5 to +18.8
2100	24.3 (± 11.5)	+3.9 to +56.3

[33] See, for example, Mote et al. 2008, NRC 2012

3.5.1. Storm Surge

Changes in sea level can affect the reach of high tides, storm surge, and coastal flooding. The highest observed tide for Seattle occurred on January 27, 1983 (12.14 feet above NAVD88) and nearly matched December 17, 2012 (12.13 feet). Extreme tidal heights associated with storms have ranged from 1.48 feet above Mean High High Water (MHHW)[34] for a storm with a return frequency of once a year to 3.19 feet above MHHW for the 100 year (1% chance) storm event.[35]

Higher sea level amplifies the inland reach and impacts of storm surges, potentially making today's 100-year (1% annual probability) storm event a much more frequent event. For example, Hamman 2012 found that combining annual storm surge with projected sea level rise[36] changed the historical (1970-1999) 100-year peak tidal event from a 100-year event to an annual event by the 2020s in the Skagit and Nisqually River estuaries. These changes could be exacerbated by projections for increased coastal storminess found in some studies.[37]

4. Conclusions

The projected changes described in this paper are expected to have direct and indirect impacts on Sound Transit operations and planning. While the specifics of those impacts will be evaluated through the workshops and other discussions planned as part of the Sound Transit Climate Change Risk Reduction Project, anticipated impacts include but are not limited to:

- More landslides and erosion along the Everett to Seattle Sound line;
- More frequent flooding of Sound Transit customer facilities located in or near the current 100-year flood zone;
- Increased demands on stormwater management infrastructure;
- Increased heat stress on traction power stations;
- Increased stress on restoration projects sensitive to changes in temperature and streamflow; and
- Reduced customer access to Sound Transit services due to impacts affecting roads and transit services provided by partner agencies.

The implications of these and other impacts are described in the results for the Sound Transit Climate Risk Reduction project.

[34] Mean Higher High Water is the average of the higher high water height of each tidal day observed over a 19 year tidal epoch. The MHHW for Seattle is 9.01 feet above NAVD88 zero feet.
[35] King County WTD 2008
[36] Hamman 2012 used the high estimate of projected sea level rise for the Puget Sound region (50 inches) calculated by Mote et al. 2008; sea level rise values for each time period were determined by evaluating a quadratic fit to the values published by Mote et al. 2008.
[37] e.g., Salathé 2006, Tebaldi et al. 2006, Yin 2005

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APPENDIX

B

Project Methodology

Project Methodology

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1. Introduction

The Sound Transit Climate Risk Reduction Project incorporated expert input from Sound Transit staff, the University of Washington's Climate Impacts Group, and the Washington State Department of Transportation (WSDOT) to:

- Complete a first-ever qualitative assessment of climate change impacts on Sound Transit services (Sounder, Link light rail, ST Express, customer facilities, and environmental mitigation);
- Identify potential adaptation options relevant to identified impacts, and
- Identify avenues for integrating climate change impacts considerations into agency decision making processes.

As one of seven national FTA funded pilots, the project also strove to:

- Create a process and a model for climate change impacts assessment and planning that is transferable to transit agencies across the United States; and
- Provide a state-to-local testing ground for WSDOT's pilot use of the Federal Highway Administration's climate change vulnerability assessment methodology. [1]

Box 1. Departmental Representation on the CCAG

- Director of Office of Planning
- Executive Program Advisor
- Government and Community Relations Director
- Senior Legal Counsel
- Director Budget and Financial Planning
- Deputy Director, Operations
- Director of Civil and Structural Design
- Director of Safety
- Director of Environmental Affairs and Sustainability
- Director of Facilities and Asset Management

This Appendix provides details on the approach used to complete the project. This includes information on the Sound Transit Climate Change Advisory Group, work completed to prepare for project workshops, and how project workshops were conducted. Lessons learned throughout the process are also noted.

2. Sound Transit Climate Change Advisory Group

A project advisory group consisting of senior managers from across the agency was established at the beginning of the project to:

- Broadly demonstrate senior level buy-in to Sound Transit staff;
- Facilitate communication between the project team and participants;
- Ensure the relevance and appropriateness of the project's approach to Sound Transit Management objectives, planning horizons, and existing risks;
- Provide overall guidance to the Project Team throughout the course of the project; and
- Help secure participation of appropriate staff members for the project's various activities.

[1] WSDOT 2011

Members of the Climate Change Advisory Group (CCAG) were drawn from an existing Environmental and Sustainability Management System (ESMS) advisory group (Box 1) because of the high amount of overlap in the ESMS group's expertise and the expertise needed for the CCAG. Building the CCAG from the ESMS group also allowed the project team to incorporate regular updates on the project into existing quarterly ESMS meetings. Additional members were asked to participate in the group to ensure representation of all relevant interests. Separate meetings focusing only on the project were also scheduled as needed.

3. Pre-workshop Activities and Materials

The following were completed to prepare for the vulnerability assessment and adaptation workshops.

3.1. Project Kick-off Briefings

Initial project briefings were held with Sound Transit's Executive leadership, the CCAG, and project participants to provide details on the project. This included presentations on the goals and approach for the project, projected climate change impacts, and WSDOT's vulnerability assessment results. The briefings also included distribution of a one page project overview sheet and opportunities for questions and answers.

3.2. Climate Change Impacts White Paper

A technical white paper on projected regional climate change impacts for the 2020s, 2040s, and 2080s was prepared in advance of the project's workshops to provide a scientific foundation for discussions. The summary drew on existing data and analyses from peer-reviewed literature and other sources to provide a summary of climate change projections for temperature, precipitation, streamflow, flooding, and sea level rise in the Puget Sound region. A full copy of the white paper is provided in Appendix A. The white paper was distributed to project participants in advance of workshops and summarized into a one page handout for use during the staff survey and project meetings and workshops.

3.3. Sound Transit Staff Survey

An anonymous survey of Sound Transit staff was conducted in summer 2012 to provide the project team with an initial understanding of staff opinions about how current and future climate conditions affect infrastructure, operations, and planning at Sound Transit. Information from the survey was used to shape the discussions planned for those workshops.

The survey consisted of 30 questions covering a range of potential climate change impacts related to increasing temperature, increasing precipitation, more extreme events, and sea level rise. Survey questions were reviewed by the CCAG prior to the survey's release. The survey was distributed broadly within the agency along with a one page summary of projected climate change impacts on the Puget Sound region.

Respondents were asked to qualitatively rate the degree to which present-day climate extremes, such as extreme heat events and storm surge, already affect Sound Transit. They were then asked to rate how projected changes in climate could affect the agency. Response options were “don't know”, “none”, “low”, “moderate” and “high”. Staff was also asked to provide specific examples of impacts to facilities, roadways, rail segments, or other aspects of Sound Transit's operations and planning.

A total of 36 responses were submitted. Respondents covered all three of Sound Transit's transit modes and customer facilities. The largest group of survey respondents was staff working on Link light rail and/or Sounder (some survey participants worked on multiple modes).

Survey results were consistent with findings from the project workshops. Staff generally thought that climate change would have a greater, but still relatively minor to moderate, impact on agency infrastructure and operations compared to the agency's current experience with these issues (e.g., heat stress, flooding). This was evident by the large number of responses that shifted from "don't know", "no impact", or "low impact" ratings for current climate to "low impact", "medium impact", or "high impact" ratings for future climate (Figure 1). Note that the largest response category in all three areas of questioning for both current and future climate was "don't know". This was seen as an indicator that staff was generally unfamiliar with climate change impacts and how they relate to Sound Transit operations and planning.

3.4. GIS Mapping

Geographic Information System (GIS) maps of sea level rise inundation zones and Federal Emergency Management Agency (FEMA) flood zones were prepared for each service to guide discussions on sea level rise and river flooding impacts. Other project-related features added to the maps included:

- Link light rail alignment and stations (existing, under construction, proposed, and potential alignments and stations);
- Sounder alignment and stations;
- Parking facilities;
- Sound Transit property;
- ST Express routes and stations; and
- Climate change impact ratings (high, moderate and low) for state-owned roads evaluated by WSDOT as part of their 2011 vulnerability assessment. [2]

Examples of maps showing the sea level rise inundation zone and FEMA flood zones are shown in

[2] WSDOT 2011

Figure 1 and Figure 2, respectively. In some cases, both features were found on the same map.

Sea Level Rise Inundation Zone Mapping. Sea level rise inundation zones were mapped for 22 inches and 50 inches of sea level rise. The 22 and 50 inch sea level rise values were selected to be consistent with values used by WSDOT. This also allowed the project team to use existing GIS layers prepared by WSDOT. The 22 inch value is close to the average rise in sea level currently projected for Seattle in 2100 while the 50 inch value is near the high end of the range currently projected for 2100 (see Appendix A). Using both an average and a high value provided the opportunity to see how high amounts of sea level rise could affect services, absent adaptation. If and when these or other levels of sea level rise occur depends on how quickly global temperatures increase and other factors noted in Appendix A.

FEMA Floodplains. Both 100-year and 500-year floodplains were mapped using information available from FEMA and King County. The 500-year flood plain was included as a discussion tool to help project participants conceptualize areas that could be affected by the larger flood events expected with climate change. Flood inundation zones produced by the U.S. Army Corps

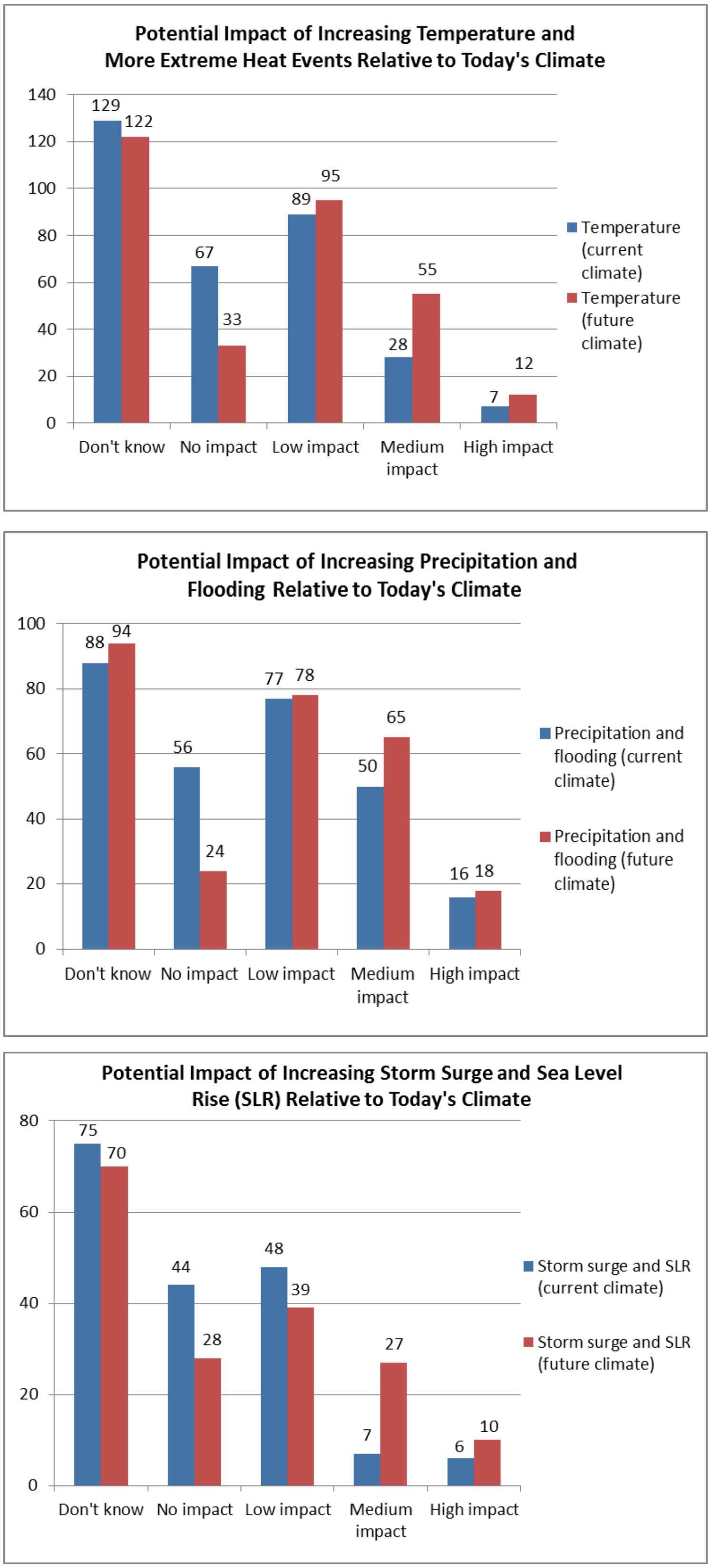

Figure 1. Rating the Impact of Projected Increases in Temperature, Precipitation, and Sea Level Rise Relative to the Impact of Present Day Extreme Heat, Precipitation, and Storm Surge Events. Results based on Sound Transit staff survey. Figures prepared by the Climate Impacts Group.

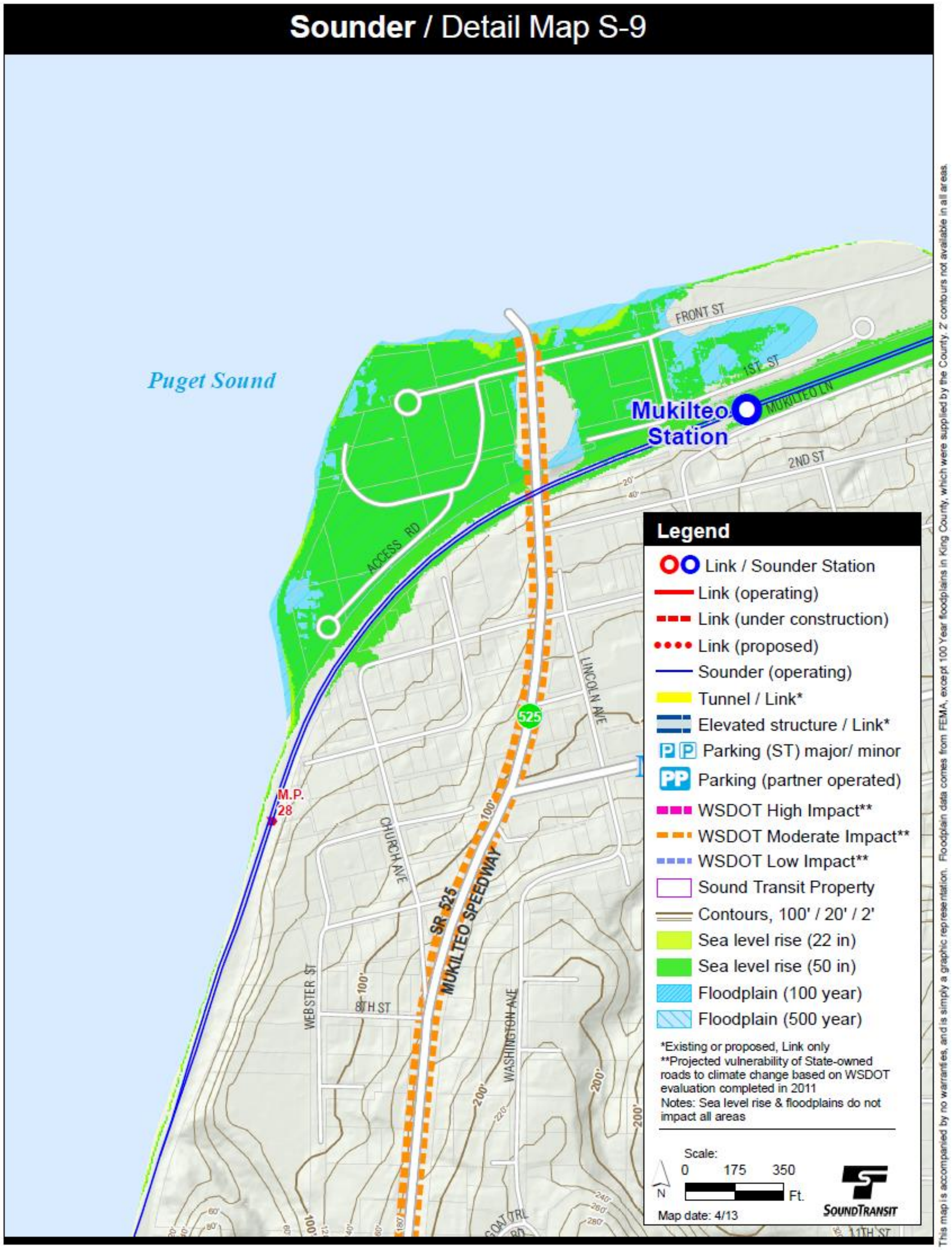

Figure 2. Projected Inundation Zones for 22 Inches and 50 Inches of Sea Level Rise in the Vicinity of the Mukilteo Station. *Map produced by Sound Transit.*

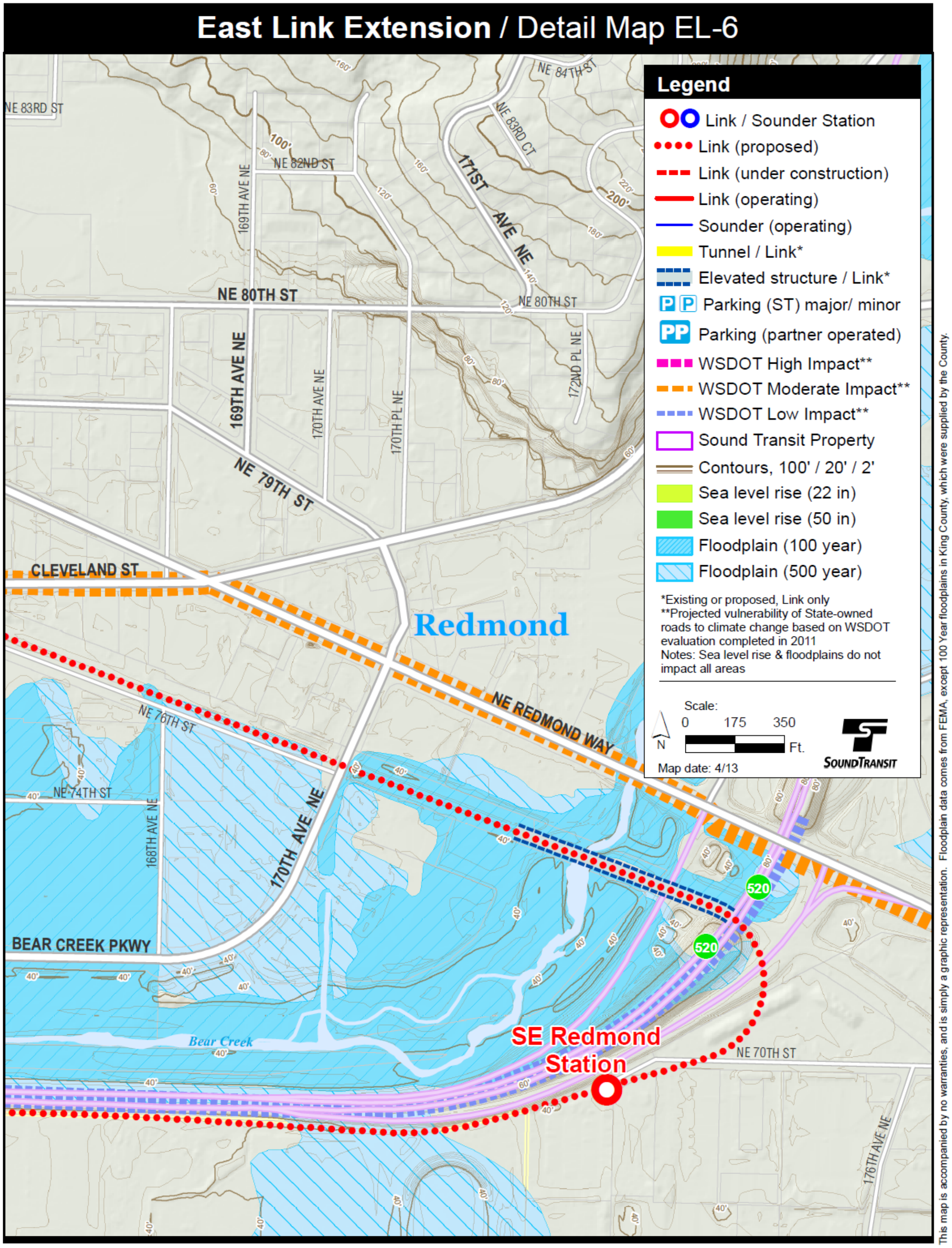

Figure 3. Proposed Alignment for the Possible East Link Extension to Redmond Relative to Present Day 100-year and 500-year FEMA Flood Zones. *Map produced by Sound Transit.*

of Engineers (USACE) for various high-impact Green River flood events were discovered after the project workshops and integrated into the analysis (but not the project GIS maps).[3] The USACE maps illustrate how deep flood waters could be in different locations at different scales of flooding.

4. Climate Change Vulnerability Assessment and Adaptation Workshops

Collection and integration of expert knowledge about transit services, infrastructure, and climate change impacts was central to the Sound Transit Risk Reduction Project. More than a dozen workshops were held with Sound Transit staff to assess how the climate change impacts listed in Table 1 might affect Sound Transit operations and planning, and how the agency might adapt to these impacts. The approach taken for these workshops is discussed in the following sections.

Table 1. Potential Climate Change Impacts, Grouped By Principal Climate Cause, That Could Affect Sound Transit Operations and Planning.

Related to Temperature *Increased potential for…*	**Related to Precipitation** *Increased potential for…*	**Related to Sea Level Rise** *Increased potential for…*
• Rail buckling[4] • Heat stress on electrical and safety equipment • Heat stress on overhead catenary system • Heat stress on pavement, structures • Summer drought stress on landscaping and environmental mitigation sites	• Mudslides and slope instability • Larger and/or more frequent river and stream flooding • Increased localized flooding due to more stormwater runoff or poor drainage • Seepage due to higher groundwater tables	• Temporary flooding of low-lying areas • Permanent inundation of low-lying areas • Higher tidal and storm surge reach • Erosion • Drainage problems • Corrosion from more frequent or prolonged exposure to saltwater

4.1. Vulnerability Assessment Workshops

The vulnerability assessment workshops used a combination of presentations, existing asset mapping and inventories, and structured workgroup activities to stimulate discussions within and across areas of expertise about climate-related hazards and risks. One workshop was held for each service (Sounder, Central Link, ST Express, each of the current Link extensions, and environmental mitigation). Two workshops were held for customer facilities due in part to the large number of customer facilities. Workshops were scheduled for one to three hours depending on the number of impacts to be discussed and staff availability; most workshops were 1.5 to two hours.

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[3] Green River Valley Flood Risk Maps, available at: http://www.nws.usace.army.mil/Missions/CivilWorks/LocksandDams/HowardHansonDam/GreenRiverFloodRiskMaps.aspx

[4] A rail buckle is an unwanted bend or kink in steel rail that occurs when rail temperatures are high enough to cause steel rail to expand, forcing the rail out of alignment

Workshop Participants. A cross-section of agency staff members from different programs were asked to participate in the workshops. This included senior operations managers and technical staff, as well as staff from environmental, safety, and other programs. Staff from partner agencies was invited to participate where relevant. The number of participants in a workshop ranged from five to more than fifteen. Smaller group sizes were ultimately preferred (i.e., six to eight people) due to the limited amount for time for the workshops and the goal of facilitating a dialogue among participants. One-on-one interviews and small group meetings with staff were also conducted to supplement information gathered during the workshops.

Pre-Workshop Interviews. Project staff held pre-workshop meetings with one or two key senior technical and management staff to discuss plans for the workshops and to develop a preliminary list of potential impacts for each workshop. This information was combined with information from the survey and relevant GIS maps to determine which climate change impacts should be discussed at specific workshops.

Workshop Format. Workshops began with a brief presentation on the goals and objectives of the project and the vulnerability assessment workshops, how the workshop would be conducted, and the climate change impacts to be evaluated. Staff was then asked to discuss and rate, using the scale provided in Table 2, how present day climate extremes such as extreme heat or precipitation events affect service delivery, operations, and infrastructure. The climate change impacts listed in Table 1 were then discussed and rated using the same rating options.

Decisions about what rating to assign to an impact were made collectively by workshop participants rather than individually. As such, the rating represented a consensus view of workshop participants. GIS maps and other visual aids produced for the workshops were also used to help guide discussion of impacts, as noted previously (see also Figure 4).

Table 2. Impacts Rating Scale Used in the Sound Transit Vulnerability Assessment Workshops. These options were used to rate the impact of present day climate impacts as well as the impacts associated with projected changes in temperature, precipitation, and sea level rise.

No Impact	**Minor Impact** *("a blip on the radar")*	**Moderate Impact** *("a nuisance")*	**Significant Impact** *("we've got a problem")*	**Extreme Impact** *("a game-changer")*
- No additional action required to maintain service levels.	- Minimal additional action required to maintain service levels.	- Some action required to maintain service levels but needed action can be easily accommodated.	- Substantial and/or costly action required to maintain service levels. - Impact affects system beyond a single day.	- No service level can be maintained. Operations must be halted for a prolonged period of time or permanently.

Climate Impacts Rating System. The rating system used for the vulnerability workshops was based in part on the WSDOT (2011) approach to rating impacts. Discussion questions for rating current impacts included the following:

Figure 4. Participants at the ST Express Vulnerability Assessment Workshop. *Photo credit: Carol Lee Roalkvalm, WSDOT*

1. Does the climate impact currently affect operations and service for the mode or facility? *(i.e., is there an impact?)*
2. If yes, how so? *(i.e., what is the impact?)*
3. Does that impact require doing anything differently to maintain service levels *(i.e., does the impact matter?)*
4. If yes, what must be done to maintain service levels? How easy is it to accommodate those needed actions? *(i.e., how much does the impact matter?)*
5. Based on the preceding answers, how would you rate the impact on Sound Transit using the choices in Table 2?

Discussion questions for rating projected impacts were nearly identical to the questions used to assess and rate current impacts:

1. Could the projected climate impact affect operations and service for the mode or facility? *(i.e., is there a potential impact?)*
2. If yes, how so? *(i.e., what is the potential impact?)*
3. Would that impact require doing anything differently to maintain service levels *(i.e., does the potential impact matter? Are there thresholds of change that make the impact matter more?)*
4. If yes, what would likely need to be done to maintain service levels? How easy is it to accommodate those needed actions? *(i.e., how much does the impact matter?)*
5. Based on the preceding answers, how would you rate the projected impact on Sound Transit using the choices in Table 2?

While the scoring was primarily rooted in how a climate change impact affected service delivery, participants were also asked to consider other factors when assessing the significance of an impact. These other considerations included:

- The cost of taking corrective actions (although no effort was made to quantify those costs),
- Duration and frequency of service impacts or repair time;
- Ridership impacts;
- Impacts on staff time and resources;
- Political feasibility, both at the agency and with jurisdictions and service partners; and
- The potential impact on Sound Transit’s reputation as a reliable service provider.

The difference between the ratings for present day versus projected impacts allowed the project team to assess which climate change impacts could present potentially new challenges to Sound Transit. Where possible, climate-sensitive thresholds or “choke points” at which point climate impacts become more significant were identified. These may include, for example, specific precipitation thresholds above which stormwater management systems are overwhelmed or specific locations where an impact in one area effectively impacts the whole system, e.g., a low-lying segment of rail that, if flooded, restricts use of the larger system.

Considerations Regarding the Use of WSDOT’s Impacts Rating Approach. One objective of the Sound Transit Climate Risk Reduction Project was testing the scalability of WSDOT’s approach for assessing climate change vulnerability (WSDOT 2011). WSDOT’s approach involved a series of one day district-level workshops where WSDOT staff discussed and rated the criticality of and climate change impacts on state-owned infrastructure in their district. The workshops allowed WSDOT to tap into the detailed field knowledge of its district staff, many of whom have decades of experience managing the roads evaluated.

The Sound Transit project team ultimately had to move away from a direct application of the WSDOT approach. A major reason was the inability to secure enough staff participation for day-long meetings; the longest Sound Transit vulnerability assessment meetings were three hours. Another challenge was the lack of a long operating history at Sound Transit. The longest-running service at Sound Transit is ST Express, which only began operating in 1999. This made it difficult to know how a range of climate events could affect service since the system has not experienced as many extreme events as older transit systems.

Time constraints and the relatively short operating history contributed to a decision to shift the workshop approach from a planned segment-by-segment analysis of impacts (e.g., virtually walking through the Link light rail alignment to score individual sections based on unique features influencing vulnerability) to a more general discussion of how different climate change impacts may affect the modes and facilities. For example, rather than asking how sea level rise could affect track between Mileposts 12 and 16, the question was broadened to more generally ask how sea level rise could affect the north rail alignment overall. This shift did not preclude discussion of impacts specific to unique locations; impacts on several individual stations were identified and discussed as well as general station impacts, for example.

While the revised approached allowed for more rapid assessment of climate impacts, it also required making generalizations about impacts on Sound Transit services that could potentially overestimate or underestimate impacts at any given location. All results should be considered starting points for more detailed site-specific examinations, when needed.

4.2. Adaptation Planning Workshops

Key vulnerabilities identified through the vulnerability assessment workshops provided the basis for the project’s adaptation planning workshops and integration meetings (Section 4.3). Adaptation workshops were held for Sounder and Central Link. Adaptation discussions for the Link light rail extensions were included in the vulnerability assessment workshops for those extensions given that most of the extensions are still in various stages of construction and planning. The adaptation workshops were typically one to 1.5 hours long and included many of the same participants from the vulnerability assessment workshops.

No adaptation planning workshops were held for ST Express, customer facilities, or environmental mitigation. In the case of ST Express and environmental mitigation, the decision was due to the limited number of impacts affecting the services. For customer facilities, adaptation options raised during discussion at the two vulnerability assessment workshops and overlap with adaptation options discussed for Sounder and Central Link provided a good range of adaptation options for customer facilities.

An initial set of possible adaptation options were identified from published literature and discussions during the vulnerability assessment workshops. These options were presented to staff, who was asked to discuss the feasibility of the different adaptation options based on the specifics of Sound Transit's infrastructure and operations. Initial options were tailored or removed from consideration when necessary. Other adaptation options were also identified in the course of the workshops. Finally, additional input on adaptation options was obtained during the document review process for all services, including those that did not have an adaptation workshop. Costing out the different adaptation options was beyond the scope of the project.

4.3. Integration Meetings

The last major focus of the project included a series of one-on-one meetings with senior managers from various departments to identify policy, management, and operational opportunities for integrating adaptation recommendations into existing Sound Transit organizational structures and activities. Each meeting lasted 30 minutes to 1 hour and typically involved one to three individuals. Integration concepts were also discussed with the CCAG.

An integration matrix mapping out key agency program areas, major activities within each program area, relevant integration questions, and potential next steps was developed in advance of the integration meetings. Meeting participants were asked to review the program area(s) most relevant to their work and provide comment. The final table is included in Section 5 of the project report.

4.4. Lessons Learned

The Project's emphasis on process and expert elicitation, rather than climate modeling and engineering analyses, provided a non-technical and easily transferable template for use by transit agencies interested in planning for climate change. Lessons learned in the course of doing the project are noted here to support use of the approach by others.

In the early stages:

1. *Allow time early on for building project support.* The Sound Transit Climate Risk Reduction Project had executive level buy-in and sponsorship. However, this support was at the broad, conceptual level. Multiple one-on-one meetings with department directors and managers were still required to ensure that the right staff could participate in project workshops. Some departments are very centralized and therefore required only one meeting with the director to get approval for staff participation. Others have many sub-departments, requiring meetings with three to five additional managers within a single department. Additionally, because Sound Transit had never done a project like this before, each meeting required basic education about the purpose of the project.

2. *Allow time for rescheduling.* Reliance on expert elicitation via meetings and workshops made the project reliant on the availability of key personnel for meetings and workshops. Cancellations by key staff often required rescheduling to ensure participation by those

participants. In some cases, it was several weeks to a month before necessary staff could be reconvened.

3. *Consider pre-screening value-based terms with a project advisory board or staff prior to workshops.* As seen in Table 2, the impacts rating system used terms like “minor”, “moderate”, and “significant” that can be interpreted differently by individuals and even by different workshop groups. Each term was defined to help standardize how people interpreted the terms. However, this attempt at standardization could have been improved by seeking feedback on, or even co-developing, the rating options and other value-based terms used in the project with the CCAG or a subset of invited workshop staff.

During the workshops:

4. *Clearly identify assumptions being used in the impacts assessment and make them visible.* Basic assumptions were provided but having them in writing can help participants process the assumptions more clearly.

5. *Time the use of your maps and other visual aids.* The GIS maps showing sea level rise and flooding were very effective in engaging staff. However, it often became difficult to move the conversation to other impacts that were not geographically based. As a result, project staff moved conversations about sea level rise and flooding to follow assessment of heat-related impacts. The team also kept the maps covered until needed.

6. *Use a generic assessment checklist for guiding impacts assessment discussion.* Use a general checklist of items to be discussed when assessing vulnerability to ensure a more consistent evaluation of climate risks across different components of a service, particularly facilities.

During synthesis and assessment:

7. *New information may require changing workshop ratings after the workshops.* The project team initially expected that the workshops would provide “the answer” regarding potential climate change impacts on the Sound Transit system. However, in some cases, new information obtained from staff who did not participate in the workshops or other sources required adjusting the impacts rating assigned by workshop participants. For example, during the Central and Tacoma Link workshop, the group considered the impacts of heat stress on the overhead catenary system (OCS) to be “no impact” for the current climate and “no impact” in the future. However, later conversations with the OCS design engineer revealed that visual monitoring and minor adjustments (depending on the OCS type) are sometimes required during heat events and would be needed in a changing climate as well. As a result, the impact rating for heat stress on the OCS was changed from “no impact” to “minor impact.” The potential for ratings to be changed based on post-workshop information should be noted up front with workshop participants. In all cases, workshop participants were given the opportunity to review the final text.

References

(WSDOT) Washington State Department of Transportation. 2011. *Climate Impacts Vulnerability Assessment.* Report prepared by the Washington State Department of Transportation for submittal to the Federal Highway Administration, Olympia, Washington. Available at: http://www.wsdot.wa.gov/NR/rdonlyres/B290651B-24FD-40EC-BEC3-EE5097ED0618/0/WSDOTClimateImpactsVulnerabilityAssessmentforFHWAFinal.pdf

APPENDIX

C

Vulnerability Assessment Results and Adaptation Options for Sound Transit Services

- Sounder: Vulnerability Assessment and Adaptation Options
- Link: Vulnerability Assessment and Adaptation Options
- ST Express: Vulnerability Assessment and Adaptation Options
- Customer Facilities: Vulnerability Assessment and Adaptation Options

Note: No report was written for environmental mitigation. The primary impact on mitigation is increased summer drought stress from higher summer temperatures and lower summer precipitation. Issues related to that were added directly to the report (see Section 3, "Increased Heat Stress on Environmental Mitigation Activities").

Sounder: Vulnerability Assessment and Options for Adaptation

Contents

Figures

Tables

1. Executive Summary

Climate change is expected to have a moderate to significant (in limited cases) impact on Sounder operations. The most broadly applicable climate change impacts facing the rail alignment used by Sounder are heat-related impacts, specifically the potential for rail buckling and heat stress on electrical equipment. These impacts can occur anywhere along the alignment but are more likely inland of Puget Sound and in areas with prolonged sun exposure.

The most significant potential impacts are associated with increased mudslide activity and higher rates of sea level rise. The potential for increased mudslide activity along the north rail corridor used by Sounder was deemed a significant impact if more than 70 trip cancellations occurred in a season on a more frequent basis.[1] More frequent mudslides could reduce customer confidence in Sounder service and increase the potential for damage to a train or a train derailment. However, this potential is mitigated by preventative measures already in place and ongoing efforts to stabilize the highest slide-prone areas along the north rail alignment.

Permanent inundation of rail used by Sounder is possible in the vicinity of Edmonds and Mukilteo in the high sea level rise scenario (50 inches of sea level rise, which currently at the high end of scenarios projected for 2100). Sea level rise below this amount would not permanently inundate the track but would still expose the length of the north rail alignment to more extreme high tides, temporary coastal flooding, saltwater corrosion, and storm surge impacts. This could result in more service interruptions and damage to track infrastructure. A small portion of the south rail alignment in Tacoma could also be inundated if sea level rises 50 inches or more.

Moderate impacts are expected from projected increases in flooding for the Green and White Rivers. Climate change may result in both larger and more frequent floods. For example, peak streamflows associated with today's 0.2% (1-in-500 year) probability flood event are expected with the 1% (1-in-100 year) flood event as early as the 2020s as a result of climate change. More frequent flooding at or above flood stage would result in more BNSF-issued slow orders and could require temporarily lowering train capacity. Flooding over rail lines would most likely result in trip cancellations until the water recedes.

Adaptation options for Sounder range from increased visual or electronic monitoring to moving or relocating sensitive Sound Transit-owned infrastructure. Because Sound Transit does not own most of the rail infrastructure used by Sounder, decisions about how, when, and where to adapt rail infrastructure to climate change impacts will fall to BNSF as the owner of most of the rail used for Sounder service. An exception to this is the 8.2 mile Tacoma to Lakewood segment owned and maintained by Sound Transit. Other adaptation decisions related to service delivery will be made by Sound Transit.

2. Vulnerability Assessment Results

2.1. Potential Climate Change Impacts Evaluated

[1] The Sounder vulnerability assessment workshop took place on October 31, 2012, three weeks prior to the start of an unprecedented mudslide season for Sound Transit (>170 train cancellations).

Table 1. Potential Climate Change Impacts Evaluated for Sounder.

Projected Climate Change	*Potential Impacts on Sounder*
Warmer average summer temperature and more extreme heat	• Rail buckling • Heat stress on electrical and safety equipment
Increasing average and more extreme winter precipitation	• Increased mudslide activity • Increased river flooding
Sea level rise and associated impacts	• Temporary flooding of low-lying areas • Permanent inundation of low-lying areas • Higher tidal and storm surge reach • Erosion • Drainage problems • Corrosion from more frequent or prolonged exposure to saltwater

Staff was asked, via participation in two workshops, to qualitatively assess the degree to which the potential climate change impacts listed in Table 1 could affect operations and planning for Sounder. The Sounder workshops specifically focused on the rails and associated infrastructure (i.e. signals, crossing). Potential impacts on facilities were discussed in a separate assessment of Sound Transit customer facilities (see Appendix C.4).

All of the impacts listed in Table 1 are considered more likely because of the projected changes in climate. Many of the listed impacts are already possible in today's climate and therefore not unique to climate change. However, climate change may alter the frequency, intensity, location, or duration of these impacts by affecting the underlying climate drivers (e.g., temperature, precipitation, sea level) that cause an impact. In other cases, climate change introduces new challenges or brings existing challenges to new areas. For more on projected changes in regional climate, see Appendix A.

Potential changes in snow and ice events were not discussed in the project given the current lack of information regarding how these types of events may change as a result of climate change. Over time, however, the frequency of snow and ice events may decrease. The potential for more localized flooding due to increased stormwater runoff and/or poor drainage was noted as a possible issue near the King Street station and is therefore included in the customer facilities assessment (see Appendix C.4).

2.2. About This Summary

The results of the Sounder vulnerability assessment and adaptation workshops are described in the following sections and summarized in Section 4. For each potential climate change impact, the nature of the impact is briefly summarized and impacts to date on Sounder operations noted. Anticipated issues are identified and discussed generally in terms of expected and possible impacts. "Expected" impacts are those that would be expected to occur even at the low end of current climate change projections. “Possible” impacts are impacts that would occur in limited cases and/or at higher amounts of climate change.

Note that while climate change makes the impacts listed in Table 1 more likely, the probability that impacts occur will be shaped by design decisions and other factors. Additionally, the assessment assumes no adaptive actions are taken on the part of Sound Transit, its partner agencies, or the communities it serves. In doing so, the assessment provides an opportunity to see—in advance—where adjustments could be needed to deal with climate change. Finally, the assessment is based on climate change projections available at the time of the workshops. Future updates to regional climate change projections may influence these conclusions, as would future changes in system design or other factors influencing these conclusions. For more information on the workshop methodology and assumptions, see Appendix B.

2.3. Heat Impacts

2.3.1. Rail Buckling

What is the Issue?

Rail buckling (or sun kinks) occur when temperatures are high enough to cause steel rail to expand and shift laterally, forcing the rail out of alignment. These events—or even the potential for these events—can cause service slowdowns, interruptions, costly repairs, and in rare cases, train derailments.

There are many factors that influence if and where a rail buckle occurs (Figure 1). Three factors of note are track type, weather and sun exposure, and rail neutral temperature.

- *Track Type.* The rail alignment used by Sounder is mostly wood tie and ballast track with continuously welded rail (CWR). Sound Transit-owned owned track between Tacoma and Lakewood has concrete ties. Rail buckling is more likely with CWR wood tie and ballast track because of the lack of expansion gaps in CWR and because wood ties and spikes are less likely, relative to concrete ties, to hold heat-stressed rail in place.

- *Weather and Sun Exposure.* Rail that is exposed to sun for extended periods of time can be as much as 40°F hotter than surrounding air temperatures.[2] Rail buckling can occur whenever temperatures are high but are more likely to occur between 1:00 pm and 4:00 pm and on isolated hot days in the spring and summer, when temperatures fluctuate more.[3] Rail buckles are also more likely on curves and in areas where rail transitions between shade and direct sun exposure.[4]

- *Rail Neutral Temperature (RNT).* Rail expansion and contraction is mitigated by heating or mechanically stretching the steel to “Rail Neutral Temperature” (RNT) during installation and maintenance. RNT is the temperature at which point the rail is neither expanding nor contracting. The July 2013 update of the Sound Transit light rail Design Criteria Manual (DCM) increased the RNT for zero thermal stress from 65°F-80°F to 95°F-105°F (Section 8.3.10). The specific RNT used by BNSF is unknown. A higher RNT can be chosen but the value of doing so must be balanced with increasing the

[2] Rossetti, M.A. 2007 and Wolf, G. 2005.
[3] Kafalenos, R.S. and K.J. Leonard. 2008 and Zhang, Y.-J. and L. Al-Nazer. 2010.
[4] Rossetti 2007, Kafalenos and Leonard 2008

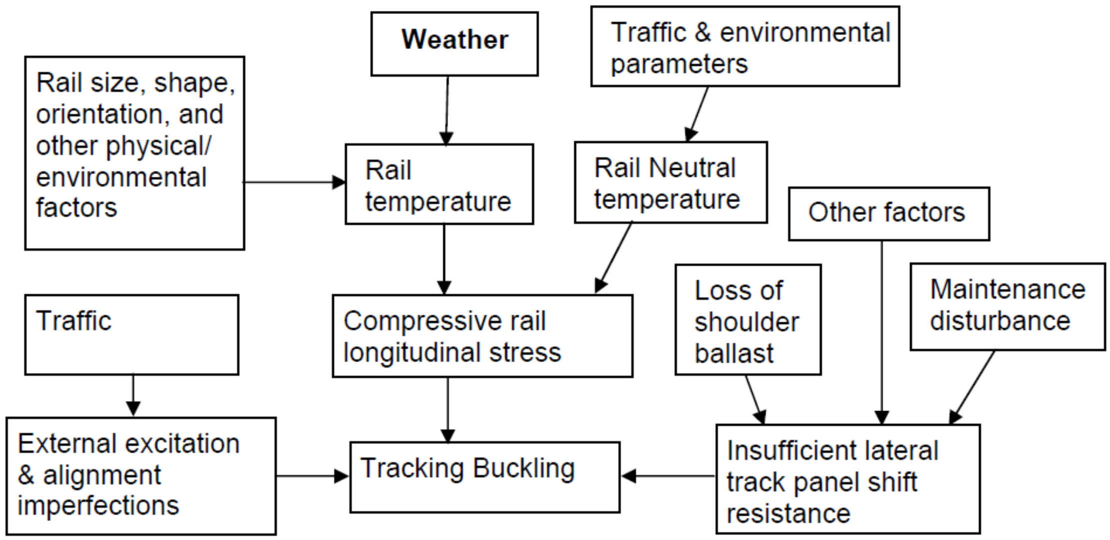

Figure 1. Factors Influencing the Occurrence of Rail Buckling. Source: Zhang and Al-Nazer 2010.

risk of rail pull-apart, which can occur when cold temperatures cause contraction strong enough to break the rail. Actual RNT (i.e., RNT after installation) will fluctuate with the season and may be affected by track maintenance activities. Daily variations are also possible; measurements of concrete tie track on Amtrak's Northeast Corridor found that daily RNT could vary by 10°F on any given day.[5] Even greater variation was found on lateral and vertical curves. Seasonal rail adjustments, often made as part of routine rail maintenance, are used to control for changes in RNT.[6]

Impacts to Date

Rail buckles are rare in the Puget Sound region and have been rated by staff to have only a minor impact to date on Sounder operations. The most common impacts are BNSF-issued slow orders and increased monitoring for rail buckling when ambient air temperature reaches 91°F. The slow orders may delay arrival times, generally on the order of several minutes. This length of delay has not created any notable service issues for Sounder.

As noted in

Table 2, rail buckles have occurred on two occasions on the Ballard Bridge, a drawbridge built in 1913 and located north of downtown Seattle between Milepost (MP) 6 and 7. The Ballard Bridge is more sensitive to heat than ground-level segments because the bridge rail is exposed to higher temperatures both above and below the bridge and must align perfectly for the bridge to close. BNSF has since removed a piece of track on the bridge and cools the rail with water during high heat events to reduce the potential for rail buckling.

[5] Zhang and Al-Nazer 2010

[6] Wolf 2005

Table 2. Rail Buckle History for Sounder, 2000-2012. Temperature data shows the high temperature for that day as measured at SeaTac Airport. Event date and description courtesy of Sound Transit. Temperature data provided by the Office of the Washington State Climatologist.

Date	*Temp.*	*Description*
8/1/06	74°F	Ballard Bridge malfunctioned due to hot temperature causing heat expansion (2 trips annulled)
7/11/07	98°F	Slow orders on south-line due to hot temperature. (1 train delayed)
8/5/08	88°F	Ballard Bridge malfunctioned, due to hot temperature (1 train late)
7/29/09	103°F	Slow orders on the south-line, due to hot temperature (2 trains delayed)

When a rail buckle occurs, the ability to work around the buckle will depend on the severity and location of the buckle. If the buckle is small, trains can travel over the buckle at low speeds. If the buckle is severe, service will be cancelled until a repair is made or, if possible, re-routed around the affected segment. Most portions of the alignment used by Sounder are double track with some areas of triple track (MP 5X-9X on the Sounder South line) and single track, particularly along the Tacoma to Lakewood extension (Table 3). If a buckle occurs in an area with double or triple track, it is possible to work around the misalignment and continue service.

Table 3. Single Rail Segments on the North and South Rail Alignment Used by Sounder. Information courtesy of Sound Transit.

Description	*Mileposts*	*Total Length (mi.)*
Sounder South		
Lakewood to Tacoma	0.0-0.7, 1.99-5.7, 6.4-8.4	6.4
Sounder North		
Edmonds	15.85-17.8	1.95
Mukilteo	27.0-27.85	0.85
Everett	1784.7-1782.6	2.10
Total		***11.3***

Projected Impact

Climate change increases the potential for rail buckling by increasing average summer temperature and the frequency, intensity, and duration of extreme heat events. The potential is assumed to be higher for Sounder South relative to Sounder North given that most of the south rail alignment is located inland and in open areas with little shading. Additionally, temperatures in the Sounder South service area are often a few degrees warmer than Seattle and areas north. Most of the north rail alignment used by Sounder runs in close proximity to Puget Sound, which buffers air temperatures in the immediate vicinity of the track.

The impact of more rail buckling, or even the potential for more rail buckling, is considered moderate. Expected impacts include more frequent heat advisories and minor trip delays on late afternoon runs due to more frequent slow orders (morning runs would not be affected by heat unless track repairs are required). Trip cancellations are possible if a buckle requires closing a track segment, which is more likely on the Tacoma to Lakewood segment given that most of that segment is single track. Trip cancellations may also be required if a buckle occurs anywhere along the 4.9 miles of single track used by Sounder North.

Any rail buckling between Seattle to Tacoma can most likely be bypassed given the availability of double and triple track. Some delays may be associated with a bypass, however. Heat-related rail repairs may also be required, although Sound Transit would only bear the cost of repairs on the Tacoma to Lakewood segment. The potential for derailment increases with the potential for more rail buckling but is still considered extremely low given existing safety measures.

2.3.2. Heat Stress on Head End Power Units and Signal Bungalows

What is the Issue?

More extreme temperatures tend to impact the reliability of mechanical equipment. High air temperatures can make it more difficult for stationary and vehicle electrical equipment to stay within safe operating temperatures, potentially affecting performance or causing equipment malfunction and damage. Temperature tolerance will vary with equipment type and location. Equipment located in areas with direct sun exposure and with inadequate ventilation is more likely to experience heat stress.

Staff identified two types of electrical equipment sensitive to heat: the Head End Power (HEP) units located on Sounder locomotives and signal bungalows positioned along the right-of-way. HEP units provide electricity for lighting, electrical, air conditioning, and other non-motive power uses needed by the train. HEP units are powered by a separate smaller diesel engine that is more difficult to cool than the main engine, making the units more sensitive to heat. Signal bungalows (or instrument houses) contain the electrical equipment for controlling bells, lights, and crossing arms at railroad crossings.

Impacts to Date

Managing heat stress on stationary and vehicle electrical equipment has had a minor impact to date on Sound Transit and largely consists of ensuring adequate cooling (via air conditioning) for signal bungalows. No HEP unit or signal bungalow failures due to heat stress were reported.

Projected Impact

Projected increases in average summer temperature and extreme heat events increase the potential for heat stress on stationary and vehicle electrical equipment. The impact of this increase on Sounder operations is considered moderate.

Increasing temperatures are expected to increase maintenance requirements for the HEP units used on Sounder locomotives. Failure of a HEP unit due to heat stress could require cancelling service. Power loss at a signal bungalow due to heat stress is unlikely because of air conditioning and back-up battery systems contained in each signal bungalow. Increasing summer temperatures are expected to increase cooling demands on the air conditioning units, potentially raising operating costs for air conditioning. This could also require more frequent maintenance or replacement of air conditioning units, and/or require increasing air conditioning capacity. If a power loss occurs, trains are required to stop at each failed signal to get permission from a dispatcher to proceed. This would likely result in minor train delays.

2.4. Precipitation Impacts

2.4.1. Increased Mudslide Activity

What is the Issue?

Mudslides occur when heavy precipitation or other factors cause soil, trees, and other debris to slide downslope. Mudslides are a regular occurrence on the north rail alignment used by Sounder, although the number of mudslides that occur in any given year is highly variable. Mudslides are most likely between November and April, a period with the highest monthly precipitation totals in the Puget Sound region (73% of annual precipitation).[7] Any landslide that affects the track (or a "blocking event", where mud travels over a rail) triggers a BNSF-mandated 48-hour wait period for passenger rail service, resulting in trip cancellations. Mudslides also have the potential to cause damage to train cars and passenger injury if a mudslide hits a Sounder train.

Several factors can contribute to mudslides, including intensity and duration of precipitation, hill slope, layering of different soil types, runoff patterns, human activities (e.g., placement of fill materials, improper drainage, leaking or broken water pipes, blocked culverts, excavation), and the occurrence of disturbance events (e.g., removal of trees or other mudslides in the vicinity).The U.S. Geological Survey closely monitors and identifies precipitation intensity and duration thresholds for the Puget Sound. When these thresholds are exceeded, the potential for mudslides increases.[8] According to USGS, the probability of mudslides is approximately 10% when precipitation is greater than 3.5 to 5.2 inches during any 18 day period (last three days plus 15 days prior). [9] The probability is much higher – between 30% and 70% - when soil conditions are already wet and precipitation intensity exceeds two to three inches over one to two days.[10]

Impacts to Date

Staff assessment of the overall impact to date of mudslides depended on the number of trip cancellations resulting from mudslides. According to staff, an average year may have as many as 33 train cancellations for Sounder North. More than 70 cancellations—a threshold reached in winter 2010-11 and the most ever experienced by Sound Transit at the time initial staff interviews—was considered problematic from a service reliability standpoint. Sound Transit provides bus service to passengers who would otherwise use Sounder service during the mandated 48-hour wait period following a mudslide. BNSF will also send personnel to observe saturation levels and determine if trains need to be further delayed.

The 70 train cancellation threshold noted by staff was dramatically exceeded during winter 2012-13 when 206 Sounder trains (as of April 9, 2013) were cancelled because of mudslides (Table 4). Much of the 2012-13 slide activity occurred in areas north of Edmonds.[11] Slides also

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[7] Chleborad et al. 2006
[8] *Ibid.*
[9] USGS "Landslide Hazards in the Seattle, Washington, Area", Fact Sheet 2007–3005, January 2007, available at http://landslides.usgs.gov/monitoring/seattle/.
[10] *Ibid.,* p.3
[11] Increased slide activity occurred between MP 11.25-13.75, 24.5-29.5, 1784.5 (Dan McDonald, BNSF; presentation to Sound Transit Board, 2/28/13)

caused two derailments near Everett: a major derailment of a BNSF freight train on December 17, 2012, and a minor derailment of an Amtrak passenger train on April 7, 2013.[12] A key factor in the 2012-13 mudslide spike was above average fall precipitation. Monthly averaged October - December precipitation was 149% above historical average in Seattle and 165% above historical average in Everett.[13] December 2012 was particularly wet in Everett (8.93 inches, or 179% of average).

Table 4. Winter Season Sounder North Train Cancellations for 2003-2013. Data courtesy of Sound Transit.

Year	*Total Trains Cancelled*	*Total Days Impacted*	*Daily Train Trips*
2003/4	3	3	2
2004/5	0	0	2
2005/6	40	10	4
2006/7	16	4	4
2007/8	18	3	6
2008/9	0	0	8
2009/10	24	3	8
2010/11	70	9	8
2011/12	41	7	8
2012/13	206	27.5	8

The current impact of mudslides was considered minor for average years (i.e., less than 33 train cancellations per winter) to significant for above average years (i.e., more than 70 train cancellations per winter). Although Sound Transit can move Sounder passengers onto alternative bus service, frequent cancellations result in lost revenue and could reduce customer confidence in the service. Frequent cancellations could also add to the existing political and operating pressures facing the Sounder North line.[14]

Sounder staff noted that the spacing of blocking events can affect public perception of the problem. In 2011-12, 30 of the winter's 41 train cancellations occurred within one week. The cancellations received attention from the public but it was relatively short-lived. In contrast, the 70 train cancellations experienced in 2010-11 were spread throughout the winter, generating more sustained attention. While media reports indicate that the record cancellations of winter

[12] See http://www.komonews.com/news/local/Freight-train-derails-in-Everett-183859751.html, http://www.komonews.com/news/local/Amtrak-train-hit-by-landslide-near-Everett-no-injuries-201835611.html

[13] Changes calculated based on average monthly precipitation data from NOAA's National Climatic Data Center (https://www.ncdc.noaa.gov/) as provided by the Office of the Washington State Climatologist.

[14] See, for example, "Sounder North: No way to run a commuter line", *Seattle Times,* October 23, 2012, http://seattletimes.com/html/editorials/2019505220_editsoundernorthxml.html; "Too many empty seats on Sounder north line", *Seattle Times,* October 15, 2012, http://seattletimes.com/html/localnews/2019441910_sounder16m.html

2012-13 may not have affected customer confidence at the time of publication, repeated years of frequent trip cancellations could change this.[15]

Projected Impact

As noted previously, there are many factors determining when and where mudslides occur. One key factor is precipitation intensity and duration, both of which are projected to increase as a result of climate change. Consequently, the potential for mudslides along the north rail alignment used by Sounder is expected to increase as a result of climate change.

At the time of the Sounder vulnerability assessment workshop (October 31, 2012), staff considered the anticipated impact of more mudslides as tolerable if the number of resulting train cancellations did not exceed 70 trips in a season. Although this number of cancellations was not desirable, staff felt that Sound Transit would not suffer long-term impacts on customer confidence up to that point. More than 70 train cancellations (with 100 cancellations identified as a possible upper threshold at the time) was considered significant because of the potential impact on customer confidence.

The large number of mudslides in 2012-13 prompted emergency slide abatement activities by BNSF, the Washington State Department of Transportation, Amtrak, and Sound Transit.[16] These activities, which began in spring 2013, are focused on six of the most slide-prone areas in 2012-13[17] and include the following:

- Stabilization efforts, which focus on surface and subsurface drainage improvements, buttresses, and retaining walls.
- Maintenance measures, which include managing vegetation, installing up to 21,000 linear feet of catchment walls and fences, and installing deeper and wider slide catchment ditches.
- Emergency management measures, which include installing electronically monitored slide fences along 13.5 miles of frequent slide areas.[18]

BNSF is also working with nearby property owners and other stakeholders to address the impact of broken pipes, residential storm drains, and development patterns in properties adjoining slide risk zones.[19] These efforts may help address the potential for more mudslides due to climate change, although that benefit would only apply in areas where slide abatement activities occur.

In addition to (but as part of) these measures, Sound Transit is working closely with BNSF to improve forecasts of potential landslide conditions along the north rail corridor. The effort includes placing additional data logging instruments (rain gages, tensiometers, and piezometers) along the north rail alignment, updating the equations and thresholds developed

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[15] See "Northline commuters keep faith as slide parks Sounder again", *Seattle Times*, January 3, 2013, http://seattletimes.com/html/localnews/2020054388_sounder04m.html

[16] See "Agencies seek fixes to mudslides, train disruptions", *The Herald,* January 31, 2013, www.heraldnet.com/article/20130131/NEWS01/701319961; see also "Rail partners explore mudslide causes, solutions", http://www.wsdot.wa.gov/News/2013/01/24_rail_mudslide_solutions.htm, January 24, 2013

[17] Work is focused on slide-prone areas near MP 24.5, 25.5, 25.9, 26.1, 29.5, and 1784.5

[18] Dan McDonald, BNSF; presentation to Sound Transit Board, 2/28/13

[19] *Ibid*

by USGS to correlate rainfall and soil moisture with slide potential, and incorporating rainfall forecast data into the model to provide reliable indicators of high landslide potential.

2.4.2. Increased River Flooding

<u>What is the Issue?</u>

River flooding can occur where the Sounder alignment crosses flood plains. The potential for river flooding is found most extensively in the Renton to Puyallup portions of the south rail alignment used by Sounder, where FEMA flood zones associated with the Green, Duwamish, White, and Puyallup Rivers are in close proximity to the tracks.

Flood risk is currently managed by the U.S. Army Corps of Engineers (USACE) through the use of dams and levees. BNSF will restrict train speeds when there is a flash flood warning from the National Weather Service or when rivers are near flood stage. BNSF will also remove signal system equipment from affected areas if there is adequate advanced warning. Minor delays may result as the signal system is reinstalled (a process that generally takes only two to six hours). Any flooding over the rails requires visual inspection of the track before resuming operations. Current design standards for Sound Transit-owned track (only the Tacoma to Lakewood segment) require building rails such that the top of rail elevation is a minimum of one foot above the 100-year flood elevation wherever feasible.

<u>Impacts to Date</u>

There has only been one instance of Sounder service being suspended as a result of flooding. On January 8, 2009, all eight south line round trips were cancelled due to the track being submerged by the Puyallup River in places between Fife and TR Junction, Tacoma. BNSF was able to reopen the tracks fairly quickly once the water subsided due in part to the rock ballast track bed, which is designed to drain quickly. Several other flood events have caused slow orders, resulting in train delays in the range of between two to 15 minutes.

<u>Projected Impact</u>

The potential for larger floods on the Green and White Rivers increases as a result of warmer winter temperatures and increasing winter precipitation. Mid-elevation watersheds, like the Green and White Rivers, are most sensitive to these hydrologic changes, as described in Appendix B and illustrated in Figure 2 and in Figure 3.

Warmer winter temperatures and increasing winter precipitation result in more winter precipitation falling as rain rather than snow. This shift causes more instantaneous runoff during the winter months, shifting the timing of peak flows earlier (Figure 2**Error! Reference source not found.**). As a result, the potential for flooding increases in winter and the volume of streamflows associated with the 5% (1-in-20 year), 2% (1-in-50 year), and 1% (1-in-100 year) flood events increases in most cases (Figure 3). For example, by the 2080s, flow volume for the 1% flood event in the Green River increases up to 76% relative to historical (1916-2006) climate. In both figures, changes are more pronounced moving forward in time as the amount of warming increases relative to historical climate.

Based on information available when meetings with staff were held, the potential impact of bigger floods on Sounder was considered moderate. This assumes that rivers reach or exceed flood stage more often; increased flooding that stays below flood stage would likely have little impact on operations. More frequent flooding at or above flood stage would result in more BNSF-issued slow orders. Temporary reductions in train capacity may also be required if the

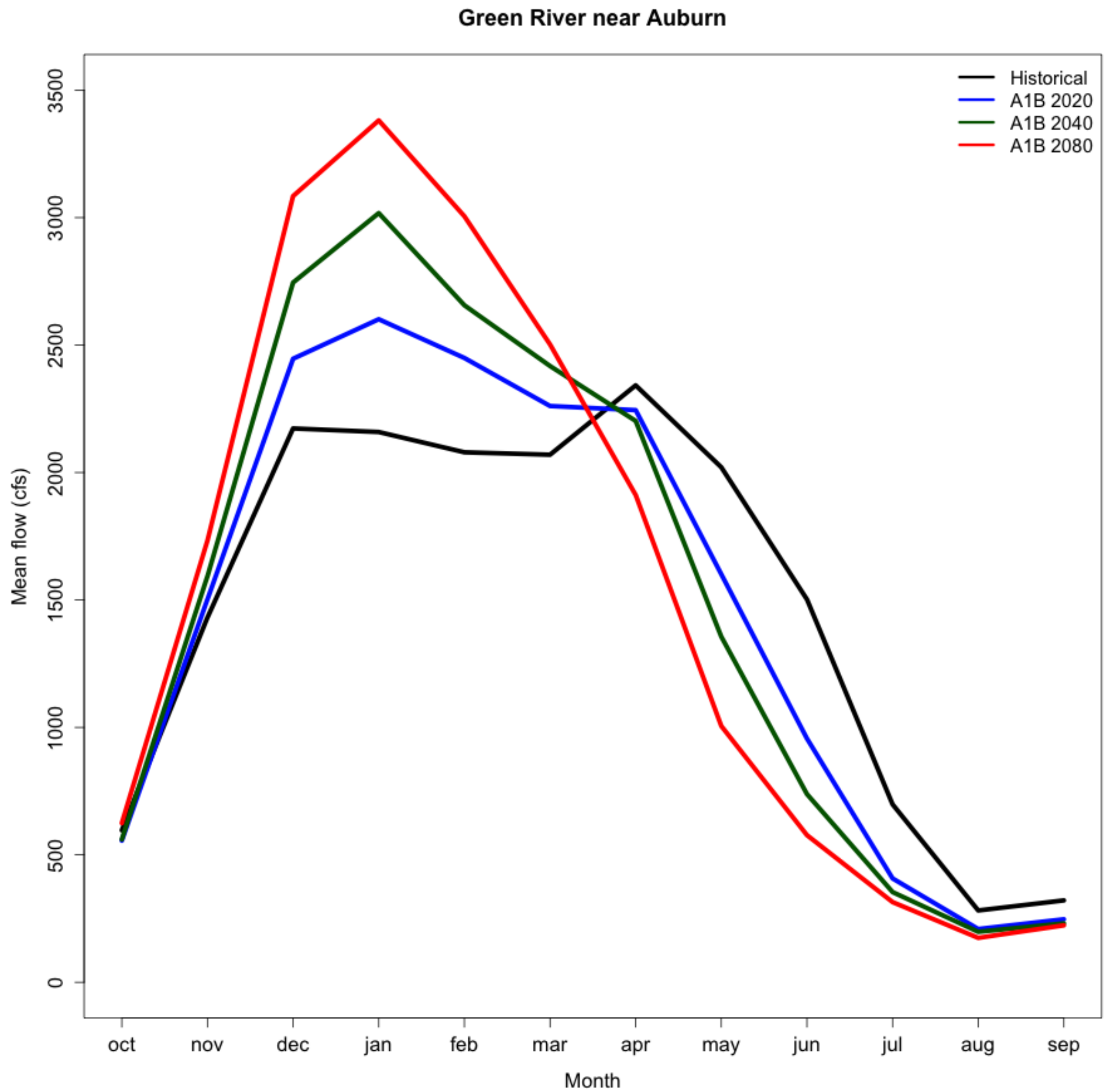

Figure 2. Projected Changes in Unregulated Streamflows for the Green River as Measured at Auburn. Historical flows (1916-2006) are shown by the black line. The blue, green, and red lines show the volume of unregulated streamflow flowing past Auburn for a moderate (A1B) warming scenario. Warmer winter temperatures cause the snowline to move up in elevation and lead to more winter precipitation falling as rain rather than snow. The net result is higher fall and winter streamflows, lower winter snowpack, lower spring streamflows, and a shift in the timing of peak streamflow from spring into winter. By the 2080s, peak runoff shifts from April-May to December-January. Unregulated streamflows are natural streamflows unaffected by dams. *Figure source: University of Washington Climate Impacts Group, Columbia Basin Climate Change Scenarios Project website (http://warm.atmos.washington.edu/2860)*.

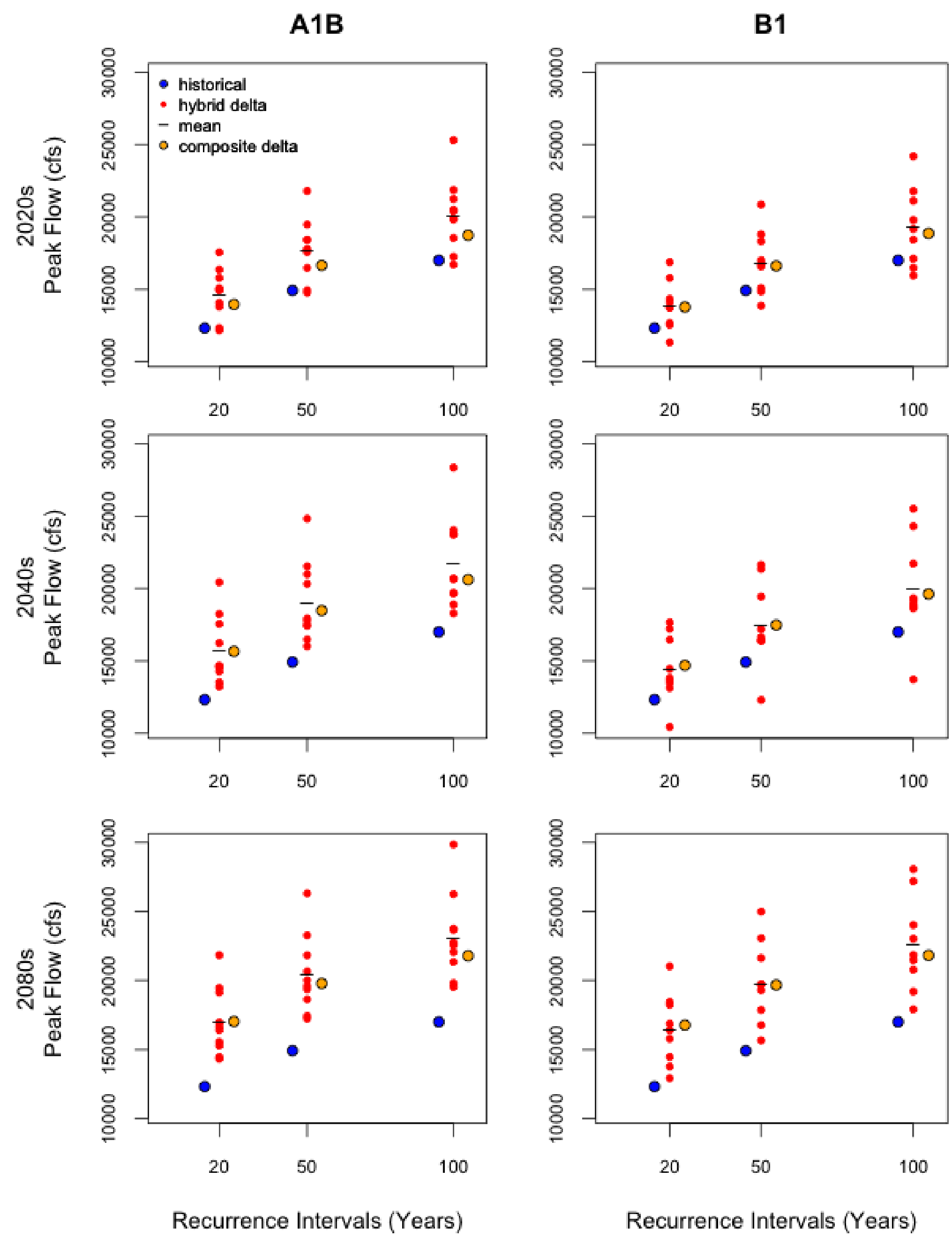

Figure 3. Projected Changes in the 20-year (5% probability), 50-year (2%), and 100-year (1%) Flood Events for Unregulated Peak Flows for the Green River at Auburn. This figure shows simulated daily flood statistics (in cubic-feet per second, or cfs) at the 20, 50 and 100-year return interval estimated using fitted Generalized Extreme Value (GEV) probability distributions and two different downscaling techniques. Blue circles show simulated historical (1916-2006) value. Red circles show the range of values for hybrid delta scenarios (horizontal line shows the ensemble average) and the orange circles show the value for the composite delta scenarios. Unregulated streamflows are natural streamflows unaffected by dams. *Figure source: University of Washington Climate Impacts Group, Columbia Basin Climate Change Scenarios Project website (http://warm.atmos.washington.edu/2860).*

tracks are exposed to more frequent saturation or inundation. Both scenarios could trigger infrastructure upgrades on the part of BNSF.

Flooding over rail lines would most likely result in trip cancellations until the water recedes and BNSF has visually inspected the tracks. If water over the top of rail is deeper than two inches, movement along the track can create waves that reach the motors mounted on the bottom of train cars for turning wheel axles. These motors are typically only eight to nine inches above the top of the rail and therefore easily shorted by standing water. Trains can operate in these circumstances when necessary but only at walking speed; this generally would not be the desirable option. More severe river flooding could also increase debris flows, which can cause trip cancellations if debris builds up against bridges or damages infrastructure.

Supplemental Information: USACE Inundation Scenario Maps for the Green River. Subsequent to meetings with Sounder staff, project staff learned about flood inundation mapping in the Tukwila-Kent-Auburn area completed by the USACE for different Green River flood stages.[20] The inundation scenarios include peak flow rates that are consistent with peak flows expected with climate change. The mapping therefore provides insight into how projected changes in flooding could affect the south rail alignment in the Green River Valley.

As shown previously in Figure 3, multiple scenarios show future 2% (50-year) and 1% (100-year) flood events with a peak flow magnitude in the range of 20,000 to 25,000 cfs (or higher in a few cases). This magnitude of flooding in the Green River is already possible in today's climate, although it is currently near the upper confidence limit for flows associated with today's 0.2% (500-year) probability flood event.[21]

Figure 4 shows modeled inundation levels associated with a 25,000 cfs flow rate at the Auburn gage. At 25,000 cfs, the entire length of the south rail alignment from Emerald Downs in Auburn to areas north of I-405 in Tukwila runs through or is adjacent to areas inundated by flood waters. The track is not necessarily overtopped by water except (possibly) near the Tukwila station. Most areas along the alignment are projected to see 0-10 feet of inundation while a few areas could see as much as 15 feet. Existing levees are assumed to be intact but the map does not reflect ongoing levee fortification efforts, which could reduce flood risk.

Both the resolution of the available maps and map features used to mark jurisdictional boundaries make it difficult to conclusively determine whether the south rail alignment is overtopped, especially in the vicinity of the Tukwila Sounder station. While the maps show a great deal of detail, the USACE emphasizes that the maps are for planning purposes only and are not intended for fine scale (e.g., less than 180 feet x180 feet) analysis. Consequently, the specific inundation levels and their location are considered projections, not predictions.

It should also be noted that both the extent and depth of inundation varies with different flood flow rates. Other modeled intervals included flows of 13,900 cfs, 17,600 cfs, and 19,500 cfs. Impacts to the south rail alignment for flow rates of 13,900 cfs are limited to Auburn in the area north of S. 277th Street and south of the Green River's horseshoe bend, where inundation levels of 2-10 feet are projected. The geographic extent of flooding, including inundation in and around the Tukwila station, becomes more significant for Sounder at flow rates of 17,600 cfs and higher.

[20] Green River Valley Flood Risk Maps, available at: http://www.nws.usace.army.mil/Missions/CivilWorks/LocksandDams/HowardHansonDam/GreenRiverFloodRiskMaps.aspx

[21] (USACE) U.S. Army Corps of Engineers. 2012.

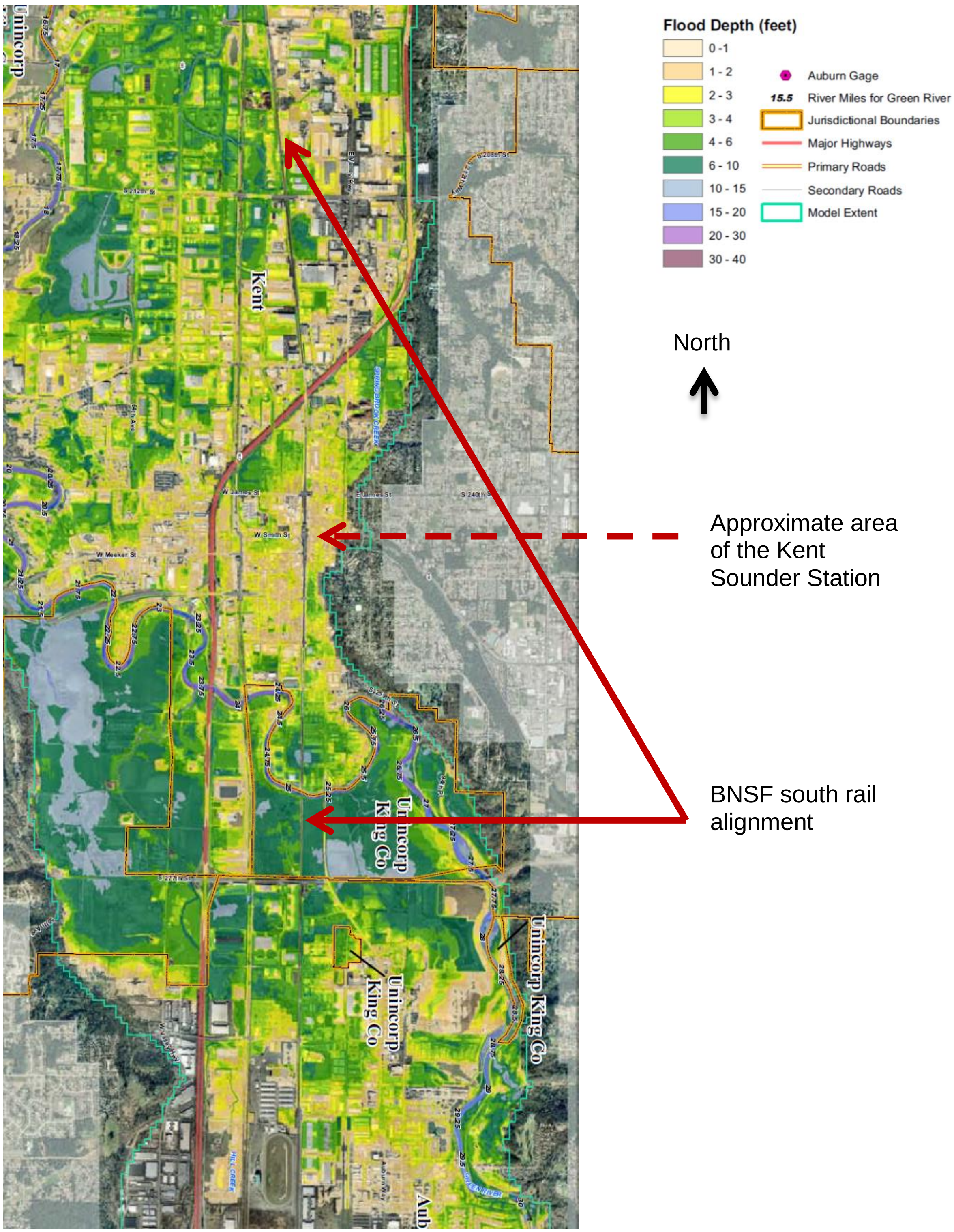

Figure 4. Potential Inundation, Shown as Simulated Water Depth, in Kent for a Peak Flow at Auburn Gage of 25,000 cubic feet Per Second. Assumes levee system is functioning. *Map produced by the U.S. Army Corps of Engineers. Available at: http://www.nws.usace.army.mil/Missions/CivilWorks/LocksandDams/HowardHansonDam/GreenRiverFloodRiskMaps.aspx*

It is important to note that the potential for bigger floods as a result of climate change is mitigated to some degree by the presence of levees and the Howard Hanson Dam. However, as emphasized by the USACE and King County, these systems only reduce–not eliminate–the increasing risk of flooding.[22] Additionally, any infrastructure located in the 100 year flood plain is subject to FEMA floodplain regulations. Any future changes in FEMA flood zones as a result of observed changes in flooding, climate change considerations, or other factors could also affect operations and long-term planning.

2.5. Sea Level Rise and Related Coastal Issues

What is the Issue?
Most of the north rail alignment used by Sounder (~30 miles of the 34 mile corridor, from Everett to Seattle) runs immediately along or in close proximity to the Puget Sound shoreline at elevations low enough to expose the alignment to extreme high tides, coastal flooding, storm surge impacts, and sea level rise (Figure 5). Additionally, small segments of the south rail alignment in the Fife-Tacoma area are located in or near areas where sea level rise could temporarily or permanently inundate track or track bridge foundations. Sea level rise can also exacerbate existing flood risks by effectively “backing up” flood waters in rivers and streams as they try to drain into Puget Sound. When this occurs, even modest river flooding can produce larger flood impacts relative to today’s flood events.

Impacts to Date
Impacts to date on the Sounder alignment from extreme high tides, coastal flooding, storm surge impacts, and observed sea level rise (which cannot be exclusively attributed to human-caused climate change at this point) were considered minor.

Monitoring of long-term sea level trends is limited in the Puget Sound region. The only long-term monitoring station located in the Sound Transit service area is in Seattle, where sea level has increased approximately 0.68 feet over the past 100 years (Figure 6). Increasing sea level is also found at the other Puget Sound monitoring stations (Port Townsend, Friday Harbor, Bellingham) although the amount of sea level rise varies with each location.

Changes in sea level can also affect tidal reach. The highest observed tide for Seattle occurred on January 27, 1983 (12.14 feet above NAVD88). This was nearly matched on December 17, 2012 (12.13 feet). Extreme tidal heights associated with storms have ranged from 1.48 feet above Mean High High Water (MHHW)[23] for a storm with a return frequency of once a year to 3.19 feet above MHHW for the 100 year (1% chance) storm event.[24]

Storm surge and erosion impacts along the north rail alignment are currently managed with a stacked block sea wall and sloped rock revetments maintained by BNSF. High tides and storm surge events can still affect rail infrastructure and operations, however. This may include

[22] “Flood preparation for the Green River Valley”, http://www.kingcounty.gov/safety/FloodPlan/GreenRiverValley.aspx, accessed April 16, 2013; Howard Hanson Dam Frequently Asked Questions, March 2011, available at: http://www.wadisasternews.com/external/content/document/1105/1030291/1/F-HHDFAQMarch 2011%20doc%20%282%29.pdf
[23] Mean Higher High Water is the average of the higher high water height of each tidal day observed over a 19 year tidal epoch. The MHHW for Seattle is 9.01 feet above NAVD88 zero feet.
[24] King County Wastewater Treatment Division. 2008.

Figure 5. The North Alignment Used by Sounder Runs in Close Proximity to Puget Sound. *Photo source: Sound Transit.*

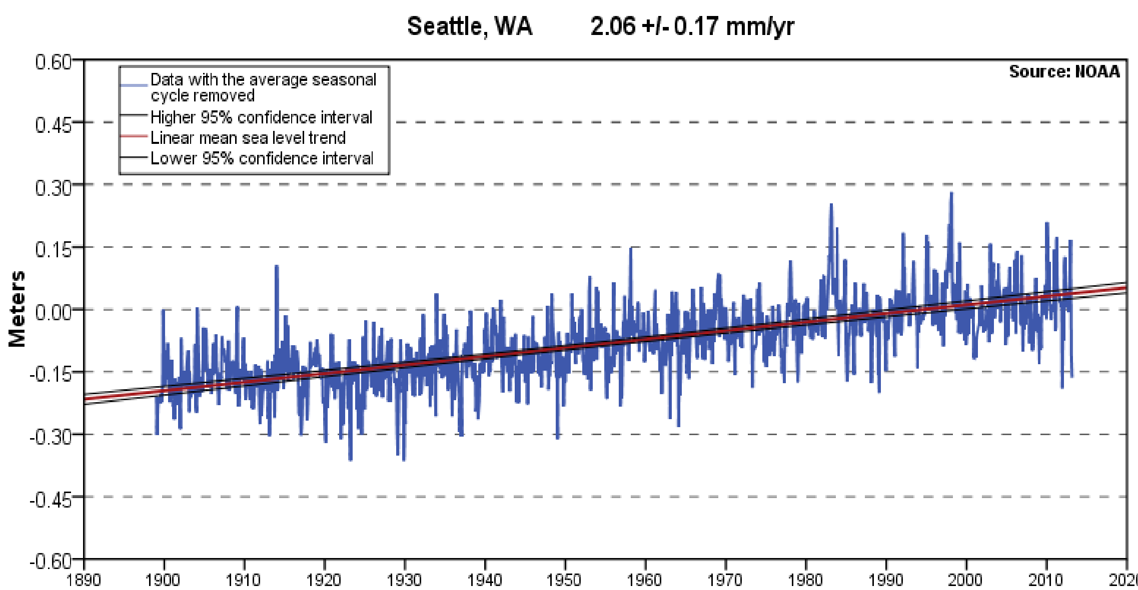

Figure 6. Long-term Linear Trend in Sea Level in Seattle, 1898-2006. The mean sea level trend is 2.06 millimeters/year with a 95% confidence interval of +/- 0.17 mm/year based on monthly mean sea level data from 1898 to 2006. This rate of change is equivalent to a change of 0.68 feet in 100 years. *Figure source: NOAA Tides and Currents*.[25]

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[25] NOAA Tides and Currents: http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=9447130%20Seattle,%20Puget%20Sound,%20WA

periodic operational delays during high tide or high wave events[26] that can cause waves to break across the tracks or against trains, or which cause damage to track infrastructure by pulling ballast from the road bed or washing away track supports.

Projected Impact

The geographic extent and severity of sea level rise impacts will vary based on how much sea level rise occurs and how quickly it rises. Staff rated the projected impact of sea level rise and related coastal issues on Sounder as moderate (if sea level rise is low) to extreme (if sea level is high).

As noted in Appendix B, two sea level rise scenarios were mapped to inform discussions with Sound Transit staff: 22 and 50 inches. These scenarios were used to provide consistency with the Washington State Department of Transportation's state-wide vulnerability assessment[27] and are currently considered average to high sea level rise scenarios for 2100 (Table 5). Segments potentially affected by sea level rise and associated impacts are listed in
Table 6.

Expected impacts, even at the low end of the projections, include more frequent service interruptions due to increased wave reach, storm surge, and more frequent temporary flooding of low-lying areas due to higher high tides. The combined effects of more flooding in rivers and streams with sea level rise can also lead to more flooding of low-lying areas, especially when flooding coincides with high tides. More frequent exposure of low-lying track infrastructure to marine water is also expected. These impacts will affect infrastructure and services in areas already affected by storm surge, flooding, and high tides in new ways while also reaching new, previously unaffected areas. Permanent inundation of low-lying track is possible under the high (50 inch) sea level rise scenario, including track leading to the Edmonds and Mukilteo stations (Figure 7 and Figure 8).[28] Potential impacts on the stations are addressed in Appendix C.4.

Table 5. Projected Sea Level Rise for Seattle, Washington, Relative to Year 2000. The projected mean is based on a moderate (A1B) greenhouse gas emissions scenario. The projected range shows results for the low (B1) to the high (A1FI) greenhouse gas emissions scenarios. Values take into account global sea level rise projections as well as regional factors, such as vertical land motion. *Source: NRC 2012.*

	Projected Average	*Projected Range*
2030	+2.6 in. *(+/- 2.2 in)*	-1.5 in. to +8.8 in.
2050	+6.5 in. *(+/- 4.1 in)*	- 1 in. to +18.8 in.
2100	+24.3 in. *(+/- 11.5 in)*	+3.9 in. to +56.3 in

[26] For example, BNSF issued a 10-15 minute delay notice for North Sounder service on 4/29/13 due to a high tide.
[27] WSDOT. 2011.
[28] The sea level rise mapping done for this project assumes no adaptive action has been taken to reduce the potential for, or consequences of, inundation

Table 6. Sounder Alignment Segments Potentially Impacted by Sea Level Rise and Associated Hazards. Mileposts rounded to the nearest whole number. Hazards assessment assumes present day conditions (i.e., no additional adaptive actions taken to reduce the risk).

Segment	*Mileposts*	*Map Nos.*	*Related Coastal Hazard*
North Sounder			
Elliot Bay Park – Myrtle Edwards Park (Seattle)	2-3	S-39 to S-40	Sea level rise inundation (22 inch and/or 50 inch zones depending on location), extreme high tides, storm surge, coastal flooding.
Golden Gardens Park (Seattle) – Pigeon Creek Beach (Everett)	8-32	S-3 to S-34	Sea level rise inundation (22 inch and/or 50 inch zones depending on location), extreme high tides, storm surge, coastal flooding.
South Sounder			
Fife, along parts of Pioneer Way E.	36X-38X	S-72 to S-74	Potential for bigger flood “footprint” due to the compounding impact of higher base sea level and flood flows in the Puyallup River
Tacoma, near Bay Street	38X-39X	S-75 to S-76	Inundation from sea level rise (50 inch scenario only) could affect track or bridge foundations.

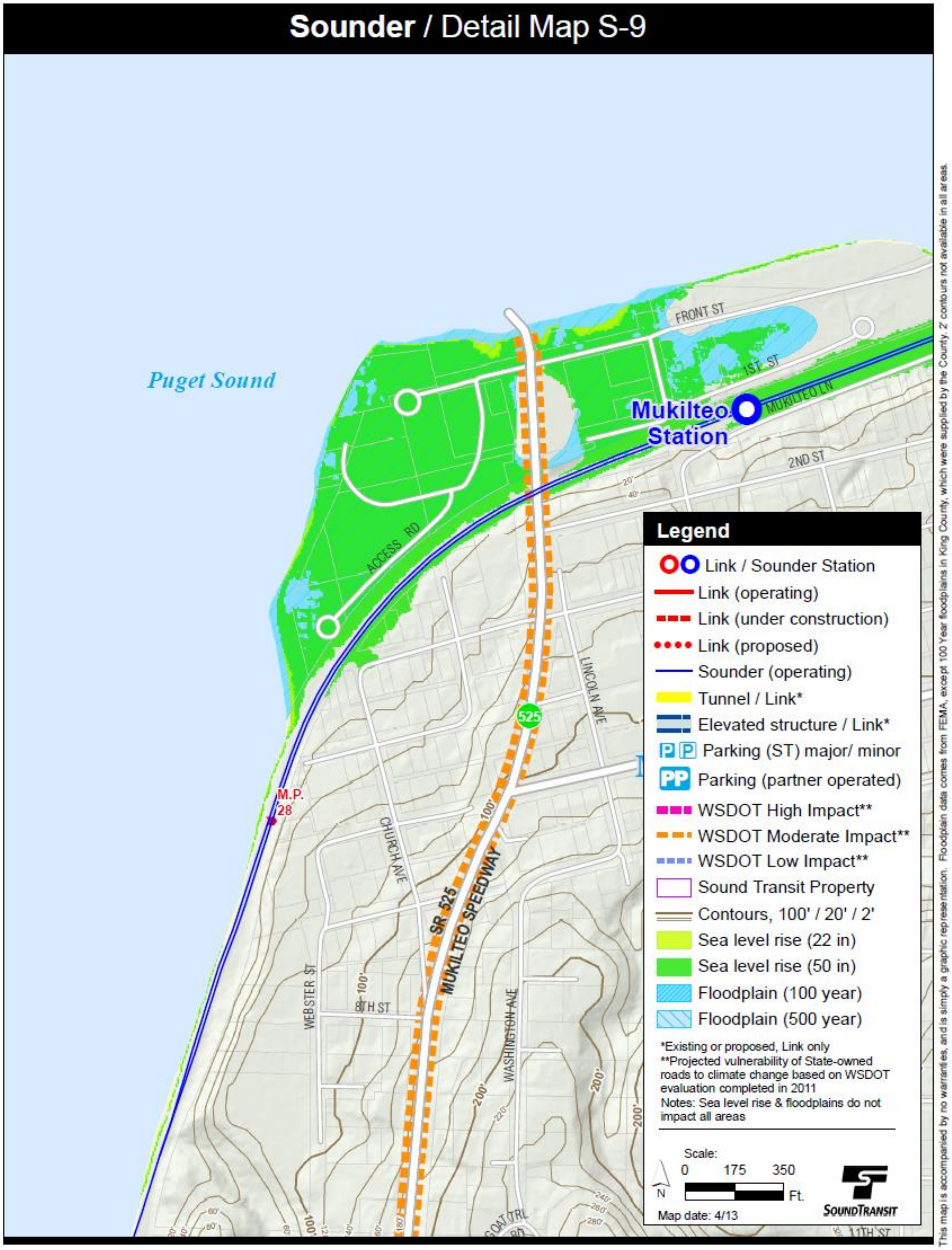

Figure 7. Projected Inundation Zones for 22 Inches and 50 Inches of Sea Level Rise in the Vicinity of the Mukilteo Station. *Map produced by Sound Transit.*

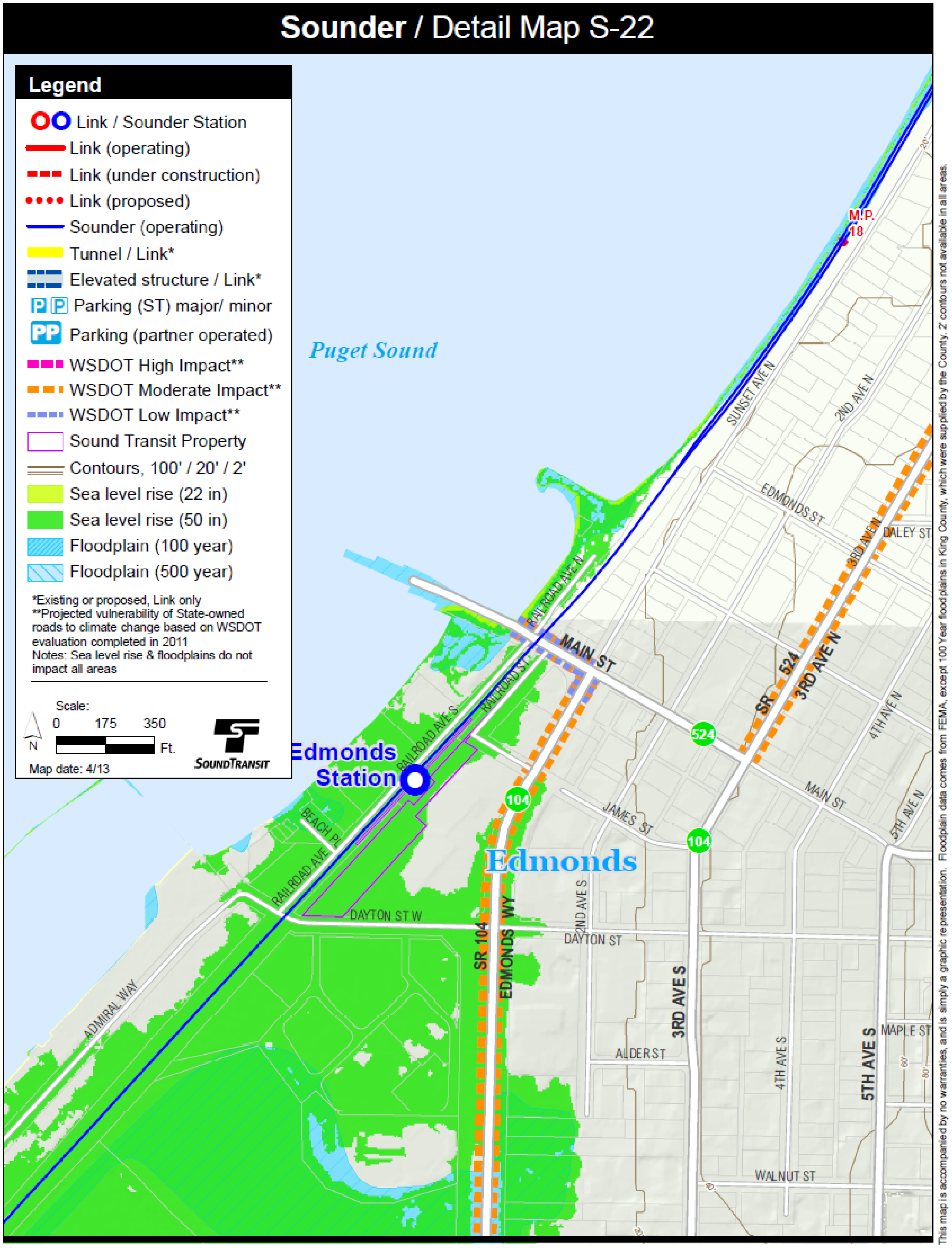

Figure 8. Projected Inundation Zones for 22 Inches and 50 Inches of Sea Level Rise in the Vicinity of the Edmonds Station. *Map produced by Sound Transit.*

3. Adaptation Options

Options for adapting to the impacts of climate change are discussed in the following sections. The adaptation options provided here are not intended to be an exhaustive list of all possible approaches; they are an initial list of options considered most relevant to Sounder based on the impacts identified through the Climate Risk Reduction Project and input from Sound Transit staff. ***In all cases, these actions should be considered optional and in some cases "if needed."***

Because climate change exacerbates many existing issues, some of the adaptation options are activities that would be pursued regardless of any knowledge about climate change or any pre-emptive efforts to adapt (i.e., as part of "business as usual"). However, climate change may accelerate the need for these adaptation options and/or require implementation at a scale larger than would normally be expected. In other cases, climate change may raise the need for new approaches or cause reprioritization of options.

Decisions about which adaptation options to employ, and when, will depend on how rapidly climate change occurs and the cost of implementing the adaptation option(s). These costs will vary with the specifics of the adaptation option, the scale of deployment, and how readily the option can be integrated into routine asset maintenance and replacement cycles, among other factors. Further discussion and analysis of these issues is required before these or other adaptation options not included here can become implementation-ready recommendations. Adapting Sounder operations and infrastructure to climate change will also be shaped by—and require effort on the part of—all three major rail users. If current agreements are carried forward, management for many issues would fall to BNSF as the owner of most of the rail used by Sound Transit for Sounder. An exception to this is the 8.2-mile Tacoma to Lakewood segment owned and maintained by Sound Transit.

3.1. Heat Impacts

<u>Potential for Rail Buckling</u>. Adaptation options for addressing the potential for rail buckling include extension of current practices as well as new options, which are grouped into one of two categories. The first category is actions that directly reduce the potential for rail buckling by making structural changes to the track or track bed. These options may include any combination of the following:

- If technically possible, evaluate how much change in temperature may be needed to require raising rail-neutral temperature given rail age and location;
- Raise rail neutral temperature;
- Increase track ballast maintenance to improve stability/rail support;
- Replace stone ballast with concrete slab where increasing ballast maintenance becomes cost prohibitive or is difficult to do;
- Replace wood ties with concrete crossties, which are better able to resist movement but may require more frequent replacement on track used by heavy freight trains; and
- Employ new technologies that allow movement of rails to accommodate expansion.

The second category helps manage the risk of rail buckling by informing decisions about when and where to issue slow orders. Information gathered through these approaches may also help inform decisions about the potential structural changes listed in the first category of adaptation options. These options may include any combination of the following:

- Directly monitoring actual rail temperature through the use of thermocouples,
- Using models to predict rail temperatures based on real time weather forecast data, e.g., the Federal Railroad Administration model tested on Amtrak's Northeast Corridor[29];

Implementation of these actions by Sound Transit may be limited to track owned by Sound Transit (Tacoma to Lakewood). Decisions about implementing these actions on other portions of the alignment used by Sounder would be made by BNSF. In all cases, implementation of the listed adaptation actions can be limited to areas with a higher risk or history of rail buckling. Cost will depend on how extensively any option is deployed and by whom.

Staff noted that the occurrence of a single rail buckle would be enough to trigger a conversation on the issue with BNSF, or within the agency if the buckle occurred in the Tacoma to Lakewood segment. Potential adaptive actions would be considered if rail buckling affected a particular stretch of track recurrently.

HEP Units and Signal Bungalows. Adaptation options for heat stress on Sounder locomotive HEP units and signal bungalows owned by Sound Transit may include any combination of the following:

- Increase the frequency of routine testing, maintenance, and replacement of HEP units on Sounder locomotives as temperatures increase;
- Increasing air conditioning capacity in equipment structures owned by Sound Transit; and
- Where possible, increase shading around signal bungalows or use more reflective roof coating to reduce demands on air conditioning systems.

Most of the identified adaptation options would be easy for Sound Transit to accommodate. Both the locomotive HEP units and back-up battery units for signal bungalows are tested, maintained, and replaced in accordance with manufacturer recommendations (in the case of the HEP units) and FRA regulations (in the case of the batteries). Increasing the frequency of routine testing, maintenance, and replacement would not be difficult given that the procedures for these steps are already in place. The primary implications of these actions are added maintenance and operations costs.

One heat stress adaptation option that could pose some challenges is the option of increasing air conditioning capacity for equipment buildings. Increasing air conditioning capacity may require structural changes to accommodate the added weight of larger or more air conditioning units.

3.2. Precipitation Impacts

Increased Mudslide Activity. As noted in Section 2.4, efforts to address mudslide risk at priority locations along the north rail alignment are ongoing as a result of the dramatic rise in mudslides affecting rail transport between Seattle and Everett in 2012-13. These efforts reduce the risk of

[29] Zhang, Y.-J. and L. Al-Nazer. 2010

mudslides for today’s climate. However, projected increases in precipitation—an important contributing cause of mudslides—will increase the potential for mudslides along the north rail corridor. Options for adapting to more frequent mudslides may include any combination of the following:

- Plan for increased use of bus bridges to transport passengers when slides occur;
- Work with rail partners (BNSF, Amtrak, and the Washington Department of Transportation) to model the frequency and location of future mudslide risk based on projected changes in precipitation to inform decisions about slide intervention activities (e.g., slope stabilization, maintenance, community outreach);
- Work with rail partners to expand the use of slide intervention activities to additional priority areas;
- Implement and continue refining predictive models for slides, including installation of additional rain gages and other monitoring devices that can help improve the accuracy of the models over time.

3.3. Increased River Flooding

As with other climate impacts, adapting to increased river flooding along the rail alignment used by Sounder is largely the domain of BNSF. Actions by the USACE and floodplain communities will also influence the degree to which river flooding affects Sound Transit.

Adaptation options for Sound Transit and/or BNSF for addressing increasing flood risk and isolated flooding on Sounder rail may include any combination of the following.

- Update emergency planning procedures and relevant design standards for longer-lived or hard-to-upgrade infrastructure to reflect a wider range of projected flood risks;
- For any future Sounder extensions built by Sound Transit, modify design standards to provide higher level of flood protection for rail that must be located in or near flood hazard zones (e.g., raising minimum top-of-rail height based on 100 year flood elevations or extending this design preference out to the 500 year flood zone);
- Work with the USACE and floodplain communities to help ensure that Sound Transit’s current and projected flood management needs are considered in flood management and hazard mitigation decisions; and
- Work with BNSF to raise track elevations in areas with recurrent flooding.

Relocating track out of the Green River floodplain or away from other flood plains by BNSF was not considered an option given the high costs of relocation relative to the anticipated short-term impacts of flooding.

3.4. Sea Level Rise

Adaptation options for sea level rise are potentially very costly and decisions about which options to pursue will require continued cooperation with BNSF and Amtrak. Adaptation options may include any combination of the following:

- Work with BNSF on improvements to and upgrading of the sea wall where needed;
- Work with BNSF to raise track elevation and relevant overheard clearances; and

- Update service interruption plans to accommodate more service interruptions from high tides and storm surges, including more frequent short-term delays associated with high tides and more frequent use of bus bridges if trains have to be cancelled due to tides or storm surge damage.

Staff noted that any decisions on the part of BNSF to raise track elevation would require costly retrofits on the part of Sound Transit to raise stations platforms and facilities to meet new track grades.

3.5. System-wide Adaptation Options

While most adaptation options could be categorized by climate impact, some options were relevant across a range of issues. These may include any combination of the following:

- Increase the use of double track where 1) single track exists, and 2) climate change impacts would warrant installation of additional track to reduce or eliminate the potential for service interruptions;
- Update relevant design standards for longer-lived or hard-to-upgrade infrastructure to reflect a wider range of potential temperatures, precipitation, flood flows, high tide levels, and storm surge impacts; and
- Evaluate, and where relevant update, metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

An additional potential adaptation need identified by staff late in the project was the need for more proactive vegetation removal to reduce the potential for fires near the track. The potential for grass fires on infrastructure was not discussed during the workshop.

4. Summary of Findings

The vulnerability assessment for Sounder explored a range of potential climate impacts on the rail alignment used by Sounder and associated train and track infrastructure. This included impacts associated with more extreme heat, increasing precipitation, increasing flood risk, and sea level rise. All of the climate change impacts evaluated by staff were expected to have the same or greater impact on Sounder operations and planning relative to experience to date with climate impacts. The most significant impacts were associated with increased mudslide activity and sea level rise, both of which are already issues for the North Sounder service to some degree. The vulnerability assessment findings are summarized in Table 7.

The extent to which climate change impacts will affect Sounder can vary depending on location and magnitude of change. While a segment by segment (i.e., milepost by milepost) assessment of climate impacts was beyond the scope of this project, it is possible to make some qualitative assessments of how climate change impacts may differentially affect the north and south rail corridors. These findings are summarized in Table 8 and discussed here.

Both the north and south corridors are exposed to a range of impacts that could result in more service interruptions and increased operating and maintenance costs for Sound Transit and/or its operating partners. The north alignment is more impacted by climate change overall because of the north corridor's extensive exposure to sea level rise and storm surge and the potential long-term implications of permanent inundation in various parts of the alignment, especially near the Edmonds and Mukilteo stations. Climate change is also projected to increase the likelihood of mudslides along the north line.

Sound Transit is generally insulated from the increased cost of repairing and maintaining the tracks in a changing climate because Sound Transit does not own the tracks on which Sounder North operates. Sound Transit's most significant direct costs for Sounder North—and likely for Sounder overall—would therefore be associated with preparing for and/or responding to the impacts of climate change on track in the vicinity of the Edmonds and Mukilteo facilities (see Appendix C.4 for more information on impacts to the facilities themselves). Sound Transit would also be directly responsible for preparing for and/or responding to any heat and drainage impacts affecting Sound Transit-owned track from Tacoma to Lakewood.

Table 7. Summary Assessment of Current and Projected Climate Impacts on the Sounder Alignment. Facilities were evaluated separately. Rating based on input from Sounder staff who participated in project workshops. Bold indicates impacts that are expected to have a larger impact on Sounder moving forward in time as a result of climate change. "Expected" impacts are those that would be expected to occur even at the low end of climate change projections. "Possible" impacts are impacts likely to occur in limited cases and/or at higher amounts of climate change.

Projected Impact *(i.e., potential for more...)*		***Current Impact Rating***	***Projected Impact Rating***	***Potential Impact(s)*** *Assumes no intervening adaptation measure taken….*	***Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact***	***Scientific Confidence Regarding Change in Underlying Climate Cause(s)***
Heat Impacts	Rail buckling	Minor	**Moderate**	*Expected impact(s):* • More frequent heat advisories, visual monitoring, slow orders. *Possible impact(s):* • For track owned by Sound Transit, more heat-related track repairs possible. • If misalignments occur, potential for derailment increases but still extremely low given existing prevention measures.	(+) Impacts would be limited to the late afternoon trips; morning operations not affected by heat unless repairs required. (+) Double and triple track in area with the heaviest ridership (Seattle to Tacoma) makes it easy to work around any rail buckles in those areas. (+) ST-owned track from Tacoma to Lakewood uses concrete ties, which are better able to constrain rail expansion than wood ties. (-) Remainder of track used by Sounder is continuously welded rail with wood ties, which is more likely to buckle than track with concrete ties.	*High*. High confidence that average and extreme summer temperatures will increase. High confidence that temperatures will more frequently cross temperature thresholds that trigger advisories and other prevention activities.

Projected Impact *(i.e., potential for more...)*		***Current Impact Rating***	***Projected Impact Rating***	***Potential Impact(s)*** *Assumes no intervening adaptation measure taken….*	***Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact***	***Scientific Confidence Regarding Change in Underlying Climate Cause(s)***
	Heat stress on HEP units and signal bungalows	Minor	**Moderate**	*Expected impact(s):* • Increased maintenance of HEP units. • Trip cancellations if HEP units fail. • Increased maintenance and replacement of ST-owned signal bungalow air conditioning units. • Increased operating costs for air conditioning. *Possible impact(s):* • Need to increase air conditioning capacity.	(+) Air conditioning is already required for all signal bungalows.	*High*. High confidence that average and extreme summer temperatures will increase.
Impacts Related to Precipitation and/or Sea Level Rise	Mudslides	Minor, for up to 33 trains cancelled	Moderate (for up to 70 trains cancelled) **Significant to extreme**, for higher levels (>70 cancellation s)	*Expected impact(s):* • More train cancellations due to mandated wait period • Increased use of bus bridges *Possible impact(s):* • Potential impact on customer confidence in service reliability with more frequent cancellations. • Potential for damage to	(+) Current efforts on the part of BNSF, Sound Transit, Amtrak, and the Washington Dept. of Transportation will reduce or eliminate mudslide risk in current problem areas. (+) Previous efforts to address mudslide risk have reduced mudslides in areas where work was conducted. (-) Exposure to mudslides extends over long	*Medium.* Based on current model runs, there is good confidence that average and extreme winter precipitation will increase but low confidence in specifically how much.

Projected Impact *(i.e., potential for more...)*		**Current Impact Rating**	**Projected Impact Rating**	**Potential Impact(s)** *Assumes no intervening adaptation measure taken….*	**Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact**	**Scientific Confidence Regarding Change in Underlying Climate Cause(s)**
				trains and/or derailment increases with more mudslides, but still a very low possibility given existing prevention measures.	portions of the North Sounder alignment, making it costly to address mudslide potential. (-) Predicting the timing and location of mudslides is difficult given the many factors (in addition to precipitation) that influence mudslide risk.	
	Increased river flooding (Green, White Rivers)	Minor	**Moderate**	*Expected impact(s):* • More frequent slow orders along the south rail alignment *Possible impact(s):* • Reduced train speeds or train capacity possible if the tracks are exposed to more frequent saturation or inundation. • Trip cancellations possible if flooding covers rail lines, or if flood debris impacts bridges or infrastructure.	(+) Potential impacts on the rails are contingent on rivers reaching or exceeding flood stage more often; increased flooding that stays below flood stage would likely have little impact on operations. (-) Impacts on south rail alignment affect larger number of passengers.	*Moderate to high.* There is high confidence that climate change will cause shifts in streamflow timing and increase winter flows in rivers influenced by snowmelt. There is less confidence in the specific size of the shift and less confidence in the amount of potential flooding in low-elevation rain-dominant rivers and streams given uncertainties about changes winter precipitation.

Projected Impact *(i.e., potential for more...)*		***Current Impact Rating***	***Projected Impact Rating***	***Potential Impact(s)*** *Assumes no intervening adaptation measure taken….*	***Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact***	***Scientific Confidence Regarding Change in Underlying Climate Cause(s)***
	Sea level rise and related coastal issues (e.g., storm surge, coastal flooding)	Minor	**Moderate** (at lower end of projections) **Extreme** (at higher end)	*Expected impact(s):* • More frequent service interruptions due to higher high tides, increased wave reach, storm surge. • Increased exposure of low-lying track infrastructure to marine water. • Increased and/or more extensive temporary flooding of low-lying areas due to higher high tides • Where relevant, increased flooding in rivers and streams. *Possible impact(s):* • Permanent inundation of low-lying track possible under high (50 inch) sea level rise scenario.	(+) Wave energy is limited in Puget Sound relative to the outer coast, although large waves are still possible. (+) Current sea wall provides protection from permanent inundation in most areas of the alignment, even under the high (50 inch) sea level scenario. Storm surge could still be an issue, however. (+) Presence of other commercially important facilities creates a large incentive enhancing coastal defenses in Edmonds, Mukilteo, and Tacoma, although drainage issues could still become a problem. (-) North Sounder service is highly exposed to sea level impacts given how close the track runs to Puget Sound and the length of the alignment.	*High* (that sea level will rise) and *low* (how much rise will specifically occur).

Table 8. Relative Likelihood of Climate-related Impacts on the North and South Alignment Used by Sounder. “System Exposure” broadly identifies which parts of the Sounder alignment (North, South, or both) come into contact with the projected impact. Likelihood for each alignment is assessed from the base assumption that all of the listed impacts are considered more likely to occur when compared to present day climate because of changes in the underlying climate drivers that influence these impacts. “More likely” means that the impact could occur sooner on a particular alignment, relative to the other, given factors specific to that alignment.

	Projected Impact (i.e., potential for more….)	*System Exposure*	*North Line Sounder*	*South Line Sounder*	*Comments*
Heat Impacts	Rail buckling	System-wide	Likely	***More likely***	Can be an issue anywhere but temperatures along Puget Sound are moderated relative to areas farther from the Sound.
Heat Impacts	Heat stress on electrical equipment	System-wide	Likely	***More likely***	Can be an issue anywhere but temperatures along Puget Sound are moderated relative to areas farther from the Sound.
Related to Precipitation and/or Sea Level Rise	Increased mudslide activity	Primarily N. Sounder	***More likely***	Likely, but geographically limited	South Sounder has few areas with steep slopes. North Sounder has history of problems with mudslides.
Related to Precipitation and/or Sea Level Rise	River flooding	System-wide	***More likely*** *but small scale (i.e., from small streams emptying into Puget Sound)*	***More likely,*** *and larger scale, but moderated by dams, levees, or high embankments in most areas*	Increased flooding expected in the Green and Duwamish Rivers, and along the White and Puyallup Rivers.
Related to Precipitation and/or Sea Level Rise	Permanent inundation of low-lying areas	N. Sounder, Tacoma	***More likely***	***More likely*** *but limited to Tacoma*	Due to sea level rise. Track in Edmonds, Mukilteo most affected. Small area of Tacoma affected.
Related to Precipitation and/or Sea Level Rise	Storm surge	North Sounder	***More likely***	n/a	Affects segments running along Puget Sound shoreline.

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Link Light Rail: Vulnerability Assessment and Adaptation Options

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1. Executive Summary

Climate change is likely to have minor to moderate impacts on the Link alignment. The only climate change impact that is potentially significant for Link is rail buckling. Rail buckling can result in costly track repairs and, in rare cases, damage to trains or derailment. The potential for buckling is higher, although still low overall, for Central Link relative to the new Link alignments due to recent design changes that raised rail neutral temperature for new Link alignments. The potential for buckling is also low because of the rail types predominantly used by Link (direct fixation and embedded track) and existing safety measures.

Other heat-related impacts include heat stress on the overhead catenary system and electrical equipment. Like rail buckling, these impacts could occur anywhere in the aboveground or at-grade portions of the Link system. However, they are more likely in areas with prolonged sun exposure and extensive paving. Both are considered to have minor impacts on Link operations and planning.

Precipitation-related impacts include the potential for river flooding and increased localized flooding due to more stormwater runoff or poor drainage. Impacts from river flooding on Central Link are currently limited to the alignment's Duwamish River crossing. Flooding in the Duwamish is expected to increase because of projected increases in Green River flooding and sea level rise, which can make it more difficult for tidally-influenced rivers like the Duwamish to drain floodwaters to Puget Sound. Other areas potentially affected by flooding include ground-level portions of the possible East Link extension in Redmond (currently unfunded) and, to a much lesser degree, the Lynnwood Extension and the ground-level portion of East Link's proposed alignment near the planned Hospital Station.

Localized flooding is associated with more intense precipitation events and has the potential to occur anywhere in the system, particularly in areas with extensive paving, flat topography, and/or low-lying areas. This includes the south downtown area (SODO Station area and Link maintenance base) and the Rainier Valley, among others.

Adaptation options for Link range from increased visual or electronic monitoring to moving or relocating sensitive infrastructure (primarily electrical equipment). Unlike other modes, Sound Transit is sole owner and operator of the Link system. This gives Sound Transit full control over decisions about adapting Link to climate change. However, this also means that any costs associated with adapting Link infrastructure will be Sound Transit's responsibility. This cost exposure will continue to grow along with the system.

2. Vulnerability Assessment Results

2.1. Potential Climate Change Impacts Evaluated

Potential climate change impacts evaluated for Link are listed in Table 1. Potential changes in snow and ice events were not discussed in the project given the current lack of information regarding how these types of events may change as a result of climate change. Over time, however, the frequency of snow and ice events may decrease. There was also no information available on projected changes in wind speeds greater than 55 miles per hour, which could cause temporary delays or cancellations for trains crossing Lake Washington on the I-90 floating bridge.

Table 1. Projected Climate Change Drivers and Related Impacts Evaluated for Link.

Projected Climate Change	*Potential Impacts on Link*
Warmer average summer temperature and more extreme heat	• Rail buckling • Heat stress on the overhead catenary system • Heat stress on Traction Power Substations, signal bungalows, and small signal boxes
Increase in average winter precipitation and more extreme precipitation	• Increased river flooding (Duwamish River) • Increased localized flooding due to more stormwater runoff or poor drainage • Increased groundwater seepage into tunnels due to higher groundwater tables

Staff was asked, via participation in two workshops, to qualitatively assess the degree to which the impacts listed in Table 1 could affect operations and planning for Central Link, Tacoma Link, and the various Link extensions currently being planned or under construction. The evaluation focused on the impact to rail and associated infrastructure; potential impacts on facilities were discussed in a separate assessment on customer facilities (see Appendix C.4). Impacts to date were evaluated for Central and Tacoma Link, while future impacts were evaluated for current and future Link alignments.

All of the impacts listed in **Error! Reference source not found.** are considered more likely because of projected changes in climate. Many of the listed impacts are already possible in today's climate and therefore not unique to climate change. However, climate change may alter the frequency, intensity, location, or duration of these impacts by affecting the underlying climate drivers (e.g., temperature, precipitation, sea level) that cause an impact. In other cases, climate change introduces new challenges or brings existing challenges to new areas. For more on projected changes in regional climate, see Appendix A.

2.2. About This Summary

The results of the Link vulnerability assessment and adaptation workshops are described in the following sections and summarized in Section 4. For each potential climate change impact, the nature of the impact is briefly summarized and impacts to date on Link operations noted. Anticipated issues are identified and discussed generally in terms of expected and possible impacts. "Expected" impacts are those that would be expected to occur even at the low end of current climate change projections. "Possible" impacts are impacts that would occur in limited cases and/or at higher amounts of climate change.

Note that while climate change makes the impacts listed in Table 1 more likely, the probability that impacts occur will be shaped by design decisions and other factors relevant to Link as a whole or individual alignments. Additionally, the assessment assumes no adaptive actions are taken on the part of Sound Transit, its partner agencies, or the communities it serves. In doing so, the assessment provides an opportunity to see—in advance—where adjustments could be needed to deal with climate change. Finally, the assessment is based on climate change projections available at the time of the workshops. Future updates to regional climate change projections may influence these conclusions, as would future changes in system design or other factors influencing these conclusions. For more information on the workshop methodology and assumptions, see Appendix B.

2.3. Heat Impacts

2.3.1. Rail Buckling

<u>*What is the Issue?*</u>
Rail buckling (or sun kinks) occur when temperatures are high enough to cause steel rail to expand and shift laterally, forcing the rail out of alignment. These events—or even the potential for these events—can cause service slowdowns, interruptions, costly repairs, and in rare cases, train derailments.

Air temperature and direct exposure to sunlight are the principle climate-related causes of rail buckles. Because of this, the potential for rail buckling is considered relevant to all non-tunneled portions of current and future Link alignments. Other factors influencing the potential for rail buckling are track and rail type, rail neutral temperature, and track age.

<u>Track and Rail Type</u>. Link system uses continuously welded rail installed as one of three track types depending on location: tie-and-ballast (ballasted) track, direct fixation track, and embedded track.

- *Ballasted Track.* Ballasted track (Figure 1) is used for various at-grade segments of Central Link[1], in the maintenance yards, and anywhere tracks converge, diverge, or cross over (known as "special trackwork"). Ballasted track is generally more sensitive to extreme heat than the other track types. However, Link's extensive use of pre-fabricated concrete ties—which are better able to constrain the force of heat-stressed rail than wood ties—reduces the probability of buckling where those ties are used. Several small sections of special trackwork in Central Link use wood ties but these ties will be replaced with concrete ties in the next 15-20 years as part of regular maintenance. The Design Criteria Manual (DCM) now requires concrete ties for all newly constructed special trackwork.

- *Direct Fixation Track.* Direct fixation track (Figure 2) is used on elevated structures, in tunnels and underpasses, and for other at-grade segments meeting a range of specified design criteria. Direct fixation track uses prefabricated concrete ties and fasteners to anchor the rail directly into a supporting concrete structure, giving direct fixation track greater latitudinal and longitudinal support than ballasted track. As a result, the sensitivity of direct fixation track to extreme heat—and therefore the potential for rail buckling—is low relative to ballasted track.

- *Embedded Track.* Embedded track (Figure 3) is used anywhere the Link system shares trackway with rubber-tired vehicles. This includes the downtown Seattle Transit Tunnel, a five mile stretch of the alignment in the Rainier Valley and all of Tacoma Link. It can also be used at times based on agency or jurisdictional urban design requirements. Embedded track is almost entirely encased in concrete or other pavement types; the only exposed portions of rail are the top and gauge sides, which are just above the adjoining road surface. This design is the least sensitive to extreme heat but can be

[1] Specifically between the south entrance of the downtown Seattle transit tunnel and SODO Station, in the Rainier Valley between the Rainier Beach Station and south of S. Norfolk Street.

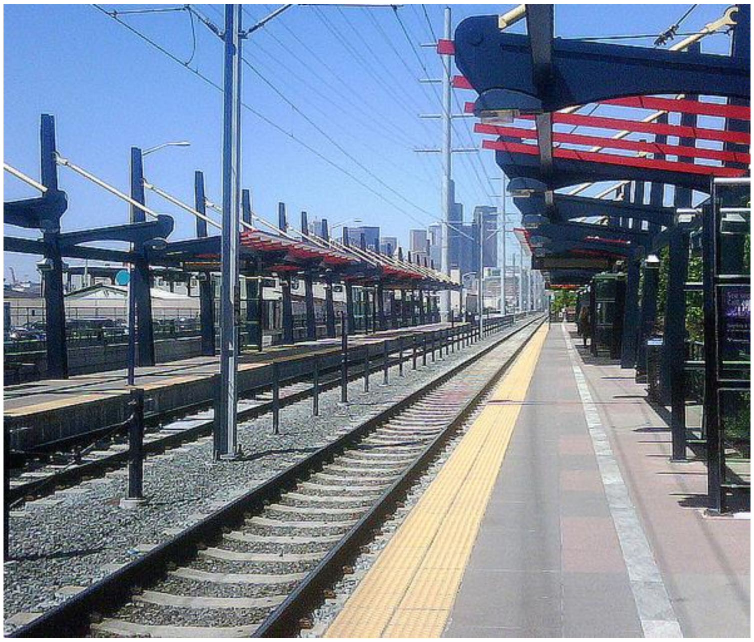

Figure 1. Concrete Tie-and-Ballast Track at the Link SODO Station.[2]

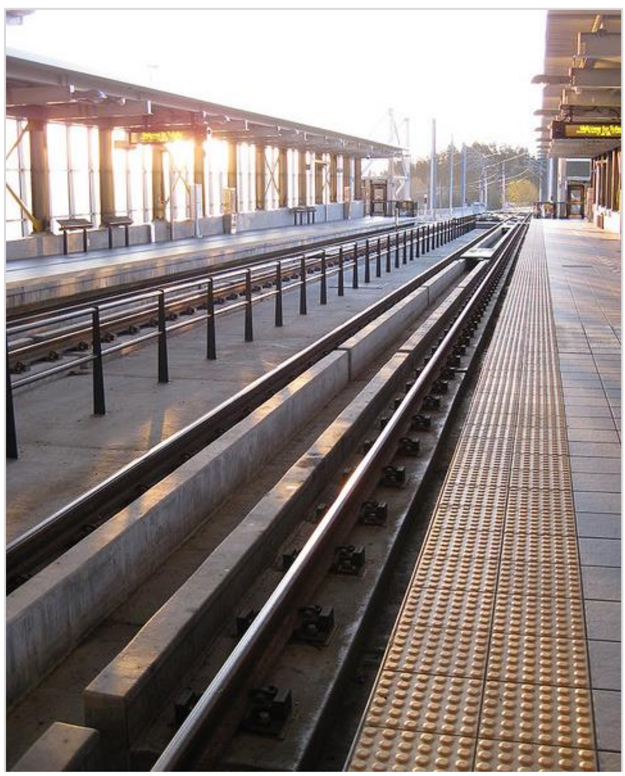

Figure 2. Direct Fixation Track at the Link Tukwila Station.[3]

[2] Image source: Flickr Creative Commons, http://www.flickr.com/photos/joebehr/7695782560/sizes/c/in/photostream/

Figure 3. Embedded Track used by Link Light Rail.[4]

more expensive to maintain because of the extensive use of paving around the track, among other issues.

<u>Rail Neutral Temperature.</u> Rail neutral temperature (RNT) is used when installing and maintaining track to limit the potential for rail buckling (see Appendix C.1 for more on RNT). The Sound Transit light rail Design Criteria Manual (DCM) specifications for RNT (referred to as “zero thermal stress”) when Central Link was built was between 65°F and 80°F (Section 8.3.10). RNT for Link was raised in 2012-13 to 95°F-105°F, providing a higher threshold of protection against rail buckling. The change also creates a differential sensitivity to heat in Central Link versus new Link alignments. The decision to raise the RNT for Link was made based on the experience of staff who have worked in other parts of the country and guidance from the American Railway Engineering and Maintenance-of-Way Association. As noted in Appendix C.1, actual RNT (i.e., RNT after installation) will fluctuate with the season and may be affected by track maintenance activities. Daily fluctuations are also possible.

<u>Impacts to Date</u>
No rail buckles have occurred to date in Central or Tacoma Link. However, temperature thresholds that trigger prevention activities have been crossed. This includes a July 2009 heat wave that brought four consecutive days of temperatures above 92°F (the 99th percentile threshold for daily high temperatures) and an all-time record high temperature of 103.5ºF in Seattle on July 29, 2009.[5]

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[3] Image Source: Flickr Creative Commons, http://www.flickr.com/photos/bsktcase/4434671904/sizes/z/in/photostream/

[4] Image source: http://www.slowtrav.com/blog/marta/archives/cat_seattle.html

[5] Highs during this four day period were 94°F (7/27/09), 97°F (7/28/09), 103°F (7/29/09), and 96°F (7/30/09).

The potential for rail buckling is currently managed by using advisories, visual monitoring, and slow orders (if necessary) when temperatures reach 94°F or higher. Separate advisories are issued for Central and Tacoma Link. Staff rated the impact of these activities as minor.

Projected Impacts

Projections for more extreme high temperatures increase the potential for rail buckling in non-tunneled portions of the Link system. The potential is generally higher, although still low overall, for Central Link relative to the new Link alignments discussed in Section 2.5 due to the different RNT ranges used for rail installation. Within Central Link, the potential for rail buckling is highest in the limited sections of Central Link that use wood tie-and-ballast track. Planned replacement of the wood ties with concrete ties will address the higher potential associated with wood ties. Rail buckling is less likely (relative to wood tie-and-ballast track) on the more widely used concrete tie-and-ballast and direct fixation track. Areas with embedded track, which includes all of Tacoma Link and a major portion of Central Link in the Rainier Valley, have the lowest potential for buckling.

Staff rated the potential for more frequent rail buckling as moderate. Expected impacts include more frequent heat advisories, increased visual monitoring, and slow orders. The slow orders could result in minor service delays or interruptions. If a minor buckle occurs, trains can operate at slower speeds through the misaligned section until repaired. More significant rail buckles would require cancelling service until a repair is made. The potential for train damage or derailment increases with the increased potential for rail buckling but is still considered low given the preventative measures in place.

2.3.2. Heat Stress on the Overhead Catenary System

What is the Issue?

Heat stress in the overhead catenary system (OCS), which transfers electricity to the train cars, occurs when high temperatures cause excessive line sag in the OCS. This may require slower train speeds or cause a loss of power if the train loses contact with the OCS. If the line sag is large enough, the train can create a wake on the wire that is transmitted in front of or behind the car, damaging the pantograph, insulators, and other OCS equipment or causing the wire to snap.

Sensitivity to temperature varies with OCS design. Link uses two types of OCS design: auto-tension and fixed termination.

- *Auto-tension OCS*. Auto-tension is used in most non-tunneled portions of Link. The auto-tension system uses counterweights at the ends of the tension lengths to maintain a constant wire tension over a range of temperatures. These counterweights self-adjust by moving up and down a guide rod to counter line sag or wire contraction (Figure 4). The length of the guide rod is calculated based on the length of the overhead line, the desired tension on the line, and the selected minimum and maximum wire temperature range, which roughly correlates to an ambient air temperature range.[6]

  The minimum-maximum wire temperature range for OCS design and operations on non-tunneled routes is 5°F-130°F (roughly equivalent to a maximum air temperature of 107°F). Auto-tension sections are not affected by changes in average temperature

[6] Other factors influencing actual wire temperature include solar heat gain, the angle of the sun, wind speed and direction, and the amount of current flowing through a wire.

Figure 4. Auto-tension Weights for Overhead Catenary Systems. The self-adjusting cylindrical weights are hanging on either side of the support pole. *Photo source: Sound Transit.*

because the counterweights can move freely between the upper and lower extreme design temperatures. Wire tension for the auto-tension OCS is monitored on a quarterly basis as part of routine maintenance.

- *Fixed Termination.* A fixed termination OCS is used in tunnels, maintenance yards, and all of Tacoma Link. A fixed termination system maintains wire tension using fixed poles or other support infrastructure (e.g., tunnel walls). Fixed termination systems are installed for a nominal tension at an average temperature (60°F in the case of Link) and the wire is allowed to sag or contract without re-tensioning as temperatures vary from that set point. For Central Link, the maximum sag limit is based on a maximum wire temperature of 120°F. Wire tension adjustments in the fixed termination system are made annually as needed.

<u>*Impacts to Date*</u>

The impacts to date of extreme heat on Central and Tacoma Link's OCS have been minor and have largely consisted of increased monitoring when temperatures exceeded 90°F, even in areas where auto-tension is used (wire watch alerts are issued along with rail watch alerts for rail buckling). Neither OCS type has experienced line sag extreme enough to cause wire wake, pantograph damage, or power loss to trains.

Projected Impacts
The anticipated impact of more heat stress on Link's OCS is minor. More frequent extreme heat events are expected to increase line sag and trigger increased visual monitoring during heat events for both OCS types. If excessive line sag is detected, slow orders would be issued until a crew can re-tension or adjust the affected line. In extreme cases, service would be halted until the adjustments or repairs are made. The estimated repair time for this scenario for Tacoma Link's fixed termination OCS is four hours, and the process would need to be repeated when temperatures dropped back to normal.

Line sag could cause auto-tension cantilevers to move beyond their designed range, potentially causing a power loss. Line sag in the rail yards could be a significant issue despite the fact trains already travel at low speed in the yards because of the number of contact wire crossings (mostly at switches) and the potential for differential line sag at these locations. Extra care must be taken through inspections and adjustments to ensure pantograph uplift does not cause damage to the OCS or pantograph where line sag may vary in the yard.

Other possible impacts include adjustments and structural changes to the OCS. Higher average temperature may require raising the set point for the fixed termination system and re-tensioning to that new average temperature. These changes are easy to implement but the specific amount of increase in average extreme temperature required to prompt these responses is uncertain.

More extreme high temperatures may ultimately require lengthening auto-tension guide rods if wire temperatures more frequently exceed the design maximum temperature. Longer guide rods would provide more room for the weights to fall in order to compensate for the additional line sag. Longer stainless steel cables may also be needed to account for the additional travel through the pulley. In a limited number of cases, pits may need to be excavated (or deepened, where already in use) to accommodate the wider range of motion.

Staff noted that guide rod adjustments would only be required if maximum temperature increased more than minimum temperature, causing the overall minimum/maximum range to increase. Changes to guide rods are not needed if the difference between the minimum and the maximum temperature stays the same. Changes to the set mid-point for the weights, however, would need to be adjusted to the new temperature range midpoint to maximize the available travel distance of the counterweights.

2.3.3. Heat Stress on Traction Power Substations, Signal Bungalows, and Small Signal Boxes

What is the Issue?
Heat stress on Traction Power Substations (TPSS), signal bungalows/housings, and small signal boxes used by Central Link[7] can result in a loss of power and traffic signal control in areas served by the affected units. This can lead to reduced operating speeds or short-term cancellation as repairs are made. Factors contributing to heat stress on electrical systems include ambient air temperature, prolonged sun exposure, the use of electrical equipment that generates heat while operating, and inadequate ventilation. Air conditioning can significantly reduce heat stress.

[7] Small signal boxes are used for Central Link to control the loop detectors along Martin Luther King Way Jr. S.

Impacts to Date
Heat stress on Link TPSS and signal bungalows to date is considered moderate. TPSS and signal bungalows built before 2012 have history of heat stress when ambient air temperatures reach the low 80s (°F) due to a lack of cooling. At these temperatures, internal structure temperatures can be well over 100°F due to heat generated by the electrical equipment.

If a single TPSS shuts down due to overheating, tie switches can connect adjoining substations together as a work-around. The resulting service disruption is about 20 minutes for Central Link and as long as 45 minutes for Tacoma Link. The loss of two or more sequential TPSS would require reducing service until the equipment cools (estimated to take no more than two hours).

Heat stress is currently managed by dispatching crews to prop open doors and put in box fans to prevent equipment from overheating. To date, only one TPSS has lost function due to heat stress in the Central Link system. This occurred prior to opening and was assumed to be caused by a faulty temperature setting that made the substation go into self-protect mode prematurely. Tacoma Link's TPSS has not been affected by heat due to partial shading by Interstate 705.

In contrast to the TPSS, Central Link's signal bungalows are frequently affected by heat, which can reduce the lifetime of batteries or communications electronics in the units. Heat stress due to high afternoon sun exposure is common in the Rainier Valley, near the Stadium Station in south downtown Seattle, at Boeing Access (112th Street and E. Marginal Way), and Tukwila. Back-up power for Central Link bungalows is provided for more than 90 minutes by a UPS battery. If input power loss occurred, generators can be brought in to run a portable air conditioner. Central Link trains may be required to operate by line-of-sight street mode, requiring reduced train speeds (35 mph) and potentially causing service delays depending on the number of intersections affected.

Tacoma Link's signal housings have not experienced heat stress because the housings contain less equipment and therefore generate less internal heat than Central Link. Tacoma Link's signal housings only contain railroad signal equipment, which will operate above 155°F; they do not have any of the communications equipment that is known to have issues at lower temperatures. The housings were also retrofitted with forced air input and output fans.

Design changes made in 2012 require air conditioning for TPSS and signal bungalows. Sound Transit will retrofit relevant Central Link TPSS (10 units) and signal bungalows with air conditioning in 2014-15 to provide a more permanent fix for existing heat stress problems. No Tacoma Link TPSS or signal housings will be retrofitted since these units have no history of heat-related problems. Small signal boxes cannot be air conditioned and therefore rely on natural ventilation.

While air conditioning can significantly reduce heat stress, air conditioning may not completely eliminate it. Staff noted that one bungalow (Stadium) was previously retrofitted to provide additional input air; this has prevented any new recordable heat stress issues, but does not keep temperature down to levels desired by the maintenance staff.

Projected Impacts
Increasing average and more extreme high summer temperatures could have differential impacts depending on the availability of air conditioning and location, as noted below. Overall, however, expanded use of air conditioning led staff to downgrade the impact of heat stress on TPSS and signal bungalows from moderate to minor.

- *Units without Air Conditioning (some Central Link TPSS, Tacoma Link TPSS, the small signal boxes).* Climate change increases the potential for heat stress in aboveground or at-grade TPSS, signal bungalows, and small signal boxes without air conditioning, even in units without a previous history of heat stress. An expected impact for these units is less effective use of natural ventilation for maintaining preferred temperatures. This could require additional steps to improve natural ventilation and/or reduce heating, including the need to install larger fans in small signal boxes.

- *Units with Air Conditioning (by summer 2015, all signal bungalows and some Central Link TPSS).* Air conditioning reduces the likelihood of heat stress. However, increasing demand for air conditioning is expected to increase operating costs and require more frequent maintenance or replacement of air conditioning units relative to today's climate. The long-term effectiveness of air conditioning depends on the installed units having enough capacity to accommodate projected cooling demand. If not, larger capacity units may be required. The ability to retrofit a signal bungalow with higher capacity cooling units may be limited if the structure is too small, if it cannot bear the additional weight, or if the existing power supply cannot handle the additional power load.

Staff noted that the impact of heat stress on Tacoma Link's signal housings would differ slightly from Central Link. Unlike Central Link, Tacoma Link's signal housings are not equipped with battery back-up. Tacoma Link is also not able to operate by line of sight through intersections. Consequently, if heat stress were to cause a signal housing shut down, Tacoma Link trains would have to stop at the affected intersection(s) and wait for authorization from a supervisor to proceed. Minor service delays are possible if one or a few intersections were affected.

2.4. Precipitation Impacts

2.4.1. Increased River Flooding

What is the Issue?
River flooding (along with flooding of streams and creeks) can occur when heavy precipitation and/or rapid snowmelt overwhelms river channels, levees, and dams. Flooding in rivers draining to Puget Sound can also be exacerbated when flooding coincides with high tides. General flood impacts can include infrastructure damage, loss of key access routes, increased maintenance costs, and service disruptions.

The potential for river flooding is primarily limited to Central Link in the vicinity of the Duwamish River crossing (Figure 5). The Duwamish River is the lower 12 miles of the Green River, emptying into Puget Sound south of downtown Seattle. Flood risk in the Duwamish is heavily influenced by flood flows in the Green River, which are regulated by Howard Hanson Dam. The river is tidally influenced up to river mile 12.[8] Current design standards require building rails such that the top of rail elevation is a minimum of one foot above the 100-year flood elevation wherever feasible. Tacoma Link does not cross any rivers or streams and is therefore not affected by river-based flooding.

Impacts to Date
There is no history to date of river flooding affecting Central Link.

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[8] http://your.kingcounty.gov/dnrp/library/2001/kcr762/PDFELEMENTS/SONR11.pdf

Figure 5. Link Light Rail Crossing of the Upper Duwamish River Just East of Tukwila International Boulevard. The Link track is the higher structure in the foreground.[9]

Projected Impacts

Climate change increases the potential for flood impacts on Link infrastructure in the vicinity of the Duwamish River, although the impacts are considered minor.

As noted in Appendix A, projected changes in temperature, mountain snowpack, and precipitation collectively increase the probability of high impact floods on the Green River; the probability of today's 0.2% (1-in-500 year) flood event increases to 1% (1-in-100 year) by as early as the 2020s in some scenarios*.* Howard Hanson Dam significantly decreases the probability of flooding in the Green River Valley below Auburn but the potential cannot be eliminated. Sea level rise also exacerbates flood risk on the Duwamish by hindering the river's ability to drain to Puget Sound, especially if flooding occurs during high tides (which will be higher as a result of sea level rise).

Central Link crosses the Duwamish 22 feet above ground level so there is no possibility of flooding on the track itself. However, higher flood flows in the Duwamish could increase the potential for erosion or create different lateral pressures around bridge supports if flood waters are high enough. The potential for this is considered low given how far back the bridge supports are from the river bank. Seismic standards for construction in the region are also likely to reduce the risk of structural damage from erosion or changing lateral forces. Increased visual monitoring of the river bank and bridge supports may be warranted, however, if higher flood events occur more often.

Severe flooding of the Duwamish could affect two nearby ground-level TPSS: the Boeing Access TPSS at 112th St and E Marginal Way and the TPSS at South 133rd Street. The need to raise or relocate the TPSS and adjacent signal bungalows at these two locations is possible if

[9] Photo by Joe Mabel, http://commons.wikimedia.org/wiki/File:Link_Light_Rail_crosses_the_Duwamish_01.jpg

flooding begins to present a greater risk. These TPSS were also identified by Sound Transit as substations to be watched in the event of flooding on the Green River. Finally, it should be noted that decisions by the City of Tukwila about how to address flood and erosion risks for the adjoining E. Marginal Way crossing (the lower bridge in Figure 5) may also affect the potential for flooding and erosion around Link infrastructure.

2.4.2. Increased Localized Flooding Due to More Stormwater Runoff or Poor Drainage

What is the Issue?

Localized flooding can occur at any facility where extreme precipitation overwhelms the drainage capacity of soils and/or stormwater system. Soil saturation can also be an issue. Impacts can include infrastructure damage, increased maintenance costs, service disruptions, and reduced customer access to services.

Many factors can influence if, where, and for how long localized flooding and soil saturation occur. These include the duration and intensity of precipitation events, stormwater drainage capacity, topography, runoff patterns from surrounding areas, and soil types. Localized flooding is more likely to occur between October and March, when the majority (70%) of annual Pacific Northwest precipitation falls. This is also the time when more extreme precipitation events are likely to occur.

Current design standards for Sound Transit-owned storm drains, parking lot sewer systems, culverts, and drainage facilities are based on the 25-year storm event. The capacity and maintenance of stormwater systems not owned or maintained by Sound Transit may also affect the potential for drainage problems near Link infrastructure.

Impacts to Date

Localized flooding or saturation has been a minor issue to date, affecting limited areas of Central and Tacoma Link, including the following:

- *SODO Station area (Central Link).* Drainage in the SODO area, including the Link maintenance base, is affected by the area's history and proximity to Puget Sound; the south downtown Seattle area was historically a tide flat up to present day Interstate 5 and has a shallow groundwater table that can fluctuate with heavy precipitation and tides. Heavy precipitation can cause standing water to collect near the Holgate crossing at 6th Ave South, and groundwater seepage through tiles at the SODO station has been observed. Track ballast in the SODO area also requires more regular inspection and maintenance than other areas. Staff noted that maintenance in the area has to be timed with non-revenue service hours and tides.

- *Rainier Valley (Central Link).* Staff identified Central Link's alignment along Martin Luther King Way Jr. S. in the Rainier Valley as a potential problem area for drainage issues. This area is actively monitored during extreme precipitation events.

- *Commerce Street (Tacoma Link).* Drainage issues for Tacoma Link are related to inadequate stormwater drainage and runoff patterns rather than high groundwater tables and soil saturation. Stormwater drainage is an issue along Commerce Street due to stormwater runoff from the hills above. The issue has not caused any problems with train service to date, however.

Projected Impacts

More extreme precipitation could exacerbate drainage and stormwater management issues in areas already affected by these problems (Commerce Street in Tacoma, the SODO area, and the Rainier Valley), although the impacts are considered minor. Expected impacts include increased monitoring during heavy precipitation events. Possible impacts include more frequent maintenance of equipment and infrastructure affected by drainage problems and more active intervention to address drainage problems (e.g., use of temporary or permanent pumps). Raising, relocating, and/or retrofitting ground level and underground equipment sensitive to flooding or groundwater seepage may also be needed.

2.4.3. Tunnel Seepage

What is the Issue?
Groundwater seepage is common in tunnels and can result in increased maintenance costs and odor issues. Sound Transit uses two tunnels in current Link operations: the Beacon Hill Tunnel and the Downtown Seattle Transit Tunnel. The Beacon Hill Tunnel consists of two parallel one mile tunnels with boarding platforms at the Beacon Hill Station, which is located 165 feet below ground (equivalent to ~16 stories). The Beacon Hill Tunnel is owned and maintained by Sound Transit. The Downtown Seattle Transit Tunnel is owned and maintained by King County. Several future Link alignments will also use tunnels, as discussed in Section 2.5.

Impacts to Date
Seepage in the Beacon Hill Tunnel has had minor impacts to date on Link operations. The Beacon Hill Tunnel was the first tunnel designed and constructed for the Link system. The tunnels are in direct contact with surrounding soils, making it easier for groundwater to seep through tunnel walls and joints. Seepage rates into the tunnel vary by season but typically flow at a rate of five gallons per minute. Seepage into the tunnel is also sensitive to storm events; staff reported that seepage inflows typically increase two days after storm events.

The primary impact of seepage into the Beacon Hill Tunnel is odor related to the interaction of groundwater with sulfur-reducing bacteria in the surrounding soil. The bacteria release hydrogen sulfide gas, which is not a hazard to passengers or equipment but can create a “rotten egg” odor in the passenger loading platform areas as trains move through the tunnels and flush the odors into the platform areas. Staff also noted that the bacteria secrete a liquid that runs with seepage flows into the tunnel’s drainage system. The secretions harden to the consistency of concrete as water evaporates. Maintenance workers must periodically clear the drainage system of these formations, a task that is sometimes challenging given the limited number of clean-out traps. The odor issues are being treated by Sound Transit.

Seepage occurs in the downtown Seattle Transit Tunnel but does not create any odor or other operational issues for Sound Transit.

Projected Impacts
Increasing winter precipitation may increase groundwater flows and seepage rates in the Beacon Hill Tunnel. The impacts of more seepage are considered minor, however. While odor issues are being treated, more seepage could exacerbate existing problems with odor, leading to customer complaints about odor and/or require additional treatment. A higher seepage rate (i.e., more gallons per minute) is not a problem given that the existing tunnel drainage system is designed to accommodate high volumes of water for fire suppression. More frequent maintenance and/or replacement of pumps (where used) may be required, however.

As noted previously, tunnels will be used extensively in some Link extensions. New design standards for Link eliminate direct soil contact with train tunnels by effectively placing the train tunnels inside boxes. This should significantly reduce or eliminate the potential for odor issues. Impacts related to more frequent maintenance and/or replacement of pumps (where used) may still be relevant, however.

2.5. Future Link Alignments

Sound Transit is currently expanding the Link system as part of ST2. Expansion north extends the Link system from downtown Seattle to Lynnwood via the University, Northgate, and Lynnwood Extensions. The Federal Way Transit Extension is evaluating alternatives to extend light rail from the future Angle Lake light rail station on South 200th Street in SeaTac to the Federal Way Transit Center. East Link, the largest of the expansions, will extend the system east from downtown Seattle to the Overlake Transit Center in Redmond. Further extension to Redmond is being considered as part of ST3 but has not yet been approved by the Sound Transit Board.

Because the Link extensions are under construction, in final design or planning, assessments about how climate change may affect these future alignments are very preliminary. The conclusions reflect staff familiarity with Central Link operations as well as their expert judgment about how planned or possible routes and design features could influence potential climate change impacts to the system.

<u>*University Link Extension*</u>
Construction of the University Link Extension began in 2009. The extension will connect the current north terminus of Central Link in downtown Seattle with the University of Washington (**Error! Reference source not found.**Figure 6). The alignment consists of two parallel underground tunnels three miles in length and two new stations: the Capitol Hill Station (65 feet deep) and the University of Washington station (110 feet deep). The track will be direct fixation track with fixed termination OCS. Service is scheduled to start in 2016.

Climate change is expected to have little impact on the University Link Extension. Because the full alignment and related electrical equipment are underground, the only climate impacts considered for University Link were increased tunnel seepage and stormwater flows into vent shafts. The potential for increased seepage rates is not a problem given the rated capacity of track drains (designed for 1,000 gallons per

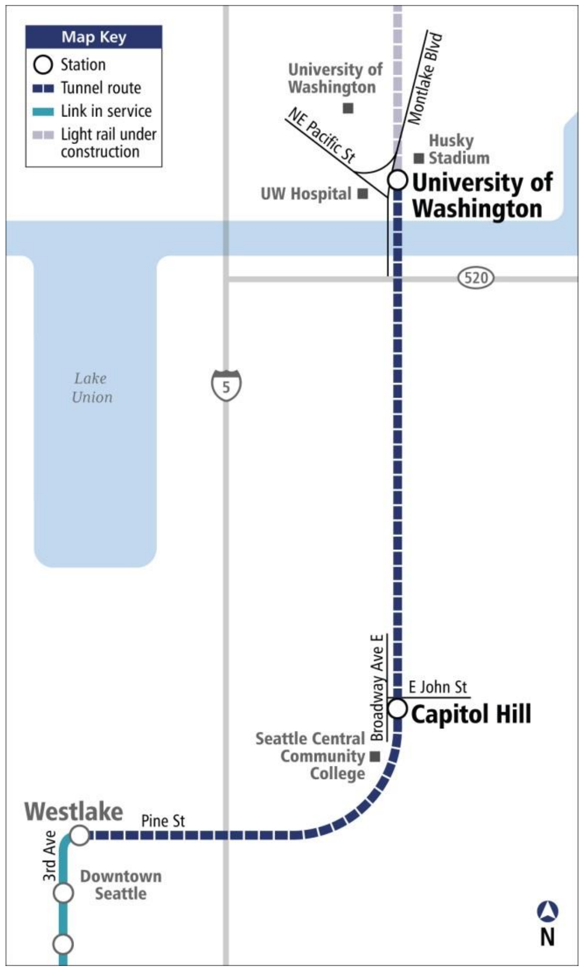

Figure 6. University Link Extension. *Map source: Sound Transit.*

minute). Any increases in the rate could require more routine maintenance and/or more frequent replacement of pumps, both of which are considered minor impacts.

The potential for odor issues like the one affecting the Beacon Hill tunnel are considered unlikely because the University Link tunnels will not have direct contact with the surrounding soil. Stormwater flow into vent shafts is also not a problem given that vent shafts for the tunnels are designed to be as high or higher than surrounding buildings to reduce noise issues.

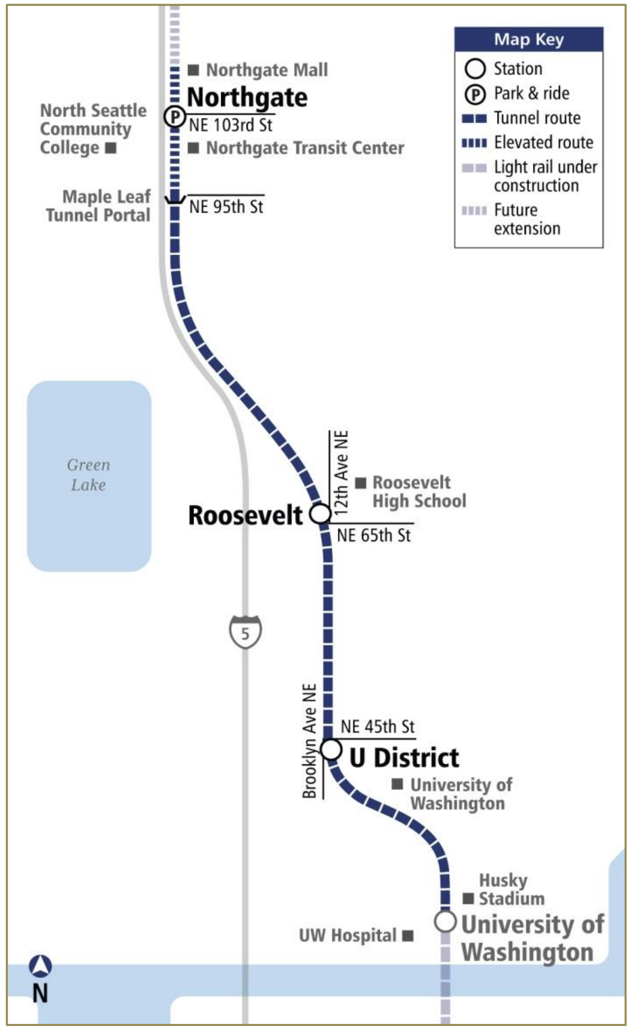

Figure 7. Northgate Link Extension. *Map source: Sound Transit.*

Northgate Link Extension

The Northgate Link Extension will continue service north from the University of Washington Station to the Northgate Station, located in the Northgate Transit Center (Figure 7). Three new stations are planned for Northgate Link: the U District Station (approximately 80 feet below ground), the Roosevelt Station (approximately 80 feet below ground), and the Northgate Station (an elevated station approximately 25-45 feet above ground). Service is expected to start in 2021.

Most of the 4.3 mile alignment will operate underground in two parallel tunnels. Direct fixation track and a fixed termination OCS are planned for the tunneled portions of the system. The only non-tunnel track is the last ~2,000 feet between NE 94nd Street and the Northgate Station. This track will transition from below grade near the tunnel portals to at-grade and then elevated. Concrete tie-and-ballast track will be used for at-grade sections. Direct fixation track will be used for elevated sections. Auto-tension OCS will be used for the non-tunneled portions of the alignment.

Climate change is expected to have minor impacts on Northgate Link. As with University Link, any increase in seepage rates in the tunnels can be easily accommodated by drains and sumps, although the additional maintenance and/or more frequent replacement of pumps may be required if seepage increases significantly. Stormwater into vent shafts is not possible given shaft height (several stories). Current tunnel design significantly reduces or eliminates the potential for odor issues.

Potential climate change impacts on the aboveground or at-grade portion of the Northgate Link Extension include heat impacts and localized flooding due to drainage issues. The use of concrete ties for ballasted track segments, direct fixation track for other portions, and air conditioning in the TPSS and signal bungalows reduces the probability of heat impacts on the non-tunnel portions of Northgate Link. Increasing line sag in the OCS is also likely but the impact is minor.

Drainage problems related to more extreme precipitation may become more of an issue over time given the low-lying geography around the Northgate Link alignment. However, stormwater management systems for Northgate Link may be better suited for this increase than other extensions. Northgate Link's stormwater management systems are designed for a 100-year storm event with an additional 20 percent "safety factor" to account for City of Seattle stormwater requirements for the Thornton Creek area. The additional capacity provided by the safety factor will help reduce the impacts of more extreme precipitation due to climate change.

Stormwater runoff into Northgate Link tunnels is not expected because of the way the track is angled at tunnel portals to direct stormwater away from the tunnel entrance and into a stormwater collection system.

Lynnwood Link Extension

The Lynnwood Link Extension is the final portion of the north extension planned under ST2. Environmental impacts related to potential route and station locations are currently being assessed. As currently planned, the alignment will consist of a combination of at-grade concrete tie-and-ballast track and elevated direct fixation track running along Interstate 5 between the Northgate Station and the Lynnwood Transit Center (Figure 8).The OCS will be auto-tension. Service is expected to start in 2023.

Heat impacts and increased creek flooding are the potential climate change impacts most relevant to the Lynnwood Extension. Both are considered minor. Heat impacts include the potential for heat stress on the track, OCS, and electrical equipment. Current design standards for the Link system reduce the probability of rail buckling and heat stress.

Increased flooding could be an issue near the Lynnwood Transit Center. Route options for the approach to the Lynnwood Transit Center cross the 100-year and 500-year FEMA flood zones for Scriber Creek (Figure 9). Projections for more winter precipitation could increase the potential for flooding in Scriber Creek, which is already a problem in the vicinity of the Transit

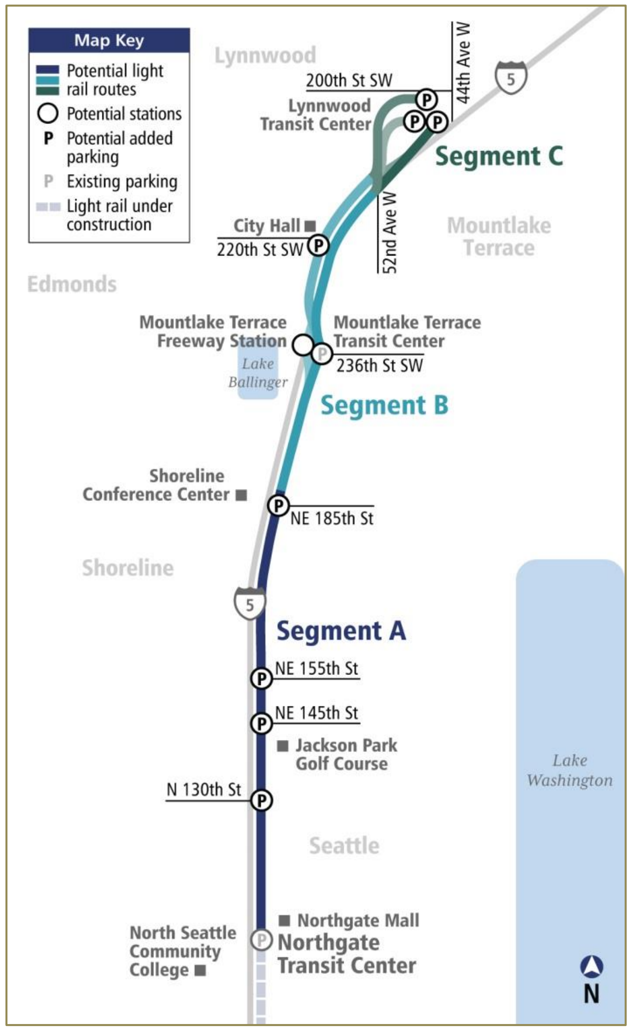

Figure 8. Proposed Lynnwood Extension.
Map source: Sound Transit.

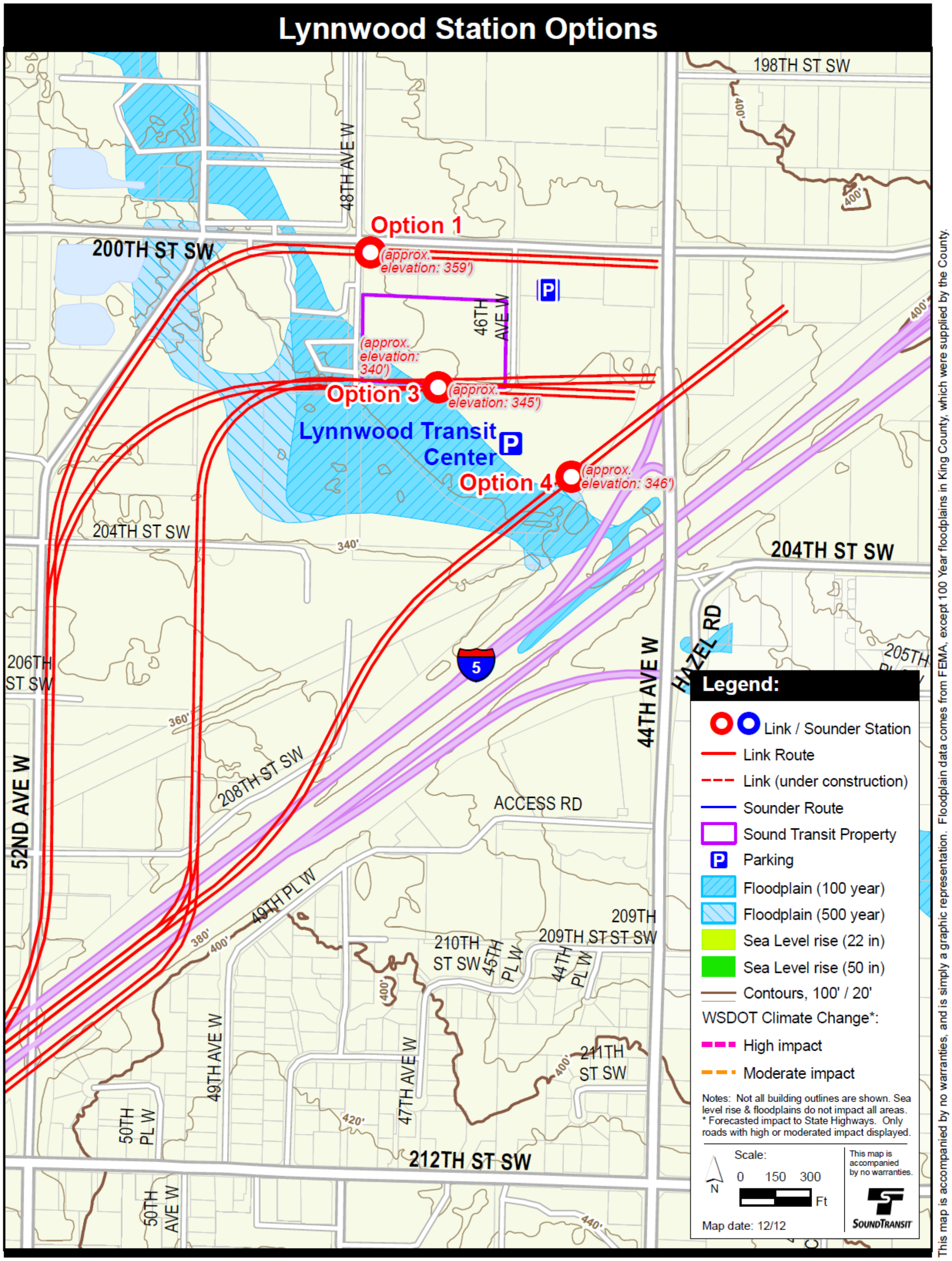

Figure 9. Lynnwood Transit Center Alignment and Station Options Relative to Existing FEMA 100-year and 500-year Flood Plains. *Map produced by Sound Transit.*

Center.[10] However, any increase is likely to have only a minor impact given the moderate size of Scriber Creek and the fact that all of the proposed approaches are elevated track. Additionally, current plans by the City of Lynnwood to address “long-standing storm drainage and sewer flooding issues” with Scriber Creek may help offset the potential for increased flooding.[11] Track supports are likely to be in the 100-year and/or 500-year flood zones and there would be exposed to more frequent flooding.

A related aspect of extending service to Lynnwood (but officially separate from the Lynnwood Extension) is the potential for a new Operations and Maintenance Satellite Facility to house and maintain additional Link trains. Location options for the maintenance facility being evaluated include locations proximate to the Lynnwood and East Link extensions. Alternative 1 places the facility near the Lynnwood Transit Center. According to staff, the satellite maintenance facility option near Lynnwood Transit Center could fall in portions of the currently mapped 500-year floodplain shown in Figure 9.

South 200th Extension

The South 200th Extension will add 1.6 miles of track from Link’s SeaTac Airport station to South 200th Street in SeaTac (Figure 10). Service is scheduled to begin in late 2016. The entire segment consists of elevated direct fixation track with auto-tension OCS. One aboveground station (the Angle Lake Station) is being constructed for this alignment.

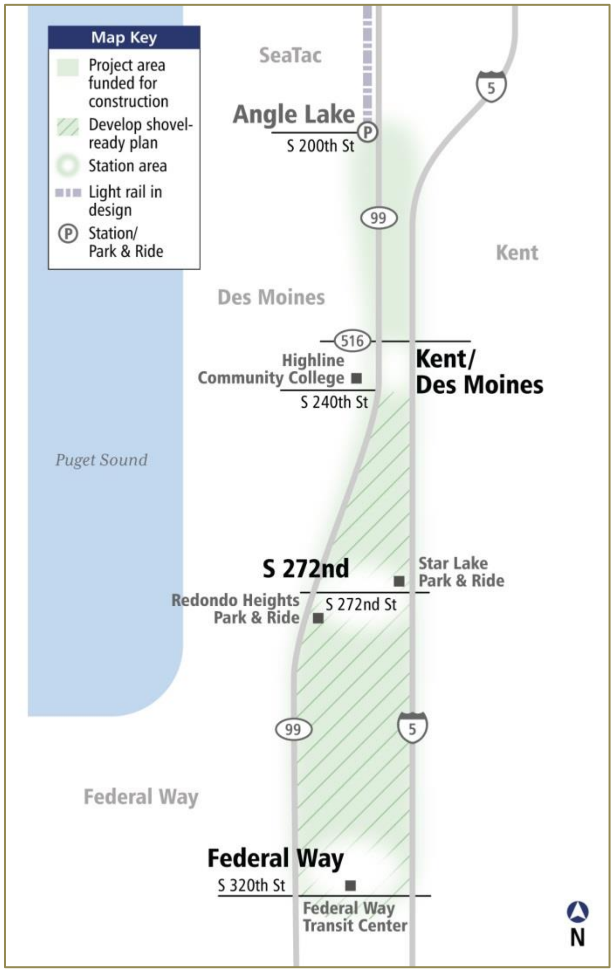

Figure 10. S. 200th Extension and Proposed Corridor for the Federal Way Extension*. Map source: Sound Transit.*

Heat stress impacts on the rail, electrical equipment, and OCS are the relevant climate change impacts for this extension, which will likely have. high sun exposure. As noted in previous sections, current design standards reduce the probability of heat stress impacts occurring but do not eliminate the potential. There are no known issues with drainage or

[10] For example, the City of Lynnwood is in the pre-design phase for planned installation of backflow preventers on low lying parking lot storm drain outfalls and construction of embankments in the vicinity of 200th Str. SW & 50th Ave. W. to protect buildings from high water levels in Scriber Creek. Options for the Lynnwood Link alignment and stations are approximately two to four blocks from this area. More information http://www.ci.lynnwood.wa.us/City-Services/Engineering-Services/Public-Projects-and-Programs/Storm-Water-Projects/Flood-Analysis---200th---50th--Backflow-Prevention-Along-Scriber-Creek.htm

[11] City of Lynnwood Public Works Department public letter, May 13, 2013, available at: http://www.ci.lynnwood.wa.us/Assets/Calendar+Assets/Public+Meeting+Notice+Scriber+Creek+Flooding.pdf

localized flooding that could affect this segment.

Federal Way Transit Extension
Corridor studies for the 7.6-mile Federal Way Extension are currently underway. The proposed extension will begin at the future Angle Lake Station and end near the Federal Way Transit Center at South 317th Street, although funding currently exists only to the proposed Kent/Des Moines station near S. 240th Street. The east/west boundaries of the proposed corridor are Interstate 5 and State Route 99 (Figure 10). Early expectations about track design are for an elevated direct fixation track with auto-tension OCS.

Based on what is currently known about the Federal Way Extension, relevant climate change impacts are the potential for heat impacts, drainage issues, and landslides. Staff noted that an Interstate 5 alignment would put the track over mostly vegetated areas while placement along SR 99 is over pavement, which exposes the rail to more heat from ground surfaces. However, current design standards reduce the probability of rail buckling and heat stress.

Increased precipitation could exacerbate any existing problems with drainage and localized flooding in the significant wetland area found between 259th and 272nd Streets. No impacts on the track are expected based on preliminary plans for an elevated structure. However, ground-level electrical equipment located in the area could be affected, depending on location.

Staff noted that steep slopes and landslides are already a challenge at the southern end of the proposed corridor along SR 99 near S. Dash Point Road (SR 509). These slope failure issues were a contributing factor in the Washington State Department of Transportation's rating of S. Dash Point Road from Brown's Point to SR 99 as "highly vulnerable" in its climate change vulnerability assessment.[12] Increased winter precipitation could exacerbate this problem.

ST2 East Link Extension
The East Link Extension is Link's largest extension under ST2. East Link expands the Link system 14 miles east from the south end of the downtown Seattle Transit Tunnel, across Lake Washington via the Interstate 90 floating bridge, and northeast to Sound Transit's existing Overlake Transit Center in Redmond (Figure 11). The East Link alignment will include a combination of tunneled, at-grade, and elevated track. All three track types (concrete tie-and-ballast, direct fixation track, and embedded) will be used depending on location. The OCS in tunneled portions will be fixed terminated while above-ground segments will have auto-tension OCS. Ten new stations will be built along the planned route. East Link is in final design, during which time Sound Transit will complete station and trackway design. Service is expected to start in 2023.

Climate change impacts relevant to East Link are the potential for heat impacts, creek-based flooding, seepage, and changes in maximum wind speed. Heat stress on track, electrical equipment, and the OCS is possible in all above-ground portions of the East Link alignment. The probability that these impacts occur is reduced by the use of concrete ties, direct fixation track, air conditioning for electrical equipment, and the auto-tension OCS design.

The potential for impacts from increased flooding exists primarily around Lake Bellevue and Sturtevant Creek but the impacts are minor. Lake Bellevue is a small, heavily developed lake with a FEMA-designated 100 year flood zone that abuts proposed ground level track. Any changes in flooding for Lake Bellevue would likely increase flows from Lake Bellevue into

[12] WSDOT 2011

Figure 11. East Link Extension, Seattle to Overlake Village. *Map source: Sound Transit.*

Sturtevant Creek. This could exacerbate existing flooding issues associated with the creek, which already required minor relocation of the planned Hospital Station. Any increases in flooding in other FEMA 100 year flood zones located near (or in one case crossed by) the East Link alignment are not expected to affect Link infrastructure because of topography or track elevation. The impact of more tunnel seepage is considered minor for reasons noted for University Link.

Staff identified two additional climate-sensitive factors unique to East Link related to its operations across Lake Washington. The first is the system's exposure to wind speeds as it crosses Lake Washington on Interstate 90. Link may not operate if wind speeds are greater than 55 miles per hour (mph) because of line sway in the OCS. While this threshold is relevant to the entire Link system, the segment crossing Lake Washington is more likely to experience these conditions. Current assumptions are that the 55 mph threshold will not be exceeded more than once in seven years (equivalent to a 14% probability in any given year). There is no information at this time as to how winds may change in the region as a result of climate change. More service delays and trip cancellations are likely if climate change causes wind intensity to exceed the 55 mph threshold more often.

Another issue unique to East Link is Lake Washington water levels. The Interstate 90 bridge is a floating bridge designed to rise and fall with controlled seasonal changes in lake level. Workshop participants questioned whether projected changes in streamflows for the Cedar River Watershed, the major tributary to Lake Washington, and other tributaries would alter lake levels beyond the range assumed for Link design. This is not expected to be the case because water levels in Lake Washington are regulated by the U.S. Army Corps of Engineers (USACE) and cannot vary from the established levels without an act of Congress.

ST3 East Link Extension
Sound Transit's next major transportation ballot measure—ST3—is being prepared and may include extending East Link approximately four miles along SR520 from the Overlake Transit Center to downtown Redmond. This extension would include of mix of at-grade concrete tie-and-ballast and elevated direct fixation track with an auto-tension OCS. Climate change increases the potential for heat impacts on rail, electrical equipment, and the OCS. The probability of those impacts is low, however, given current design standards.

One other climate change impact of note for the possible East Link route is the route's crossing of several large FEMA flood zones near downtown Redmond (Figure 12). While much of the track crossing these areas is elevated, several segments of the potential route are at-grade as they pass through current 100-year and 500-year flood zones, particularly between the proposed locations for the SE Redmond and Downtown Redmond stations. The flooding is primarily associated with Bear Creek. A 500-year flood zone area for Lake Sammamish is also crossed at-grade.

The City of Redmond's Hazard Mitigation Plan Update for 2009 - 2014[13] notes that while flooding is frequent in Redmond, the flooding is not very deep. FEMA inundation maps show inundation levels of one foot in most of the Bear Creek flood zone. Deeper flooding (in the range to two to three feet) occurs west of downtown near the convergence of Bear Creek and the Sammamish River. Link track is elevated in these areas so the track is not directly impacted by current or projected changes in flooding for Bear Creek and the Sammamish River. Support structures could be exposed to deeper or more frequent flooding, however, due to increasing precipitation. The potential for more frequent or larger floods could also affect ground-level electrical infrastructure located in or near these flood zones.

3. Adaptation Options

Options for adapting current and future Link operations to the impacts of climate change are discussed in the following sections. Adaptation options for Link share many similarities with Sounder. However, unlike Sounder—which largely relies on infrastructure owned and maintained by BNSF—Sound Transit has full ownership and control over Link. This means that Sound Transit can take direct action when needed. It also means that the majority of the costs associated with adaptation will be borne by Sound Transit.

The adaptation options provided here are not intended to be an exhaustive list of all possible approaches; they are an initial list of options considered most relevant to Link based on the impacts identified through the Climate Risk Reduction Project and input from Link staff. ***In all cases, these actions should be considered optional and in some cases "if needed."***

Because climate change exacerbates many existing issues, some of the adaptation options are activities that would be pursued regardless of any knowledge about climate change or any pre-emptive decisions to adapt to projected climate change impacts (i.e., as part of "business as usual"). However, climate change may accelerate the need for these adaptation options and/or require implementation at a scale larger than would normally be expected. In other cases,

[13] Available at http://www.redmond.gov/PublicSafety/DisasterPreparedness/plans/hazardplan/

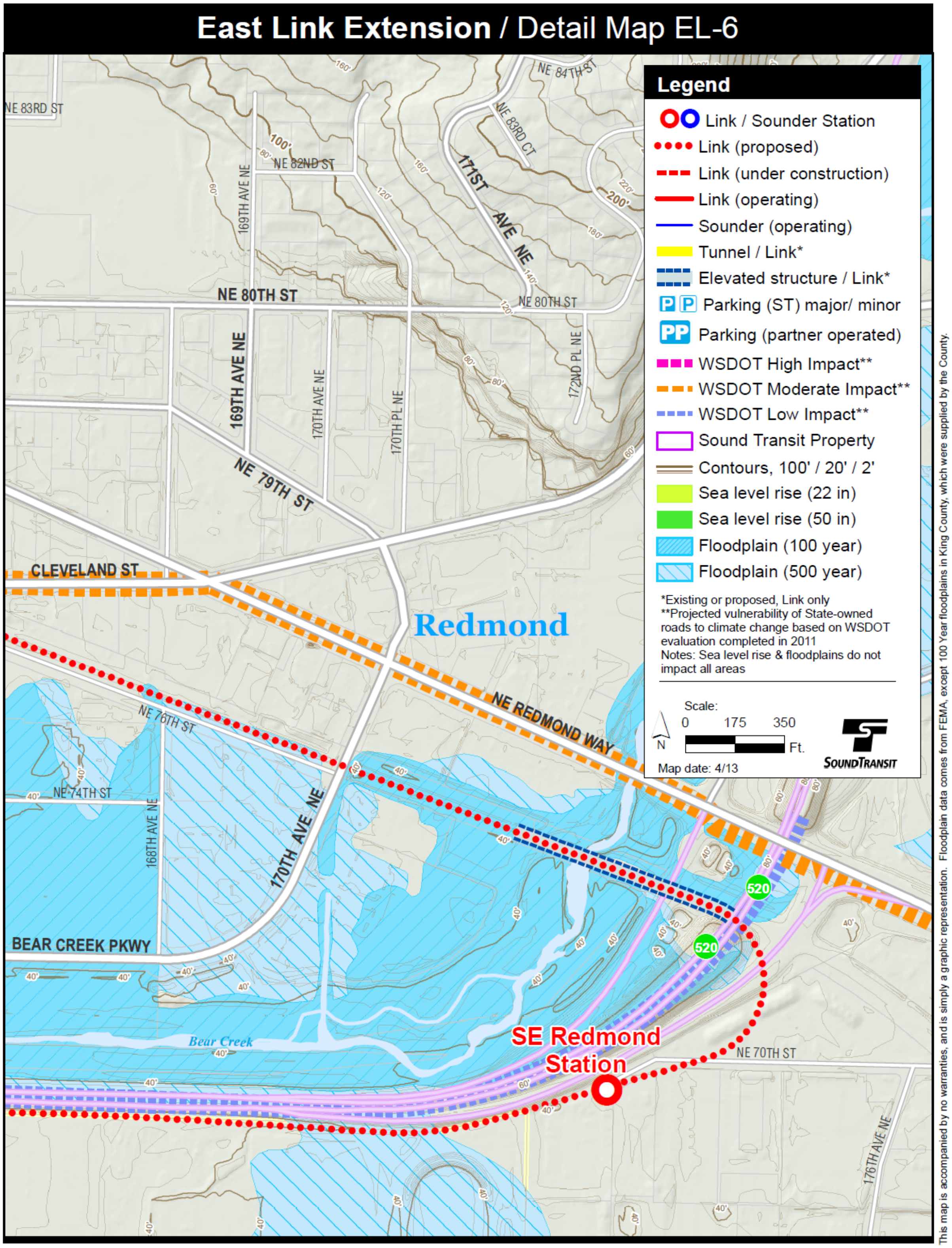

Figure 12. Proposed Alignment for the Possible East Link Extension to Redmond Relative to Present Day 100-year and 500-year FEMA Flood Zones. *Map produced by Sound Transit.*

climate change may raise the need for new approaches or cause reprioritization of existing approaches.

Decisions about which adaptation options to employ and when will depend on how rapidly climate change occurs and the cost of implementing the adaptation option(s). These costs will vary with the specifics of the adaptation option, the scale of deployment, and how readily the option can be integrated into routine asset maintenance and replacement cycles, among other factors. Further discussion and analysis of these issues is required before these or other adaptation options not included here can become implementation-ready recommendations.

3.1. Heat Impacts

Potential for Rail Buckling. Adaptation options for addressing the potential for rail buckling include extension of current practices as well as new options, which are grouped into one of two categories. The first category is actions that directly reduce the potential for rail buckling by making structural changes to Link track or supporting infrastructure. These options include:

- If technically possible, evaluate how much change in temperature may be needed to require raising rail-neutral temperature given rail age and location;
- Raise rail-neutral temperature;
- Re-install expansion joints in areas prone to misalignment (option limited by noise abatement requirements); and
- Employ new technologies that allow movement of rails to accommodate expansion.

The second category helps manage the risk of rail buckling by informing decisions about when and where to issue slow orders. Information gathered through these approaches may also help inform decisions about the potential structural changes listed in the first category of adaptation options. These options may include any combination of the following:

- Evaluate temperature variations in urban areas (the “urban heat island effect”) and how those variations may affect the potential for rail buckling in Link rail (would also benefit evaluation of other heat-related impacts);
- Directly monitor actual rail temperature through the use of thermocouples;
- Use models to predict rail temperatures based on real time weather forecast data, e.g., the Federal Railroad Administration model tested on Amtrak’s Northeast Corridor[14];

Heat Stress on the OCS. Adaptation options for heat stress on the OCS are primarily focused on adjustments to future OCS based on projections about warmer temperatures. Options for adapting the existing OCS are actions that would be expected as part of normal operations and are noted here as well. These options may include any combination of the following:

- If technically possible, evaluate how much change in average and extreme temperature may be needed to require changes in auto tension guide rod lengths and the fixed-termination nominal tension temperature set point;
- Adjust auto-tension and fixed-termination set points to a higher average temperature;
- Install longer guide rods on auto-tension poles during installation to provide a longer travel range for auto-tension weights; and

[14] Zhang, Y.-J. and L. Al-Nazer. 2010

- Install taller poles for auto-tension systems during installation to provide a longer travel range for auto-tension weights.

Heat Stress on TPSS, Signal Bungalows/Houses, and Small Signal Boxes. Adaptation options for heat stress on the TPSS, signal bungalows/houses, and small signal boxes include options for both air conditioned units and non-air conditioned units. These options may also be relevant to any other heat-sensitive equipment not discussed as part of this project. Adaptation options may include any combination of the following:

- Where possible, use more reflective roof coating or increase shading around TPSS, signal bungalows, and small signal boxes to maximize passive cooling or to reduce demands on air conditioning systems;
- Install larger fans in small signal boxes;
- Provide structural flexibility to increase air conditioning or fan capacity at a later date if needed by providing adequate space and opportunity to upgrade power feeds; and
- Add new (for Tacoma Link TPSS) or increase existing air conditioning capacity where heat stress becomes or continues to be an issue.

3.2. Precipitation Impacts

Increased River Flooding. Adaptation options for increased river-based flooding are limited in scale due to the small amount of area potentially affected by flooding. Because flooding on the Duwamish is tied to flood impacts on the Green River (in addition to sea level rise), Sound Transit's participation in broader regional efforts to address flood risk on the Green River is also considered part of Link's adaptation options. Adaptation options may include any combination of the following:

- Increase visual monitoring of the Duwamish river bank to check for signs of erosion or other changes that could affect Link bridge supports;
- Raise or relocate sensitive ground-level infrastructure to reduce or eliminate potential for flooding;
- Modify design standards to provide higher level of flood protection for infrastructure that must be located in or near flood hazard zones (e.g., raising minimum top-of-rail height based on 100-year flood elevations or extending this design preference out to the 500 year flood zone);
- Work with the USACE and floodplain communities to help ensure that Sound Transit's current and projected flood management needs are considered in flood management and hazard mitigation decisions; and
- If and when relevant, work with the City of Tukwila on any future efforts to address flood and erosion risks at Link's Duwamish crossing and the City of Tukwila's adjoining E. Marginal Way crossing.

Increased Localized Flooding. Adaptation options for managing and reducing the impacts of increased localized flooding due to more stormwater runoff or poor drainage may include any of combination of the following:

- Increase visual and/or electronic monitoring in areas with drainage problems;
- Raise or relocate sensitive ground-level infrastructure to reduce or eliminate potential for localized flooding;

- Modify design standards to provide higher level of flood protection for equipment that must be located in areas where drainage could be an issue;
- Design for more intense and/or longer duration rain events (i.e., planning for amounts higher than the 25-year storm event);
- Expand used of Low Impact Development, bioswales and other green stormwater management to add design robustness to hard infrastructure;
- Modify drainage patterns to re-direct surface flows and improve drainage;
- Partner with Seattle Public Utilities and other community utility programs to target problem drains/drainages;
- Change track ballast, or if necessary track bed, where drainage affects track performance or maintenance costs are escalating; and
- Move or relocate infrastructure in areas chronically affected by drainage problems.

Tunnel Seepage. The potential impacts of tunnel seepage are minor and primarily limited to more frequent maintenance of pumps and the potential for more odor issues. Adaptation options for managing and reducing the impacts of increased tunnel seepage may include any combination of the following:

- Increase maintenance of pumps and drains used to manage seepage;
- Explore alternate approaches to reducing or redirecting groundwater flows away from Beacon Hill Tunnel or reducing the growth of sulfur-producing bacteria in the Beacon Hill Tunnel.

3.3. System-wide Adaptation Options

While most adaptation options could be categorized by climate impact, the following adaptation option is relevant across a range of issues.

- Evaluate, and where relevant update, metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

4. Summary of Findings

Climate change is likely to have minor to moderate impacts on the current Link system, as summarized in Table 2.

Heat Impacts. The most prevalent category of impacts potentially affecting the current and future Link infrastructure and operations are heat-related impacts, which can affect the rails, the OCS, and electrical equipment for any at-grade or above-ground portion of the Link alignment. The potential for impacts to occur depends on the equipment types and site-specific characteristics such as the exposure to afternoon sun and the amount of paving (versus natural vegetation) in the vicinity of the alignment.

Current design requirements for the Link system reduce the probability of any major heat impacts on Link. The most likely impact of increasing average and extreme temperatures is more visual monitoring and slow orders as temperatures exceed heat advisory thresholds more often. Retrofitting track for a higher RNT is cost prohibitive but could be integrated into the system if needed as part of asset management. The potential for rail buckling in the system overall is low given the extensive use of direct fixation and embedded track, both of which are less likely to buckle than tie-and-ballast track. Furthermore, the areas with tie-and-ballast track predominantly use concrete ties, which are better able to constrain expansion forces than wood ties. Planned replacement of wood ties with concrete ties in the “special trackwork” segments will address the small set of areas with the highest potential for buckling. Differences in RNT used for Central Link and the new Link extensions make it more likely that Central Link could experience heat impacts on rail, however.

Design requirements for the auto-tension OCS have a maximum wire temperature that is expected to provide adequate buffer against more extreme temperatures. Furthermore, any required changes to deal with more extreme temperature are easy to accommodate. Changes in average temperature will require adjusting the set point for both the auto-tension and fixed termination systems.

Finally, heat stress on TPSS and signal bungalows, which has been an issue for Central Link, is being remedied by air conditioning retrofits to the units with a history of heat stress and requirements for air conditioning in new units. Small signal boxes cannot be air conditioned and are therefore more likely to experience heat stress as a result of increasing summer temperatures.

Precipitation Impacts
Impacts related to increasing average and extreme precipitation could affect multiple locations in the existing and future Link alignments, including areas south of downtown Seattle (e.g., SODO Station) and the Rainier Valley. Most notable is the potential for increased localized flooding due to more stormwater runoff or poor drainage. These impacts could require more frequent inspection and monitoring during heavy precipitation, more frequent maintenance of ground-level and underground equipment affected by drainage problems, increased ballast maintenance due to saturation, use of temporary or permanent pumps to manage problem flooding, and raising, relocating, and/or retrofitting sensitive ground level or underground equipment.

Any increases in tunnel seepage are expected to have minor impacts related primarily to increased maintenance of sumps and drains, although more seepage in the Beacon Hill Tunnel could exacerbate existing odor issues at the tunnel. Tunnel design changes should significantly reduce or eliminate odor issues in extension tunnels.

Finally, the potential for infrastructure damage from river-based flooding is low and limited currently to the Duwamish River, which will be affected by increasing flood risk in the Green River as well as sea level rise. The potential for increased flooding could also be an important issue for the possible ST3 East Link extension to Redmond and, to a lesser degree, the planned Lynnwood Extension and the ST2 East Link extension to the Overlake Transit Center.

Table 2. Summary Assessment of Current and Projected Climate Impacts on the Central Link and Tacoma Link Alignments. Scores based on input from Link staff who participated in project workshops. Bold indicates impacts that are expected to have a larger impact on Link moving forward in time as a result of climate change. Climate impacts on planned Link extensions were discussed but not rated and therefore are not included in this table. Facilities were evaluated separately. "Expected" impacts are those that would be expected to occur even at the low end of climate change projections. "Possible" impacts are impacts likely to occur in limited cases and/or at higher amounts of climate change.

Projected Impact *(Potential for more...)*		***Current Impact Rating***	***Projected Impact Rating***	***Potential Impact(s)*** *Assumes no intervening adaptation measure taken….*	***Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact***	***Scientific Confidence Regarding Change in Underlying Climate Cause(s)***
Heat Impacts	Rail buckling	Minor	**Moderate**	*Expected impact(s):* • More frequent heat advisories. • Increased visual monitoring. • Slow orders. *Possible impact(s):* • Heat-related track repairs. • Train damage or derailment, although the probability is low even in a changing climate given existing safety measures.	(+) Extensive use of track types less likely to buckle (direct fixation, embedded track). (+) Extensive use of concrete ties (rather than wood) in ballast track. Use of wood ties is limited and will be replaced with concrete ties in coming years. (+) The recently updated RNT range (95-105°F) is expected to provide a good buffer against increasing temperatures in the next few decades or longer, based on current projections. (-) Central Link rail was installed using a lower (65°F -80°F) RNT, making it more sensitive to heat impacts relative to new Link extensions.	*High*. High confidence that average and extreme summer temperatures will increase. High confidence that temperatures will more frequently cross temperature thresholds that trigger advisories and other prevention activities.

Projected Impact *(Potential for more...)*		***Current Impact Rating***	***Projected Impact Rating***	***Potential Impact(s)*** *Assumes no intervening adaptation measure taken….*	***Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact***	***Scientific Confidence Regarding Change in Underlying Climate Cause(s)***
	Heat stress on overhead catenary system (auto-tension and fixed termination)	Minor	Minor	*Expected impact(s):* • More frequent visual monitoring for both OCS types. *Possible impact(s):* • Slow orders or short-term train cancellations if line sag exceeds design tolerance. • Adjustments to OCS set points. • Installation of longer guide bars and related structural adjustments for auto-tension OCS if min/max temperature range increases.	(+) Auto-tension system designed to adjust to a range of temperatures, reducing need for frequent adjustment. (+) Current min/max range is high. Likely to provide a buffer against increasing temperatures in the near-term (based on current projections). (-) Fixed termination is more sensitive to changes in average temperature and more extreme heat events.	*High.* Same as above.
	Heat stress on TPSS, signal bungalows/ houses, and small signal boxes	Moderate	Minor	*Expected impact(s):* • Less effective use of natural ventilation to maintain preferred temperature. • More naturally ventilated units affected by heat. • Minor train delays due to slow orders and line-of-sight operations where heat stress	(+) AC is required for all new TPSS and signal bungalows. (+) Existing non-air conditioned units with a history of heat stress are being equipped with AC. (-) Small signal boxes cannot be air conditioned, but use is currently limited. (-) More AC use increases	*High.* Same as above.

Projected Impact *(Potential for more...)*		***Current Impact Rating***	***Projected Impact Rating***	***Potential Impact(s)*** *Assumes no intervening adaptation measure taken….*	***Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact***	***Scientific Confidence Regarding Change in Underlying Climate Cause(s)***
				causes small signal boxes to shut down. • Increased demands on air conditioning (AC). • Increased operating and maintenance costs for AC units. *Possible impact(s):* • Need to increase AC capacity. • Need to install larger fans in small signal boxes.	construction and operating costs, and may conflict with other agency objectives (e.g. sustainability). (-) Increasing AC capacity, if needed, can be difficult in some locations. (-) Tacoma Link signal housings do not have battery back-up, increasing potential for minor delays.	
Related to Precipitation and/or Sea Level Rise	River flooding (Duwamish River)	No impact	**Minor**	*Expected impact(s):* • Increased visual monitoring of Duwamish river bank and bridge supports. *Possible impact(s):* • Need to raise or relocate the Boeing Access and S. 133rd Street TPSS and adjacent signal bungalows.	(+) Track is elevated (+22 feet) as it crosses the Duwamish and therefore not subject to flooding. (+) Track supports are placed back from the river channel. (-) TPSS and signal bungalows are located at ground level, although likely to be impacted only in severe flooding given distance from the river channel. (-) Sea level rise may compound increasing	*Moderate to high.* There is high confidence that climate change will cause shifts in streamflow timing and increase peak flows in rivers influenced by snowmelt. There is less confidence in the specific size of the shift. There is also less confidence in the size of potential flooding in low-elevation rain-dominant rivers and

Projected Impact *(Potential for more...)*		**Current Impact Rating**	**Projected Impact Rating**	**Potential Impact(s)** *Assumes no intervening adaptation measure taken….*	**Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact**	**Scientific Confidence Regarding Change in Underlying Climate Cause(s)**
					flood risk originating upstream of the Duwamish (Green River).	streams given uncertainties about changes winter precipitation.
	Localized flooding and soil saturation due to increased stormwater runoff or poor drainage	Minor	Minor	*Expected impact(s):* • Increased inspection and monitoring during heavy precipitation. *Possible impact(s):* • More maintenance of ground-level and underground equipment affected by drainage problems. • Increased track ballast maintenance due to saturation. • Use of temporary or permanent pumps to manage problem flooding. • Raising, relocating, and/or retrofitting sensitive ground level or underground equipment.	(+) Many portions of Link are elevated, eliminating impact on track (although ground level and underground equipment still potentially affected). (-) Sea level rise may compound drainage issues in SODO by raising groundwater tables. (-) Capacity and maintenance of stormwater systems not owned or maintained by Sound Transit can affect potential for drainage problems on Link. (-) For areas where drainage is already a problem, even modest increases in precipitation are expected to exacerbate drainage problems.	*Medium.* Based on current model runs, there is good confidence that average and extreme winter precipitation will increase but low confidence in specifically how much.
	Tunnel seepage	Minor	Minor	*Possible impact(s):* • Increased	(+) New tunnel design standards do not put	*Low to medium,* for reasons specified in

Projected Impact *(Potential for more...)*		***Current Impact Rating***	***Projected Impact Rating***	***Potential Impact(s)*** *Assumes no intervening adaptation measure taken….*	***Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact***	***Scientific Confidence Regarding Change in Underlying Climate Cause(s)***
	(Beacon Hill Tunnel)			maintenance or replacement of pumps and drains. • Increased odor abatement efforts.	tunnels in direct contact with soil, reducing problems for new tunnels. (-) Design of the Beacon Hill Tunnel puts the tunnels in direct contact with soil. (-) Soils around Beacon Hill Tunnel are high in naturally occurring sulfur-reducing bacteria, triggering odor issues. (-) Limited number of drain clean-outs can make maintenance of some seepage issues a minor inconvenience.	previous row High uncertainty as to how groundwater flows change in response to projected increases in temperature.

References

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ST Express: Vulnerability Assessment and Options for Adaptation

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Figures

Tables

1. Executive Summary

Climate change is likely to have mostly minor impacts on ST Express overall, with moderate or significant impacts possible only in limited cases.

The most notable climate change impact potentially affecting ST Express is increased river flooding. Flooding of the Green or White Rivers would have a moderate impact on ST Express if the flooding was severe enough to impact use of State Route 167. This would affect two ST Express routes, one of which (Route 566) is considered critical in terms of ridership. Route 566 would be more difficult to reroute in a severe flood scenario given the limited availability of alternate roads in proximity of State Route 167. Other critical routes potentially affected by increased flooding are Routes 522 and 545.

Flooding of maintenance bases could have a significant impact on ST Express although no ST Express maintenance bases are currently located in or near a flood zone. The scenario was discussed, however, given possible location of a maintenance base in the Kent-Auburn area, which could be heavily impacted by flooding of the Green River. Flooding of a maintenance base would affect day-to-day operations for as long as a month. A key concern is fuel storage and the potential for contamination from underground storage tanks. Possible impacts include temporary loss of access to the bases, infrastructure damage, and remediation of any contamination from damaged underground storage tanks.

Other climate change impacts evaluated included heat stress on pavement and bridges, heat stress on buses, increased localized flooding due to more stormwater runoff or drainage issues, and sea level rise. In each case, the expected and possible impacts were considered minor with the most common impact being minor service delays due to reroutes or congestion. Traffic delays could also results in minor increases in operating costs for fuel and man hours, and increased service for air conditioning units is likely. Finally, it was noted that climate change impacts on other modes, most notably North Sounder, could temporarily impact ridership on ST Express as riders look to other modes for transit.

Adaptation options for ST Express are limited primarily because a) ST Express is relatively unaffected by climate change impacts, and 2) Sound Transit does not own or maintain the road infrastructure used for ST Express service. Many adaptation options emphasize working with state and local transportation departments, utilities, and others to address problems associated with heat, flooding, or sea level rise that could affect ST Express service. The only area where Sound Transit has direct control over adaptation decisions and costs is with the buses themselves.

2. Vulnerability Assessment Results

2.1. Potential Climate Change Impacts Evaluated

Potential climate change impacts evaluated for ST Express are listed in Table 1. The potential for changes in snow and ice events were not discussed in the project given the current lack of information regarding how these types of events may change. Over time, however, the frequency of snow and ice events may decrease.

Table 1. Projected Climate Change Drivers and Related Impacts Evaluated for ST Express

Projected Climate Change	*Potential Impacts Relevant to ST Express*
Warmer average summer temperature and more extreme heat	• Heat stress on pavement (softening, buckling) and bridges • Heat stress on buses
Increase in average winter precipitation and more extreme precipitation	• More frequent or severe river flooding of ST Express routes • Increased localized flooding of ST Express routes due to more stormwater runoff or poor drainage
Sea level rise and related coastal impacts	• More frequent temporary flooding or permanent inundation of ST Express routes

Staff was asked, via participation in a workshop, to qualitatively assess the degree to which the climate change impacts listed in Table 1 could affect operations and planning for ST Express. The assessment specifically focused on bus routes and buses; impacts on park-and-ride and other customer facilities were discussed in a separate assessment of customer facilities (see Appendix C.4). The potential for climate change impacts on Sounder and Link to affect ST Express was also briefly discussed.

All of the impacts listed in Table 1 are considered more likely because of the projected changes in climate described in Appendix A. Many of the listed impacts are already possible in today's climate and therefore not unique to climate change. However, climate change may alter the frequency, intensity, location, or duration of these impacts by affecting the underlying climate drivers (e.g., temperature, precipitation, sea level) that cause an impact. In other cases, climate change introduces new challenges or brings existing challenges to new areas.

2.2. About This Summary

The results of the ST Express vulnerability assessment are described in the following sections and summarized in Section 4. Potential adaptation options are also presented. For each climate change impact, the nature of the impact is briefly summarized and impacts to date on ST Express operations noted. Anticipated issues are identified and discussed generally in terms of expected and possible impacts. "Expected" impacts are those that would be expected to occur even at the low end of current climate change projections. "Possible" impacts are impacts that would occur in limited cases and/or at higher amounts of climate change.

Note that while climate change makes the impacts listed in Table 1 more likely, the probability that impacts occur will depend in part on routing decisions made by Sound Transit and, to a larger degree, decisions made others to manage heat impacts on roads, flood risk, stormwater runoff, and sea level rise. Additionally, the assessment assumes no adaptive actions are taken on the part of Sound Transit, its partner agencies, or the communities it serves. In doing so, the assessment provides an opportunity to see—in advance—where adjustments could be needed to deal with climate change. Finally, the assessment is based on climate change projections available at the time of the workshop. Future updates to regional climate change projections may influence these conclusions, as would future changes in system design or other factors influencing these conclusions. For more information on the workshop methodology and assumptions, see Appendix B.

2.3. Heat Impacts

2.3.1. Heat Stress on Pavement and Bridges

What is the Issue?
High temperatures (e.g., in or near the 90s°F) can cause pavement to soften or buckle, damaging road surfaces and requiring lane or road closures as repairs are made. Heat stress on pavement can occur anywhere but is more likely on older road surfaces and in areas with high solar loading. Drawbridges are also sensitive to heat; thermal expansion of steel and/or concrete can prevent bridges from opening and closing properly. Drawbridges used by ST Express include the Montlake Bridge near the University of Washington and the State Route 520 drawbridge.

Impacts to Date
Road buckling and heat stress on bridges occurs on occasion in the Puget Sound region but have not had any notable impacts to date on ST Express operations. There are no known incidents of heat stress on the current State Route 520 floating bridge or the Montlake Bridge; a new SR 520 bridge is under construction and will built to current standards for heat tolerance. A neighboring draw bridge, the University Bridge, is often closed for brief periods during heat events of time to allow for cooling via watering.[1] This has no direct impact on ST Express, which does not use the bridge, but can contribute to traffic delays in the vicinity of the University.

Projected Impacts
Projections for increasing average and more extreme high temperatures increase the potential for heat stress on pavement and bridges, although the impacts are considered minor for ST Express. Expected impacts include minor service delays due to congestion associated with road construction or detours. Service delays would also be expected if heat stress caused closure of the University Bridge. This would increase congestion in the University District and push more traffic onto the Montlake Bridge, delaying ST Express buses using the Montlake Bridge. Possible impacts include temporary re-routes and slightly higher operating costs for fuel and man-hours (e.g., for drivers) as a result of delays or re-routes.

Both expected and possible impacts of more heat stress on pavement or bridges are easy to accommodate given how readily ST Express can be re-routed. Sound Transit’s financial exposure is limited only to fuel and man-hour costs since ST Express uses publically owned roads built and maintained by the Washington State Department of Transportation (WSDOT) or local transportation departments.

[1] See, for example: “The University Bridge Can Overheat, Will Be Getting Cooling Baths All Day”, July 1, 2013 (http://slog.thestranger.com/slog/archives/2013/07/01/the-university-bridge-can-overheat-will-be-getting-cooling-baths-all-day/) and the Seattle Department of Transportation blog, July 2009, http://sdotblog.seattle.gov/2009/07/

2.3.2. Heat Stress on Buses

What is the Issue?
High temperatures may result in heat stress on buses. The system most likely to be affected is the air conditioning system, which has to work harder during heat events to compensate for warmer air temperatures entering the bus every time the doors open and close. Air conditioning units on the current ST Express bus fleet are standard to the Midwest and the East Coast and therefore have good capacity for cooling. The units undergo regular service as part of routine maintenance.

Impacts to Date
There are no known impacts to date on ST Express operations from heat stress on buses.

Projected Impacts
Increasing temperatures and more extreme heat increase the potential for heat stress on buses, although the impacts are considered minor. Overloaded air conditioning systems may not be able to adequately cool buses, affecting rider comfort. No trip cancellations would be required, however, since all ST Express buses have windows that can open.

Expected impacts from more high heat events are increased maintenance requirements for air conditioning systems and increased battery cooling for hybrid buses. Possible impacts include reduced rider comfort if units fail or underperform, decreased fuel efficiency due to increased air conditioning use, and the need to purchase higher capacity air conditioning systems and upgrades to hybrid battery cooling systems to protect batteries from higher temperatures. Higher temperatures may also affect electronic modules used to control engine, transmission, cooling, and head sign systems, although unlikely.

2.4. Precipitation Impacts

2.4.1. Increased River Flooding

What is the Issue?
River flooding (along with flooding of streams and creeks) can occur when heavy precipitation and/or rapid snowmelt overwhelms river channels, levees, and dams. Flooding in rivers draining to Puget Sound can also be exacerbated when flooding coincides with high tides. General flood impacts on roads can include infrastructure damage and temporary (hours to months) road closure.

Several ST Express routes, including three routes considered critical by Sound Transit staff, run through or adjacent to delineated 100 and 500 year flood zones (

Table 2). For most routes, exposure to potential flooding is limited to short stretches as routes cross in and out of flood zones. The most extensive exposure occurs along State Route 167 between Renton and Auburn, which runs through the 100-year flood zone for the Green River. Two ST Express routes use State Route 167: Routes 566 and 578. Flooding on State Route 522 near Woodinville can also be an issue (Figure 1).

Impacts to Date

There is no history to date of river flooding affect ST Express operations.

Table 2. Summary of Ground-Level ST Express Routes Potentially Affected by Flooding Based on Proximity to Delineated Flood Zones. Routes on elevated interstates or where buses cross over flood zones on overpasses are not included here. * indicates routes identified as critical by Sound Transit staff.

Route	Route Name	Related Project Map(s)	Related Flood Issue(s)	Related WSDOT Vulnerability Assessment Rating[2]
522*	Woodinville-Seattle	2f, 2g, 3c, 3d, 3e	Route runs through or adjacent to several 100-year flood zones between Lake Forest Park and, more significantly, in the vicinity of the State Route (SR) 522 and I-405 interchange up to NE 195th Street. Flood zones associated with Sammamish River, North Creek.	SR 522: moderate vulnerability due to flooding from Little Bear Creek (undersized culverts; water can get 4-5 feet deep). “NE 195th Street interchange goes first”
532	Everett-Bellevue (532)	3b	Route runs through flood zones for the Sammamish River and North Creek in the vicinity of the SR522 and I-405 interchange (up to NE 195th Street).	I-405: low vulnerability rating
542 & 545*	Redmond-University District (542); Redmond-Seattle (545)	3e, 3g, 3h	Portions of the route near NE 85th and 154th Ave NE run through the Sammamish River 100-year flood zone (542 & 545); route also travels through Bear Creek 100 and 500-year flood zones near NE Redmond Way and NE 76th Street, Avondale Way NE, NE Union Hill Road (545)	NE 85th and 154th Ave NE: no WSDOT rating Redmond Way: moderate vulnerability due to potential for flooding.
554, 555/556	Issaquah-Seattle (554); Issaquah-Northgate (555/556)	6c, 6d, 6e, 6f, 6g	All three routes access the Issaquah Transit Center using 17th Ave NW, which runs through the 100-year flood zone for Tibbets Creek. Route 554 uses a portion of NE Redmond-Fall City Road, which runs through the 100 year flood zone for Evans Creek (between 192nd Drive and 208th Ave NE), and W. Sunset Way, which crosses the 100 and 500-year flood zone for Issaquah Creek (between Newport Way SW and Front Street South).	17th Ave NW: No WSDOT rating Redmond-Fall City Rd: moderate vulnerability due to potential for flooding.

[2] WSDOT. 2011.

Route	Route Name	Related Project Map(s)	Related Flood Issue(s)	Related WSDOT Vulnerability Assessment Rating[2]
566*	Auburn-Overlake	8a, 8d-I, 9h, 9i, 9k	Uses SR167, which runs through or parallel to extensive portions of the Green River's 100 and 500-year flood zones from Renton to Auburn. Central Ave North in Kent also cross 100-year flood zone.	SR 167 in this area: moderate vulnerability, due to potential for flooding.
578	Puyallup-Seattle	10e, f	Uses SR 167 from Sumner to Auburn, which crosses the 100-year flood zone for the White River near Sumner	SR 167 in this area: low vulnerability
595	Gig Harbor-Seattle	14a, 14d	Small portions of SR16 cross over the McCormick Creek 100-year flood zone north of Borgen Blvd. Purdy Lane NW and 144th Street NW run through the 100-year flood zone for Purdy Creek near Purdy Creek Park-and-Ride	SR 16: low vulnerability

Figure 1. Trucks on Washington State Route 522 Near Woodinville. *Photo source: Jim Danninger, WSDOT.*[3]

[3] http://www.flickr.com/photos/sdot_photos/3786348371/

Projected Impacts

Climate change increases the potential for more frequent or severe river flooding within the ST Express service area, resulting in minor to moderate impacts to service routes.

As noted previously, the most significant exposure is on State Route 167 between Renton and Auburn. WSDOT staff considered State Route 167 moderately vulnerable to climate change because of the amount of highway at risk of flooding by the Green and White Rivers.[4] Climate change is expected to shift the probability of today's 0.2% (1-in-500 year) flood event in the Green River to a 1% (1-in-100 year) probability event as early as the 2020s in some scenarios as a result of projected changes in temperature, mountain snowpack, and precipitation (see Appendix A for more information). Mapping of this type of flood event by the U.S. Army Corps of Engineers shows extensive inundation in the valley, with flood water depths ranging from 0-20 feet. Parts of State Route 167 are inundated with modest amounts of water (0-2 feet); access roads to State Route 167 are also affected.[5]

Other areas potentially affected by more frequent or larger flooding include those near the Sammamish River and other low-elevation creeks and streams. The degree of flooding in these systems is more dependent on changes in winter precipitation than the Green or White Rivers, where changes in mountain snowpack are the biggest factor contributing to increasing flood risk.

Increased river flooding would have minor to moderate impacts on the ST Express routes listed in

in

[4] WSDOT. 2011.

[5] Green River Valley Flood Risk Maps, available at: http://www.nws.usace.army.mil/Missions/CivilWorks/LocksandDams/HowardHansonDam/GreenRiverFloodRiskMaps.aspx

Table 2. Expected impacts include service re-routes and delays, minor increases in fuel costs and man-hours, and potential short-term service cancellations at specific locations. Possible impacts include opening temporary park-and-ride locations. In general, these impacts are easy to accommodate. ST Express is accustomed to periodic service interruptions and re-routing due to weather events, construction, and traffic accidents. Every route that is susceptible to disruption, usually due to snow or ice, has identified contingency routes. Critical routes at risk of flooding (Routes 522, 545, 566) and routes with few work-arounds (e.g., portions of ST Express Routes 566 and 578 using State Route 167) could be slightly more challenging to alter.

Staff Discussion on Maintenance Bases. No ST Express maintenance bases are currently located in or near a flood zone, however a possible base in the Kent-Auburn area was noted by staff at the time of the assessment. Potential flood impacts on maintenance bases were therefore discussed to help inform decisions about future maintenance base locations but have no probability of occurring based on current base locations.

Flooding of maintenance bases could have a significant impact on ST Express, affecting day-to-day operations out of that base for as long as a month. A key concern is fuel storage. Flooding increases the risk of contamination from underground storage tanks; any flooding would require verifying that no leaks occurred. Minor adjustments to fuel caps for buses running on diesel would allow refueling at any location. Buses running on compressed natural gas (CNG) have less flexibility to fuel at alternate locations, although CNG buses currently represent less than 10% of the fleet.

Flooding of a maintenance base would likely result in temporary loss of maintenance services at the base, deferred maintenance on buses, redistribution of maintenance services and bus storage to other locations, modification of diesel bus caps to allow fueling at other locations, and/or the need to verify that underground storage tanks did not leak. Possible impacts include temporary loss of access to the bases, infrastructure damage, and remediation of any contamination from damaged underground storage tanks. Sound Transit would be responsible for any costs associated with damage to ST Express maintenance bases.

2.4.2. Localized Flooding due to Increased Stormwater Runoff or Poor Drainage

What is the Issue?

Localized flooding and soil saturation can occur anywhere in the ST Express service area where inadequate stormwater capacity or poor drainage creates ponding on roadways during heavy rainfall events. This can impede traffic flow and potentially require re-routing traffic.

The duration and intensity of precipitation events, stormwater drainage capacity, topography, runoff patterns from surrounding areas, and soil type are all factors that influence if, where, and for how long localized flooding occurs. The majority (70%) of annual Pacific Northwest precipitation falls between October and March, increasing soil saturation levels and making it more likely that drainage issues will develop during those months. This is also when the region is most likely to have extreme precipitation events.

Impacts to Date

There is no history to date of localized flooding affecting ST Express service in a notable way.

Projected Impacts

More extreme precipitation could exacerbate drainage and stormwater management issues in the ST Express service area, leading to localized flooding on roads used by ST Express. Impacts associated with this type of flooding are minor, however. An expected impact is minor bus delays caused by traffic having to navigate around or through standing water. A possible impact is short-term re-routing of buses until flooding subsides (typically a matter of hours). Any repairs or interventions required to address localized flooding on roads would need to be addressed by state or local transportation departments.

2.5. Sea Level Rise and Related Coastal Impacts

What is the Issue?

Sea level rise, higher high tides, storm surge, and other related impacts (including increased drainage problems) can inundate roads used by ST Express, leading to temporary or permanent loss of road access. Sea level is expected to increase an average of 24 inches by 2100 in the Seattle area with a possible range of +3.9 inches to +56.3 inches (see Appendix A for more on sea level rise projections). Projections for other areas between Everett and Tacoma are assumed to be the same or very similar.

Proximity, elevation, and connectivity to Puget Sound are the major factors influencing exposure to sea level rise and related impacts. Roads in close proximity to Puget Sound may be directly exposed to marine waters as the Sound rises. Roads further inland can be exposed if topography channels higher coastal flood waters inland through low-lying areas, or where stormwater infrastructure allows marine water to flow *into* parking lots, roads, and other features connected through stormwater pipes. Finally, sea level rise can exacerbate river flooding in the tidally-influenced reaches of rivers and streams draining to Puget Sound.

The only roads currently used by ST Express that are potentially affected by sea level rise are small portions of River Road (State Route 167 S.)/East Bay Street, East Portland Ave, and Puyallup Ave in the Tacoma industrial area between the Puyallup River and downtown Tacoma. These roads, which are used by Routes 574, 586, 590, and 594, are on the outer edge of the 50 inch sea level rise inundation zone mapped for this project.

Impacts to Date

There is no history to date of high tides, storm surge, or other coastal-related impacts affecting ST Express service.

Projected Impacts

Sea level rise and related coastal impacts are expected to have a minor impact on ST Express primarily because of the small amount of area potentially affected by sea level rise and the high amount of sea level rise required to inundate identified routes. An expected impact of sea level rise below 50 inches (the high scenario evaluated for the project) is minor traffic delays due to increased localized flooding and drainage problems brought on by higher coastal groundwater tables. Sea level rise greater than 50 inches could result in partial inundation of River Road (State Route 167 S.)/East Bay Street, East Portland Ave, and Puyallup Ave. Permanent re-routing may be necessary in this case but would be easy to accommodate given the diversity of alternate routes available in the area.

2.6. Potential Effect of Other Modal Impacts

Climate change impacts on other Sound Transit modes, most notably Sounder North, could have secondary impacts on ST Express ridership. Sea level rise and the potential for more mudslides along the north rail alignment increase the potential for service interruptions on Sounder North. Riders using Sounder North may shift to ST Express Routes 510, 511, and 512 as an alternate transit option. This shift is already known to occur when North Sounder service is halted for mudslides, but could become more frequent moving forward in time.

Service interruptions on South Sounder are less likely than Sounder North but would be more difficult to accommodate because of the heavy ridership on South Sounder. Additionally, any service interruption on South Sounder due to large-scale flooding of the Green or White Rivers would also likely flood roads used by Sound Transit customers to access ST Express services. The duration of any impacts on Sounder, ST Express routes, or ridership would depend on the duration and severity of flooding. Finally, ST Express routes in the north Seattle area could also pick up riders affected by temporary service interruptions on Link, although the probability of climate-related interruptions on Link is considered low relative to Sounder.

3. Adaptation Options for ST Express

Options for adapting current and future ST Express operations to the impacts of climate change are discussed in the following sections. The adaptation options provided here are not intended to be an exhaustive list of all possible approaches; they are an initial list of options considered most relevant to ST Express based on the impacts identified through the Climate Risk Reduction Project. ***In all cases, these actions should be considered optional and in some cases "if needed."***

Because climate change exacerbates many existing issues, some of the adaptation options are activities that would be pursued regardless of any knowledge about climate change or any pre-emptive decisions to adapt to projected climate change impacts (i.e., as part of "business as usual"). However, climate change may accelerate the need for these adaptation options and/or require implementation at a scale larger than would normally be expected. In other cases, climate change may raise the need for new approaches or cause reprioritization of existing approaches.

Decisions about which adaptation options to employ and when will depend on how rapidly climate change occurs and the cost of implementing the adaptation option(s). These costs will vary with the specifics of the adaptation option, the scale of deployment, and how readily the option can be integrated into routine asset maintenance and replacement cycles, among other factors. Further discussion and analysis of these issues is required before these or other adaptation options not included here can become implementation-ready recommendations.

3.1. Heat Impacts

<u>Heat Stress on Pavement and Bridges</u>. Sound Transit is not responsible for building or maintaining any of the roads used for ST Express service with the exception of road surfaces on Sound Transit properties (covered as part of Customer Facilities in Appendix C.4). Because of this, adaptation options related to heat stress on pavement and bridges are limited but include any combination of the following:

- Work with the WSDOT and local transportation departments to make sure that chronic heat stress problems on roads or bridges used by ST Express are addressed; and

- If and when warranted, implement seasonal re-routes of routes affected by chronic heat stress problems.

Heat Stress on Buses. Adaptation options for heat stress on buses are primarily focused on adjustments to air conditioning systems and batteries for hybrid buses. Options include any combination of the following:

- Increase air conditioning and battery maintenance frequency during summer months;
- Check air conditioning systems in advance of predicted heat events to optimize performance;
- Retrofit existing, or purchase higher capacity, cooling systems for buses; and
- If possible, purchase battery systems for hybrid buses with a higher heat tolerance.

3.2. Precipitation Impacts

Increased River Flooding. Adaptation options for addressing the impacts of increased river flooding on ST Express routes are limited because Sound Transit does not own or maintain the roads used by ST Express. Options include any combination of the following:

- Work with federal, state, and local partners to help ensure that Sound Transit's current and projected flood management needs are considered in flood management and hazard mitigation decisions;
- Review, and where relevant, update emergency operations plans to reflect the potential for more frequent or severe flood impacts in key areas; and
- If and when warranted, implement seasonal or permanent re-routes of routes affected by regular flooding.

Adaptation options for any *future* ST Express maintenance bases that must be located in or near a flood zone focus on infrastructure modifications. Options include any combination of the following:

- Modify design standards for the 100-year flood zone to provide higher level of protection for new infrastructure that must be located in or near flood hazard zones;
- Extend design standards required for the 100-year flood zone to the 500-year flood zone; and
- Raise or relocate sensitive ground-level infrastructure to reduce or eliminate potential for flood damage.

Where possible, however, the most robust adaptation option is avoiding installing maintenance bases in or near any existing 100-year or 500-year flood zones.

Increased localized flooding due to more stormwater runoff or poor drainage. Adaptation options for managing and reducing the impacts increased localized flooding include the following:

- Partner with local utilities and state and local transportation departments to target problem drains/drainages; and
- If and when warranted, implement seasonal or permanent re-routes of routes affected by problematic flooding.

3.3. Sea Level Rise Impacts

As noted previously, sea level rise potentially affects only a small portion of ST Express routes running along River Road (State Route 167 S)/East Bay Street, East Portland Ave, and Puyallup Ave in the industrial area between the Puyallup River and downtown Tacoma. Adaptation options include any combination of the following:

- Partner with local utilities and state and local transportation departments to address any localized flooding and drainage issues that may emerge as a result of rising coastal groundwater tables; and
- If and when warranted, re-route bus routes that could be inundated.

3.4. System-wide Adaptation Options

While most adaptation options could be categorized by climate impact, the following adaptation option is relevant across a range of issues.

- Evaluate, and where relevant update, metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

4. Summary of Findings

Climate change is likely to have mostly minor impacts on ST Express, as summarized in Table 3. The only moderate impact was associated with flooding of the White or Green River if it is large enough to restrict use of State Route 167. The moderate rating was driven primarily by the use of State Route 167 for a critical route (Route 566) and the limited number of alternate routes available for continuing service in that area. River or creek flooding also had the potential to impact other routes in the ST Express service area, including two other critical routes (Route 522 and Route 545) but are likely to be less affected than the State Route 167 routes. In all cases, service reroutes, delays, and potential short-term cancellations are expected if a route is flooded.

Other climate change impacts evaluated included heat stress on pavement and bridges, heat stress on buses, increased localized flooding due to more stormwater runoff or drainage issues, and sea level rise. In each case, the expected and possible impacts were considered minor with the most common impact being minor service delays due to reroutes or congestion. Traffic delays could also results in minor increases in operating costs for fuel and man hours, and increased service for air conditioning units is likely. Finally, it was noted that climate change impacts on other modes, most notably North Sounder, could temporarily impact ridership on ST Express as riders look to other modes for transit.

Adaptation options for ST Express are limited primarily because a) ST Express is relatively unaffected by climate change impacts, and 2) Sound Transit does not own or maintain the road infrastructure used for ST Express service. This has the advantage of virtually eliminating any cost obligation to Sound Transit for repairing or upgrading infrastructure as a result of heat, precipitation, or sea level rise impacts. However, it also means that Sound Transit is reliant on decisions made (or not made) by others to address climate-related impacts affecting ST Express service. This is not an issue, however, given how easily ST Express can accommodate reroutes. The only area where Sound Transit has direct control over adaptation decisions and costs is with the buses themselves.

Table 3. Summary Assessment of Current and Projected Climate Impacts on Current ST Express Operations. Scores based on input from Sounder staff who participated in project workshops. Bold indicates impacts that are expected to have a larger impact on Link moving forward in time as a result of climate change. ST Express facilities were evaluated separately. "Expected" impacts are those that would be expected to occur even at the low end of climate change projections. "Possible" impacts are impacts likely to occur in limited cases and/or at higher amounts of climate change.

Projected Impact *(Potential for more...)*		***Current Impact Rating***	***Projected Impact Rating***	***Potential Impact(s)*** *Assumes no intervening adaptation measure taken….*	***Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact***	***Scientific Confidence Regarding Change in Underlying Climate Cause(s)***
Heat Impacts	Heat stress on pavement and bridges	No impact	**Minor**	*Expected impact(s):* • Minor service delays due to congestions associated with road construction or detours. *Possible impact(s):* • Temporary re-routes. • Slightly higher operating costs for fuel and man-hours (e.g., for drivers) as a result of delays or re-routes.	(+) Heat impacts on roads and bridges are isolated to specific areas and do not have widespread impacts in the region, unless it causes closure of a key arterial or bridge (+) Sound Transit is not responsible for any climate-related repairs to roads or bridges used by ST Express (+) ST Express can easily accommodate re-routes and delays.	*High*. High confidence that average and extreme summer temperatures will increase.
	Heat stress on buses	No impact	**Minor**	*Expected impact(s):* • Increased maintenance requirements for air conditioning systems. • Increased battery cooling for hybrid buses. *Possible impact(s):*	(+) ST Express buses have windows that can be opened if air conditioning is under-performing or not working	*High.* High confidence that average and extreme summer temperatures will increase.

Projected Impact *(Potential for more...)*		***Current Impact Rating***	***Projected Impact Rating***	***Potential Impact(s)*** *Assumes no intervening adaptation measure taken….*	***Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact***	***Scientific Confidence Regarding Change in Underlying Climate Cause(s)***
				• Reduced rider comfort if units fail or underperform. • Decreased fuel efficiency due to increased air conditioning use. • Need for higher capacity air conditioning systems. • Need for hybrid bus batteries with a higher temperature tolerance.		
Related to Precipitation and/or Sea Level Rise	River flooding (Green, White, Puyallup, Sammamish Rivers; various creeks)	No impact	**Minor to Moderate**	*Expected impact(s):* • Service re-routes and delays. • Minor increases in fuel costs and man-hours due to re-routes and delays. • Potential short-term service cancellations at specific locations. *Possible impact(s):* • Temporary opening of alternate park-and-rides.	(+) ST Express can easily accommodate re-routes and delays on most routes. (-) Route 566 and 578 may be more difficult to re-route if flooding impacts SR 167 given limited alternate routes.	*Moderate to high.* There is high confidence that climate change will cause shifts in streamflow timing and increasing winter flows in rivers influenced by snowmelt. There is less confidence in the specific size of the shift and less confidence in the amount of potential flooding in low-elevation rain-dominant rivers and streams given uncertainties

Projected Impact *(Potential for more...)*		***Current Impact Rating***	***Projected Impact Rating***	***Potential Impact(s)*** *Assumes no intervening adaptation measure taken….*	***Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact***	***Scientific Confidence Regarding Change in Underlying Climate Cause(s)***
						about changes winter precipitation.
	Localized flooding due to increasing stormwater runoff or poor drainage	No impact	**Minor**	*Expected impact(s):* • Minor bus delays caused by traffic having to navigate around or through standing water. *Possible impact(s):* • Short-term re-routing of buses until flooding subsides.	(+) ST Express can easily accommodate re-routes and delays on most routes. (-) Sea level rise may contribute to drainage issues on or near low-lying roads used by ST Express in industrial areas near downtown Tacoma. (-) For areas where drainage is already a problem, even modest increases in precipitation are expected to exacerbate drainage problems. (-) Capacity and maintenance of stormwater systems not owned or maintained by Sound Transit can affect if, where, and to what extent drainage issues affect ST Express service.	*Medium.* Based on current model runs, there is good confidence that average and extreme winter precipitation will increase but low confidence in specifically how much.

Projected Impact *(Potential for more...)*		***Current Impact Rating***	***Projected Impact Rating***	***Potential Impact(s)*** *Assumes no intervening adaptation measure taken….*	***Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact***	***Scientific Confidence Regarding Change in Underlying Climate Cause(s)***
	Sea level rise (Tacoma area only)	No impact	**Minor**	*Expected impact(s):* • Minor traffic delays due to increased localized flooding and drainage problems in the vicinity of the routes as sea level rise raises the underlying groundwater table. *Possible impact(s):* • Permanent re-routing of buses using roads inundated by sea level rise	(+) Most extreme impact (permanent inundation of roadway) only possible under high (50 inch) sea level rise scenario, and potentially affected roads are at the edge of the inundation zone. (+) ST Express can easily accommodate re-routes and delays associated with temporary or permanent inundation. (+) Presence of other commercially important facilities creates a large incentive enhancing coastal defenses, although drainage issues could still become a problem.	*High* (that sea level will rise) and *low* (how much rise will specifically occur).

References

(WSDOT) Washington State Department of Transportation. 2011. *Climate Impacts Vulnerability Assessment.* Report prepared by the Washington State Department of Transportation for submittal to the Federal Highway Administration, Olympia, Washington. Available at: http://www.wsdot.wa.gov/NR/rdonlyres/B290651B-24FD-40EC-BEC3-EE5097ED0618/0/WSDOTClimateImpactsVulnerabilityAssessmentforFHWAFinal.pdf

Customer Facilities: Vulnerability Assessment and Adaptation Options

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1. Executive Summary

Sound Transit's customer facilities currently include 12 Sounder stations, 21 Link light rail stations, and 10 major and five minor parking facilities throughout the Sound Transit service area. Many facilities serve multiple modes and/or transit agencies (e.g., Amtrak, King County Metro, Community Transit, Pierce Transit). More than 20 additional facilities are currently under construction or planned as part of system expansion funded under the 2008 ST2 ballot measure.[1]

With the exception of the Edmonds and Mukilteo facilities, climate change is likely to have minor to moderate impacts on most of Sound Transit's customer facilities. Heat impacts are the most widespread impact, affecting ticket vending machines, non-air conditioned uninterruptable power supply rooms, structural components (e.g., facades), and facility landscaping. These impacts could occur at any aboveground station depending on station location, design, and length of exposure to direct sunlight.

Increased river flooding could impact the Green River Valley stations (specifically Tukwila, Kent, and Sumner Stations). While potentially significant flood inundation depths are possible for Tukwila based on mapping of extreme (0.5% and 0.2% annual probability) peak flows by the USACE, flood impacts are likely to be limited to parking facilities and access roads at both the current and future facility. Inundation levels at the Kent Station are likely to minor (less than two feet) and flooding of the White River in Sumner would likely only impact access roads. While these impacts are associated with flood flows considered rare in today's climate, flood flows of that magnitude could become more likely (e.g., shifting to a 1% annual probability event) as a result of climate change as soon as the 2020s in some scenarios.

Increased localized flooding due to more storm water runoff or poor drainage could also occur at any aboveground facility but is more likely in low-lying areas and/or in areas where drainage is already an issue, including stations south of downtown (e.g. SODO Station) and Tukwila. Stormwater is managed on Sound Transit properties through a variety of approaches, including Low Impact Development (LID). The robustness of LID system design relative to the size of extreme rainfall projections is unknown at this time. Sound Transit operations and infrastructure can also be affected by high volumes of stormwater runoff and drainage problems beyond Sound Transit's properties.

Sea level impacts on customer facilities are limited geographically but could result in significant impacts at the Edmonds and Mukilteo Sounder Stations. Assuming no changes in current coastal defenses (which is considered unlikely), sea level rise of 50 inches or more—currently at the high end of the range projected for Seattle for 2100—would result in permanent inundation of important access roads (e.g., Front Street, Railroad Street) at both stations, parking areas, track leading to the facilities, and areas around boarding platforms. Underground or low-lying equipment and infrastructure (e.g., elevator pits, junction boxes, transformers, signal bungalows) would also be flooded.

Sea level rise of 22 inches, which is close to the average rise projected for Seattle for 2100, would increase the likelihood of localized flooding and drainage issues at or near the Edmonds and Mukilteo facilities. This amount of sea level rise would likely not result in any significant or permanent impacts to the facilities, however, and could result in more frequent service

[1] For the purposes of this analysis, the term "facility" applies to current and future stations or parking facilities unless specified otherwise.

interruptions along the north rail alignment serving those facilities, as noted in the Sounder summary (Appendix C.1).

Adaptation options for customer facilities range from increased inspection to moving or relocating sensitive Sound Transit-owned infrastructure. Decisions made by the Burlington Northern Santa Fe (BNSF) railroad and others (including Sound Transit) about adapting the rail alignment used by Sounder could affect how the Edmonds and Mukilteo facilities are adapted. For example, any decisions on the part of BNSF to raise track elevation would require costly retrofits on the part of Sound Transit to raise stations platforms and facilities to meet new track grades.

2. Vulnerability Assessment Results

2.1. Potential Climate Change Impacts Evaluated

Sound Transit facilities are distributed throughout the service area and therefore exposed to a wide range of potential climate change impacts (Table 1). Additionally, each facility is unique with respect to its size, design, and access. As a result, the relevance of these impacts to any individual facility will depend on the specific location of the facility as well as the unique characteristics of the facility. Potential changes in snow and ice events were not discussed in the project given the current lack of information regarding how these types of events may change as a result of climate change. Over time, however, the frequency of snow and ice events may decrease. All of the impacts listed in Table 1 are considered more likely because of projected changes in climate.

Table 1. Projected Climate Change Drivers and Related Impacts Evaluated for Sound Transit Facilities.

Projected Climate Change	*Potential Impacts on Facilities*
Warmer average summer temperature and more extreme heat	• Heat stress on structures, electrical & safety equipment • Increased heat/drought stress on facility landscaping (also affected by projections for lower summer precipitation)
Higher average winter precipitation and more extreme precipitation	• Large scale river flooding affecting facilities and/or access to facilities • Increased localized flooding due to more stormwater runoff or poor drainage • Increased seepage in underground structures due to higher groundwater tables
Sea level rise and related coastal issues	• Increased drainage problems • More frequent temporary flooding of facilities and/or access roads • Permanent inundation of low-lying facilities and/or access roads

Staff was asked, via participation in two workshops, to qualitatively assess the degree to which the climate change impacts listed in Table 1 could affect customer facilities. Many of the listed impacts are already possible in today's climate and therefore not unique to climate change. However, climate change may alter the frequency, intensity, location, or duration of these impacts by affecting the underlying climate drivers (e.g., temperature, precipitation, sea level) that cause an impact. In other cases, climate change introduces new challenges or brings existing challenges to new areas. For more on projected changes in regional climate, see Appendix A.

2.2. About This Summary

The results of the customer facilities vulnerability assessment are described in the following sections and summarized in Section 4. Potential adaptation options are also presented. The assessment started with evaluation of heat impacts on facilities in general given the broad relevance of heat issues to facility infrastructure and equipment. The remainder of the assessment was also based on categories of impacts (e.g., precipitation, sea level rise), however staff evaluation of those impacts occurred in the context of specific facilities known to have a history with the impact being evaluated. As such, the conclusions from these discussions are presented here both generally (in the case of heat impacts) and by facility (in the case of precipitation and sea level rise impacts). Potential impacts on Sounder and Link alignments and ST Express routes were discussed in separate workshops (see Appendices C.1-C.3).

For each climate change impact, the nature of the impact is briefly summarized and impacts to date on customer facilities noted. Anticipated issues are identified and discussed generally in terms of expected and possible impacts. "Expected" impacts are those that would be expected to occur even at the low end of current climate change projections. "Possible" impacts are impacts that would occur in limited cases and/or at higher amounts of climate change. Conclusions for specific facilities are considered relevant to other current and future facilities as well.

Note that while climate change makes the impacts listed in Table 1 more likely, the probability that impacts occur will be shaped by design decisions and other factors. Additionally, the assessment assumes no adaptive actions are taken on the part of Sound Transit, its partner agencies, or the communities it serves. In doing so, the assessment provides an opportunity to see—in advance—where adjustments could be needed to deal with climate change. Finally, the assessment is based on climate change projections available at the time of the workshops. Future updates to regional climate change projections may influence these conclusions, as would future changes in system design or other factors influencing these conclusions. For more information on the workshop methodology and assumptions, see Appendix B.

2.3. Heat Impacts

2.3.1. Heat Stress on Structures

<u>*What is the Issue?*</u>
Heat stress can occur any time temperatures cause building materials to expand beyond design specifications. This can result in damaged infrastructure, more frequent repairs, and reduced asset life. Building features that may be affected include expansion joints, concrete, building facades, and metalwork.

Impact to Date

Sound Transit has experienced minor impacts to date with temperature fluctuations and heat stress on facility structures. The Auburn Station has had problems with brick veneer cracking and falling off due to differential expansion between the structure's brick and steel. Expansion also caused glasswork at the King Street Station to crack when temperatures warmed, although this was attributed to incorrect installation of the glasswork. Other facilities have had occasional problems with ceramic tiles dislodging and metal roofing joints "popping off" when temperatures warm. With the exception of the glasswork at the King Street Station, a consistent issue in each of these cases was the lack of expansion joints or inadequate expansion joints.

No issues to date with concrete were identified. The Design Criteria Manual currently specifies that concrete and steel structures must provide "for stresses and deformations" associated with temperature variations above and below 64°F (Section 8.3.10).

Projected Impact

Increasing summer temperatures and more extreme heat events increase the likelihood that facility structures will experience heat stress. The impacts are expected to be minor provided the scale and cost of repairs remain consistent with what staff has observed to date. An expected impact is increased maintenance of facility features affected by higher temperatures. Staff also expects the mix ratio for concrete to change in Seattle with future warming.

Possible impacts include more frequent repairs and/or replacement of affected infrastructure. This could result in temporary minor inconveniences to customers during maintenance and repair activities. Staff noted that designs are now specifying expansion joints, which will help prevent some of the impacts experienced to date. Staff speculated that the temperature tolerances of the design numbers being used now are adequate for the 2020s. Additional research would be required to answer that question.

2.3.2. Heat Stress on Electrical Equipment

What is the Issue?

Heat stress on electrical equipment occurs when equipment temperatures exceed operational limits. This can result in equipment failure that affects a range of issues from customer service to safety, depending on the affected equipment. Factors contributing to heat stress on electrical equipment include exposure to direct sunlight, above average ambient air temperatures, and inadequate ventilation. Internally-generated heat associated with equipment operations can amplify heat issues, making heat stress possible even when air temperatures are moderate.

Impact to Date

Heat stress impacts to date on facility electrical equipment have been minor. Workshop participants focused on two systems with heat histories: the Uninterruptible Power Supply (UPS) battery system and Ticket Vending Machines (TVMs).

Uninterruptible Power Supply (UPS). The UPS battery system provides 90 minutes of emergency and standby power for critical systems (e.g., signaling, fire and safety) in the event of power loss. UPS battery systems are designed for a minimum 20-year life when operating at 74°F. Warmer temperatures can halve this life span, requiring more frequent replacement of the battery systems. The cost is not insignificant; each battery system can cost between $20,000 and $50,000. Sound Transit has already experienced problems with reduced UPS battery life at the Issaquah Highlands and Mercer Island Park-and-Ride stations, where inadequate natural ventilation led to operating temperatures as much as 15°F above design standards during a prolonged heat event. Air conditioning is currently required for elevated and underground UPS rooms.

Ticket Vending Machines (TVMs). TVMs collect revenue at Sound Transit facilities. Heat impacts to date on the TVMs have been due primarily to direct sunlight on the units and warm air temperatures. Units with a plasma touch screen are easily disabled by direct sunlight. While this issue has been resolved by design changes, TVMs are still sensitive to warmer air temperatures because they cannot be air conditioned. The impact of TVM failure—losing the ability to collect revenue at that unit until the unit cools and repaired if necessary—is considered minor.

Projected Impact

Higher average and more extreme summer temperatures increase the potential for heat stress in UPS rooms and on TVMs. The impact of more heat stress will vary with the type of equipment and the availability of air conditioning. The impact is considered moderate overall.

Naturally Ventilated Equipment (Aboveground At-grade UPS Rooms and All TVMs). Expected impacts for naturally ventilated equipment include more difficulty using natural ventilation to maintain preferred temperatures, an overall increase in the number of units affected by heat stress, and revenue loss due to TVM failure. Possible impacts include reduced UPS battery life and more frequent replacement of UPS battery systems, which could become costly. Retrofitting UPS rooms for air conditioning also may be needed and can be difficult depending on location and room size.

Air Conditioned Equipment (Elevated and Underground UPS Rooms). Expected impacts for UPS rooms with air conditioning include higher demands on existing air conditioning units and increased operating and maintenance costs for running air conditioning. The need to increase air conditioning capacity is also possible and can be difficult depending on the facility's location and design (e.g., the Mount Baker Station retrofit).

2.3.3. Heat Stress on Facility Landscaping

What is the Issue?

Facility landscaping can be stressed by high summer temperatures, requiring more frequent irrigation or replacement of plants. Sound Transit's facility design criteria emphasize using drought tolerant and native plants capable of surviving without supplemental water after a three year establishment period.[2] Planting areas without irrigation must be able to survive with natural rainfall.

Impact to Date

Minor problems with facility landscaping and heat stress have occurred, although the problems were primarily due to maintenance and oversight issues (e.g., irrigation systems not properly functioning).

[2] Parsons et al. 2007.

Projected Impact
Warmer average summer temperatures and more extreme heat events could place additional heat stress on both established and new plantings, particularly when combined with projected decreases in summer precipitation. Expected impacts include increased irrigation costs. Possible impacts include increased plant mortality and susceptibility to disease, reduced facility aesthetics, and the need to extend or expand the use of irrigation. These impacts are considered minor.

2.4. Precipitation Impacts

2.4.1. Increased River Flooding and Localized Flooding Due to More Stormwater Runoff or Poor Drainage

What is the Issue?
River flooding can affect Sound Transit facilities located in or near present-day FEMA 100-year flood zones. Localized flooding can occur at any facility where extreme precipitation overwhelms the drainage capacity of soils and/or stormwater system. Stormwater is managed on Sound Transit properties through a variety of approaches, including Low Impact Development (LID). The robustness of LID system design relative to the size of extreme rainfall projections is unknown at this time. Additionally, Sound Transit operations and infrastructure can be affected by high volumes of stormwater runoff and drainage problems beyond Sound Transit's properties. If either type of flooding is large enough, the flooding can limit access to facilities and damage infrastructure.

Staff identified several facilities that already experience problems with, or are more susceptible to, river and localized flooding. These include the Tukwila, Kent, and Sumner Stations to the south (river flooding and/or drainage issues), the King Street/SODO area south of downtown Seattle (drainage issues), and the Lynnwood Transit Center to the north (creek flooding). Because the factors exposing facilities to both types of flooding are site-specific, analysis of these issues is presented on a facility-by-facility basis. Drainage issues at the Mukilteo and Edmonds facilities are discussed with other coastal impacts in Section 2.5.

Tukwila Sounder Station
The Tukwila Sounder Station has parking for 208 vehicles and is served by Sounder, Amtrak, and King County Metro. The station sits in the vicinity of FEMA's 100-year flood plain for the Green River. The area is also notable for having a shallow groundwater table, which impacts drainage around the station. The current Tukwila station is considered a temporary station and will be replaced by a larger facility south and slightly west of the current facility. Climate change impacts were evaluated during the workshop for the existing facility only but plans for the new facility were factored into this assessment and are discussed here.

Impact of Increased River Flooding on the Current Tukwila Station. No river flooding has affected the Tukwila Station to date, although one workshop participant remarked that two 50-year flood events had previously caused flooding of the neighboring Union Pacific line. Larger floods due to climate change would most likely have a moderate impact on the Tukwila Station itself given the height of the station and the track relative to the parking area and access roads.

Flood inundation mapping for the Green River by the U.S. Army Corps of Engineers (USACE)[3] (which was obtained after staff interviews) shows that flooding would likely limit access to the station before impacting the station platforms and track, which are approximately 17 feet above the parking lot. Projected inundation depths in the vicinity of the station are 0-2 feet at a peak flow rate of 17,600 cubic feet per second (cfs) and as much as 10 feet at a peak flow of 25,000 cfs.[4] Flooding at these levels could last as long as four days.

The mapped USACE flow rates are relevant to this analysis because the potential for this magnitude of flooding already exists in today's climate; the modeled peak flow rates are in the range of a 0.5% to 0.2% annual probability event. The potential for flooding of this magnitude increases with climate change. The mapped USACE flow rates are consistent with the peak flows projected for the 100-year (1% annual probability) event as early as the 2020s under some climate change scenarios (see Appendix A for more detail).

An expected impact is damage to low-lying infrastructure exposed to flood waters. Potential impacts include loss of parking services and blocked customer access until flooding recedes. Ridership levels at the station could also be affected by widespread flooding of valley roads. Those impacts may be positive or negative depending on how the flooding affects the Green River Valley.

Impact of Increased Localized Flooding on the Tukwila Station. Localized flooding due to extreme precipitation and poor drainage is already an issue with moderate impacts on the Tukwila Sounder Station. Stormwater vaults and pumps are used extensively in the parking lot and pumps are required to keep Long Acres Way clear of water when it rains. Staff noted that without the pumps, even moderate amounts of rain (greater than one inch in two hours) can overwhelm pumps and create isolated flooding capable of cutting off access to the station. Sound Transit recently installed a new, larger capacity pump station along Long Acres Way designed for a larger 100-year (1% annual probability) storm event to help ensure enough capacity for back-to-back 25-year storm events or a single 100-year storm event.

Projections for more winter precipitation, as well as more extreme precipitation, could exacerbate existing drainage issues at the facility and its current access road, although the impact is still considered moderate. At a minimum this would require that facility and access road pumps work harder, although recently installed larger capacity pumps on Long Acres Way will help address this impact. Access to the station could be impeded more frequently as well. However, because transit services at this facility only occur during peak periods, increased localized flooding will only impact access to the station if the flooding occurs during those periods or persists long enough to impact those times.

Impact of Increased River and Localized Flooding on the Proposed Tukwila Station. A larger permanent station is being built south and west of the existing facility between the BNSF tracks used by Sound Transit and tracks used by Union Pacific. The new facility will include parking for approximately 350 vehicles. The facility will be accessed from the north by Long Acres Way and from the south by Strander Boulevard, which is being extended west by the City of Renton to provide access to the station.

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[3] Green River Valley Flood Risk Maps, available at: http://www.nws.usace.army.mil/Missions/CivilWorks/LocksandDams/HowardHansonDam/GreenRiverFloodRiskMaps.aspx

[4] USACE inundation maps were prepared for planning purposes only and are not intended for fine scale (e.g., less than 180 feet x180 feet) analysis. Consequently, the specific inundation levels and their location are considered projections, not predictions.

Access road drainage will continue to be an issue for the new facility. Strander Boulevard will go under the BNSF tracks, requiring pumps to manage stormwater flows. Staff noted that extensive pumping has been required during construction, even during the dry summer months.

River flooding will also likely remain an issue, although to a lesser degree than at the current location. One factor contributing to the reduced impact is the fact that facility structures at the new location will be constructed +2.5 feet above ground level. For floods at 17,600 cfs, inundation depths of 0-2 feet at the facility are possible but the area inundated is fairly limited. Long Acres Way could be covered by up to six feet of water but Strander Blvd would not be flooded, ensuring that access is open from the south.

More significant flooding is possible for flood flows at 25,000 cfs. The new location sits in an area where inundation depths for a 25,000 cfs peak flood event quickly transition from 6-10 feet to zero feet of inundation. However, both Long Acres Way and Strander Blvd would be heavily impacted at 25,000 cfs, as would extensive areas leading to the station.

Kent Station

The Kent Station is a major transit hub with 996 parking spaces and service by ST Express, King County Metro DART (Dial-A-Ride Transportation), and Sounder. Like the Tukwila Station, the Kent Station sits in proximity to FEMA 100-year flood zones for the Green River and both the USACE and Sound Transit analyses show that the Kent Station could be impacted by Green River flooding.

Impact of Increased River Flooding on the Kent Station. No flooding has been experienced at the Kent Station to date. Climate change projections for more significant river flooding increase the potential for inundation at the Kent facility and/or of access roads but the impact is considered minor. Surrounding roads could see up to two feet of inundation at 17,600 cfs but the facility itself would be unaffected at that level of flooding. The potential for inundation at the facility only emerges only at the high end of the peak flow rates mapped by the USACE (19,500 cfs and 25,000 cfs). The depth of inundation that could occur at those levels is low (less than two feet). Access to the facility would also be affected in each of these scenarios.

An expected impact of river flooding at the Kent Station is damage to low-lying infrastructure exposed to flood waters. Possible impacts include closure of the parking facility due to flooding of the lower level of the garage and loss of service from the elevators that connect the parking garage to the overhead bridge leading to the station. Service out of the station could still run, albeit with reduced service.

Impact of Localized Flooding at the Kent Station. No existing or anticipated problems with localized flooding were noted for the Kent Station.

Sumner Station

The Sumner Station is a Sounder station also served by ST Express and Pierce Transit. The facility has parking for 343 vehicles at the station and an additional 41 spaces in a nearby lot. The Sumner Station is located near the confluence of the White and Puyallup Rivers but sits well outside current 100 and 500-year flood zones. Several key access roads are located within those zones, however. This includes State Route 410, which was reported to carry 50% of the boardings at the Sumner facility.

Staff noted that the area has a history with flooding as well as standing water, although neither has directly impacted the facility or access to the facility to date. The potential impact of increased river or localized flooding on the Sumner Station is considered minor. Both the White and the Puyallup Rivers are sensitive to projected increases in winter temperature and precipitation as a result of climate change (see Appendix A). Any increases in flooding large enough to affect State Route 410 could impact a significant number of riders by limiting use of a key access route to the facility, although the probability is considered low and alternate routes are available.

King Street, Stadium, and SODO Stations

The south downtown Seattle stations (King Street, Stadium, and SODO Stations) are high volume stations served by one or more modes. The King Street Station is used by Amtrak and Sounder. The Stadium and SODO stations are used by Link. The potential for flooding at these stations is limited to localized flooding from increased stormwater runoff or poor drainage.

Localized flooding and drainage issues have had a minor impact to date on the King Street, Stadium, and SODO Stations. Drainage is a challenge at these stations due to the area's flat topography and conversion from tidal flats in the early 1900s. High groundwater due to heavy precipitation and/or tides can soften the ground around the SODO station and wet the concrete when the tide comes in despite the station's distance from the shoreline. Heavy precipitation can also cause localized flooding on S. Royal Brougham Way and overwhelm underground and low lying vaults. This can create additional maintenance issues. In some cases, maintenance activities have to be timed with the tides as well as non-revenue service hours.

Increasing winter precipitation and more extreme precipitation events could increase groundwater levels and lead to increased localized flooding around the south downtown Seattle transit facilities. The impact of this increased flooding is considered moderate. Expected impacts include more difficulties draining water and more frequent flooding of at-grade or underground equipment. Possible impacts include expansion of drainage issues to new areas, increased wear-and-tear on pump systems where they exist, changes in the grounding properties of electrical systems, reduced customer access during heavy precipitation events, and the need to resize stormwater vaults in some locations (where relevant).

Sea level rise is not expected to have any direct impacts on the South downtown stations because of the Seattle sea wall, which is currently being replaced as part of a major overhaul of State Route 99 along the Seattle waterfront. Fifty inches of sea level rise was taken into account when redesigning the sea wall.[5] Although inundation is not expected, higher sea level could compound drainage issues by increasing groundwater levels in the area.

Lynnwood Transit Center

The Lynnwood Transit Center is currently a ST Express facility with parking for 1,368 vehicles. The Lynnwood Link Extension will bring Link light rail service to the Transit Center in 2023. As discussed in Appendix C.2, the southwest corner of the Lynnwood Transit Center's parking lot overlaps with current 100-year FEMA flood zone for Scriber Creek, although no flooding has occurred at the facility to date.

Projections for more winter precipitation could increase the potential for flooding in Scriber Creek and exacerbate "long-standing storm drainage and sewer flooding issues" with Scriber

[5] For more information, see the Seattle Department of Transportation "Sea level and the seawall?" blog post, January 23, 2013, http://sdotblog.seattle.gov/2013/01/23/sea-level-and-the-seawall/

Creek.[6] Possible impacts include minor flooding of the parking area and any ground-level or underground electrical equipment in a small portion of the overall facility. Staff rated this impact as minor. Efforts by the City of Lynnwood to address chronic flooding issues in the general vicinity may reduce the potential for flooding at the Transit Center.

2.4.2. Tunnel Station Seepage

Sound Transit tunnel stations currently include four Link and ST Express stations in the Downtown Seattle Transit Tunnel and Link's Beacon Hill Station. The downtown tunnel and station facilities are owned and maintained by King County Metro, which also uses the tunnel stations for local bus service. Sound Transit owns and maintains Link's Beacon Hill Station.

Several future Link alignments will also have tunnel stations (see Appendix C.2). Seepage potential was not evaluated for these stations, although many of the conclusions about the projected impact of tunnel seepage could apply to those facilities. The one notable conclusion that may not apply to new tunnel stations is the potential for odor issues; new tunnel designs should significantly reduce or eliminate that issue.

Impact to Date

Tunnel seepage has a minor impact on the Beacon Hill Station and the Downtown Seattle Transit Tunnel. As noted in Appendix C.2, seepage currently causes problems with odor issues in the 1.6-mile Link tunnel that cuts through Beacon Hill. These odor issues impact the station when odors are flushed into the station platform by passing trains. The odor issues are currently being treated by Sound Transit. Seepage in the Downtown Seattle Transit Tunnel has no impact on Sound Transit operations; managing seepage in the downtown tunnel is the responsibility of King County.

Projected Impact

Increasing winter precipitation and more extreme precipitation events could increase seepage rates around the Downtown Seattle Transit Tunnel and Beacon Hill Tunnel by raising hydrostatic pressure. The projected impact of more seepage at tunnel facilities was considered minor. Possible impacts of higher seepage rates include more frequent maintenance or replacement of pumps. Increased seepage into tunnel infrastructure (e.g., elevator pits) is also possible. Finally, odor issues at the Beacon Hill Station may become more intense or last for longer periods of time if higher seepage rates stimulate more of the sulfur-reducing bacteria that cause odor. This particular issue could have more notable impacts depending on how much odor issues increase (if at all).

2.5. Sea Level Rise and Related Coastal Issues

What is the Issue?

High tides and storm surge can cause temporary flooding of low-lying areas, increased erosion, and problems with stormwater drainage. Sea level rise can compound these existing issues while also creating new problems. Sea level is expected to increase an average of 24 inches by 2100 in the Seattle area with a possible range of +3.9 in. to +56.3 inches (see Appendix A). Projections for the area between Seattle and Everett are assumed to be the same or similar.

[6] City of Lynnwood Public Works Department public letter, May 13, 2013, available at: http://www.ci.lynnwood.wa.us/Assets/Calendar+Assets/Public+Meeting+Notice+Scriber+Creek+Flooding.pdf

Assuming “business as usual” (i.e., no changes in current coastal defenses, where they exist), sea level rise of this magnitude increases the potential for reduced access to facilities, damage to infrastructure exposed to marine water and increased wave energy, and potential loss of use due to permanent inundation.

Proximity, elevation, and connectivity to Puget Sound are the major factors influencing exposure to storm surge and sea level rise. Facilities located further inland may also be exposed if topography provides the necessary connectivity to the coast by channeling higher coastal flood waters (e.g., higher tides) inland through low-lying areas. Connectivity can also occur via stormwater drainage infrastructure, which can act as a conduit for marine waters when high tides cause marine water to flow *into* parking lots, roads, and other features connected through stormwater pipes.

Only two facilities—North Sounder’s Mukilteo and Edmonds facilities—are potentially affected by sea level rise. Current and projected impacts for these facilities are discussed in the following sections. Sea level rise impacts on the north rail alignment leading to/from these facilities are discussed in Appendix C.1.

Impact to Date

Edmonds Station. The Edmonds Station (elevation: 8 feet) is a shared Sounder/Amtrak station that includes a street-level open-air station platform and parking for 209 cars. The station underwent a $12.9 million remodel in 2010-2011 to provide longer boarding platforms, better lighting, repaved parking facilities, bus bays, and other improvements.

The Edmonds Station has a history of periodic flooding (once or twice a year) during King Tides[7] and/or heavy rain events that coincide with normal tides, all of which are most likely to occur between November and February. Key access roads, including intersection of Main Street and State Route 104 (located 0.2 miles north of the Edmonds Station), also flood periodically. Staff rated the impact of this periodic flooding on the Edmonds Station as moderate.

Electrical shorts have also been a problem. Ice melt or heavy rain can flood the underground junction boxes used that contain wiring for lighting, ticket vending machines (TVMs), and other electrical needs. The shorts cause power losses lasting as long as a couple of hours, prohibiting revenue collection at the TVMs and use of the elevators. Service can still be maintained to track, however.

An underground stormwater vault was installed with the 2010-2011 Edmonds Station remodel to address flooding at the site but the adjacent Dayton Street parking lot, which is not equipped with a vault, is still subject to flooding from stormwater flows. The vault has backflow preventers to make sure tides do not fill the vault.

Staff noted that timing of high tide events relative to heavy precipitation events and flooding matters. If the flooding occurs at noon or midnight, for example, operations are not impacted because Sounder trains are not running at that time. The most sensitive time for impacts based on the current Sounder weekday operating schedule, therefore, is generally between 5:30 am to 8:00 am and 4:00 pm to 6:30 pm.

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[7] “King tides” are the highest tides of the year. King tides typically occur in winter when the sun and the moon align, causing an increased gravitational pull on the Earth’s oceans. For more on King Tides in Washington, see http://www.ecy.wa.gov/climatechange/ipa_hightide.htm

Mukilteo Station. The Mukilteo station (elevation: 18 feet) is a single platform Sounder station with 63 parking spaces. Construction of a second boarding platform on the south side of the tracks, a pedestrian bridge, and permanent passenger shelters is scheduled to begin in summer 2013. In contrast to the Edmonds Station, the Mukilteo Station has no history of flooding from high tides or intense precipitation events. An adjacent lot not associated with Sound Transit has flooded in the past, however.

<u>*Projected Impact*</u>

Edmonds Station. Sea level rise is likely to have moderate to extreme impacts for the Edmonds and Station depending on how much sea level rise occurs. As noted in Appendix B, two sea level rise inundation zones were mapped for this project: a 22 inch and 50 inch inundation zone. No inundation occurs at the Edmonds Station and surrounding access points (Railroad Avenue, Dayton Street, James Street, State Route 104) under the 22 inch sea level rise scenario, although existing drainage problems would be exacerbated. This expectation led the Washington State Department of Transportation (WSDOT) to classify State Route 104 as having moderate vulnerability to climate change.[8] With 50 inches of sea level rise, the Edmonds station and its access roads are inundated (Figure 1).

Expected impacts even at the low end of projected increases are for more problems with drainage, increased exposure of low-lying infrastructure and equipment to marine water, and periodic minor issues with access because of more tidally-induced flooding along access roads and potentially in parking areas. Note that as sea level rises, even moderate precipitation events could cause more drainage problems and localized flooding. Possible impacts include an increase in the frequency of impacts expected at low to moderate sea level rise amounts and eventual loss of service at the facility due to permanent inundation.

Electrical equipment potentially at risk of flooding and increased corrosion from saltwater include power supply transformers, TVMs, junction boxes, and signal bungalows. The TVMs are on station platforms and would only be impacted directly if marine waters were higher than station platforms. The power supply transformers that power the TVMs, as well as fire and safety equipment, are more easily affected because they are located only eight to ten inches above ground. Transformer electrical equipment can get wet if installed properly but it is unknown if they can withstand prolonged exposure to saltwater. If the transformers were to go out, train service can be continued but revenue cannot be collected from the TVMs. Signal bungalows and gates would also be affected, however these are owned by BNSF.

Mukilteo Station. The impact of sea level rise at the Mukilteo Station will also vary depending on the scenario. Because of this, impacts were similarly rated moderate to extreme. At 22 inches of sea level rise, storm surge could reach parts of Front Street, which is the only access road for the Mukilteo Station. Fifty inches of sea level rise would permanently inundate much of Front Street, most of the parking along First Street, the tracks leading to the station (from the south), and areas around the boarding platform (Figure 2).

Expected and possible impacts for the Mukilteo Station are the same as the Edmonds Station. Staff considered increased flooding and permanent inundation of Front Street as the “weak link” in these scenarios given that more frequent temporary flooding would start restricting access to the station before permanent inundation affected the facility itself. In addition to the electrical equipment identified in the Edmonds assessment, more frequent temporary flooding and

[8] WSDOT. 2011.

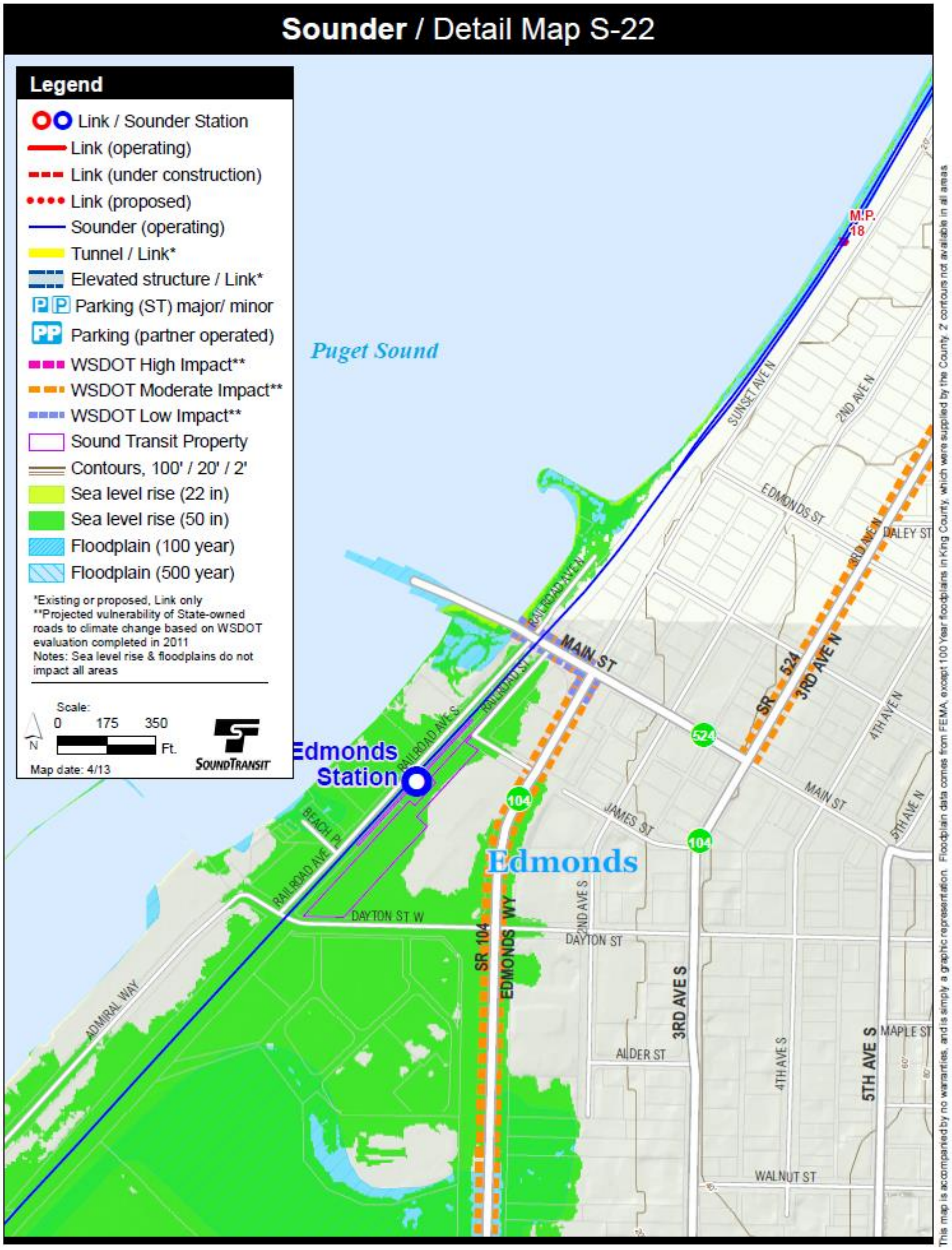

Figure 1. Projected Inundation Zones for 22 Inches and 50 Inches of Sea Level Rise Near the Edmonds Station. *Map produced by Sound Transit.*

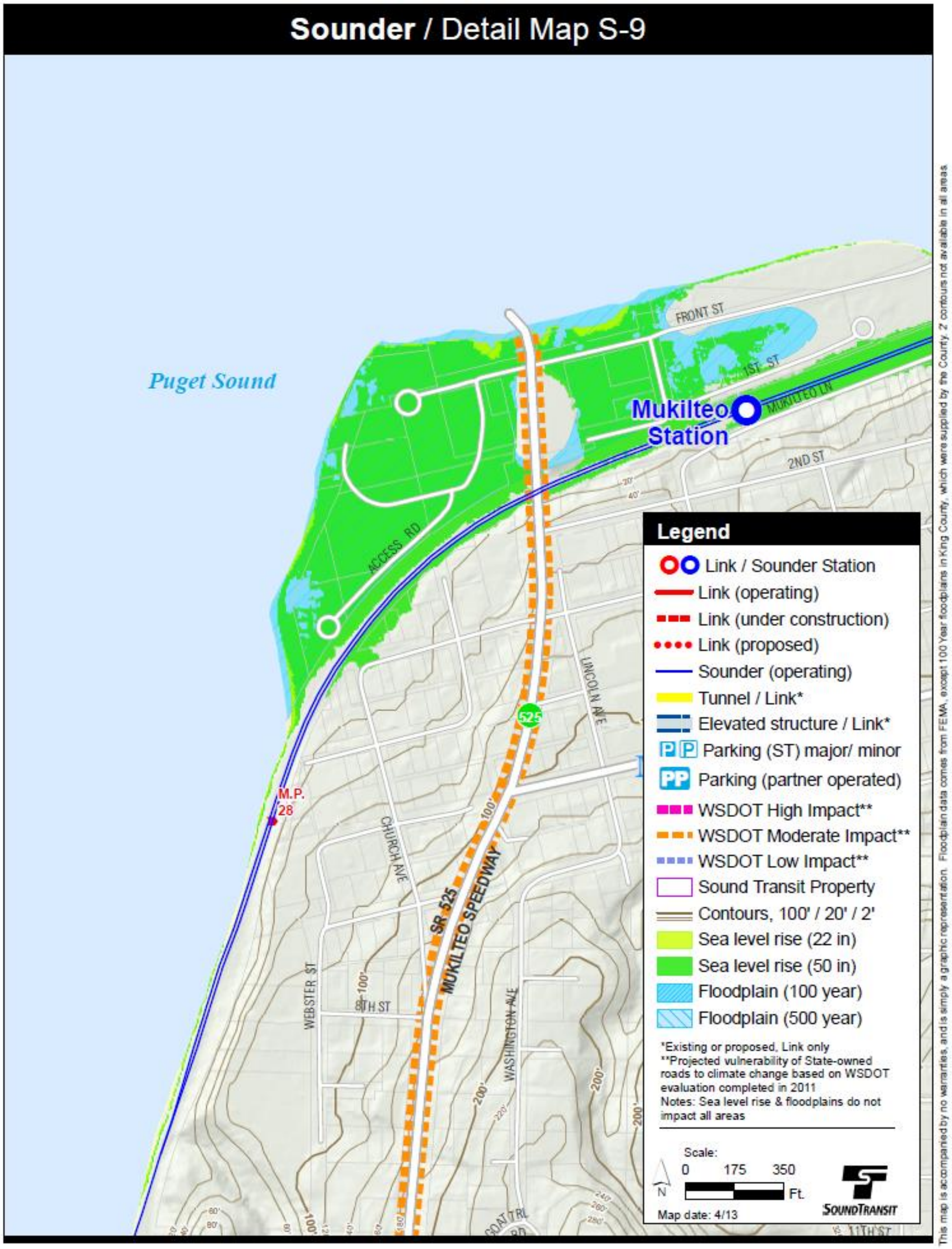

Figure 2. Projected Inundation Zones for 22 Inches and 50 Inches of Sea Level Rise Near the Mukilteo Station. The station platform is located near the traffic circle on First Street. *Map produced by Sound Transit.*

permanent inundation of hydraulic elevators planned for the pedestrian bridge being constructed at Mukilteo is also possible.

Important Considerations for the 50 Inch Sea Level Rise Impacts. While the inundation projected with the 50 inch sea level rise scenario has a significant impact for both stations, the probability that these areas will be permanently inundated is low given the importance of other locally and state-owned infrastructure (including two Washington state ferry terminals) near the stations. There will be a strong incentive on the part of the cities of Edmonds and Mukilteo, as well as WSDOT, BNSF, and Amtrak, to ensure the long-term viability of the areas likely to be inundated by sea level rise. The cost of installing additional coastal defenses to prevent permanent inundation is unknown. Additional adaptive actions are still likely to be required on the part of Sound Transit and/or BNSF, as discussed in Section 0.

3. Adaptation Options for Customer Facilities

Options for adapting Sound Transit facilities to the impacts of climate change are discussed in the following sections. The adaptation options provided here are not intended to be an exhaustive list of all possible approaches; they are an initial list of options considered most relevant to customer facilities based on the impacts identified through the Sound Transit Climate Risk Reduction Project. In all cases, these actions should be considered optional and “if needed.”

Because climate change exacerbates many existing issues, some of the adaptation options are activities that would be pursued regardless of any knowledge about climate change or any pre-emptive decisions to adapt to projected climate change impacts (i.e., as part of “business as usual”). However, climate change may accelerate the need for these adaptation options and/or require implementation at a scale larger than would normally be expected. In other cases, climate change may raise the need for new approaches or cause reprioritization of existing approaches.

Decisions about which adaptation options to employ and when will depend on how rapidly climate change occurs and the cost of implementing the adaptation option(s). These costs will vary with the specifics of the adaptation option, the scale of deployment, and how readily the option can be integrated into routine asset maintenance and replacement cycles, among other factors. Further discussion and analysis of these issues is required before these or other adaptation options not included here can become implementation-ready recommendations.

3.1. Heat Impacts

<u>*Heat Stress on Structures.*</u> Adaptation options for managing and reducing the impacts of heat stress on structures may include any combination of the following:

- Increase visual monitoring for premature wear related to heat stress on structures;
- Periodically evaluate assumed design temperature tolerances and temperature benchmarks (e.g., Uniform Temperature and Temperature Gradient benchmarks set for 64°F) in relation to projected changes in climate. If potentially inadequate, evaluate the cost and benefits of changing the standards to increase robustness of the designs; and
- Increase the use of shading around structures and more reflective roof coating to reduce solar loading and potential for heat stress on structures.

Heat Stress on Electrical Equipment (UPS rooms and TVMs). Adaptation options for managing and reducing the impacts of heat stress on electrical equipment may include any combination of the following:

- Evaluate the remaining non-air conditioned UPS rooms to determine which units may require air conditioning in the future as a result of warming temperatures;
- Increase battery heat tolerance (i.e., the average temperature to which batteries are designed);
- Add new or increase existing air conditioning capacity where heat stress becomes or continues to be an issue;
- Where possible, increase shading around TVMS to maximize passive cooling;
- Increase the specified heat tolerance for TVM units and/or evaluate options for more heat-tolerant TVMs.

Heat Stress on Facility Landscaping. Current Sound Transit landscaping standards already require the use of native and drought-tolerant species and use of "sustainable alternative approaches" to stormwater management that provide benefit to landscaping. Even species native to this region can experience heat and/or drought stress, however. Adaptation options for heat stress on landscaping may include any combination of the following:

- Extending (in duration) and/or expanding (in geography) the option to use irrigation during and after the establishment period, when necessary; and
- Reducing the use of small planter areas (e.g., narrow planting strips) that may be more prone to heat stress because of irrigation challenges, reflected pavement heat, or other factors.

3.2. Precipitation Impacts

Increased River Flooding. Adaptation options for managing and reducing the impacts of increased river flooding may include any combination of the following:

- Raise or relocate sensitive ground-level infrastructure to reduce or eliminate potential for flooding;
- Modify design standards to provide higher level of flood protection for infrastructure that must be located in or near flood hazard zones;
- Extend design standards required for the 100 year flood zone out to the 500 year flood zone for flood-sensitive equipment, facilities, and other infrastructure; and
- Work with the USACE and floodplain communities to help ensure that Sound Transit's current and projected flood management needs are considered in flood management and hazard mitigation decisions.

Increased Localized Flooding. Adaptation options for managing and reducing the impacts of increased localized flooding due to more stormwater runoff or poor drainage may include any of combination of the following:

- Increase visual and/or electronic monitoring in areas with drainage problems;
- Raise or relocate sensitive ground-level infrastructure to reduce or eliminate potential for localized flooding;
- Modify design standards to provide higher level of flood protection for equipment that must be located in areas where drainage could be an issue;

- Design for more intense and/or longer duration rain events (i.e., planning for amounts higher than the 24 hour 25-year storm event);
- Expand used of Low Impact Development, bioswales and other green stormwater management to add design robustness to hard infrastructure;
- Modify drainage patterns to re-direct surface flows and improve drainage; and
- Partner with Seattle Public Utilities and other community utilities to target problem drains/drainages.

Tunnel Seepage. Adaptation options for managing and reducing the impacts of increased tunnel seepage may include any combination of the following:

- Increase maintenance of pumps and drains used to manage seepage;
- Explore alternate approaches to reducing or redirecting groundwater flows away from Beacon Hill Tunnel or reducing the growth of sulfur-producing bacteria in the Beacon Hill Tunnel.

3.3. Sea Level Rise and Related Coastal Impacts

Adaptation options for sea level rise incorporate options identified in Section 3.2 for reducing the impacts of poor drainage since tidally-influenced drainage problems are already an already issue for the Edmonds and Mukilteo Stations. Adaptation options for adapting the Edmonds and Mukilteo facilities to sea level rise may include any combination of the following:

- Increase visual and/or electronic monitoring in areas with drainage problems;
- Raise or relocate sensitive ground-level infrastructure to reduce or eliminate potential for flooding;
- Modify design standards to provide higher level of protection for infrastructure that must be located in or near coastal flood zones, sea level rise zones, or areas with poor drainage;
- Design for more intense and/or longer duration rain events (i.e., planning for amounts higher than the 24-hour 25-year storm event);
- Install (or work with partner communities to install, where relevant) tide flaps or other controls that will prevent high tides from flooding parking lots and facilities via backflow into stormwater drains;
- Modify drainage patterns to re-direct surface flows away from flood-prone areas and improve drainage;
- Partner with community utility programs to target problem drains/drainages; and
- Work with Mukilteo, Edmonds, the State of Washington, and others to help ensure that Sound Transit's current and projected needs related to sea level rise are considered in decisions about adapting the area to sea level rise.

It is important to note that decisions made by BNSF and others about adapting the north rail alignment could affect how the Edmonds and Mukilteo facilities are adapted. For example, any decisions on the part of BNSF to raise track elevation would require costly retrofits on the part of Sound Transit to raise stations platforms and facilities to meet new track grades.

3.4. System-wide Adaptation Options

While most adaptation options could be categorized by climate impact, the following adaptation option is relevant across a range of issues.

- Evaluate, and where relevant update, metrics used for operations, maintenance, and asset management decisions to include climate-related information that can be used to evaluate trends over time and inform adaptation decisions.

4. Summary of Findings

Climate change will affect facilities in varying ways depending on the location and specific characteristics of each facility. Overall, however, climate change is likely to have minor to moderate impacts on most of Sound Transit's customer facilities, as summarized in Table 2.

As with the modes, the most prevalent impact potentially affecting facilities is heat. Heat stress on structures, electrical equipment, and facility landscaping could potentially affect any aboveground facility but is expected to have mostly minor impacts on facility operations and maintenance. The primary heat impact of note is the potential for more heat stress on TVMS and non-air conditioned UPS rooms, which could reduce battery life.

Increased river flooding could impact the Green River Valley stations (specifically Tukwila, Kent, and Sumner Stations). While potentially significant flood inundation depths are possible for the Tukwila Station based on mapping of extreme (0.5% and 0.2% annual probability) peak flows by the USACE, flood impacts are likely to be limited to parking facilities and access roads at both the current and future facility. Inundation levels at the Kent Station are likely to minor (less than two feet) and flooding of the White River in Sumner would likely only impact access roads. While these impacts are associated with flood flows considered rare in today's climate, flood flows of that magnitude could become more likely (e.g. shifting to a 1% annual probability event) as a result of climate change as soon as the 2020s in some scenarios.

Drainage issues are potentially relevant to any customer facility and are already a problem at the Tukwila and King Street, Stadium, and SODO Stations. Projected increases in winter precipitation and extreme precipitation are expected to exacerbate drainage issues in current problem areas while potentially bringing the problem to new areas. Sea level rise will also compound existing drainage issues at the Edmonds Station.

Significant impacts are possible at only two facilities—the Edmonds and Mukilteo Stations—for the high (50 inch) sea level rise scenario. The probability of seeing that level of sea level rise is low, however. Expected impacts even at the low end of projected increases are for more problems with drainage, increased exposure of low-lying infrastructure and equipment to marine water, and periodic minor issues with access because of more tidally-induced flooding along access roads and potentially in parking areas. Possible impacts at the 50 inch level include eventual loss of service at the facilities due to permanent inundation.

Table 2. Summary Assessment of Current and Projected Climate Impacts on Customer Facilities. Rail alignments for Sounder and Link were evaluated separately. Rating based on input from Sound Transit staff who participated in project workshops. Bold indicates impacts that are expected to have a larger impact on customer facilities moving forward in time as a result of climate change. "Expected" impacts are those that would be expected to occur even at the low end of climate change projections. "Possible" impacts are impacts likely to occur in limited cases and/or at higher amounts of climate change.

	Projected Impact *(i.e., potential for more...)*	***Current Impact Rating***	***Projected Impact Rating***	***Potential Impact(s)*** *Assumes no intervening adaptation measure taken….*	***Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact***	***Scientific Confidence Regarding Change in Underlying Climate Cause(s)***
Heat Impacts	Heat stress on structures	Minor	Minor	*Expected impact(s):* • Increased maintenance. • Change in concrete mix ratios. *Possible impact(s):* • More frequent repairs • More frequent replacement of stressed infrastructure. • Minor inconveniences to customers during maintenance and repair activities.	(+) Designs now specify expansion joints but temperature tolerance for design numbers uncertain.	*High*. High confidence that average and extreme summer temperatures will increase. High confidence that temperatures will more frequently cross temperature thresholds that trigger advisories and other prevention activities.
	Heat stress on electrical equipment (UPS, TVMs)	Minor	**Moderate**	*Expected impact(s):* • More difficulties using natural ventilation to maintain preferred temperatures. • More naturally ventilated units affected by heat	(+) AC required in all elevated and underground UPS rooms. (-) TVMS cannot be air conditioned. (-) Aboveground non-AC UPS rooms may still be vulnerable to heat stress.	*High*. High confidence that average and extreme summer temperatures will increase.

Projected Impact *(i.e., potential for more...)*		**Current Impact Rating**	**Projected Impact Rating**	**Potential Impact(s)** *Assumes no intervening adaptation measure taken….*	**Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact**	**Scientific Confidence Regarding Change in Underlying Climate Cause(s)**
				stress. • Lost revenue from TVMs affected by heat. • Increased demands on (and for) air conditioning (AC) units. • Increased operating and maintenance costs for AC. *Possible impact(s):* • Reduced UPS battery life. • More frequent replacement of UPS battery systems. • Retrofits to existing UPS rooms to allow for installing AC or increasing existing AC capacity.	(-) Retrofitting UPS rooms can be difficult depending on location and room size.	
	Heat stress on facility landscaping	Minor	Minor	*Expected impact(s):* • Increased irrigation costs, even for native species. *Possible impact(s):* • Increased plant	(+) Facility design criteria emphasize using drought tolerant and native plants. (-) Projected decreases in summer precipitation will compound warmer summer temperatures.	*High*. High confidence that average and extreme summer temperatures will increase. Good confidence that summer precipitation

Projected Impact *(i.e., potential for more...)*		Current Impact Rating	Projected Impact Rating	Potential Impact(s) *Assumes no intervening adaptation measure taken….*	Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact	Scientific Confidence Regarding Change in Underlying Climate Cause(s)
				mortality. • Greater susceptibility of plants to disease. • Reduced facility aesthetics. • Need to increase use of irrigation.		will decrease.
Related to Precipitation and/or Sea Level Rise	River flooding (*Green and White Rivers:* Tukwila, Kent, Sumner *Scriber Creek:* Lynnwood Transit Center)	No impact	Minor to **Moderate**, depending on facility	*Expected impact(s):* • Damage to low-lying infrastructure exposed to flood waters. • Impacts on ridership levels during flood events (may increase or decrease depending on flood event) *Possible impact(s):* • Temporary loss of access roads and parking areas	(+) New Tukwila station location less affected by inundation, although Strander Blvd still inundated at higher flood levels.	*Moderate to high.* There is high confidence that climate change will cause shifts in streamflow timing and increasing winter flows in rivers influenced by snowmelt. There is less confidence in the specific size of the shift and less confidence in the amount of potential flooding in low-elevation rain-dominant rivers and streams given uncertainties about changes winter precipitation.
	Localized flooding due to creeks or poor	No to moderate impact, dependin	No to **moderate** impact, depending	*Expected impact(s):* • More difficulties draining water • More frequent flooding	(+) New Tukwila station will have additional access route, providing an option to Long Acres Way, which	*Medium.* Based on current model runs, there is good confidence that

Projected Impact *(i.e., potential for more...)*		***Current Impact Rating***	***Projected Impact Rating***	***Potential Impact(s)*** *Assumes no intervening adaptation measure taken….*	***Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact***	***Scientific Confidence Regarding Change in Underlying Climate Cause(s)***
	drainage *(Tukwila, Kent, King Street, and SODO area stations, Lynnwood Transit Center)*	g on facility	on the facility	of at-grade and underground equipment. *Possible impact(s):* • Expansion of drainage issues to new areas. • Increased wear-and-tear on pump systems where they exist. • Changes in the grounding properties of electrical systems. • Reduced customer access during periods of heavy precipitation. • Need to resize vaults, where relevant.	can be easily inundated… (-) …however, new access route to Tukwila Station also in an area where inundation is a problem.	average and extreme winter precipitation will increase but low confidence in specifically how much.
	Tunnel seepage *(Downtown Seattle Transit Tunnel stations and Beacon Hill Station)*	Minor	Minor	*Possible impact(s):* • Increased maintenance or replacement of pumps used to manage seepage. • Increased seepage into below-ground tunnel infrastructure (e.g., elevator pits). • Additional odor control activities if odor issues	(+) King County is responsible for seepage management in the downtown tunnel. (+) New tunnel design standards do not put tunnels in direct contact with soil, reducing potential for problems in new tunnels. (-) Design of the Beacon Hill Tunnel puts the tunnels in	*Low to medium,* for reasons specified in previous row High uncertainty as to how groundwater flows change in response to projected increases in temperature.

Projected Impact *(i.e., potential for more...)*		**Current Impact Rating**	**Projected Impact Rating**	**Potential Impact(s)** *Assumes no intervening adaptation measure taken….*	**Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact**	**Scientific Confidence Regarding Change in Underlying Climate Cause(s)**
				increase in Beacon Hill Tunnel.	direct contact with soil, making seepage and odor issues more likely. (-) Soils around Beacon Hill Tunnel are high in naturally occurring sulfur-reducing bacteria, triggering odor issues. (-) Limited number of drain clean-outs can make maintenance of seepage issues in the Beacon Hill Station a minor inconvenience.	
	Sea level rise and related coastal impacts *(Edmonds and Mukilteo Stations)*	No to moderate impact, depending on facility	**Moderate** to **Extreme**	*Expected impact(s):* • More problems with drainage. • Increased exposure of low-lying infrastructure and equipment to localized flooding and marine water. • Periodic minor issues with access due to localized flooding. *Possible impact(s):* • More frequent occurrence of the "expected impacts"	(+) A new (2010-11) underground stormwater vault installed at the Edmonds Station will help address existing issues with flooding related to high tides and heavy precipitation. (+) Most extreme impacts (permanent inundation of facilities) only possible under high sea level rise scenario. (+) Presence of other commercially important local and state facilities (e.g. Washington State	*High* (that sea level will rise) and *low* (how much rise will specifically occur).

Projected Impact *(i.e., potential for more...)*		***Current Impact Rating***	***Projected Impact Rating***	***Potential Impact(s)*** *Assumes no intervening adaptation measure taken….*	***Factors that May Reduce (+) or Increase (-) the Likelihood of the Projected Impact***	***Scientific Confidence Regarding Change in Underlying Climate Cause(s)***
				listed above • Eventual loss of service at the facilities due to permanent inundation at high (50 inch) sea level rise scenario.	ferry terminals) creates a large incentive enhancing coastal defenses, although drainage issues would still be a problem. (-) Addressing impacts could be costly	

References

Parsons Brinckerhoff Quade & Douglas, Inc., 2007. *Design Standards and Guidelines for Sound Transit Projects: Sounder and ST Express* Facilities. Seattle, WA.

(WSDOT) Washington State Department of Transportation. 2011. *Climate Impacts Vulnerability Assessment.* Report prepared by the Washington State Department of Transportation for submittal to the Federal Highway Administration, Olympia, Washington. Available at: http://www.wsdot.wa.gov/NR/rdonlyres/B290651B-24FD-40EC-BEC3-EE5097ED0618/0/WSDOTClimateImpactsVulnerabilityAssessmentforFHWAFinal.pdf

APPENDIX

D

Integration Examples: Sound Transit ESMS and WSDOT

Integration Examples:
Sound Transit ESMS and WSDOT

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This Appendix provides an example of how climate change adaptation could be integrated into Sound Transit's Environmental and Sustainability Management System and information on the Washington State Department of Transportation's current approach to integration.

1. An Approach to Integrating Climate Change Adaptation into Sound Transit's Environmental and Sustainability Management System

Sound Transit maintains an internationally certified Environmental and Sustainability Management System (ESMS) that holds the agency accountable for identifying and controlling environmental impacts, setting and achieving objectives and targets, and demonstrating continual improvements in performance. The ESMS provides the management tools to successful execute the agency's environmental and sustainability vision as reflected in the Board-adopted Environmental Policy and Sustainability Initiative.

Integrating Climate Adaptation into the ESMS

Since 2007, Sound Transit has been one of a select number of transit agencies nationwide to achieve certification to the international ISO 14001 standard. Sound Transit's ESMS follows the ISO 14001 model of "Plan, Do, Check and Act." Climate change adaptation considerations and requirements may be integrated as follows.

- **Plan:** Establish objectives and processes

    - **Environmental aspects** – Sound Transit evaluates the environmental aspects and impacts of its activities. This evaluation and prioritization informs the system's priorities for implementation and control. Sound Transit could further explore better integrating environmental aspects and impacts related to climate change or could analyze how to integrate a suite of climate change considerations as evaluation criteria for the scoring of environmental aspects.
    - **Legal and other requirements** – Environmental regulatory requirements (including any potential future state or federal requirements regarding climate change) are an essential element of the ESMS. The agency also controls other agency requirements, such as policies and voluntary initiatives. Such agency commitments could include any agency-adopted climate adaptation policies or strategies.
    - **Objectives and targets** – Sound Transit establishes and maintains objectives and targets on an annual basis to drive continual improvement. The agency designates responsibilities, resources, action steps and timeframes for all targets. Annual objectives and targets may address development or implementation of climate adaptation strategies for the agency to drive continual improvement in our sustainability performance.

- **Do:** Implement the processes

- **Resources, roles, responsibility and authority** – Sound Transit establishes and maintains a procedure outlining agencywide roles and responsibilities for the ESMS to define clear ownership and facilitate effective ongoing environmental management and authority. The current ESMS structure is sufficient to address and integrate climate adaptation decisions.
- **Competence, training and awareness** – Sound Transit requires that all employees engaged in activities that may affect the environment be aware of the ESMS, properly qualified and adequately trained. The agency's training requirements provide a good backbone for the development of climate-related special training sessions for staff.
- **Communication** – The agency maintains procedures on internal and external communication. Employees are encouraged to communicate ideas and suggestions to the ESMS Steering Committee. The ESMS procedure on communication currently covers any agency communication related to climate adaptation discussions.
- **Control of documents** – Control of ESMS documents is a critical part of an effective system for change and improvement—keeping system procedures organized and ensuring that all employees are using the correct and current versions of ESMS documents. Climate adaptation related documents would be maintained as part of the agency's current document control process.
- **Operational control –** Sound Transit develops and maintains controls for all identified significant environmental aspects. These controls include basic operating criteria for situations where their absence could lead to deviations from the Environmental Policy, Sustainability Initiative and/or legal or other requirements. They also document process flow for the agency's significant environmental activities. Operational control procedures may be developed to provide specific staff technical guidance on implementation of specific climate adaptation processes. Current ESMS Operational Control Procedures, such as maintenance of stormwater systems, could be revised to better integrate future climate adaptation requirements.
- **Emergency preparedness and response** – The agency develops project and facility specific plans to identify the potential for accidents and emergency situations, to respond appropriately and to prevent or mitigate the associated environmental impacts. Climate adaptation considerations and/or requirements may be integrated into the agency's Emergency Management Plan and project emergency response plans.

▪ **Check:** Measure the processes

- **Monitoring and measurement** – Monitoring and measuring environmental indictors allows tracking of ESMS effectiveness and environmental progress. The agency regularly monitors and measures key characteristics of its operations and activities that may have a significant impact on the environment or may impact the agency's sustainability performance. The agency may choose to track climate adaptation related performance metrics, such as weather-related incidents, or may choose to monitor additional features of infrastructure due to climate change concerns.
- **Evaluation of compliance –** Sound Transit periodically evaluates environmental regulatory compliance as well as compliance with its other requirements through ESMS auditing. If any future climate change requirements were required at the state or federal level, Sound Transit's compliance with those regulations would be integrated into ESMS compliance audits.
- **Nonconformity and corrective and preventive action** – To achieve continual improvement, the agency identifies, investigates and resolves ESMS

nonconformities and initiates preventive actions where applicable to ensure future proactive response. Any deviations from agency commitments to climate adaptation, as integrated into the ESMS per the options described above in “Plan” and “Do,” would be called out in the ESMS as nonconformities requiring corrective and preventive action.

- **Control of records** – The agency identifies and maintains ESMS records to demonstrate that environmental performance is consistent with internal and external requirements and provide evidence that required activities have been performed. Climate adaptation related records would be maintained as part of the agency’s current records control process.
- **Internal audit** – Sound Transit performs ESMS audits to gauge effectiveness of the ESMS and conformance to the international ISO 14001 standard. Any agency climate adaptation related requirements integrated into the ESMS, as described in the above sections, would be periodically audited during regular ESMS audits.

▪ **Act:** Make process improvement changes

- **Management review** – The agency completes periodic management reviews to ensure continued suitability, adequacy and effectiveness of the ESMS and its policies and procedures. Management reviews includes reports on all elements of the ESMS. If climate adaptation were integrated into the ESMS per the options described in this section above, management review reports would include climate adaptation appropriately.

2. Washington State Department of Transportation Guidance for Project-Level Climate Change Evaluations

The Washington State Department of Transportation (WSDOT) has developed guidance for agency project teams for integrating climate change impacts and adaptation actions into National and State Environmental Policy Acts (NEPA and SEPA) documents. The guidance recommends that staff draw from WSDOT’s 2011 climate change vulnerability assessment results (WSDOT 2011), the University of Washington Climate Impacts Group’s *Washington Climate Change Impacts Assessment* (CIG 2009), and other sources to answer the question “how will my project be affected by climate change?” via the following steps:

1. Examine the results of WSDOT’s Climate Impacts Vulnerability Assessment for the specific project area to identify existing vulnerabilities and/or strengths in the WSDOT facilities;
2. Contact WSDOT Environmental Services Policy Branch Manager, (360) 705-7126, for assistance in creating an up-to-date summary of climate threats in your project area;
3. Direct project technical specialists to consider the available information (steps 1 and 2) in their NEPA and SEPA analysis, as well as their proposals for mitigating impacts;
4. Document findings regarding anticipated climate threats in the cumulative effects section (if separate) or in specific discipline sections (Fish and Wildlife, Wetlands, Land Use, etc.);
5. Document how the project will be designed to be resilient or resistant to climate threats (such as the use of drilled shafts or site selection to avoid a potential threat). (WSDOT 2012, p.4)

Example language for use in NEPA and SEPA documentation is provided in Box 1.

Box 1. Example Language for Use in WSDOT Documents.

The standard qualitative language template below is recommended for the Cumulative Effects section of environmental documentation for NEPA EA and for SEPA/NEPA Environmental Impacts Statements (EIS). This text should be tailored to specific projects.

EA and EIS Template Language – Cumulative Effects Section

How did the project team consider future conditions related to climate change?

WSDOT acknowledges that effects of climate change may alter the function, sizing, and operation of our facilities. To ensure that our facilities can function as intended for their planned 50, 70, or 100 year lifespan, they should be designed to perform under the variable conditions expected as a result of climate change. For example, drainage culverts may need to be resized to accommodate more intense rainfall events or increased flows due to more rapid glacial thawing.

The Pacific NW climate projections are available from the Climate Impacts Group at the University of Washington (http://cses.washington.edu/cig/fpt/ccscenarios.shtml). Washington State is likely to experience over the next 50 years:

- increased temperature (extreme heat events, changes in air quality, glacial melting)
- changes in volume and timing of precipitation (reduced snow pack, increased erosion, flooding)
- ecological effects of a changing climate (spread of disease, altered plant and animal habitats, negative impacts on human health and well-being)
- sea-level rise, coastal erosion, salt water intrusion

The project team considered the information on climate change with regard to preliminary design as well as the potential for changes in the surrounding natural environment. The project is designed to last (30, 50, 70 Years) years. As part of its standard design, this project has incorporated features that will provide greater resilience and function with the potential effects brought on by climate change. (Describe the features such as stormwater flow control, bridge height or design, ...)

Source: WSDOT 2012, p. 7

References

(CIG) Climate Impacts Group 2009. The Washington Climate Change Impacts Assessment. M. McGuire Elsner, J. Littell, and L. Whitely Binder (eds). Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, Washington. Available at http://cses.washington.edu/db/pdf/wacciareport681.pdf.

(WSDOT) Washington State Department of Transportation. 2011. Climate Impacts Vulnerability Assessment. Report prepared by the Washington State Department of Transportation for submittal to the Federal Highway Administration, Olympia, Washington. Available at: http://www.wsdot.wa.gov/NR/rdonlyres/B290651B-24FD-40EC-BEC3-EE5097ED0618/0/WSDOTClimateImpactsVulnerabilityAssessmentforFHWAFinal.pdf

(WSDOT) Washington State Department of Transportation. 2012. Guidance for Project-Level Climate Change Evaluations, Washington State Department of Transportation, Olympia, WA. Available at http://www.wsdot.wa.gov/NR/rdonlyres/52471A20-C6FA-48DF-B1A2-8BB96271D755/0/WSDOT_Climate_Guidance_Mar_2013.pdf.

APPENDIX E

Suggested Resources

The following are suggested resources for learning more about regional climate change, climate change impacts, and planning for climate change. Sources for climate change data that can be used for more detailed impacts analyses are also listed here. This list is not a comprehensive listing; more reports and data are (and will become) available.

Synthesis Reports: Pacific Northwest Projections and Impacts

- *National Climate Assessment (NCA) (2014)* – The NCA provides a synthesis of how climate change could affect American people and resources, and strategies for adapting to a changing climate. The NCA report will contain chapters focused on sectors and regions of the U.S., including the transportation sector and the Pacific Northwest region. Will be available at: http://ncadac.globalchange.gov/
- *Northwest Climate Assessment Report (2014)* – The Northwest Climate Assessment Report is the unabridged version of the Northwest chapter included in the NCA. The report will be published by Island Press in 2013/2014. Will be available at: http://cses.washington.edu/cig/ and http://ncadac.globalchange.gov/
- *Washington Climate Change Impacts Assessment (WACCIA) (2009)* – A comprehensive assessment of climate change impacts on key sectors of Washington State's human and natural resources (agriculture, coasts, energy, forests, human health, hydrology and water resources, salmon and urban stormwater infrastructure). Produced for the Washington State legislature. Available at: http://cses.washington.edu/cig/res/ia/waccia.shtml

Transit-Related Climate Risk & Vulnerability Assessments and Adaptation Plans

Regional Studies and Reports

- *Climate Change Impact Assessment for Surface Transportation in the Pacific Northwest and Alaska (2012)* – Provides a preliminary assessment of the risks climate change poses to the surface transportation infrastructure system in the Pacific Northwest and Alaska region, and associated vulnerabilities. Available at: http://www.wsdot.wa.gov/Research/Reports/700/772.1.htm

- *Preparing for a Changing Climate: Washington State's Integrated Climate Response Strategy (2012)* – The WA State Department of Ecology worked closely with the CIG to craft the State's response strategy to climate change and its impacts on the State. Available at: http://www.ecy.wa.gov/climatechange/ipa_responsestrategy.htm
- *Impacts of Climate Variability and Climate Change on Transportation Systems and Infrastructure in the Pacific Northwest (2011)* – A white paper for the Western Federal Lands-Highway Division describing the many potential impact pathways for transportation systems and infrastructure associated with climate variability and climate change in the PNW. Available at: http://cses.washington.edu/db/pubs/abstract743.shtml
- *Climate Impacts Vulnerability Assessment (2011)* – A report prepared by the Washington State Department of Transportation concerning the vulnerability of State-owned transportation infrastructure to the impacts of climate change projected by the Climate Impacts Group. Available at: http://www.wsdot.wa.gov/NR/rdonlyres/B290651B-24FD-40EC-BEC3-EE5097ED0618/0/WSDOTClimateImpactsVulnerabilityAssessmentforFHWAFinal.pdf

National or Other Studies and Reports

Metrics for Tracking Climate Change Adaptation (2013) – This presentation, prepared by the Urban & Environmental Policy Institute for the Los Angeles Regional Transit Climate Adaptation Roundtable, identifies potential metrics for tracking progress on agency adaptation efforts. Available at: http://media.metro.net/projects_studies/sustainability/roundtable/metrics_for_tracking_climate_change_adaptation.pdf

Climate Action and Adaptation Plan (2012) – Impacts assessment and adaptation plan prepared by the Los Angeles Metropolitan Transportation Authority. Available at: http://media.metro.net/projects_studies/sustainability/images/Climate_Action_Plan.pdf

Adapting Transportation to the Impacts of Climate Change: State of the Practice 2011 (2011) – This Transportation Research Board report focuses on transportation adaptation practices that can be implemented to yield potential benefits now and in the longer term. The document highlights what climate change adaptation means for the transportation industry. Available at: http://www.trb.org/Main/Blurbs/165529.aspx

MTA Adaptations to Climate Change: A Categorical Imperative (2008) - New York State Metropolitan Transportation Authority report on adapting transit services to climate change. Available at: http://www.mta.info/sustainability/?c=ClimateAdaptation

Methods & Guidance for Preparing for Climate Change

Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation (2011) - U.S. Federal Transit Administration report that examines anticipated climate impacts on U.S. transit and current climate change adaptation efforts by domestic and foreign transit agencies. The report also explores the availability of vulnerability assessment, risk management, and adaptation planning tools as well as their applicability to public transportation agencies. Available at: http://www.fta.dot.gov/documents/FTA_0001_-_Flooded_Bus_Barns_and_Buckled_Rails.pdf

Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments (2007) – The Climate Impacts Group developed this guidebook, co-authored with King County, WA, to help local, regional, and state governments prepare for climate change by providing a detailed, easy-to-understand process for assessing and preparing for climate risks. Available at: http://cses.washington.edu/cig/fpt/guidebook.shtml

Data Products and Tools

In collaboration with local stakeholders, the Climate Impacts Group has developed a variety of products providing locally specific climate change data to support impacts/risk assessment and adaptation planning, including the following:

- *Pacific Northwest Climate Change Scenarios* – A database of historical and future climate and hydrologic conditions, including snowpack, soil moisture, streamflow, flood risk, low flow conditions for the Puget Sounder region and other areas of the Pacific Northwest. Products include data sets as well as summary figures. Available at: http://warm.atmos.washington.edu/2860/
- *Fine-scale projections of extreme high and low runoff conditions* – A finer scale analysis of historical and projected future extreme high and low runoff. Developed to support climate change adaptation efforts regarding culvert design and fish habitat management. Data available upon request. (Contact cig@uw.edu)
- *Water temperature projections for Washington State* – A database of historical and projected future stream temperature scenarios for over 100 sites in Washington State. Data available at: http://cses.washington.edu/data/hb1303/stream_temperatures/
- *Other CIG datasets covering various locations and spatial scales:* http://cses.washington.edu/data/data.shtml

Climate Change Information Clearinghouses and Websites

USDOT Climate Change Clearinghouse – includes a variety of publications related to mitigation (i.e., reducing greenhouse gas emissions), climate change impacts, and adaptation in the transportation sector (http://climate.dot.gov/about/resources.html)

USEPA Climate Changes Impacts on Transportation – includes summary information on how climate change may affect transportation infrastructure and links to relevant reports (http://www.epa.gov/climatechange/impacts-adaptation/transportation.html)

University of Washington Climate Impacts Group – for regionally-specific information on observed and projected changes in climate variability and climate change (http://cses.washington.edu/cig/)

Georgetown Law Climate Center's Adaptation Clearinghouse – adaptation plans, agency guidance, assessment reports, case studies, legislation, etc: http://www.georgetownclimate.org/adaptation/clearinghouse

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U.S. Department of Transportation
Federal Transit Administration
East Building
1200 New Jersey Avenue, SE
Washington, DC 20590
http://www.fta.dot.gov/research