Sound Transit Guidance Document:

Climate Change Vulnerability Assessment

December 2021

Cascadia Consulting Group

Sound Transit

SOUNDTRANSIT

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Revision History

Version	Title	Date	Notes
1	Sound Transit Guidance Document: Climate Change Vulnerability Assessment	11/24/2021	Initial draft 50% for review and discussion
2	Sound Transit Guidance Document: Climate Change Vulnerability Assessment	12/17/2021	100% draft for red flag review
3	Sound Transit Guidance Document: Climate Change Vulnerability Assessment	12/31/2021	Final document

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1 INTRODUCTION TO CLIMATE CHANGE VULNERABILITY ASSESSMENTS

1.1 Purpose of this Climate Change Vulnerability Guidance Document

The purpose of this climate change vulnerability assessment (CCVA) guidance document is to inform climate-smart decisions for future Sound Transit rail infrastructure investments and projects. This guidance document shares methodology for conducting a CCVA for future Sound Transit rail projects. While the region's climate has much natural variability, the climate in western Washington has been rapidly changing since the 1900s due to anthropogenic climate change. Within the Puget Sound region, we have already seen warmer air temperatures, reduced mountain snowpack, sea level rise, winter storms, and changing water availability. Climate change in the region will continue to affect infrastructure, including Sound Transit's rail projects, over the next century and beyond.

Conducting a CCVA in advance of project design and implementation can ensure that Sound Transit infrastructure will be more resilient and prepared for future climate change. By conducting a CCVA during project planning stages, Sound Transit can prepare for them and include adaptation measures to support resilient infrastructure and operations over the next century.[1]

Potential climate impacts to Sound Transit infrastructure and operations include extreme heat, coastal flooding, riverine flooding, mudslides and landslides, heavy rain, and extreme events. These impacts as well as other environmental and system conditions can affect rail and track systems, overhead catenary systems (OCS), electrical equipment, bridges and elevated structures, tunnels as well as service operations and infrastructure construction.

To ensure that a CCVA is germane and useful, a CCVA should be referenced or conducted at each project phase (see: Sound Transit, Project phases: from plans to construction). This can account for phase-specific considerations. However, if a CCVA is only conducted once during the lifecycle of a project, it should be conducted during the project Planning stage when alternatives, preliminary design, and an Environmental Impact Statement are conducted. By conducting a CCVA during project planning stages, Sound Transit can prepare for them and include adaptation measures in the final design to support resilient infrastructure and operations over the next century.

[1] Sound Transit projects should also reference federal regulatory requirements

HOW TO USE THIS DOCUMENT

This Guidance Document will help guide Sound Transit staff through a CCVA. The table below identifies the key phases of the CCVA and the relevant sections to reference for that respective phase. Additionally, example outcomes and templates are also linked to provide the CCVA team an example of a phase's final product.

CCVA Phase	Purpose and Description	Relevant Guidance Document Sections	Example Outcomes and Templates
Setting the project boundary	This phase helps the CCVA team identify 1) geographic boundaries of the project, 2) key attributes within the project boundaries, and 3) key project elements to consider in the CCVA.	• Section 2 • Meeting #1 Agenda in Appendix B	WSBLE Case Study in section 2.1.1 presents the project map for the WSBLE project.
Climate risks and impacts assessment	This phase helps the CCVA team identify 1) a comprehensive list of potential climate change impacts and risks, 2) site-specific climate impacts using a mapping exercise, and 3) a prioritized list of key climate change impacts of concern, relevant to the Sound Transit project.	• Section 3 • Meeting #1 Agenda and Meeting #2 Agenda in Appendix B	See Appendix C for a list of all climate change impacts identified for the WSBLE project.
Adaptive capacity assessment	This phase helps the CCVA team identify 1) a comprehensive list of potential adaptation options and 2) a list that categorizes each project element of having low, medium, or high adaptive capacity.	• Section 4 • Meeting #3 Agenda in Appendix B	See Appendix C for a list of all adaptation options identified for the WSBLE project.
Climate change vulnerability assessment	This phase helps the CCVA team determine the final climate change vulnerability ratings for each project element.	• Section 5.1 • Meeting #4 Agenda in Appendix B	See Appendix C for a list the final vulnerability rankings for the WSBLE project.
Appling the CCVA	This phase helps the CCVA team undergo a risk analysis, which includes identifying 1) risk tolerance for climate change impacts and 2) feasible adaptation options to mitigate climate change impacts.	• Section 5.2 • Meeting #5 Agenda in Appendix B	N/A

1.2 Climate Change Vulnerability Assessment Frameworks and Key Definitions

1.2.1 Climate Change Vulnerability Assessment Framework

Climate change vulnerability is defined as the degree to which a system is susceptible to adverse effects of climate change, or the climate risks and impacts moderated by the capacity to adapt and cope with those risks and impacts (Figure 1). Risks and impacts are understood in relation to project components that could be impacted by changes in climate, the likelihood of the climate impact occurring, and the severity of the consequence to the project component.

Climate risks and impacts can be moderated, or reduced, by adaptive capacity. For Sound Transit projects, there are multiple adaptation considerations. For example, siting and location, design, and operations considerations can be made to increase the adaptive capacity and thus reduce the climate risks and impacts.

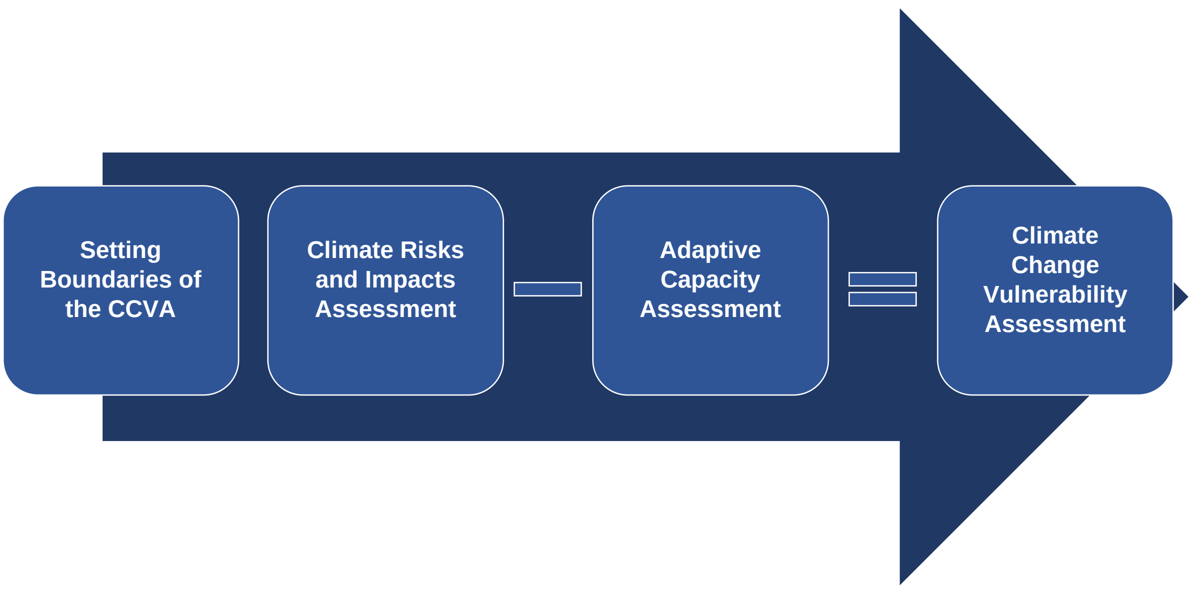


Figure 1. Climate Change Vulnerability Assessment Process

The CCVA process includes:

(1) Setting the project boundary.
(2) Identifying and assessing climate risks and impact.
(3) Identifying and assessing adaptive capacity.
(4) Considering both the risks and adaptive capacities to assess the project elements' climate vulnerability.
(5) Climate risk analysis to integrate step 4 into the final design process.

1.2.2 Key Definitions

Risk is the possibility of an adverse consequences. While there is always risk inherent in every system, risks are identified in the context of the likelihood of a particular event or climate event and the consequence of that impact occurring. Sometimes, risk is operationalized as likelihood multiplied by consequence.

- **Likelihood** is understood both in the context of whether a particular climate impact would occur and in terms of the consequence of an impact occurring. Likelihood should be assessed for both climate impacts and consequences on the Sound Transit system of those impacts.
- **Consequence** is understood as the severity of a specific impact or risk.

Climate impact is the outcome of the climate impact on the Sound Transit system.

Sensitivity tells us how much the climate would have to change to affect the consequence or outcome, for example, how hot it would need to be to impact track lines. Quantifying sensitivity can be easy in some cases where predicting a climate change impact has fewer confounding variables (e.g., water overtopping a levee) and more challenging in others (e.g., social consequences of service outages).

Assessing sensitivity incorporates identifying *when* impacts will become a problem and expressed in terms of *how often* the impact will cause a problem and by *how much*. *Modeling* and *observations* can be used to quantify the sensitivity. Observations include linking past events to relate to projected trends and are helpful for gaining an understanding of impact trends from climate change. Models can also be used to assess the consequences of anticipated changes from climate change. For example, stormwater modeling could be run with different precipitation frequencies and intensities to see how the system might be impacted by those changes.

Exposure is the nature and extent to which a system or region is exposed to climate variation. Climate change exposure is understood through different global models downscaled to local impacts.

Adaptive Capacity is the ability for a system to moderate or cope with change. There are pre-construction and post-construction adaptation considerations, with multiple adaptive capacity considerations, including:

- **Siting and location** of key project elements to ensure that they are not located in high-risk areas. For example, not siting rail tracks in landslide-prone areas can prevent damage to the guideway and minimize service disruption. These adaptation options happen pre-construction.

- **Design** of key project elements to ensure that there is the ability of the project to cope with future climate impacts. For example, utilizing expansion joints on rail tracks can alleviate heat stress to prevent or mitigate rail buckling risk. These adaptation options happen pre-construction.

- **Operations** can ensure that the project can continue to adapt to future climate change during or post-construction. For example, regular maintenance can pre-empt and mitigate flooding events or slow orders during extreme heat days can ensure that the Light Rail continues to safely operate.

1.2.3 Contextual Considerations

While general methodology considers all the elements identified in our CCVA framework, this framework can be adapted to a variety of contexts considering:

- Data availability
- Teaming capacity
- Project timeline

1.3 Overall Climate Change Vulnerability Assessment Timeline and Tasks

While the timeline of a CCVA process is flexible, typically a CCVA includes the following key milestones:

1. **Identifying a CCVA Team.** Conducting a CCVA involves significant project staff engagement to identify key components of the climate change vulnerability framework. Sound Transit CCVAs have included both agency and consultant staff on the combined project team. The members of the Sustainability Discipline Meeting were the core staff involved in the CCVA, with other staff brought in as needed. The CCVA Team typically will include:
    - **Project Managers**, including project managers, segment leads, environmental staff, and sustainability staff.
    - **Engineering Team,** including engineering leads, segment leads, systems staff, and utility/hydrology staff.
    - **Operations Team,** including Operations Director for project and Light Rail operations staff.

2. **Identifying key phases or steps in the CCVA process**. Key phases typically align with key elements of a CCVA, and can include:
    - Setting the boundaries of the CCVA (Section 2)
    - Identifying and prioritizing climate risks and impacts (Section 3)
    - Undertaking the adaptive capacity assessment (Section 4)
    - Developing the vulnerability rating (Section 5)
    - Create a climate risk analysis with Engineering staff (Section 5)

3. **Scheduling a series of CCVA meetings**. Align CCVA Team meetings and meetings with other key stakeholders to discuss key CCVA elements. (As noted above, the Sustainability Discipline Meeting was used as the forum for the CCVA). These meetings typically follow the following timeline:

- **Meeting 1:** Sound Transit staff confirms the project boundaries and uses the WSBLE vulnerability assessment to generate an initial list of potential climate impacts and risks to the planned project.
- **Meeting 2:** Sound Transit staff utilizes maps to identify climate impacts and considerations across the planned project route, including alternatives.
- **Meeting 3:** Sound Transit staff identify key adaptation considerations and opportunities.
- **Meeting 4:** Sound Transit staff confirm the vulnerability rating of prioritized climate impacts.
- **Meeting 5:** Sound Transit Sustainability Staff work with Operations and Engineering staff to undertake a climate risk analysis for the project and identify feasible climate change adaptation options.

As a note, these meetings will use the WSBLE project as a foundation to build off from. Meeting agendas for each meeting can be found in Appendix B. These meetings should be coordinated with the different phases of the CCVA process as noted in Table 1.

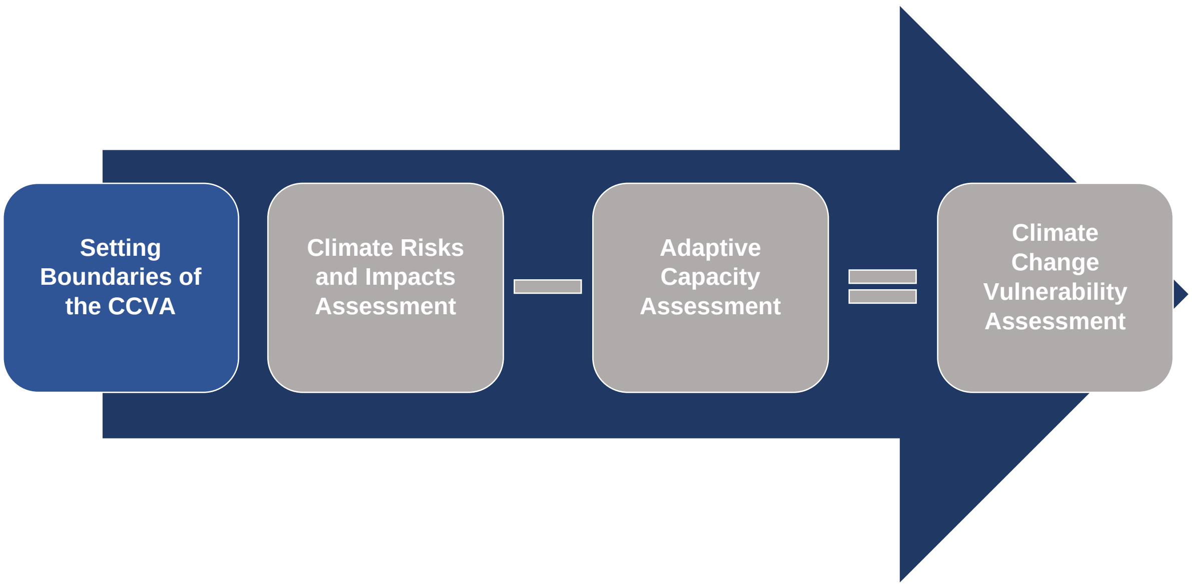
Table 1. CCVA Meeting Coordination across Phases of the CCVA.

	Project Elements			
	Setting Boundaries	Climate Risks & Impacts Assessment	Adaptive Capacity Assessment	Climate Change Vulnerability Assessment
Meeting #1	→	→		
Meeting #2		→		
Meeting #3			→	
Meeting #4				→
Meeting #5				→

2 SETTING THE BOUNDARIES OF THE CLIMATE CHANGE VULNERABILITY ASSESSMENT

The first step of the CCVA is to set boundaries and parameters of the CCVA. At the end of this phase, the CCVA team should have documents that:

- Identify **geographic boundaries** of the project.
- Identify key **environmental attributes** in or near the project.
- Identify key **project components** to focus on in the CCVA.



CCVA Team Meeting #1

During this CCVA phase, the CCVA team should use **Meeting #1** agenda (see Table 1; agenda in Appendix B) to confirm the CCVA project boundaries.

2.1 Project Area

Setting the project area, which can include geographic boundaries and environmental attributes, will provide parameters and considerations throughout the CCVA.

2.1.1 Geographic Boundaries

The geographic boundaries of the CCVA are often already determined by the project design and alternatives. Key project boundaries would include the rail route as well as a buffer around the route. The buffer accounts for surrounding and nearby impacts that will have indirect impacts to the rail route and system. For example, flooding in low-lying surrounding areas can have spillover flooding impacts to a guideway or tree branches can fall or be blown onto guideways during storms. Buffer size will be determined by any relevant impacts or attributes – such as potential for flooding or landslides, access routes and nearby roads, or other attributes such as utility infrastructure. While the buffer for WSBLE was 0.5 miles and was determined during the EIS process, buffers will vary from project to project.

Case Study: West Seattle – Ballard Link Extension Project Boundaries

The map below shows the project boundaries for the CCVA for the West Seattle – Ballard Link Extension (WSBLE) project. The West Seattle Extension would operate on a 4.7-mile guideway from downtown Seattle to West Seattle's Alaska Junction neighborhood and include a new fixed-span bridge across the Duwamish Waterway. The Ballard Extension would operate 7.1 miles from downtown Seattle to Ballard's Market Street area and include a new 3.3-mile rail tunnel from Chinatown/International District to Seattle Center/Uptown. The project boundaries included the rail system buffer and a half-mile buffer to account for additional risks (e.g., landslides, flooding). The half-mile buffer was determined during the draft EIS process.

Additional key environmental attributes we considered included the Duwamish River crossing (prone to flooding), rail routes through Interbay (steep hills prone to landslides), and the Salmon Bay crossing. Finally, WSBLE included both elevated, at-grade, and tunnel tracks. Thus, we included multiple project components in the CCVA.

2.1.2 Environmental Attributes of the Geography

Identifying key environmental attributes within or adjacent to the project is important. Environmental attributes can include water bodies, specific habitats such as wetlands, geologic characteristics such as steep slopes, or other ecologically sensitive areas that will affect permitting processes. For example, building over or alongside a wetlands habitat may elevate localized flooding risks for specific areas of the project system.

2.2 Identifying Components of the Climate Change Vulnerability Assessment

There are a variety of different project elements and components that should be considered for the CCVA. These elements could include:

- Infrastructure elements
    - Rail and track systems
    - Overhead catenary system (OCS)
    - Electrical equipment, such as traction power substations (TPSS), signal bungalows, and signal boxes
    - Bridges and elevated structures
    - Tunnels
- Service elements
    - Operations and maintenance
    - Passenger access and experience[2]
- Construction siting and policies

While most projects will have service elements, infrastructures and construction elements will likely be dependent on the project. For example, a project that includes at-grade and elevated structures will not need to consider climate risks to tunnel systems.

[2] This is inclusive of stations and station access.

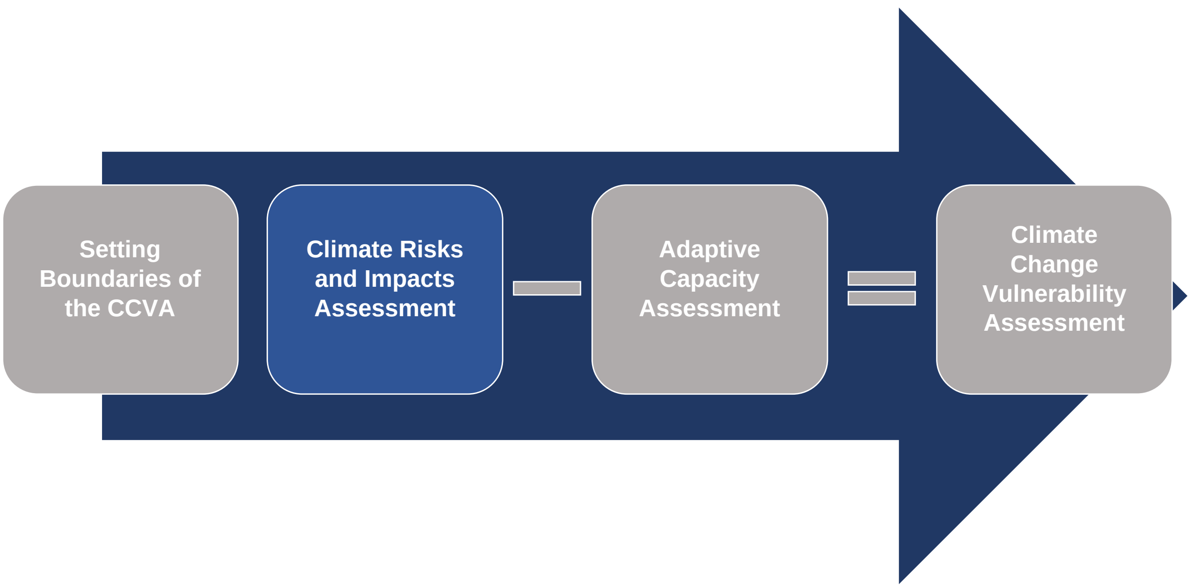
3 CLIMATE RISKS AND IMPACTS ASSESSMENT

After setting the boundaries of the project, the next phase is to assess climate risks and impacts to the project. Identifying climate risks and climate change impacts will provide a comprehensive picture of the potential for system-wide impacts and route-specific impacts. This can help inform adaptation strategies that can preempt these issues.

This section provides a high-level summary of the different types of climate impacts and risks on a variety of project elements. This summary is meant to provide a starting point for the CCVA team to expand on. To get an understanding of future climate projections, please see Appendix A.

At the end of this phase, the CCVA team should have:

- An initial set of all potential system-wide and site-specific **climate impacts and risks**.
- **Project maps** that include site-specific and project-specific climate impacts and risks.
- A final list of climate impacts and risks that **categorizes each impact as low, medium, or high impact**.



CCVA Team Meeting #1 and Meeting #2
Meeting #1 (see Table 1; agenda in Appendix B) will help the CCVA team generate an initial list of system-wide and project-specific climate risks and impacts. Please use section 3.1 as a jumping off point for this meeting. **Meeting #2** (see Table 1; agenda in Appendix B) will help the CCVA team identify site-specific risks and considerations through a mapping exercise. Please use section 3.2 and section 3.3 as a jumping off point for this meeting.

3.1 Summary of Key Climate Impacts

There is a range of climate impacts that will affect Sound Transit's infrastructure and projects. These impacts include:

- Extreme heat, heat waves, and warmer temperatures
- Flooding due to coastal flooding, river flooding, and heavy rains
- Mudslides and landslides
- Extreme events, such as winter storms and associated high winds

Table 1 provides a crosswalk of the potential climate risks for key project elements. The sections below detail the specific climate risks and considerations and are meant to be a departure point for CCVA teams to tailor to their respective projects. While these risks and impacts are broadly generalized to the project element or even the entire Sound Transit system, there may be additional project-specific impacts that you should consider. For example, if elements are adjacent to wetlands, there may be additional location-specific risks that the CCVA Team needs to consider. For specific references and resources, please refer to Appendix E.

Generating a list of potential climate impacts will help the CCVA team to assess the severity of that climate impact (low, medium, or high impact), allowing the CCVA team to prioritize adaptation measures that mitigate medium or high climate change impacts and risks.

Table 2. Crosswalk of Climate Change Impacts and Project Elements.

	Climate Impact			
Project Element	**Extreme heat**	**Flooding**	**Mudslides & landslides**	**Extreme events**
Rail & Track	✓	✓	✓	✓
OCS	✓			✓
Electrical Equipment	✓	✓		
Tunnels		✓		✓
Bridges & Elevated Structures	✓	✓		✓
Vertical Conveyance Systems		✓		✓
Rail Service Operations	✓	✓	✓	✓
Passenger Experience	✓	✓		✓
Construction	✓	✓		

3.1.1 Infrastructure Elements

3.1.1.1 Rail and Track Systems

Extreme Heat Impacts

Future extreme heat will increase the risk for **rail buckling, fatigue cracking, pavement rutting, and switch failures**. This can lead to service slowdowns, interruptions, increased maintenance costs, costly repairs, and in rare cases, train derailments.

- **Ballasted tracks**—typically used for at-grade segments, maintenance yards, or for trackwork where tracks converge, diverge, or cross over—are more sensitive to extreme heat than other track types.

Flooding Risks

Flooding risk will likely increase from a variety of impacts, including: 1) riverine flooding, 2) stormwater-related flooding, and 3) coastal flooding. The confluence of multiple climate impacts will likely lead to substantial flooding events in the future. Flooding events along rail corridors can **damage rail infrastructure**. Additionally, standing water over rail lines can cause **issues with visual monitoring and signaling**.

WSBLE Case Study

In the WSBLE project, specific areas of flooding risk include:

- **Low-lying areas near the Duwamish River**, which is particularly high risk for flood damage during extreme rainfall events, high tide events, and future sea level rise.
- **SODO area** which has a shallow groundwater table that fluctuates with heavy precipitation events and tidal cycles. There is already existing issues with standing water near Holgate crossing at 6th Avenue South.
- Construction projects in the **International District/Chinatown** area is already diverting water onto existing rail structures. More intense rain events and continued development in the area can cause more frequent flooding events.

Landslides and Mudslides

While there is emerging science on modeling the correlation between climate change, rain and precipitation patterns, and landslide and mudslide risk, the risk for landslides and mudslides will likely increase for areas with steep slopes due to more intense heavy rain events. Landslides and mudslides can **damage rail infrastructure** and **disrupt rail service**.

WSBLE Case Study

In the WSBLE project, specific areas of concern include:

- Hilly areas or areas with steep slopes—such as **Pigeon Point** and **Queen Anne**—are of particular concern.
- Landslides and mudslides can also lead to **tree debris** falling on the guideway or tunnel portals in areas such as **Delridge** and the **Duwamish crossing**.

3.1.1.2 Overhead Catenary System

Heat Stress and Extreme Heat Impacts

While the Puget Sound area has historically enjoyed mild summer temperatures, heat waves over the past several years – including the 2021 Heat Dome event – have exposed potential sensitivities to extreme heat for Sound Transit. Extreme heat can cause **excessive line sags** in the overhead catenary system (OCS). This can lead to **slower train speeds** or **power loss** if the train loses contact with the OCS. In severe cases, line sags can cause the **OCS wire to snap** or cause **damage to the pantograph, insulators, and other OCS equipment**.

- **Fixed-termination OCS is more susceptible to heat stress** than auto-tension OCS because the system uses fixed poles or support structures to maintain wire tension at pre-set temperatures.
- Future intense heat waves can put **undue stress on the electricity grid**, leading to a mismatch of energy demand and supply, **potentially leading to power loss**.

Severe Winter Storms

Though **very unlikely** in the Seattle area, **severe winter storms could also impact OCS through continuous exposure to snow and ice**, which can build up and affect OCS functionality (Rossetti, 2002). For Sound Transit, this risk might be a consideration during La Niña years, or other times when the region experiences abnormal winter storms.

3.1.1.3 Electric Equipment

Heat Stress and Extreme Heat Impacts

Electrical equipment—such as traction power substations (TPSS), signal bungalows, and signal boxes—generates substantial heat from normal operations, which can amplify **ambient heat and future extreme heat stress**. This can lead to **loss of power and traffic signal control** for TPSS, signal bungalows, and small signal boxes, leading to **reduced operating speeds** or **service interruptions**.

Flooding Risks

Electrical equipment, depending on location, can be **exposed and vulnerable to flooding**. This can **damage electrical equipment**, causing cascading effects for light rail operations. This impact was a high priority impact for Sound Transit staff.

WSBLE Case Study

In the WSBLE project, specific areas of concern include:

- Electrical equipment near the Duwamish River—the **Boeing Access TPSS** and the **South 133rd Street TPSS**—had already been identified as vulnerable areas due to **tidally-influenced flooding**.
- Other locations—such as areas near the **Duwamish River, SODO, and Smith Cove**—had already been identified as flood-prone due from **stormwater-related flooding**.
- Potential siting locations for the WSBLE— **areas near Delridge, Duwamish River, Chinatown/International District, and Ballard**—have been flagged as areas that might be sensitive to stormwater-related flooding.

3.1.1.4 Tunnels

Flooding and Groundwater Seepage

Flooding risk will likely increase in the future, **affecting tunnel systems and groundwater seepage**. This can affect **vertical conveyance equipment** (see 3.1.1.6 Vertical Conveyance Systems), cause **odor** issues from groundwater seepage, and require **more maintenance**.

> **WSBLE Case Study**
>
> In the WSBLE project, specific areas of concern include:
>
> - WSBLE route alternatives in the **SODO**, **Stadium**, and **Chinatown/International District** areas were identified as vulnerable to flooding because:
>   - For SODO:
>   - Rising sea levels may **raise the groundwater table** and **back up a major SPU sewer line** that runs east/west between Puget Sound and Sound Transit's Operations and Maintenance Facility.
>   - Potential for additional **copper pollution** and **soil/water contamination** from stormwater runoff.
>   - For Stadium and Chinatown/International District:
>   - **Existing tunnel drains currently drain to the Stadium District** area, likely leading to more frequent or intense flooding events due to future climate. Change.
>   - Existing flooding already in **the BNSF tunnel**.
>   - Other construction projects **diverting water**, potentially amplifying climate-related flooding risk.

Extreme Events

Hazard preparedness will ensure that Sound Transit's infrastructure will be resilient to extreme and rare events. There is a very low likelihood of an extreme hazard or event—**such as earthquakes, tsunamis, or dam failures**—that could lead to catastrophic flooding damage to tunnels. While not expressly a climate-related risk, climate change impacts—such as sea level rise and shifting groundwater tables—can create conditions more favorable for extreme hazards like liquefaction to happen.

3.1.1.5 Bridges and Elevated Structures

Extreme Heat and Ambient Air Pollution

Extreme heat impacts can affect bridges and elevated structures in multiple ways. For moveable bridges, extreme heat can cause **expansion joint malfunctions**. Additionally, heat stress can **increase creep rate**. Increased ambient air pollution—which is associated with warmer temperatures—can **increase carbonation-induced damage** for bridge structures.

WSBLE Case Study
In the WSBLE project, specific areas of concern include: • Bridges will span the **Duwamish River** and the **Queen Anne/Ballard** crossing. • Elevated structures are being considered to be used at various segments of the WSBLE, including areas in **West Seattle, SODO, and Queen Anne**.

Flooding, Hydrology, and Sea Level Rise

Flooding due to hydrological changes, sea level rise, and extreme rainfall can accelerate bridge corrosion and scour. These coupled impacts can aggravate and weaken bridge foundations and substructural supports, potentially leading to bridge failure or decreased lifespans. Additionally, heavy rain events can overwhelm bridge drainage systems and increase hydrostatic pressure building up behind bridge abutments.

WSBLE Case Study
In the WSBLE project, specific areas of concern include: • The WSBLE bridge that spans the **lower Duwamish River** is particularly at risk due to: o Increased exposure to saltwater in the tidally influenced river. o Increased rains – especially during winter months – can induce bridge scour.

Extreme Events

Extreme hazards and events—such as winter storms, windstorms, and earthquakes—can have a variety of impacts on bridges and elevated structures. While there is some uncertainty in the causal connections between these extreme events and climate change, the interaction of extreme events and future climate conditions can create circumstances that can amplify the magnitude of consequences.

- Freeze and thaw cycles and de-icing salt application can **accelerate bridge deterioration**.
- Climate change can create conditions—such as sea level rise affecting groundwater tables—more favorable for **liquefaction** to happen.
- High winds during extreme storms can **increase wind static loading**, which was a primary reason for the 1940 failure of the Tacoma Narrows Bridge.

3.1.1.6 Vertical Conveyance Systems

Extreme Heat

Extreme heat can cause many operational issues for vertical conveyance systems. The 2021 Heat Dome event caused many of these impacts to also happen simultaneously, which can strain Sound Transit's adaptation and response capacity.

- **Elevator belts slipping due to overheated oil**, leading to difficulty in levelling units.
- **Overheated escalators**, leading to unplanned shut offs.

- **Overheated hoistways**, leading to delays and malfunctions of elevators.

Heavy Rainfall and Flooding

Heavy rain events and associated flooding will have several consequences for vertical conveyance systems, including:

- Inhibit **function** or **damage vertical conveyance equipment**, such as elevators, escalators, and other facility equipment. This will disproportionately affect people with physical disabilities that prevent them from using alternative options, such as stairs.
- **Flooding of vertical transportation** equipment – even at elevated stations – due to storm runoff.

3.1.2 Service Elements

3.1.2.1 Rail Service Operations

Extreme Heat Impacts

Extreme heat events and heat waves can delay or disrupt service operations in multiple ways, including:

- Affecting various rail elements, such as causing:
  - **Rail buckling, fatigue cracking, pavement rutting, and switch failures** for rail and trackways.
  - **Line and wire sags** on the OCS.
  - **Overheated electrical equipment**, such as TPSS and signal bungalows.
  - **Malfunction of expansion joints** for moveable bridges.
- Increasing energy demand and stress during summer months, increasing the likelihood of brown outs and power outages.

Flooding Risks

Future flooding risk will likely increase across the Puget Sound area due to sea level rise, heavy rainfall, and changes in hydrological patterns. Increased flooding risks can disrupt rail service operations in multiple ways, such as causing service delays and disruptions due to flooding on the guideways, tunnels, and equipment.

- Flooding damage to rail corridors that **impede track visibility**, leading to slow orders or delays.
- Flooding **damage to electrical equipment**, such as TPSS and signal bungalows, in flood-prone areas or areas with limited drainage capacity.
- **Tunnel flooding** due to extreme storms, leading to service delays and disruptions.
- **Inundating hi-rail vehicle entry points** on guideways for regular maintenance or emergency services.

Mudslides and Landslides

Mudslide and landslide risk may increase with increased heavy rainfall frequency, which can cause soil saturation and destabilization. This can disrupt rail service operations, especially in locations adjacent to steep slopes.

WSBLE Case Study

In the WSBLE project, specific areas of concern include:

- Slope failures and landslides are most likely to occur in areas with steep slopes – specifically areas of **West Seattle near the Duwamish River** and the hills adjoining **Interbay**.

Additionally, the WSBLE mapped out known landslide locations and potential landslide areas within the project area.

3.1.2.2 Passenger Access and Experience

Heavy Rains, Storms, and Flooding

Customer experience will likely be affected with increasing intensity of heavy rain events, storms, and flooding in tunnels and low-elevation stations. While climate change impacts may not alter transit infrastructure or operations at specific stations, there may be impacts that effect the public's ability to comfortably access transit. Specific impacts include:

- **Heavy rains and high winds** negatively affecting customer experience, especially on the platform at exposed and/or elevated stations.
- **Service delays** and **trip cancellations** when wind intensity exceeds 55 mph on elevated bridges and crossings as well as similar impacts from excess water on light rail tracks.
- Floods or standing water can **inhibit customer access** to a station's motorized and non-motorized entrances and exits.

Extreme Heat Impacts

Extreme heat can affect customer experience in multiple ways. In June 2021, the Northwest region—including the Puget Sound region and the Greater Seattle Metropolitan Area—experienced multiple consecutive days of extreme heat, with temperatures in the Greater Seattle Area reaching multiple consecutive days with temperatures over 100°F. Specific extreme heat impacts on customer service and experience include:

- **Line sagging in the OCS**, leading to disengagement. This will cause service delays via slow orders or service disruption.
- **Elevator belts slipping due to overheated o**il, leading to difficulty in levelling units.
- **Overheated escalators**, leading to unplanned shut offs.
- **Overheated hoistways**, leading to delays and malfunctions of elevators.
- **Station finishes**, such as metal panels and expansion/contraction joints, are affected by heat stress.

Severe Winter Storms

Severe winter storms and snowstorms can also affect various station elements – such as entrances, vertical conveyance systems, exposed platforms – leading to inhibited passenger access to stations and platforms, disruption of vertical conveyance systems, and potential damage to station elements.

3.1.3 Construction Impacts

With more frequent and more intense extreme heat events, there are multiple construction-related impacts that can happen. These include:

- Heat impacts on concrete—such as **distress, rutting, or cracking**—early on in its lifespan that can lead to worsening conditions and other subsequent impacts (e.g., flooding leakage into facilities through cracks).

- **Labor-related extreme heat considerations** for outdoor construction laborers, especially during summer months.

WSBLE Case Study
While flooding risk will increase in the future, WSBLE construction as well as other non-WSBLE construction projects around the WSBLE project and Sound Transit sites, can amplify flooding risk. For example, other nearby construction project can redirect water onto the WSBLE tracks, causing issues with **signaling** and **damaging rail infrastructure**. One adaptation option available to Sound Transit is to **ensure that construction risks are included and integrated in the WSBLE project plan** to ensure that there are contingency plans to avoid or mitigate flooding risk during heavy rainfall events.

3.2 GIS and Mapping

Mapping data can help the CCVA Team identify key at-risk areas. Below are some GIS and mapping **resources:**

- **FEMA Flood Zones.** Mapping 100-year and 500-year floodplains. www.fema.gov/flood-maps/national-flood-hazard-layer.
- **King County Extreme Heat Maps.** Community heat map for all of King County made during the extreme heat event. https://www.arcgis.com/apps/webappviewer/index.html?id=84709c65c08a40bbb47d0723ef1c797a&extent=-13604644.7965%2C6019787.1095%2C-13561266.7829%2C6046616.5065%2C102100.
- **Landslide Maps**. The City of Seattle has landslide hazard maps available, through the Seattle Hazard Explorer. https://seattlecitygis.maps.arcgis.com/apps/MapSeries/index.html?appid=0489a95dad4e42148dbef571076f9b5b.
- **Sea Level Rise.** NOAA Office for Coastal Management has map layers available for 2, 3, and 5 feet of sea level rise. https://coast.noaa.gov/slr/#/layer/slr.
- **Pierce County Maps.** Pierce County Spatial Services maintains a variety of maps for Pierce County geographies. https://www.piercecountywa.gov/491/Maps-Data.
- **Snohomish County Maps.** Snohomish County Maps & GIS Portal maintains a variety of maps for Snohomish County geographies. https://snohomishcountywa.gov/1402/Maps-GIS.

3.3 Analyzing and Categorizing Climate Risks and Impacts

To assess impact, the CCVA Team should consider each unique impact (i.e., each impact within each element) and assess the probability of that impact to happen and the severity of that impact. Table 3 provides an overview of how to conduct this assessment (see Appendix E for more resources to assess probability and likelihood of climate impacts).

Table 3. Rating Impact Severity and Probability of Climate Change Impacts on Sound Transit Infrastructure and Operations.

Impact Rating	Description	Probability Rating	Description
No Impact	No additional action required to maintain service levels.	**Zero Probability**	An impact that has not happened and is not projected to happen given future climate change.
Minor Impact *("a blip on the radar")*	Minimal additional action required to maintain service levels.	**Low Probability**	An impact that has rarely occurred in the past and is projected to happen rarely in the future (e.g., extreme heatwaves happening more frequently, but not a common occurrence).
Moderate Impact *("a nuisance")*	Some action required to maintain service levels but needed action can be easily accommodated.	**Medium Probability**	An impact that has rarely occurred in the past and is projected to happen more frequently in the future (e.g., flooding in the 100-year floodplain).
Major Impact *("we've got a problem")*	Substantial and/or costly action required to maintain service levels. Impact affects system beyond a single day.	**High Probability**	An impact that has occurred in the past and is projected to happen more frequently in the future (e.g., extreme rain events and associated flooding now happening multiple times a year).
Extreme Impact *("a game-changer")*	No service level can be maintained. Operations must be halted for a prolonged period of time or permanently.	**Virtually Certain**	An impact that has occurred in the past and is projected

After determining the impact severity and probability for each unique climate change impact to happen, the CCVA team should crosswalk those results to identify whether each climate change impact is a minor, moderate, or major climate change risk. Figure 2 below demonstrates an easy methodology to conduct this assessment. Generally, impacts within green areas are considered minor impacts, impacts within yellow areas are considered moderate impacts, and impacts within red areas are considered major impacts.

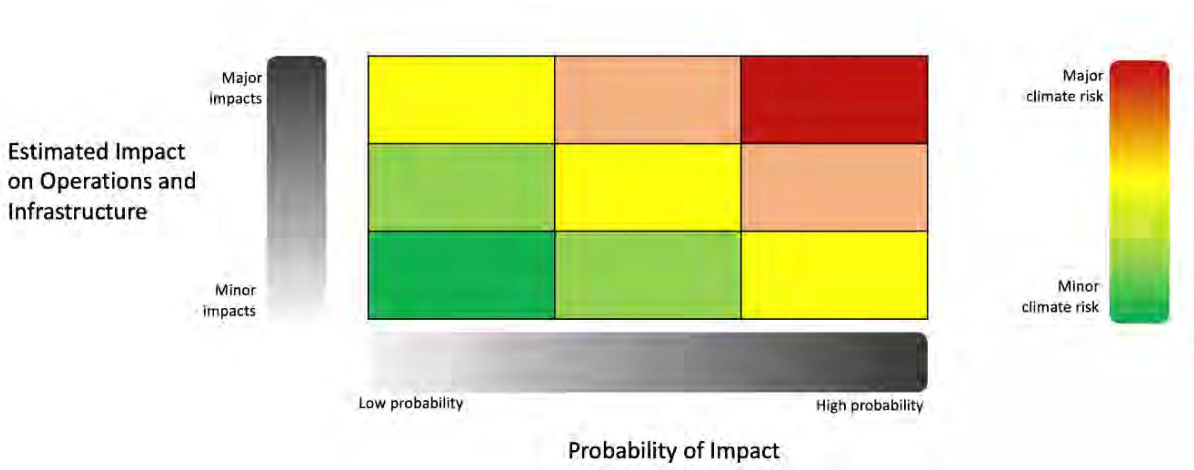


Figure 2. Framework to Evaluate Climate Risks.

WSBLE Case Study

The table below documents how we evaluated climate risks and impacts for the WSBLE project.

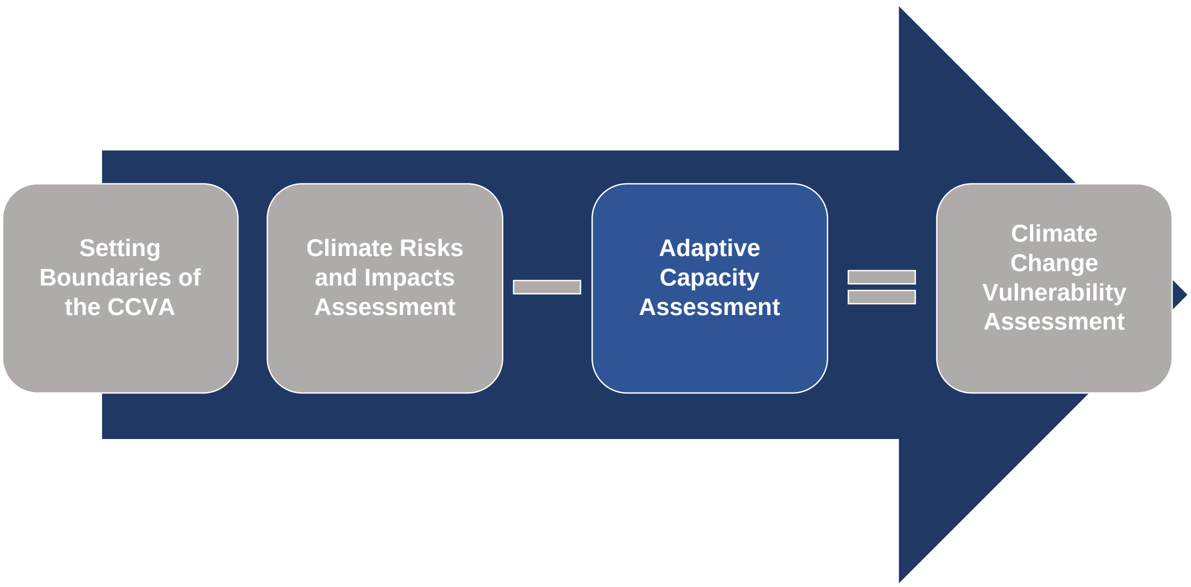
Estimated Impacts on Infrastructure and Operations	Estimated Probability of Climate Change Impacts: Low	Medium	High
Major	• **Cascading and compounding impacts from extreme heat and flooding** across Sound Transit's system could amplify the magnitude and severity of an extreme event (such as earthquake, tsunami, or dam failure) and cause system failures.	• **Increased major flooding risk** due to the confluence of high tide events, sea level rise that exceeds 5.2 feet by 2100 (1% likelihood of exceedance), extreme storms and heavy rainfall event, heavy wind and wave activities, and poor stormwater drainage, particularly in West Seattle and Duwamish Valley areas.	*(No high-probability / high-impact risks identified in this category.)*
Moderate	• Increased activity of **large mudslides and landslides** in the West Seattle, Duwamish Valley, and Queen Anne areas could disrupt Link service. • Regional **energy demand during summer months exceeds energy supply** and could disrupt Link service. • **Heat stress on moveable bridges** that causes components of bridge structures to malfunction.	• Increased **flooding risk to rail infrastructure in previously unaffected areas** in West Seattle and Duwamish Valley due to: o River flooding from heavy rainfall. o Coastal flooding from storm surges and sea level rise. o Stormwater-related flooding. • **Increased moderate flooding risk** due to the confluence of high tide events, sea level rise that exceeds 3.1 feet by 2100 (17% likelihood of exceedance), extreme storms and heavy rainfall events, heavy wind and wave activities, and poor stormwater drainage in West Seattle and Duwamish Valley.	• Increased **flooding risk to rail infrastructure in currently affected areas** in West Seattle and Duwamish Valley due to: o River flooding from heavy rainfall. o Coastal flooding from storm surges and sea level rise. o Stormwater-related flooding.
Minor	• **Flooding risk to rail infrastructure** in multiple areas from stormwater-related flooding. • **Heat stress to the auto-tension overhead catenary system** (OCS). • **Heat stress on air-conditioned electrical equipment.** • **Icing** of the OCS and elevated structures from extreme winter storms.	• Increased **flooding risk to electrical equipment** in West Seattle and Duwamish Valley areas due to: o River flooding from heavy rainfall. o Coastal flooding from storm surges and sea level rise. o Stormwater-related flooding. • Increased **rates of corrosion and wear** for rail/track and bridge infrastructure from more frequent and intense flooding and extreme heat events. • **Tunnel seepage from heavy rainfall events.** • Increased activity of **moderate mudslides and landslides** in the West Seattle, Duwamish Valley, and Queen Anne areas.	• **Heat stress on rail/track infrastructure**, especially ballasted tracks, with potential for rail buckling. • **Heat stress on non-tunnel fixed-termination OCS.** • **Heat stress on naturally ventilated electric equipment.** • Increased activity of **small mudslides and landslides** in the West Seattle, Duwamish Valley, and Queen Anne areas.

4 ADAPTIVE CAPACITY ASSESSMENT

Adaptive capacity is the ability of a system to cope with or adapt to future climate change impacts. This phase is important because it identifies the capacity to adapt – both from a systems-wide and route-specific perspective. In doing this, this phase helps **identify potential areas and opportunities to reduce or eliminate climate risks altogether via adaptation measures and strategies**. While this step does not necessarily commit Sound Transit or the CCVA team to implement all identified potential adaptation measures, this step will provide the realm of adaptation opportunities for the CCVA team to consider and prioritize during Step 5.

At the end of this phase, the CCVA team should have:

- A **comprehensive list of all potential adaptation measures, strategies, and opportunities** for each unique climate change risk.
- **Adaptive capacity assessment** that determines the potential for each project element to adapt to each unique climate change impact.



CCVA Team Meeting #3
Meeting #3 (see Table 1; agenda in Appendix B) will help the CCVA team identify all potential adaptation measures and considerations and assess the adaptive capacity of each element to potentially adapt, cope, or mitigate each climate change impact.

4.1 Elements of Adaptive Capacity

For Sound Transit, adaptation strategies can either be preemptive or reactive. Preemptive adaptation strategies are strategies and measures that Sound Transit can integrate into siting, location, and design, thereby preempting an impact. Reactive adaptation strategies are strategies and measures that Sound Transit can implement in advance of or in response to a climate impact. Examples of preemptive and reactive adaptation options are below.

- **Preemptive Adaptation Strategies**
    - o **Siting and location**. Siting and location of key project elements to ensure that they are not located in high-risk areas. For example, not siting rail tracks in landslide-prone areas can prevent damage to the guideway and minimize service disruption. These adaptation options happen pre-construction.
    - o **Design.** Design of key project elements to ensure that there is the ability of the system to cope with future climate impacts. For example, utilizing expansion joints on rail tracks can alleviate heat stress to prevent or mitigate rail buckling risk. These adaptation options happen pre-construction.
- **Reactive Adaptation Strategies**
    - o **Operations.** Operations can ensure that the WSBLE system can continue to adapt to future climate change during or post-construction. For example, regular maintenance can pre-empt and mitigate flooding events or slow orders during extreme heat days can ensure that the Light Rail continues to safely operate.

4.2 Summary of Climate Adaptation Options

4.2.1 Infrastructure Elements

4.2.1.1 Rail and Track Systems

Below is a comprehensive list of many of the proactive and reactive adaptation options that can be integrated into Sound Transit projects.

	Proactive Adaptation Options	Reactive Adaptation Options
Extreme Heat	• Provide **shading** whenever possible to cool tracks. • Install **sensors** or temperature monitoring equipment. • Install **rail expansion joints** to relieve heat stress. • **Map heat island hotspots** and identify potential solutions for specific areas. King County recently conducted a heat mapping study.	• **Run water to cool switches** and prevent failure. • **Visual monitoring** and **slow orders**.
Flooding	• Site and construct rail infrastructure so that the **top rail elevation is above the 500-year** floodplain and 3 feet above 100-year floodplain. • In addition to water pumps, adding **flood gates** to the tunnel portal can mitigate flood risks. • Adhering to DCM and **stormwater and flood standards**.	• Installing **water pumps** and updating water pumps. • **Visual monitoring** and **slow orders**.

	Proactive Adaptation Options	Reactive Adaptation Options
Landslides and Mudslides	• Make **slope stability** improvements in landslide-prone areas. • **Site key facilities** away from landslide-prone areas. • Build **walls** around the guideway to protect it from landslides.	• Install **camera monitoring** capabilities along the route known to be more sensitive to landslides.

4.2.1.2 Overhead Catenary System

Below is a comprehensive list of many of the proactive and reactive adaptation options that can be integrated into Sound Transit projects.

	Proactive Adaptation Options	Reactive Adaptation Options
Heat Stress and Extreme Heat	• Build more **robust foundations** to support higher loading and tension from extreme heat for fixed-termination OCS. • **Map heat island hotspots** and identify potential solutions for specific areas.	• Changing the **midpoint for weights** and installing **longer guide rods** in auto-tension OCS to accommodate a broader temperature range. • Regularly **maintain** the OCS. • **Raise the set point** for a fixed-termination OCS. • Increase **visual monitoring** of the OCS and implement slow orders or halt service as needed to re-tension lines.
Severe Winter Storms	None identified.	• Run **ice trains with heated pantographs** to melt ice on OCS lines. • Increase **visual monitoring** of the OCS and implement slow orders or halt service as needed.

4.2.1.3 Electrical Equipment

Below is a comprehensive list of many of the proactive and reactive adaptation options that can be integrated into Sound Transit projects.

	Proactive Adaptation Options	Reactive Adaptation Options
Heat Stress and Extreme Heat	• Increase **shading** around electrical equipment. • Adopt design criteria that allows for **natural ventilation and air flow**. • Provide **HVAC** for new and existing signal bungalows.	• Add **fans or other temporary cooling equipment** if HVAC systems are unable to meet cooling needs.
Flooding	• Site electrical equipment in **elevated locations** (e.g., not in tunnels) or **away from flood-prone areas**.	None identified.

	Proactive Adaptation Options	Reactive Adaptation Options
	• Design grading around TPSS to **slope away** to divert water away.	

Brownouts

With future climate change pressure on energy systems due to extreme heat, there may be future mismatches between energy supply and demand, potentially leading to **brownouts**, which can affect rail service. Some adaptation options to proactively address this concern include:

- Work with Seattle City Light to have a **dedicated line** for Sound Transit.
- Utilize **renewable energy** (e.g., solar panels) and place them near TPSS. This could be useful since energy reliability concerns will very likely occur during summer months.

4.2.1.4 Tunnels

Below is a comprehensive list of many of the proactive and reactive adaptation options that can be integrated into Sound Transit projects.

	Proactive Adaptation Options	Reactive Adaptation Options
Flooding and Groundwater Seepage	• **Site locations** of tunnel portals, station entrances, and at-grade ventilation systems in areas that reduces flood risk (including risk of stormwater runoff). • Construct **water protection structures** to prevent water entry. • Install **watertight conduits, pipes, and doors**. Watertight doors—which is used by Taipei Metro—can mitigate flood risk by placing them at station entrances, underground connections, and joint developments. • **Design for more severe flooding scenarios,** such as designing for the 100-year flood plus 3 additional feet or using the 500-year floodplain as a baseline.	• **Ensure water pumps function** during critical events and provide **back-up pumps or generators** in case of failure.

4.2.1.5 Bridges and Elevated Structures

Below is a comprehensive list of many of the proactive and reactive adaptation options that can be integrated into Sound Transit projects.

	Proactive Adaptation Options	Reactive Adaptation Options
Extreme Heat	• Install **sensors** to detect high track temperatures.	• Use **special monitoring equipment** to protect the bridge's moving parts—

	Proactive Adaptation Options	Reactive Adaptation Options
	• Map current **urban heat islands** to identify potential vulnerable spots. • **Reduce, modify, or relocate new development** in vulnerable areas. • Use more **robust, heat-resilient components**, such as nuts and bolts, that are designed for sufficient heat impacts.	including seismic monitoring equipment.
Flooding, Hydrology, and Sea Level Rise	• **Reduce, modify, or relocate new development** away from vulnerable regions. • **Integrate increased potential for damage under extreme hydraulic loads i**nto design and management procedures. • **Elevate bridg**es that are vulnerable to deck unseating – even though it is unlikely due to height of planned bridges.	• Reduce scour damage through **armoring or measures such as riprap, collars, and scour monitoring devices**.

4.2.1.6 Vertical Conveyance Systems

Below is a comprehensive list of many of the proactive and reactive adaptation options that can be integrated into Sound Transit projects.

	Proactive Adaptation Options	Reactive Adaptation Options
Extreme Heat	• Install **sensors** to detect high track temperatures. • Map current **urban heat islands** to identify potential vulnerable spots. • **Reduce, modify, or relocate new development** in vulnerable areas. • Use more **robust, heat-resilient components**, such as nuts and bolts, that are designed for sufficient heat impacts.	• Use **special monitoring equipment** to protect the bridge's moving parts—including seismic monitoring equipment.
Flooding, Hydrology, and Sea Level Rise	• **Reduce, modify, or relocate new development** away from vulnerable regions. • **Integrate increased potential for damage under extreme hydraulic loads i**nto design and management procedures. • **Elevate bridg**es that are vulnerable to deck unseating – even though it is unlikely due to height of planned bridges.	• Reduce scour damage through **armoring or measures such as riprap, collars, and scour monitoring devices**.

4.2.2 Service Elements

4.2.2.1 Rail Service Operations

Below is a comprehensive list of many of the proactive and reactive adaptation options that can be integrated into Sound Transit projects

	Proactive Adaptation Options	Reactive Adaptation Options
Mudslides and Landslides	• **Locate tracks away** from steep slopes. • **Contain and diverting moving debris** using walls, berms, ditches, and catchment basins. • **Stabilize slopes** by grading unstable slopes to lower gradients, constructing buttresses or retaining walls, or improving drainage systems.	• Continue to contract with Community Transit, King County Metro, Pierce Transit, and Starline Luxury Coaches to **provide coach service when mudslides affect rail service**.

4.2.2.2 Passenger Access and Experience

Below is a comprehensive list of many of the proactive and reactive adaptation options that can be integrated into Sound Transit projects.

	Proactive Adaptation Options	Reactive Adaptation Options
Heavy Rains, Storms, and Flooding	• Provide **canopy coverage and additional coverage** to protect passengers from heavy winds and rains at exposed and/or elevated stations. • Work with other jurisdiction to ensure **stormwater conveyance systems can accommodate f**uture heavy rain events and flooding.	• **Ensure water pumps function** during critical events and provide **back-up pumps or generators** in case of failure.
Extreme Heat	• See OCS adaptation options. • **Reduce, modify, or relocate station elements** (e.g., vertical conveyance systems, metal panels, expansion/contraction joints) away from vulnerable areas (e.g., areas with high sun exposure). • Use more **robust, heat-resilient components**, such as nuts and bolts, that are designed for sufficient heat impacts.	• See OCS adaptation options. • Provide **cooling options** (i.e., fans, HVAC) for vertical conveyance systems prone to overheating impacts.
Severe Winter Storms	•	

4.2.3 Construction Impacts

	Proactive Adaptation Options	Reactive Adaptation Options
Extreme Heat	• Site construction sites in areas that have **adequate shading** to prevent heat impacts on concrete and provide cooling options for workers.	• Provide additional cooling options, **such as iced water,** during extreme heat days. • Update and adhere to **worker safety policies** that prohibit outdoor construction during extreme heat days.

4.3 Adaptive Capacity Assessment

After identifying all potential adaptation considerations for the project, the CCVA team can assess the adaptive capacity of each project element to each unique climate change impact. Adaptive capacity is assessed on a scale of limited adaptive capacity, moderate adaptive capacity, or high adaptive capacity. See Figure 4 for adaptive capacity ratings for the WSBLE project.

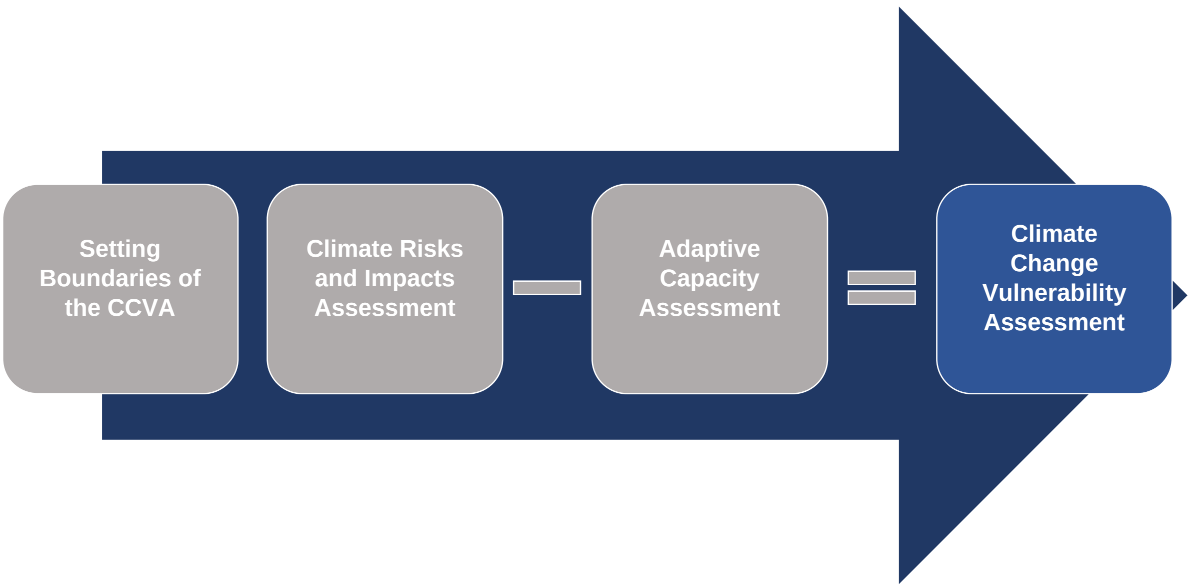
- **Limited adaptive capacity** means that there is not an adaptation option that adequately mitigates the climate risk.
- **Moderate adaptive capacity** means that there are proactive or reactive options available that can mitigate some of the climate risk.
- **High adaptive capacity** means that there are both proactive and reactive options available that mitigate most of the climate risk.

5 BRINGING IT TOGETHER: ASSESSING CLIMATE CHANGE VULNERABILITY

The final step of the CCVA process is to bring all the components together into a final vulnerability rating. The steps below will guide the CCVA Team in determining key vulnerabilities and considerations.

At the end of this phase, the CCVA team should have:

- A final **climate vulnerability rating** for each project element.
- A **roadmap on priority adaptation measures and strategies** to integrate into the project design and planning stage (see: https://www.soundtransit.org/system-expansion/building-system/project-phases-plans-to-construction for the full project lifecycle).



CCVA Team Meeting #4 and Meeting #5

Meeting #4 (see Table 1; agenda in Appendix B) will help the CCVA team prioritize and confirm the final climate vulnerability ratings of all prioritized climate impacts.

Meeting #5 (see Table 1; agenda in Appendix B) will help the CCVA team undertake a climate risk analysis for the project, identifying and selecting which adaptation measures to prioritize during the design and planning stage of the Sound Transit project.

5.1 Assessing Climate Change Vulnerability

After identifying risk/impact and adaptive capacity ratings, adjusting for additional specific considerations, the CCVA Team should bring them into a final climate change vulnerability rating (Figure 3). Climate change vulnerability is rated as the risks and impacts moderated by adaptive capacity. To assess climate change vulnerability, the CCVA Team should use the framework below to conduct their final vulnerability ratings.

Figure 3. Framework to Assess Climate Change Vulnerability Rating

		Adaptive Capacity		
		Limited	**Moderate**	**High**
Risks & Impacts	**Major**	**High Vulnerability** Major impacts with limited adaptive capacity	**Moderate Vulnerability** Major impacts with moderate adaptive capacity	**Low Vulnerability** Major impacts with high adaptive capacity
	Moderate	**Moderate Vulnerability** Moderate impacts with limited adaptive capacity	**Low Vulnerability** Moderate impacts with moderate adaptive capacity	**Low Vulnerability** Moderate impacts with high adaptive capacity
	Minor	**Low Vulnerability** Minor impacts with limited adaptive capacity	**Low Vulnerability** Minor impacts with moderate adaptive capacity	**Low Vulnerability** Minor impacts with high adaptive capacity

Following this exercise, the CCVA Team should have a final summary table that outlines final climate change vulnerability ratings. For example, Figure 4 shows the final summary table with associated ratings for climate risks and impacts, adaptive capacity, and climate change vulnerability.

Figure 4. Final Climate Change Vulnerability Ratings for the WSBLE Project.

WSBLE Project Elements & Effects	Risks and Impacts	Adaptive Capacity	Vulnerability
Rail/Track			
Rail buckling, fatigue cracking, pavement rutting, and switch failures	Moderate	Moderate	Low
Flooding	Moderate to Major	Moderate	Moderate
Mudslides and landslides	Minor	Moderate	Low
Overhead Catenary System			
Heat stress	Minor to Moderate	High	Low
Severe winter storms	Very Minor	High	Low
Electrical Equipment			
Heat stress	Minor to Moderate	High	Low
Flooding	Moderate to Major	Moderate	Moderate
Tunnels			
Flooding	Moderate to Major	Moderate	Moderate[a]
Extreme events	Moderate to Major	High	Low
Bridges and Elevated Structures			
Extreme heat and air pollution	Moderate	Moderate	Low
Flooding	Minor	High	Low
Extreme events and winter storms	Minor	Moderate	Low
Rail Service Operations *(cross-cutting)*			
Extreme heat	Minor	Moderate	Low
Flooding	Moderate	Limited	Moderate
Mudslides and landslides	Minor	Moderate	Low
Customer Experience *(cross-cutting)*			
Heavy rains and storms	Moderate	Moderate	Low
Flooding	Moderate	Moderate	Low
Construction *(cross-cutting)*			
Extreme Heat	Minor	Moderate	Low
Flooding	Moderate	Moderate	Low

[a] Likely low to moderate depending on tunnel location.

Utilizing a detailed table – such as the WSBLE project – can help provide the different types of risks, adaptation options, and site-specific considerations (see Appendix C for a template of this detailed templates).

WSBLE Case Study

The figure below shows how a CCVA Team can consider specific climate impacts and adaptation options for the associated project, using an example of extreme heat impacts on rail and track systems.

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Rail/Track	**Extreme heat impacts**: • Rail buckling. • Fatigue cracking. • Pavement rutting. • Switch failures.	• Map current heat island effects to identify potential trouble spots and site tracks away from these areas. • *Site in shaded areas to reduce heat impacts.*	• Install sensors to detect high track temperatures in at-risk areas. • Use rail expansion joints to relieve heat stress. • Update DCM to reflect appropriate temperature range. • Use heat resistant materials that are less prone to rail buckling.	• Slow rail traffic during hours or days of extreme heat. • Increase visual monitoring of tracks and issue heat advisories. • Run garden hose to cool switches during hot days. • Adjust temperature monitoring thresholds or policies to pre-empt rail buckling. • *Deploy staff during extreme heat events to identify and mitigate emerging issues.*	**Low**
Rail/Track *(continued)*	**SLR + Heavy Rains + Hydrological Impacts:** • Flooding and corrosion of infrastructure and damage to rail corridors	• Ensure top rail elevation is above 500-year floodplain and 3 feet above 100-year floodplain levels. • Relocate ground-level and underground equipment and structures.	• Partner with jurisdictions on design standards and stormwater management. • Sizing drains on elevated structures to accommodate future flows. • Adhere to design criteria (e.g., not placing tracks at lowest point) to minimize flooding issues. • Design for more severe flooding scenarios, such as designing for the 100-year flood plus 3 additional feet or using the 500-year floodplain as a baseline.	• Increase visual monitoring of riverbanks, bridge supports, and infrastructure. • Maintain infrastructure and equipment with drainage problems. • Adjust policies related to rainfall, wind speed, etc. for when to begin monitoring for rail damage (e.g., extremes in the future will change thresholds, but systems are in place). • Utilize pumps to mitigate flooding issues.	**Moderate**

5.2 Applying the Climate Change Vulnerability Assessment: What's Next?

A CCVA us only as useful as it is applied for decision-making processes. After assessing the climate vulnerability of each project element, the CCVA team will use the CCVA to directly inform which adaptation options – especially proactive adaptation options – to include into the planning and design phase of the Sound Transit project (see: Sound Transit, Project phases: from plans to construction).

The CCVA team – specifically the Operations and Design/Engineering teams within the CCVA team – should consider some of the following questions (can be done in Meeting #5, see agenda in Appendix B):

- **How much climate change vulnerability does Sound Transit want to tolerate**? The CCVA and Sound Transit may have varying tolerance levels depending on the project element, adaptation options available, and severity of projected climate change impacts. For example, the CCVA team may have a higher tolerance for project elements that may be affected by winter storms or snowstorms, since those are fairly infrequent events. Conversely, the CCVA team may want to implement multiple adaptation measures to adequately prepare multiple project elements (OCS, electrical equipment, vertical conveyance systems, rail/track systems) for future extreme heat impacts.
- **What adaptation options (identified in section 4.2 or Meeting #3 in Appendix B) are feasible given project constraints (agency priorities, geography, financial considerations, timing considerations, jurisdictional considerations, community buy-in)?** Some adaptation options may not be feasible given a number of reasons. For example, designing for a 500-year flood – rather than a 100-year flood – may not be feasible given local geographic contexts or competing jurisdictional authority. Other adaptation options may be extremely feasible – such as integrating cooling capabilities into station elements – due to a variety of reasons, such as regulatory requirements or marginal financial investment for more resilient elements. There may be adaptation options that may have already been implemented because they address system-wide impacts.
- **Given feasible adaptation options, is there sufficient measures to fully address climate change impacts given Sound Transit's tolerance level?** After identifying feasible adaptation options, the CCVA team should qualitatively assess whether those adaptation options are sufficient to address the key climate change risks. If feasible adaptation options are insufficient to mitigate climate change risks, the CCVA team should strategize what additional support or resources will be needed to implement additional adaptation options.

After answering these questions, the CCVA team should have a **final list of adaptation options** – specifically proactive adaptation options – to integrate into the planning and design phase of the Sound Transit project. Additionally, this process may also identify key elements or sites that will be particularly vulnerable despite climate adaptation measures taken. This can help inform requests for additional resources to implement more ambitious adaptation measures or indicate that reactive adaptation measures will be necessary to mitigate additional vulnerability. This CCVA can also be used as a foundation for future CCVA iterations, especially as the Sound Transit project progresses into later project phases or as new research is published.

Appendices

APPENDIX A: CLIMATE SCIENCE PRIMER

This section provides a summary of the foundational climate science projections for the Puget Sound area based on best available science and research. Data primarily comes from downscaled climate models provided by the University of Washington's Climate Impacts Group.

This section primarily uses **the RCP8.5 climate scenario**. While this scenario is currently the most extreme scenario and assumes no global climate mitigation and GHG emissions reduction, this scenario is considered the "business-as-usual" scenario. Sound Transit uses this scenario because they want to ensure they are comprehensively planning for all potential climate scenarios, especially considering Sound Transit investments now will likely have a lifespan that extends for the next century. This section should be updated every several years to ensure that these numbers are accurate and precise. For example, new climate scenarios are currently being developed (Shared Socioeconomic Pathways = SSPs).

Extreme Heat

Warming is projected to continue in the Puget Sound region for all four emissions scenarios across all seasons, with summer seeing the most substantial temperature increases. Average annual temperature in the region is anticipated to warm 4.3 °F or more after 2040, relative to the 1970–1999 average, and will be accompanied by more frequent and intense heat waves and fewer and less intense cold periods. Table 4 summarizes projected temperature increases.

Table 4. Projected changes in Puget Sound region's temperature, relative to the 1970-1999 average.

Factor	2040–2069	2079–2099
Average annual temperature	**+5.5 °F** +4.3 to +7.1 °F	**+9.1 °F** +7.4 to +12 °F
Summer (June–August) temperature	**+6.8 °F** +4.8 to +9.7 °F	**+11 °F** +8.8 to +15 °F
Winter (December–February) temperature	**+4.9 °F** +3.2 to +6.5 °F	**+8.3 °F** +6.0 to +10 °F
Temperature of hottest days	**+6.5 °F** +4.0 to +10.2 °F	**+9.8 °F** +5.3 to +15.3 °F
Temperature of coolest nights	**+5.4 °F** +1.3 to +10.4 °F	**+8.3 °F** +3.7 to +14.6 °F

Notes: Projections are consistent with the RCP8.5 scenario. Values within the table are the average (first line of each row, in boldface) and range (second line of each row) of projections from 10 climate models.

As of 2019, four of the five hottest years on record in Seattle happened since 2013, with 2015 having a total of 12 days over 90 °F and 2018 seeing a total of 11 days over 90 °F (Baker, 2019;

Sundell, 2019). Furthermore, 2019 and 2020 also continued to set heat records in Seattle and Western Washington (Sistek, 2020). Figure 5 shows average annual temperatures in Seattle.

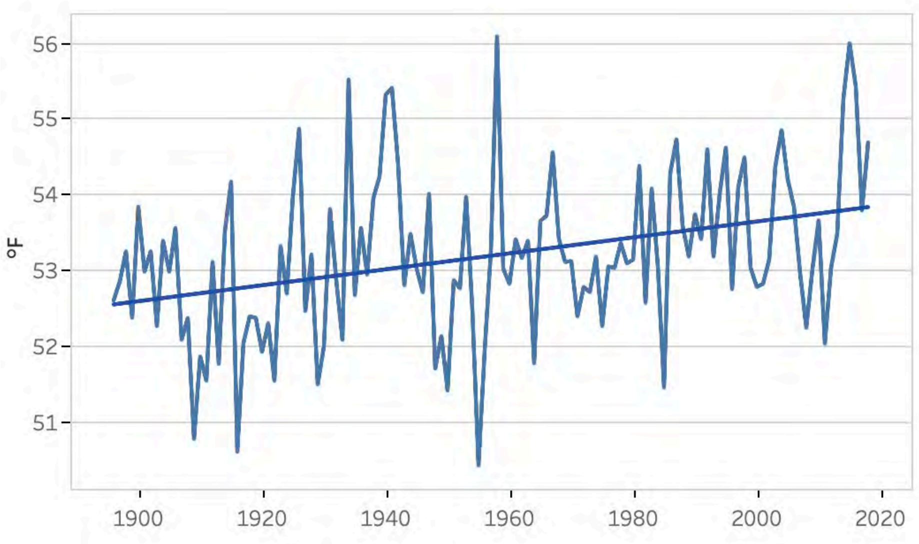


Figure 5. Average annual temperature between 1895 to 2018 for downtown Seattle.

Notes: Temperature dataset from the U.S. Historical Climatology Network, version 2.5.5.20190405 (through March 2019) and has been data adjusted for biases and inhomogeneities resulting from changes in the environment or operation of individual observing sites (e.g., urbanization, station moves, instrument upgrades, and time of observation changes). Data visualized by the Office of the Washington State Climatologist.

Coastal Flooding

The rate at which sea level rises in Puget Sound depends on the rate of global absolute sea level rise and regional factors such as ocean currents, wind patterns, location, and elevation. For example, in Neah Bay, the land elevation is rising at a rate of +1 inch per decade, compared to Seattle, which is decreasing at a rate of approximately -0.5 inches per decade (Petersen, et al., 2015). In areas where the land is sinking, the regional *relative* sea level rise will be greater than the *absolute* sea level rise, and in regions where the land is rising, *relative* sea level rise will be less than the *absolute* sea level rise. A large earthquake along the Cascadia subduction zone could result in sudden changes in land elevation and reverse vertical land movement trends, resulting in rapid relative sea level rise. Smaller earthquakes along the Seattle fault can also result in changes in land elevation levels, although the magnitude of changes is dependent on the earthquake epicenter (Miller, et al., 2018).

In the Elliott Bay area, there is a 50% probability of exceedance of sea levels to rise by 0.8 feet by 2050 and 2.3 feet by 2100. In the Ballard area, there is a 50% probability of exceedance of sea levels to rise by 0.9 feet by 2050 and 2.4 feet by 2100 (Table 5).

Table 5. Projected relative sea level change, in feet, for Elliott Bay and Ballard, compared to 1991-2009.

Period	2050	2100
Elliott Bay	**0.8 feet** 0.6 to 1.1 feet	**2.3 feet** 1.7 to 3.1 feet
Ballard	**0.9 feet** 0.7 to 1.1 feet	**2.4 feet** 1.8 to 3.1 feet

Notes: This table reports relative sea level rise projections from the Washington Coastal Resilience Project for Seattle near Elliott Bay (47.6 N, 122.4 W) and Ballard (47.7 N, 122.4 W). Projections are centered on 2050 (2040–2069) and 2100 (2090–2109). The boldface number (first line of each row) indicates the probability of exceeding the indicated relative sea level rise is 50%. The range of values (second line of each row) represent the 83% and 17% probability of exceeding the indicated relative sea level rise, respectively. Data were downloaded from www.wacoastalnetwork.com/wcrp-documents.html (updated January 27, 2021).

As sea level rises, studies suggest increased potential for higher tidal and storm surge, leading to coastal inundation, erosion, and flooding. The rate and amount of inundation varies by the projected sea level rise and shoreline characteristics. Compounding events—such as the combined effects of high tide, winter storm surge, and sea level rise—can lead to coastal flooding events (Mauger, et al., 2015).

For coordination and permitting purposes for WSBLE, Sound Transit is aligning with the City of Seattle's draft climate adaptation planning work, which uses the sea levels shown in Table 6**.**

Table 6. Sea level rise projections for the City of Seattle for 2100, in feet.

Condition	2020 Water Levels	Sea Level Rise by 2100	2100 Water Levels
Daily high tide	0	+3	3
Monthly high tide	1	+3	4
Annual high tide	2	+3	5
100-year storm surge	3	+3	6

Notes: Water levels are relative to the average daily high tide (mean higher high water mark, MHHW) in 2020, which is 9 feet above the official "zero" point of North American Vertical Datum of 1988 (NAVD88). Sea level rise of 3 feet by 2100 corresponds to 17% probability for the high emissions scenario (RCP8.5) (Miller, et al., 2018).

Riverine Flooding

Consistent with projected changes in precipitation, climate change is expected to alter the volume and timing of seasonal streamflow in the Green-Duwamish, Cedar, Chehalis, Nisqually, Sammamish, Snohomish, and White rivers. Increased winter flooding and a 15–73% increase in the frequency of 100-year flood events are projected in the Green-Duwamish watershed. In summer, streamflow is expected to decline 7–21% by the 2080s, and the duration of low-flow periods is projected to increase.

Current trends in annual streamflow are mixed, without a statistically meaningful trend in annual average streamflow. Dry years are becoming more prevalent for some rivers. Peak streamflow is shifting earlier in the spring in watersheds historically dominated by snow, and peak flow is shifting later in the spring in watersheds historically dominated by rain (Mauger, et al., 2015).

As the climate warms and precipitation shifts to the winter months, the Pacific Northwest is projected to face decreased snowpack, increases in summer stream temperatures, and changes to streamflow timing, seasonal minimums, and flooding. While total annual streamflow volumes are not projected to change consistently, seasonal streamflow volume and timing are expected to shift based largely on a higher portion of precipitation falling as rain rather than snow (Mauger, et al., 2015).

Heavy rainfall events in Western Washington will intensify by 22% by the 2080s. Heavier rainfall events, coupled with increased 100-year flood events from streamflow, will create more frequent and intense river and inland flooding events. Regional models indicate a 35% increase for 10-year flood events and a 32% increase for 100-year flood events in the Green-Duwamish River (Table 7).

Table 7. Anticipated changes for streamflow timing and volume for the 2080s.

Watershed	Earlier Peak Streamflow Timing	Streamflow 100-Year Flood	Streamflow 10-Year Flood	Summer Minimum Flows
Green-Duwamish	**−38 days** −50 to −31 days	**+32%** +15 to +73%	**+35%** +14 to +73%	**−16%** −21 to −7%

Notes: Projections are for unregulated flows under the A1B (SRES) emissions scenario.

Mudslides and Landslides

Climate projections indicate that there will be more intense rain events in the future (Mauger G. , et al., 2018). As a result, soils can become saturated and are destabilized, resulting in landslide and mudslide conditions, which has happened to various routes including the Sounder's North Line. While emerging science is progressing the correlation between climate change projections and landslide/mudslide risk, an increase in landslides and mudslides can have significant impacts on rail systems, including **causing damage to rail infrastructure** and **disrupt rail services**, especially in areas with steep slopes that are more susceptible to soil destabilization and sediment transport—such as West Seattle and Queen Anne. While consequences can be significant, these major landslide events are also rare. Damage to rail systems from landslides or mudslides are often caused by debris landing on the tracks, such as fallen branches or tree trunks (Sound Transit, 2021a).

Rail service disruptions can cause negative customer experience when forced to wait longer due to service shutdowns or re-routing. While the entire geographic scope of Sound Transit's work is susceptible to these natural events, Pigeon Point in West Seattle and Queen Anne have both been identified as particularly high-risk areas due to their hilly terrain (Sound Transit, 2021a).

Sound Transit can take many different actions in terms of design and re-enforcement to address mudslide and landslide risk. For current sites, making improvements to slope stability can be done, reducing the risk of a landslide or mudslide causing damage to current infrastructure. Additionally, building walls around rail structures to protect the infrastructure from debris or installing camera monitoring on sensitive or known landslides areas are both methods of preparing for increased intensity of rainfall events. When siting future locations, choosing areas located away from landslide areas can mitigate future landslide risk (Sound Transit, 2021b).

Heavy Rains

Average annual precipitation in the Pacific Northwest is expected to increase slightly in the coming decades. Seasonal precipitation is expected to shift, with summer rainfall declining 22% and winter precipitation increasing 11% by 2050, as shown in Table 8**.**

Historical records indicate that the frequency of heavy rainfall events has increased over the 20th century in the Puget Sound region. Climate models suggest that this trend will likely continue into the 21st century. Winter extreme precipitation, including atmospheric rivers, is projected to increase and become more severe (Ralph, Neiman, & Wick, 2004). A recent study of extreme precipitation projections for King County showed the potential for substantial increases in future precipitation intensity. For example, there is a projected 54% increase in the 10-year hourly rainfall event by 2080 (Mauger & Won, Projecting Future High Flows on King County Rivers: Phase 2 Results, 2020).

Table 8. Projected changes in Puget Sound seasonal precipitation.

Period	2040–2069	2070–2099
Summer (June-August)	**−22%** −50% to −1.6%	**−27%** −53% to +10%
Winter (December-February)	**+11%** +1.8% to +19%	**+15%** +6.2% to +23%

Notes: All changes are relative to the average for 1970–1999. Values in the table are the average (first line of each row) and range (second line of each row) or projections from 10 climate models for RCP8.5.

Extreme Events

Extreme events—such as winter storms, windstorms, and earthquakes—can have a variety of impacts on bridges and elevated structures. While there is some uncertainty in the causal connections between these extreme events and climate change, the interaction of extreme events and future climate conditions can create circumstances that can amplify the magnitude the impacts of climate change. Specific examples and considerations for the WSBLE include:

- Freeze and thaw cycles and de-icing salt application can **accelerate bridge deterioration**.
- Climate change can create conditions—such as sea level rise affecting groundwater tables—more favorable for **liquefaction** to happen.

- High winds during extreme storms can **increase wind static loading**, which was a primary reason for the 1940 failure of the Tacoma Narrows Bridge.

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APPENDIX B: AGENDA TEMPLATES FOR CLIMATE CHANGE VULNERABILITY ASSESSMENT TEAM

- **Climate impacts meeting**: meeting to discuss key climate impacts and considerations for the project.
- **Climate impact mapping meeting**: meeting to map key climate impacts and how that may impact key project elements in certain locations.
- **Adaptation meeting**: meeting to discuss adaptation options for the project.
- **Vulnerability meeting**: meeting to discuss final vulnerability ratings and considerations for the project.

  - **Meeting 1:** Sound Transit staff confirms the project boundaries and identifies potential climate impacts to the planned project and prioritize these climate impacts.
  - **Meeting 2:** Sound Transit staff utilizes project boundaries and maps out prioritized climate impacts and considerations across the planned project route, including alternatives.
  - **Meeting 3:** Sound Transit staff identify key adaptation considerations and opportunities.
  - **Meeting 4:** Sound Transit staff confirm the vulnerability rating of prioritized climate impacts.
  - **Meeting 5:** Sound Transit Sustainability Staff work with Operations and Engineering staff to undertake a climate risk analysis for the project and identify feasible climate change adaptation options.

Meeting #1 Agenda

Anticipated meeting time: 1 hour and 20 minutes

Meeting objective(s):

- Identify or confirm project boundaries (refer to section 2.1 and section 2.2)
- Review and prioritize potential climate change impacts on WSBLE light rail infrastructure and operations (refer to section 3.1)

Meeting materials (review in advance of meeting):

- Climate impacts summary (summary of section 3.1 – can be represented in a matrix/table or other accessible format).

Participants

☐ Project Manager(s) ☐ Segment Lead(s) ☐ Environmental Staff ☐ Sustainability Staff ☐ Engineer Lead(s) ☐ Engineer / Systems Staff ☐ Utility / Hydrology Staff ☐ Operations Director for project ☐ Light Rail Operations Staff ☐ Consultant Team	*Optional:* ☐ Additional Relevant Staff	Facilitator: Note Taker:	*TBD* *TBD*

Time:	Agenda item and description:	Lead:
0:00 10 min	**Welcome and Introductions** • Use this time for project team members to introduce themselves.	Facilitator
0:10 10 min	**Overview of Meeting Objectives** • Provide an overview of the meeting objective(s). • Review the Sound Transit project to provide a common operational understanding for the whole group to determine or confirm the project's boundaries. • Review climate change impacts for the Sound Transit projects. Some resources that can be used can include: o 2013 FTA-funded project o Summary of climate change impacts documented in section 3.1 o Summary of climate science projections in Appendix A	Facilitator and/or Project Manager(s)
0:20 25 min	**Discussion of Project Boundaries** • If available, provide an overview of proposed project boundaries. If none are available, please do the following as a CCVA team:	Group discussion

	o Refer to section 2.1 to determine the geographic boundary of the project, size of the project buffer, and additional environmental, geographic, or infrastructure attributes of the geographic boundary and buffer. o Refer to section 2.2 to determine the project elements the CCVA team should be evaluating for climate change vulnerability.	
0:45 25 min	**Discussion of Climate Impacts to Sound Transit Project** • Brief overview of climate change impacts on light rail infrastructure and operations (see Climate Impacts Summary, adapted from section 3.1): o **Climate change impacts**: extreme heat, sea level rise, heavy rain events, hydrology changes, mudslides/landslides o **Light rail infrastructure and operations**: rail/track, OCS, other electrical equipment, tunnels/portals, bridges, vertical conveyance system, passenger service and experience, other service/operations • Discussion based on the following questions: o Any other topics/concerns not covered? o Are there specific project-specific considerations to flag (e.g., specific sites are vulnerable to flooding or other impacts; other potential risks – such as an industrial facility or an ecologically sensitive area – within project geography that might lead to other environmental impacts)? • Ratings to prioritize key areas of concern o Can utilize a virtual voting exercise of in-person dot voting exercise for the CCVA team to prioritize the key impacts that are of most concern for the project.	Group discussion
1:10 10 min	**Priorities and Next Steps** • Review the results of today's discussion, specifically: o Project boundary and other considerations o Comprehensive list of potential climate change impacts and a prioritized list of key impacts of concern • Review upcoming meetings and their objectives. This will help frame each meeting within the overall CCVA timeline. o **Meeting 2:** Sound Transit staff utilizes project boundaries and maps out prioritized climate impacts and considerations across the planned project route, including alternatives. o **Meeting 3**: Sound Transit staff identify key adaptation considerations and opportunities. o **Meeting 4:** Sound Transit staff confirm the vulnerability rating of prioritized climate impacts. o **Meeting 5:** Sound Transit Sustainability Staff work with Operations and Engineering staff to undertake a climate risk analysis for the project and identify feasible climate change adaptation options.	Facilitator

Key outcomes and decisions:

The following items should be the key outcomes that emerge from Meeting #1:

- Project boundary and other considerations
- Comprehensive list of potential climate change impacts and a prioritized list of key impacts of concern
- Additional parking lot questions for CCVA team to answer before Meeting #2

Parking lot:

Please use this section for additional questions that emerge but are unable to be answered due to timing or expertise limitations. The CCVA team – most likely the project manager(s) and consultant team – will follow-up on these parking lot items before the next meeting.

Meeting Agenda #2

Anticipated meeting time: 1 hour and 20 minutes

Meeting objectives:

- Identify site-specific concerns for Sound Transit infrastructure and operations (refer to section 3.2)
- Analyze and categorize climate impacts of concern, which were identified in Meeting #1 (refer to section 3.3)

Meeting materials (review in advance of meeting):

- Updated climate impacts summary (summary of section 3.1 but adapted based on outcomes from Meeting #1 – can be represented in a matrix/table or other accessible format).
- Map(s) of the Sound Transit project area (usually provided by consultant team). Refer to Appendix D for examples. These maps should document:
  - Rail type (at-grade, elevated, tunnel)
  - Station options
  - Alternative routes
  - Project buffer
  - Key climate change impacts (sea level rise, FEMA 100-year and 500-year floodplains, landslide hazard areas). Please refer to section 3.2 for mapping and GIS resources.

Participants

☐ Project Manager(s) ☐ Segment Lead(s) ☐ Environmental Staff ☐ Sustainability Staff ☐ Engineer Lead(s) ☐ Engineer / Systems Staff ☐ Utility / Hydrology Staff ☐ Operations Director for project ☐ Light Rail Operations Staff ☐ Consultant Team	*Optional:* ☐ Additional Relevant Staff	Facilitator: Note Taker:	*TBD* *TBD*

Time:	Agenda item and description:	Lead:
0:00 10 min	**Welcome and Introductions** • Use this time for project team members to introduce themselves. • Review meeting objectives.	Facilitator
0:10 10 min	**Review of Climate Change Impacts Assessment from Meeting #1** • Review outcomes of Meeting #1, specifically the key climate change impact concerns for the Sound Transit project. • Review the updated summary of climate change impacts, which was updated following Meeting #1.	Facilitator

	• Brief discussion: what did we miss from Meeting #1? Any additions topics, questions, or discussions the CCVA team should discuss?	

0:20
50 min
	Discussion of Site-Specific Climate Change Impacts to Project through Map Review
	• Use the map(s) of the Sound Transit and discuss the following questions (please see this MURAL Board link for an example of how to use a visual facilitation tool for this meeting):
	  o Based on the key climate impacts of concern, what are the site-specific concerns? Some examples could be:
	    ▪ Project elements are near a creek, which can cause creek flooding.
	    ▪ Heavily wooded areas could lead to tree debris falling on guideways during storms.
	    ▪ A bridge crossing can be affected by extreme heat or high wind concerns.
	• Depending on the size of the Sound Transit project, there may be more localized maps that the CCVA team will need to discuss. For example, the WSBLE had maps to facilitate discussion of site-specific considerations:
	  o West Seattle/Duwamish
	  o SODO
	  o Downtown Tunnel
	  o Interbay
	  o Ballard
	• Any other topics/concerns not covered?
		Group discussion

1:10
10 min
	Priorities and Next Steps
	• Review the results of today's discussion, specifically:
	  o Site-specific climate change impacts documented on project map(s)
	• Review upcoming meetings and their objectives. This will help frame each meeting within the overall CCVA timeline.
	  o **Meeting 3**: Sound Transit staff identify key adaptation considerations and opportunities.
	  o **Meeting 4:** Sound Transit staff confirm the vulnerability rating of prioritized climate impacts.
	  o **Meeting 5:** Sound Transit Sustainability Staff work with Operations and Engineering staff to undertake a climate risk analysis for the project and identify feasible climate change adaptation options.
		Facilitator

Key outcomes and decisions:

The following items should be the key outcomes that emerge from Meeting #2:

- Site-specific climate change impacts documented on project map(s)
  - See Appendix D for example of the final map(s).

Parking lot:

Please use this section for additional questions that emerge but are unable to be answered due to timing or expertise limitations. The CCVA team – most likely the project manager(s) and consultant team – will follow-up on these parking lot items before the next meeting.

Meeting Agenda #3

Anticipated meeting time: 1 hour and 20 minutes

Meeting objectives:

- Review and identify a comprehensive list of adaptive capacity considerations for the Sound Transit project (refer to section 4.2 for an initial set of adaptation options as a jumping off points for this meeting).
- Assess the adaptive capacity of each project element to climate change impacts (refer to section 4.3).

Meeting materials (review in advance of meeting):

- Updated summary of climate impacts and affected WSBLE Project elements (continuously updated from Meeting #1 and #2)
- Table of potential adaptive capacity options and considerations for the Sound Transit project (see section 4.2 for an initial list of adaptation options; see Appendix C for an example of how climate impacts and adaptation can be combined into a single summary matrix)

Participants

☐ Project Manager(s) ☐ Segment Lead(s) ☐ Environmental Staff ☐ Sustainability Staff ☐ Engineer Lead(s) ☐ Engineer / Systems Staff ☐ Utility / Hydrology Staff ☐ Operations Director for project ☐ Light Rail Operations Staff ☐ Consultant Team	*Optional:* ☐ Additional Relevant Staff	Facilitator: Note Taker:	*TBD* *TBD*

Time:	Agenda item and description:	Lead:
0:00 10 min	**Welcome and Introductions** • Use this time for project team members to introduce themselves. • Review meeting objectives.	Facilitator
0:10 10 min	**Review of Climate Impacts Assessment and Climate Impact Maps** • Review outcomes of Meeting #2, specifically the key climate change impacts mapped onto the Sound Transit project map(s). • Brief discussion: Any additional topics or questions?	Facilitator
0:20 50 min	**Discussion of Adaptive Capacity and Climate Change Vulnerability** • Review adaptive capacity definition and considerations (refer to section 4.1). Specifically, adaptation options can include: o Siting o Design o Operations	Facilitator

	o Proactive vs. reactive adaptation strategies • Assess the adaptive capacity of each project element using approach outlined in section 4.3. • Any other topics or considerations?	
1:10 10 min	**Priorities and Next Steps** • Review the results of today's discussion, specifically: o Site-specific climate change impacts documented on project map(s) • Review upcoming meetings and their objectives. This will help frame each meeting within the overall CCVA timeline. o **Meeting 4:** Sound Transit staff confirm the vulnerability rating of prioritized climate impacts. o **Meeting 5:** Sound Transit Sustainability Staff work with Operations and Engineering staff to undertake a climate risk analysis for the project and identify feasible climate change adaptation options.	Facilitator

Key outcomes and decisions:

The following items should be the key outcomes that emerge from Meeting #3:

- Comprehensive list of adaptation options for each project element, using section 4.2 as a jumping off point.
- Adaptive capacity assessment of each project element that determines the ability of the element to cope or adapt to future climate change impacts (using approach in section 4.3).

Parking lot:

Please use this section for additional questions that emerge but are unable to be answered due to timing or expertise limitations. The CCVA team – most likely the project manager(s) and consultant team – will follow-up on these parking lot items before the next meeting.

Meeting Agenda #4

Anticipated meeting time: 1 hour and 20 minutes

Meeting objectives:

- Review the vulnerability ratings of anticipated climate change impacts on Sound Transit Project elements.

Review in advance of meeting:

- Draft summary matrix of climate impacts, WSBLE elements, adaptive capacity, and vulnerability ratings (use blank table in Appendix C as a template for this discussion)

Participants

☐ Project Manager(s) ☐ Segment Lead(s) ☐ Environmental Staff ☐ Sustainability Staff ☐ Engineer Lead(s) ☐ Engineer / Systems Staff ☐ Utility / Hydrology Staff ☐ Operations Director for project ☐ Light Rail Operations Staff ☐ Consultant Team	*Optional:* ☐ Additional Relevant Staff	Facilitator: Note Taker:	*TBD* *TBD*

Time:	Agenda item and description:	Lead:
0:00 10 min	**Welcome and Introductions** • Use this time for project team members to introduce themselves. • Review meeting objectives.	Facilitator
0:10 10 min	**Review Work to Date** • Review work to date, including: o Summary matrix and prioritization of climate impacts on project (Meeting #1 outcomes) o Site mapping of key climate impacts (Meeting #2 outcomes) o Adaptive capacity table (Meeting #3 outcomes) • Additional topics, questions, and brief discussion?	Facilitator
0:20 50 min	**Discussion: Review Climate Change Vulnerability Ratings** • Using the approach documented in section 5.1, please review and discuss vulnerability ratings of each climate impact. Questions to consider can include:	Group discussion

	o Does this vulnerability rating make sense for this project element? If not, how should the vulnerability rating be adjusted? o Are there any site-specific climate change impact considerations that may alter the vulnerability rating? • Confirm or revise vulnerability ratings based on discussion	
1:10 10 min	**Priorities and Next Steps** • Review the results of today's discussion, specifically: o Site-specific climate change impacts documented on project map(s) • Review upcoming meetings and their objectives. This will help frame each meeting within the overall CCVA timeline. o **Meeting 5:** Sound Transit Sustainability Staff work with Operations and Engineering staff to undertake a climate risk analysis for the project and identify feasible climate change adaptation options.	Facilitator

Key outcomes and decisions:

The following items should be the key outcomes that emerge from Meeting #4:

- Climate change vulnerability rating for each project element (see the blank table in Appendix C as a template for this discussion).

Parking lot:

Please use this section for additional questions that emerge but are unable to be answered due to timing or expertise limitations. The CCVA team – most likely the project manager(s) and consultant team – will follow-up on these parking lot items before the next meeting.

Meeting Agenda #5

Anticipated meeting time: 2 hours (*this meeting can be broken into two separate 1-hour meetings*)

Meeting objectives:

- Determine risk tolerance for Sound Transit Project elements based off of final climate vulnerability ratings (refer to section 5.1).
- Identify a final list of adaptation options to integrate into Design phase of the project (refer to section 5.2).

Review in advance of meeting:

- Final summary matrix of climate impacts, WSBLE elements, adaptive capacity, and vulnerability ratings (use blank table in Appendix C as a template for this discussion). Please pay particular attention to the adaptive capacity considerations.

Participants

☐ Project Manager(s) ☐ Segment Lead(s) ☐ Environmental Staff ☐ Sustainability Staff ☐ Engineer Lead(s) ☐ Engineer / Systems Staff ☐ Utility / Hydrology Staff ☐ Operations Director for project ☐ Light Rail Operations Staff ☐ Consultant Team	*Optional:* ☐ Additional Relevant Staff	Facilitator: Note Taker:	*TBD* *TBD*

Time:	Agenda item and description:	Lead:
0:00 10 min	**Welcome and Introductions** • Use this time for project team members to introduce themselves. • Review meeting objectives.	Facilitator
0:10 10 min	**Review Work to Date** • Review work to date, including: o Summary matrix and prioritization of climate impacts on project (Meeting #1 outcomes) o Site mapping of key climate impacts (Meeting #2 outcomes) o Adaptive capacity table (Meeting #3 outcomes) o Final climate vulnerability ratings (Meeting #4 outcomes) • Additional topics, questions, and brief discussion?	Facilitator

0:20
45 min
	Discussion: Engineering and Design Adaptation Options
	(If needed, this section can be a stand-along meeting with Operations staff)
	• Using the final climate change vulnerability matrix (see Appendix C for a blank matrix template), use the following discussion questions to review and identify feasible adaptation options.
	  o Has Sound Transit experienced these impacts before? If so, how have they been addressed in Design & Engineering?
	    ▪ What is already in the DCM version 5? What can be added for future DCM versions? (E.g., base temperature, stormwater sizing, etc.).
	    ▪ Are these DCM updates sufficient? What are additional gaps or concerns?
	  o What practices has Sound Transit already adopted to prepare for and respond to climate change impacts?
	  o What changes are planned or under consideration?
	  o What else is needed to reduce climate change problems?
	    ▪ What can be prevented in design/engineering?
	    ▪ What can be avoided or managed in operations?
	    ▪ What level or risk or impacts is tolerable?
	  o What adaptation options are not feasible? Why?
		Group discussion

1:10
45 min
	Discussion: Operations and Experience Adaptation Options
	(If needed, this section can be a stand-along meeting with Engineering staff)
	• Using the final climate change vulnerability matrix (see Appendix C for a blank matrix template), use the following discussion questions to review and identify feasible adaptation options.
	  o Has Sound Transit experienced these impacts before? If so, how have they been addressed in Operations?
	    ▪ Standard operation procedures vs. ad-hoc responses?
	    ▪ Prevention and avoidance vs. responding to events?
	  o What else could Operations staff do or implement to address key climate change impacts? What changes in planning or design would help?
	  o What practices has Sound Transit already adopted to prepare for and respond to climate change impacts?
	  o What changes are planned or under consideration?
	  o What else is needed to reduce climate change problems?
	    ▪ What can be prevented in design/engineering?
	    ▪ What can be avoided or managed in operations?
		Group discussion

	▪ What level or risk or impacts is tolerable? o What adaptation options are not feasible? Why?	
1:50 10 min	**Next Steps** • Identify how the final list of climate change adaptation options will be integrated into the planning and design phases. • Opportunities to utilize or update the CCVA. Updating the CCVA can be dependent on: o Future project phases that require a new or updated CCVA. o Emerging issues that were unanticipated during the initial CCVA process. o Publication of new research, best practices, or resources.	Facilitator

Key outcomes and decisions:

The following items should be the key outcomes that emerge from Meeting #5:

- Final list of adaptation options to include into the Planning and Design phases of the Sound Transit project (refer to section 5.2).

Parking lot:

Please use this section for additional questions that emerge but are unable to be answered due to timing or expertise limitations. The CCVA team – most likely the project manager(s) and consultant team – will follow-up on these parking lot items before the next meeting.

APPENDIX C: CLIMATE CHANGE VULNERABILITY MATRIX

Climate Change Vulnerability Matrix Template

The table below provides a template for the CCVA Team to conduct a detailed summary of key climate impacts and adaptation options. Climate change impacts have already been ranked as minor (green), moderate (yellow), and major (orange) based off the WSBLE Climate Vulnerability Assessment. These categorizations should be used as the jumping off point for the CCVA team and can be modified based on specific projects and routes.

Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Rail/Track	**Extreme heat impacts**				
	SLR + Heavy Rains + Hydrological Impacts				
	Mudslides and landslides				
Overhead Catenary System (OCS)	**Extreme heat impacts**				
	Extreme winter storms:				
Electrical Equipment & TPSS	**Extreme heat impacts:**				
	Brownouts				
	Flooding impacts				

Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Tunnels	**Flooding and Groundwater Seepage**				
	Heavy Rains and Extreme Events				
Bridges & Elevated Structures	**Extreme heat impacts**				
	Flooding Impacts				
	Extreme winter storms				
Rail Service Operations *(cross-cutting)*	**Extreme heat impacts**				
	Flooding impacts				
	Mudslides and landslides				
Customer Experience *(cross-cutting)*	**Heavy rains, storms, and flooding**				
	Extreme heat impacts				
Construction *(cross-cutting)*	**Heat impacts**				
	Flooding				

WSBLE Climate Change Vulnerability Matrix

The table below provides the detailed summary of the WSBLE Climate Matrix. This is for reference to help the CCVA Team fill out their own detailed summary matrix.

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Rail/Track	**Extreme heat impacts**: • Rail buckling. • Fatigue cracking. • Pavement rutting. • Switch failures.	• Map current heat island effects to identify potential trouble spots and site tracks away from these areas. • Site in shaded areas to reduce heat impacts.	• Install sensors to detect high track temperatures in at-risk areas. • Use rail expansion joints to relieve heat stress. • Update DCM to reflect appropriate temperature range. • Use heat resistant materials that are less prone to rail buckling.	• Slow rail traffic during hours or days of extreme heat. • Increase visual monitoring of tracks and issue heat advisories. • Run garden hose to cool switches during hot days. • Adjust temperature monitoring thresholds or policies to pre-empt rail buckling. • Deploy staff during extreme heat events to identify and mitigate emerging issues.	**Low**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
	SLR + Heavy Rains + Hydrological Impacts: • Flooding and corrosion of infrastructure and damage to rail corridors	• Ensure top rail elevation is above 500-year floodplain and 3 feet above 100-year floodplain levels. • Relocate ground-level and underground equipment and structures.	• Partner with jurisdictions on design standards and stormwater management. • Sizing drains on elevated structures to accommodate future flows. • Adhere to design criteria (e.g., not placing tracks at lowest point) to minimize flooding issues. • Design for more severe flooding scenarios, such as designing for the 100-year flood plus 3 additional feet or using the 500-year floodplain as a baseline.	• Increase visual monitoring of riverbanks, bridge supports, and infrastructure. • Maintain infrastructure and equipment with drainage problems. • Adjust policies related to rainfall, wind speed, etc. for when to begin monitoring for rail damage (e.g., extremes in the future will change thresholds, but systems are in place). • Utilize pumps to mitigate flooding issues.	**Moderate**
	Mudslides and landslides: • Damage to rail infrastructure at specific sites (e.g., Pigeon Point, Queen Anne)	• Locate tunnel portals away from slide-prone areas. • Explore different siting options. For example, consider risks to at-grade options in West Seattle/Pigeon Point.	• Make slope stability improvements as part of project. • Build walls around column to protect it from slides. • Control groundwater to manage slope stability. • Build retaining walls. • Install slope underdrain to prevent chance of mudslide. • Adopt seismic standards for construction to prepare for erosion impacts and lateral forces. • Design columns of elevated structures for sufficient lateral impact.	• Install CCTV around Pigeon Point and Queen Anne to monitor that there is no mud on rail. For example, Sounder operations and USGS program monitor slope conditions and environmental events.	**Low**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Overhead Catenary System (OCS)	**Extreme heat impacts on:** • Excessive line and wire sags • Possible power loss during extreme heat	• Consider where the most likely locations are to have wire sagging and line impacts and install sensors to monitor. • Map current heat island effects to identify potential trouble spots. • Provide shading to reduce heat impacts.	• Consider OCS design and assumptions using the DCM earlier in the process, such as OCS lifespan and length. Typically, the OCS design comes later in the process civil engineering design. • Use more robust foundations to support higher loading and tension from extreme heat. • Change midpoint for weights and install longer guide rods in auto-tension systems to compensate for line sag from extreme temperatures. • Coordinate new OCS infrastructure with existing OCS structure system.	• Regularly maintain OCS. • Raise set point for a fixed termination system, re-tension for a higher average temp. • Increase visual monitoring of OCS. • Implement slow orders or halt service until lines are re-tensioned.	**Low**
	Extreme winter storms: • Repeated snow and ice could impair OCS functionality	—	• Consider changes to OCS requirements for future projects.	• Run ice trains with heated pantographs to melt ice on power lines. • Regularly monitor OCS and issue slow orders during extreme winter storms.	**Low**
Electrical Equipment & TPSS	**Extreme heat impacts:** • Overheating electrical equipment delays or disrupts service.	• Increase shading around equipment. • Provide redundancy in TPSS infrastructure – especially	• Continue to require HVAC for all signal bungalows. • Update design criteria that allow for natural ventilation and air flow, particularly around signal boxes.	• Provide regular maintenance checks—especially for vulnerable TPSS locations.	**Low**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
	Brownouts: • Electricity and power demand during summer months can lead to brownouts.	—	• Work with Seattle City Light to install a dedicated SCL line for Sound Transit to meet system power demand during summer months and brownouts. • Investigate the role of wayside power systems. • Install solar panels on top of TPSS.	—	**Low**
	Flooding impacts: • Damage to TPSS in flood-prone areas (e.g., flood risk zones, areas with limited drainage capacity).	• Locate or relocate TPSS and other sensitive equipment above or away from flood-prone areas (e.g., don't place TPSS in tunnels or underground). • Site TPSS and construct them above the floodplain elevation.	• Partner with City of Seattle and Port on reducing flood and erosion risks. • Raise ground-level and underground equipment (i.e., elevate "housekeeping pad") to avoid flooding. • Design grading around TPSS to slope away from the TPSS. • Consider drainage and rain screens around elevators and escalators to avoid damage and service interruptions.	• Inspect and monitor equipment in flood-prone areas more frequently. • Ensure that pumps and drains are working properly to mitigate flooding events. • Ensure that there is easy access to TPSS and heavy equipment for ongoing maintenance.	**Moderate**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Tunnels	**Flooding and Groundwater Seepage:** • Groundwater seepage leading to odor issues and higher maintenance.	• Build outside of hazard-prone areas.	• Design standards avoid direct soil contact, which should help prevent odor. • Design tunnel portals and vent shafts to prevent water intrusion. • Create compartments that can serve as temporary flood barriers where tunnels run under water bodies. • Work with SR-99 tunnel design staff to learn what they did to incorporate SLR and flooding considerations.	• Conduct routine preventative maintenance of drains and sump pumps, such as cleaning and inspections, to ensure they are working and prevent future issues.	**Moderate**
	Heavy Rains and Extreme Events: • Increased risk of extreme flooding. • Low risk of catastrophic events—such as earthquakes, tsunamis, dam failures, or flash floods.	• Consider locations of portals, station entrances, at-grade ventilation systems like grates in the street to protect from water entry.	• Install floodgates at tunnel portals. • Install pumps in tunnel. • Continue to design for the 100-year storm event for tunnels (e.g., site station entranced above the floodplain, provide watertight conduit and pipes, provide watertight doors on station entrances and underground connections). • Consider facility lifespan when designing and installing pumps. • Size drains sufficiently to handle flows.	• Plan for pump failures by installing back-up pump failures. Continue to monitor and maintain pumps so they function during critical events.	**Low to Moderate, depending on location**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Bridges & Elevated Structures	**Extreme heat impacts:** • Malfunction of expansion joints for moveable bridges. • Increased creep rate.	• Map current urban heat islands to identify vulnerable spots. • Reduce, modify, or relocate new development away from vulnerable regions.	• See **Rail & Track** Extreme Heat Adaptive Capacity Options if rail structures are on elevated structures. • Install special monitoring equipment to protect and monitor moveable bridge parts, including seismic monitoring equipment. • Use more robust and heat-resilient components, even nuts and bolts. Mechanical and electrical systems often use off-the-shelf products that meet specs, not a custom design. Are those products designed for sufficient heat impacts? • Learn adaptation option from other transit systems in AZ, TX, NM.	• Spray water on moveable bridges during heat events. However, this might impact service.	**Low**
	Flooding Impacts: • Drainage capacity and hydrostatic pressure build-up behind bridge abutments. • Accelerated rates of bridge corrosion and scour.	• Reduce, modify, or relocate new development away from vulnerable regions.	• Integrate increased potential for damage under extreme hydraulic loads into design and management procedures. • Elevate bridges that are vulnerable to deck unseating (unlikely to be an issue given high planned bridge heights).	• Reduce scour damage through armoring or measures such as riprap, collars, and scour-monitoring devices.	**Low**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
	Extreme winter storms: • Ice impacts on elevated guideways. • Pipes/standpipes on elevated guideways exposed to freezing temperatures.	—	• Consider types of wind screens and walkway types used elsewhere that don't allow ice to build up. Learn from other transit agencies in cold geographies, such as Minnesota.	—	**Low**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Rail Service Operations (cross-cutting)	**Extreme heat impacts on:** • Disruption of service due to extreme heat and increased energy demands.	• See **Rail & Track** Extreme Heat Adaptive Capacity Options.	• See **Rail & Track** Extreme Heat Adaptive Capacity Options.	• See **Rail & Track** Extreme Heat Adaptive Capacity Options.	**Low**
	Flooding impacts: • Disruption of service due to flooding issues. • Limits access to hi-rail vehicle entry points on guideway for regular maintenance or emergency services.	• See **Rail & Track** SLR + Heavy Rains + Hydrological Impacts Adaptive Capacity Options.	• See **Rail & Track** SLR + Heavy Rains + Hydrological Impacts Adaptive Capacity Options.	• See **Rail & Track** SLR + Heavy Rains + Hydrological Impacts Adaptive Capacity Options.	**Moderate**
	Mudslides and landslides: • Disruption of service at vulnerable locations.	• Locate tracks away from slopes.	• Contain and divert moving debris using walls, berms, ditches, and catchment basins. • Stabilize and grade unstable slopes to lower gradients, construct buttresses or retaining walls, improve drainage systems.	• Continue to contract with Community Transit, KC Metro, Pierce Transit, and Starline Luxury Coaches to provide coach service when mudslides affect rail service (Sounder).	**Low**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Customer Experience (cross-cutting)	**Heavy rains, storms, and flooding:** • Impede customer access and experience, especially at elevated stations. • Elevators, escalators, and other facility equipment may be damaged.	—	• Consider heat impacts and HVAC needs when enclosing elevators and escalators in glass boxes. • Provide canopy coverage from rain and accordingly update the DCM. Current DCM requires 65% roof coverage; Seattle Municipal Code require 100% coverage. • Provide full continuous canopy coverage from station entrance to train cars. • Size canopy drainage in response to climate change. • Caulking glazing panels and roof and envelope details can mitigate leakage into hoistways. • Provide wind protection at elevated stations. • Install louvers, which can prevent water inside hoistway, vertical conveyance equipment, and in the station. However, they do not always protect against wind-driven rain and water leaks.	• Regular maintenance and detailing to prevent water leaks.	**Low**

<table>
<tr><th rowspan="2">WSBLE Project Elements & Effects</th><th rowspan="2">Climate Change Impacts</th><th colspan="3">Adaptive Capacity Options</th><th rowspan="2">Vulnerability Draft Rating</th></tr>
<tr><th>Siting/Location</th><th>Design</th><th>Operations</th></tr>
<tr><td></td><td>Extreme heat impacts:
• Service interruptions of vertical circulation equipment
• Overheating or heat exhaustion</td><td>—</td><td>• Installing durable elevator cab fans.
• Mount AC split units in areas away from direct sun exposure.
• Use opaque or lighter designs and panels.
• Continue to use oil coolers.
• Retrofit older light rail vehicles (LRVs) with HVAC systems and implement requirements for HVAC units in new LRVs.</td><td>—</td><td>Low</td></tr>
</table>

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Construction (cross-cutting)	**Heat impacts on:** • Concrete during construction. • Construction workers and overheating.	• Site construction sites with adequate shade.	• Build temporary canopies to provide shade to construction workers.	• Provide cooling options—such as iced water—during extreme heat days.	**Low**
	Flooding: • Nearby construction redirecting water flow onto guideway, causing issues with signaling. • Retaining wall construction, excavation – cover in **Construction Risks** section of the project.	—	• Ensure that planning for construction risks includes considerations for more extreme weather and potential flooding. • Create water and rain diversions to divert water flow away from key construction sites.	—	**Low**

APPENDIX D: GIS MAPPING AND LAYERS

The maps below show how key climate impacts affect the project area and boundaries.

Figure 6: Climate Change Impacts within Half Mile Buffer or Design Centerlines

Figure 7: Climate Change Impacts in Duwamish and West Seattle

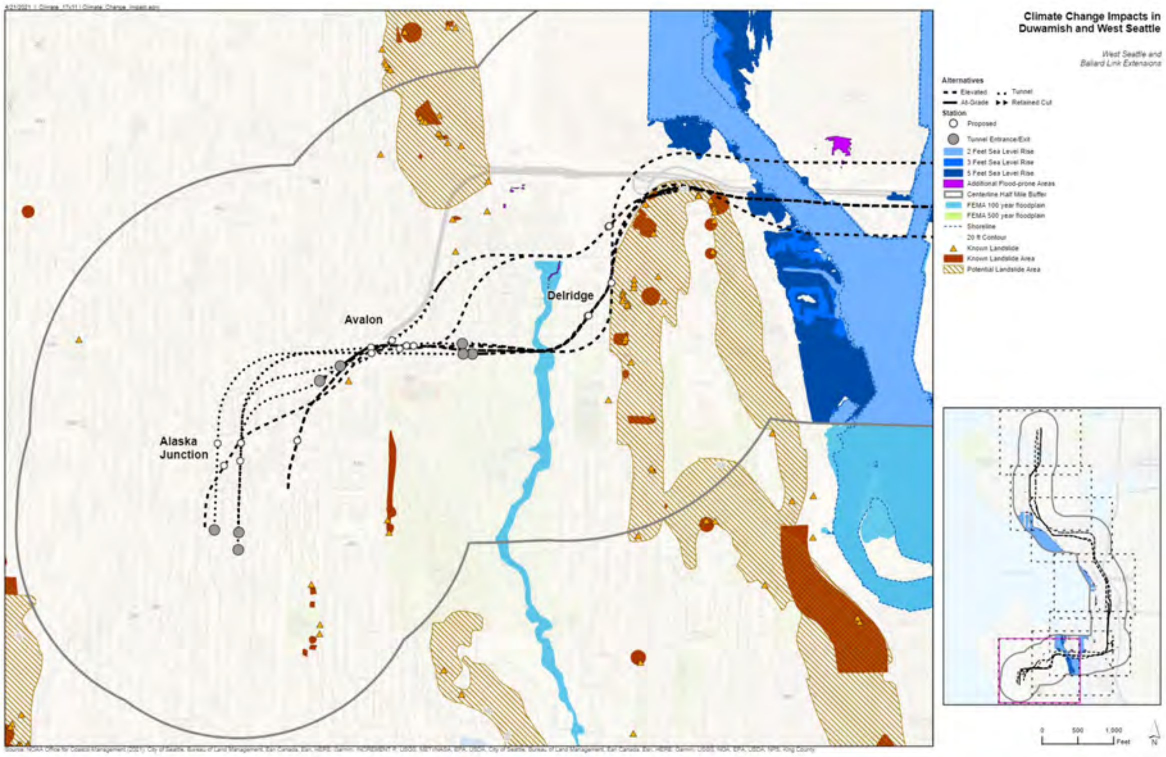


Figure 8: Climate Change in Duwamish Crossing

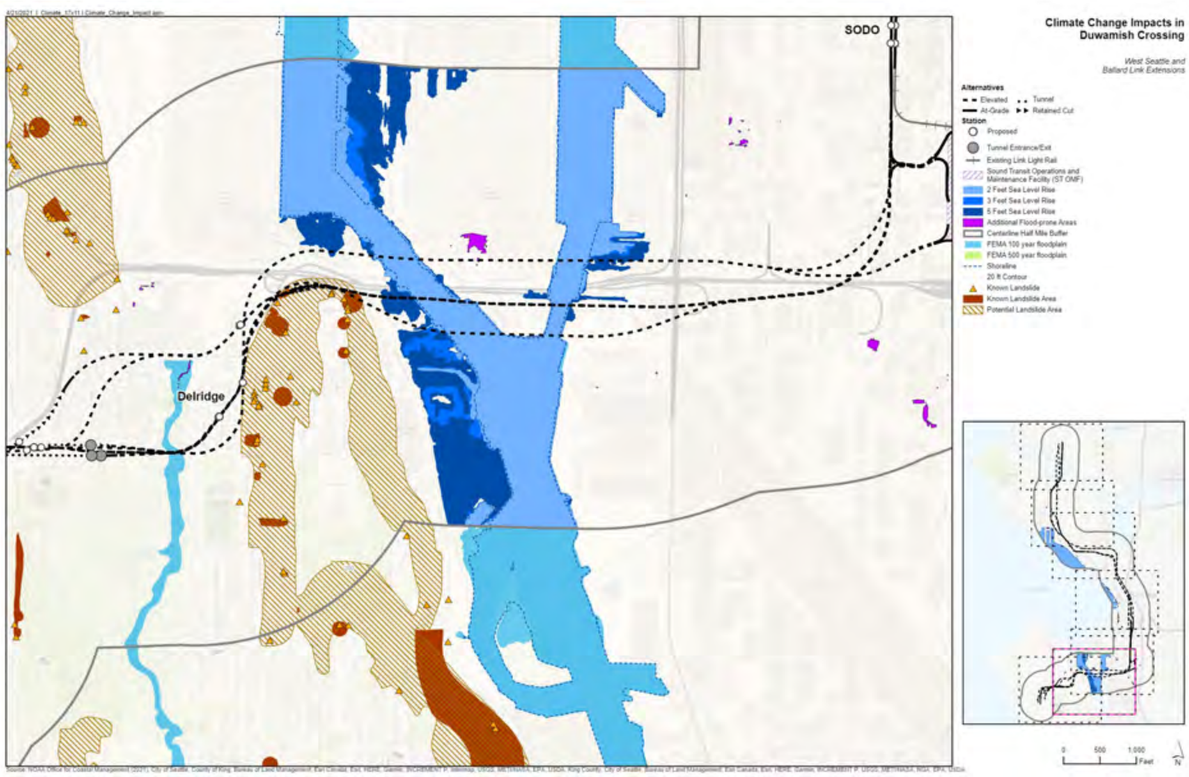


Figure 9: Climate Change Impacts in Duwamish and West Seattle

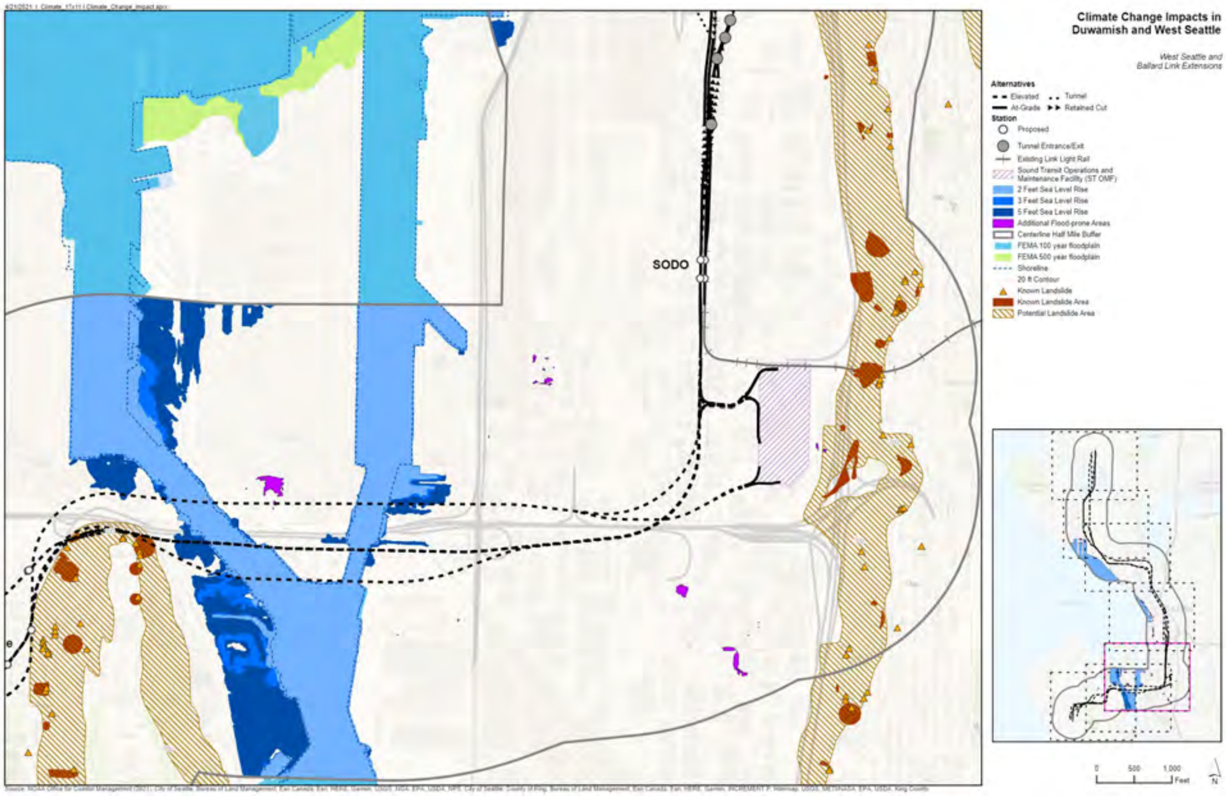


Figure 10: Climate Change Impacts in International District and SODO

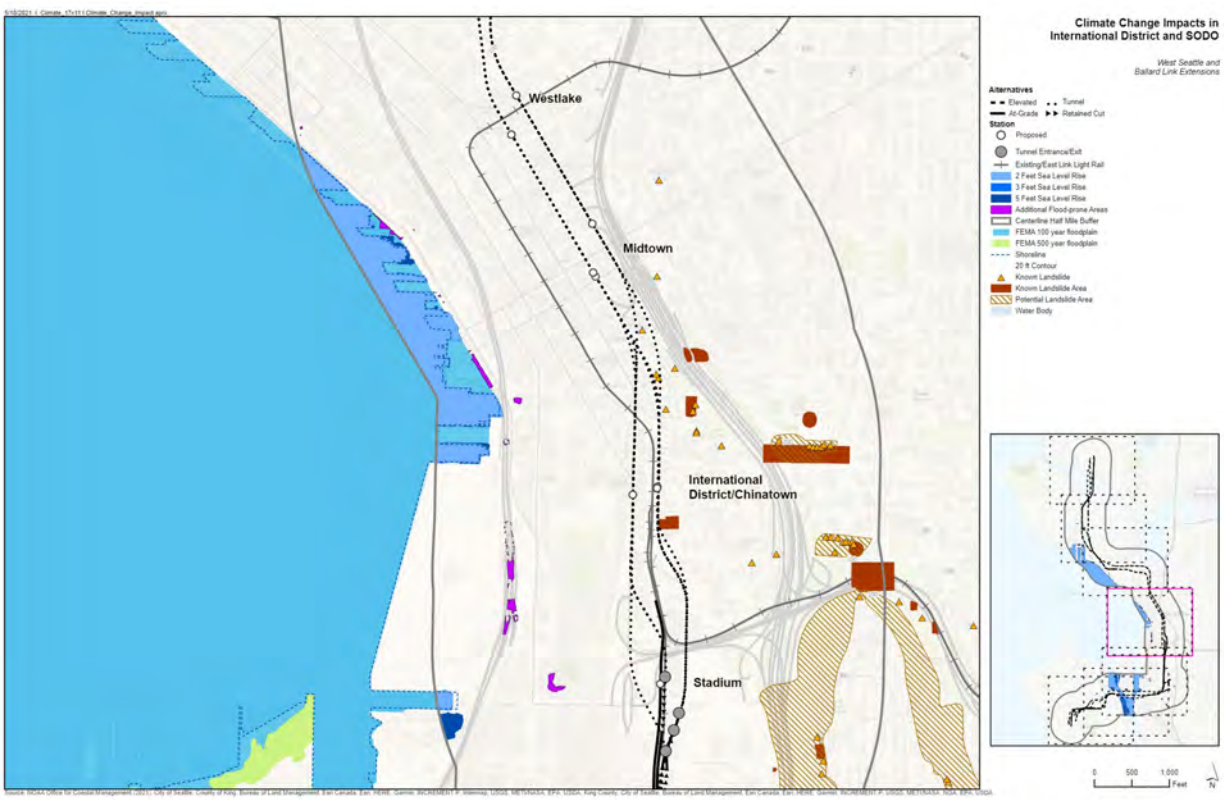


Figure 11: Climate Change Impacts in Downtown and South Interbay

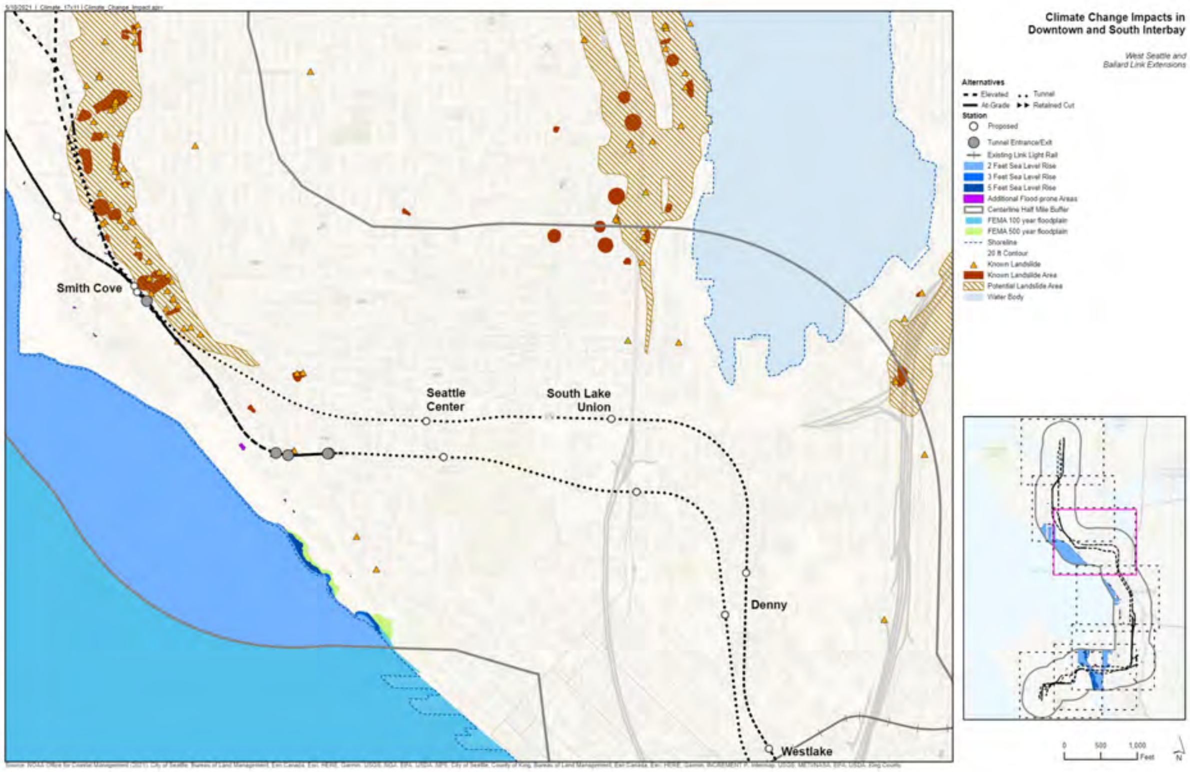


Figure 12: Climate Impacts in Ballard and South Interbay

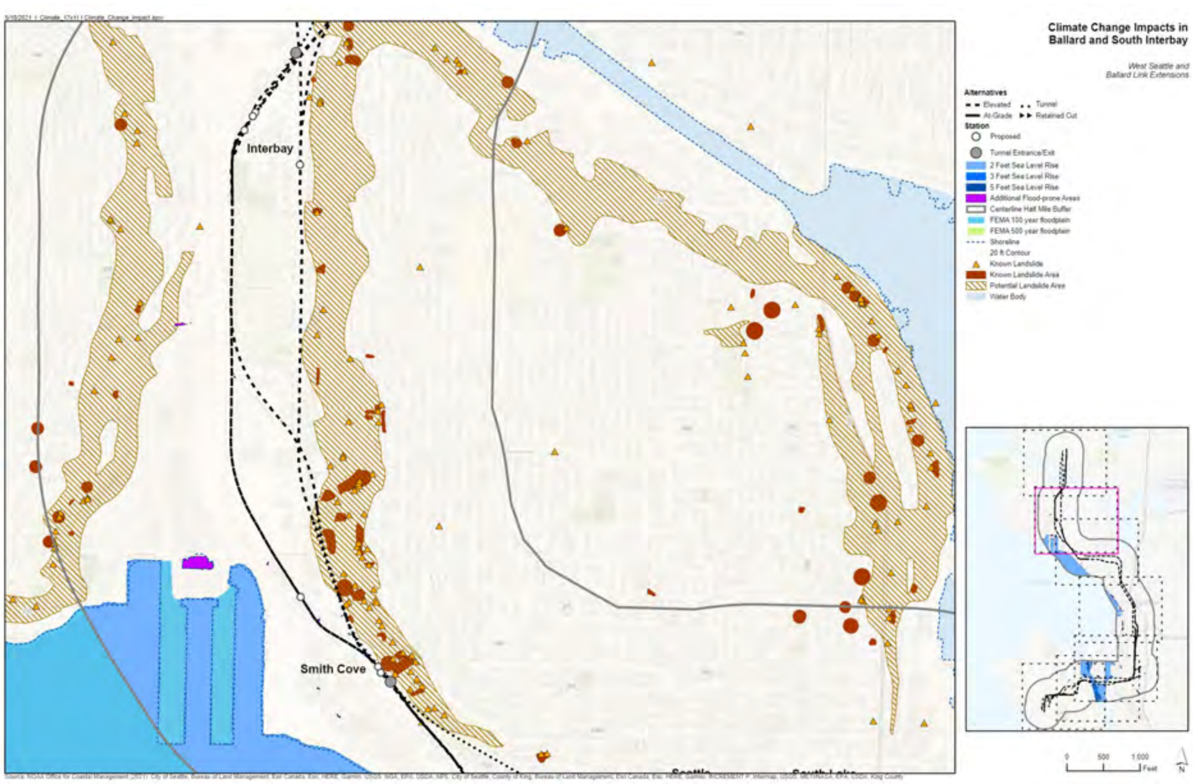
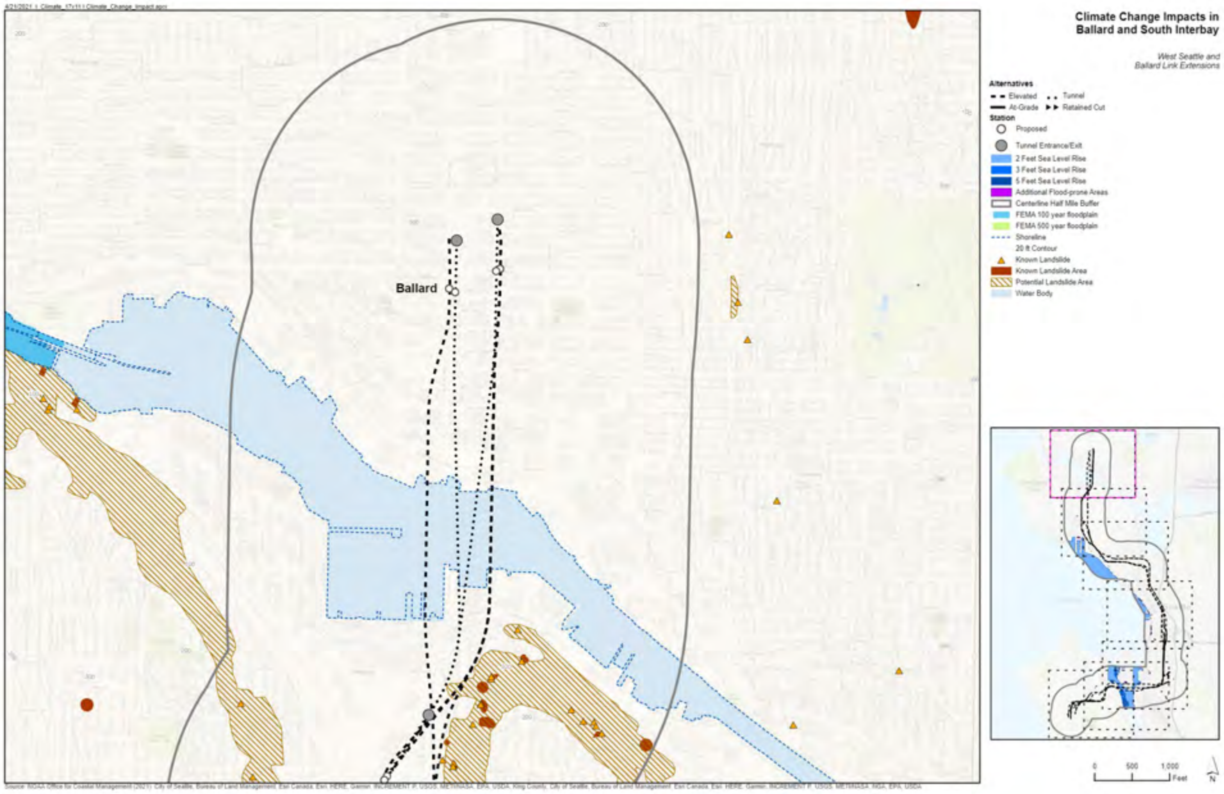


Figure 13: Climate Change in Ballard and South Interbay



APPENDIX E: RESOURCES AND REFERENCES

Transportation – Impacts, Risks and Adaptation in the United States: Fourth National Climate Assessment, Volume II

This national assessment of climate impacts on transportation infrastructure across the United States provides helpful contexts, resources, and approaches to understanding and addressing climate impacts on transportation infrastructure.

Jacobs, J.M., M. Culp, L. Cattaneo, P. Chinowsky, A. Choate, S. DesRoches, S. Douglass, and R. Miller, 2018: Transportation. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 479–511. doi: 10.7930/NCA4.2018.CH12 https://nca2018.globalchange.gov/chapter/transportation.

Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance

This guide is published by the U.S. Department of Transportation Federal Highway Administration has information and resources to help transportation agencies understand climate risks and identify actions to address those risks.

Asam, S., C. Bhat, B. Dix, J. Bauer, D. Gopalakrishna. 2015. Climate change adaptation guide for transportation systems management, operations, and maintenance. United States Department of Transportation Federal Highway Administration. https://ops.fhwa.dot.gov/publications/fhwahop15026/fhwahop15026.pdf

Technical Guidance: Quantifying Climate Change Impacts

This guide published by the University of Washington Climate Impacts Group shares resources and strategies for quantifying sensitivity and exposure, as well as managing uncertainty when assessing climate impacts. It also includes helpful definitions and information about where and how to access climate change datasets.

Rogers, M. and G. Mauger. 2021. Technical Guidance: Quantifying climate change impacts. University of Washington Climate Impacts Group. https://cig.uw.edu/projects/supporting-climate-resilient-floodplain-management-in-whatcom-and-snohomish-counties

Climate Change and Extreme Weather Adaptation Options for Transportation Assets in the Bay Area Pilot Project

This report produced by the Metropolitan Transportation Commission, San Francisco Bay Conservation and Development Commission, California Department of Transportation, and Bay Area Rapid Transit includes an overview of climate and extreme weather vulnerability and risk for Alameda County, California. It includes sea level rise and storm event exposure, and other impacts and adaptation actions for transportation assets.

http://files.mtc.ca.gov/pdf/MTC_ClmteChng_ExtrmWthr_Adtpn_Report_Final.pdf

Resilience Strategies for Critical Infrastructures and their Interdependencies

This report presents an overview of climate vulnerabilities on critical infrastructure in New York using literature review, previous reports, and expert and stakeholder input.

Zimmerman, R., Foster, S., González, J. E., Jacob, K., Kunreuther, H., Petkova, E. P., & Tollerson, E. (2019, March 15). New York City Panel on Climate Change 2019 Report Chapter 7: Resilience Strategies for Critical Infrastructures and Their Interdependencies. *Annals of the New York Academy of Sciences*. Retrieved from https://www.researchgate.net/publication/331796136_New_York_City_Panel_on_Climate_Change_2019_Report_Chapter_7_Resilience_Strategies_for_Critical_Infrastructures_and_Their_Interdependencies

Climate Impacts and the Safety and Performance of Bridges

A synthesis of 190 research articles to identify the risks that climate change may have on bridges. Mor than 30 climate risks are identified and can be used to help bridge managers prioritize climate resilience actions.

Nasr, A., Björnsson, I., Honfi, D., Ivanov, O. L., Johansson, J., & Kjellström, E. (2019). A review of the potential impacts of climate change on the safety and performance of bridges. *Structure and Infrastructure Engineering*, 738-749. https://www.tandfonline.com/doi/full/10.1080/23789689.2019.1593003

Projected Sea Level Rise for Washington State

Report with information and updated sea level rise projections for Washington State. It includes updated science since previous projections, community-scale projections for 171 locations, and probabilistic likelihoods for a given greenhouse gas scenario.

Miller, I. M., Morgan, H., Mauger, G., Newton, T., Weldon, R., Schmidt, D., . . . Grossman, E. (2018). *Projected Sea Level Rise for Washington State – A 2018 Assessment.* Washington Sea Grant, University of Washington Climate Impacts Group, University of Oregon,. Seattle, WA: Washington Coastal Resiliency Project. https://cig.uw.edu/wp-content/uploads/sites/2/2019/07/SLR-Report-Miller-et-al-2018-updated-07_2019.pdf

APPENDIX F: WEST SEATTLE-BALLARD LINK EXTENSION, CLIMATE CHANGE VULNERABILITY ASSESSMENT

The full white paper memo that outlines the WSBLE CCVA is attached in the PDF following this page.

West Seattle and Ballard
Link Extensions

Climate Change Vulnerability Assessment for WSBLE Project:
Amended White Paper

October 2021

SoundTransit

Revision History

Version	Title	Date	Notes
1	Climate Change Vulnerability Assessment for WSBLE Project: *Over-the-Shoulder Review DRAFT*	03/24/21	Initial draft for over-the-shoulder review and workshop discussion
2	*Amended Outline*	06/23/21	Amended the draft into a new outline form to accommodate revision requests.

Summary

Purpose

This report identifies projected climate change impacts that may create infrastructure, access, or operational vulnerabilities for the West Seattle and Ballard Link Light Rail Extensions (WSBLE) Project.

Background

The climate in western Washington has been rapidly changing since the 1900s—with warmer air temperatures, reduced mountain snowpack, sea level rise, winter storms, and changing water availability. Climate change in the region will continue to affect infrastructure, including the WSBLE Project, over the next century and beyond.

Approach

This report updates Sound Transit's 2013 *Climate Risk Reduction Project* with new research from the scientific literature, other agencies, and Sound Transit's experience.

Conclusions

Climate change impacts may affect multiple elements of the WSBLE Project, including rail/track, the overhead catenary system and other electrical equipment, tunnels, bridges, and operations, as identified in this report. While climate impacts may affect different parts of the system, they should not be considered in a vacuum. The potential of cascading and compounding impacts should be considered, as a series of low to moderate effects can combine to produce major climate-related impacts. By assessing climate-related impacts and vulnerabilities in the project planning stages, Sound Transit can prepare for them and include adaptation measures to support resilient infrastructure and operations over the next century.

Table of Contents

Figures

Tables

Acronyms and Abbreviations

CIG	Climate Impacts Group (at the University of Washington)
DEIS	Draft Environmental Impact Statement
EIS	Environmental Impact Statement
FTA	Federal Transit Administration
GHG	Greenhouse gas
GIS	Geographic information system
RCP	Representative Concentration Pathway (a GHG emissions scenario)
SDOT	Seattle Department of Transportation
SLR	Sea level rise
SODO	South of Downtown
ST3	Sound Transit 3 Plan
UW	University of Washington
WSBLE	West Seattle and Ballard Link Extensions

1 CLIMATE VULNERABILITY FOR WEST SEATTLE AND BALLARD LINK EXTENSIONS

1.1 Overview

WSBLE Project. Sound Transit is advancing the West Seattle and Ballard Link Extensions (WSBLE) Project to provide fast, reliable light rail connections to dense residential and job centers throughout the region and add a new downtown Seattle light rail tunnel to provide efficient operating capacity for the entire regional system. The West Seattle Extension would operate on a 4.7-mile guideway from downtown Seattle to West Seattle's Alaska Junction neighborhood and include a new fixed-span bridge across the Duwamish Waterway. The Ballard Extension would operate 7.1 miles from downtown Seattle to Ballard's Market Street area and include a new 3.3-mile rail tunnel from the Chinatown/International District to Seattle Center/Uptown. A map of the WSBLE Project study area is shown in **Figure 1-1**.

Climate Change Impacts. The climate in western Washington has been rapidly changing since the 1900s—with warmer air temperatures, reduced mountain snowpack, sea level rise, winter storms, and changing water availability. Climate change in the region will continue to affect infrastructure, including the WSBLE Project, over the next century and beyond. This report updates Sound Transit's 2013 *Climate Risk Reduction Project* with new research from the scientific literature, other agencies, and Sound Transit's experience.

This vulnerability assessment was informed by a series of workshops with Sound Transit staff held over four months. Dates and workshop objectives are listed below.

- **March 26, 2021** – Sound Transit staff identified potential climate impacts to the WSBLE and prioritized these climate impacts.
- **April 21, 2021** – Sound Transit staff mapped out prioritized climate impacts and considerations across the WSBLE alternative routes.
- **May 19, 2021** – Sound Transit staff identified key adaptation considerations and opportunities.
- **June 30, 2021** – Sound Transit staff confirmed the final vulnerability rankings of prioritized climate impacts.

Purpose of this Report. This report identifies projected climate change impacts that may create infrastructure, access, or operational vulnerabilities for the WSBLE Project.

1.2 Summary of Impacts

Potential climate change impacts to the WSBLE Project—including rail/track, overhead catenary system and other electrical equipment, tunnels, bridges, and operations—are identified in **Table 1-1** below and described in this report. While climate impacts may affect different parts of the system, they should not be considered in a vacuum. The potential of cascading and compounding impacts should be considered, as a series of low to moderate effects can combine to produce major climate-related impacts. By assessing climate-related impacts and vulnerabilities in the project planning stages, Sound Transit can prepare for them and include adaptation measures to support resilient infrastructure and operations over the next century.

Table 1-1. Summary of Climate Change Probability and Potential WSBLE Project Impacts

Estimated Impacts on Infrastructure and Operations	Estimated Probability of Climate Change Impacts: Low	Medium	High
Major	• **Cascading and compounding impacts from extreme heat and flooding** across Sound Transit's system could amplify the magnitude and severity of an extreme event (such as earthquake, tsunami, or dam failure) and cause system failures.	• **Increased major flooding risk** due to the confluence of high tide events, sea level rise that exceeds 5.2 feet by 2100 (1% likelihood of exceedance), extreme storms and heavy rainfall event, heavy wind and wave activities, and poor stormwater drainage, particularly in West Seattle and Duwamish Valley areas.	*(No high-probability / high-impact risks identified in this category.)*
Moderate	• Increased activity of **large mudslides and landslides** in the West Seattle, Duwamish Valley, and Queen Anne areas could disrupt Link service. • Regional **energy demand during summer months exceeds energy supply** and could disrupt Link service.	• Increased **flooding risk to rail infrastructure in previously unaffected areas** in West Seattle and Duwamish Valley due to: o River flooding from heavy rainfall. o Coastal flooding from storm surges and sea level rise. o Stormwater-related flooding. • **Increased moderate flooding risk** due to the confluence of high tide events, sea level rise that exceeds 3.1 feet by 2100 (17% likelihood of exceedance), extreme storms and heavy rainfall events, heavy wind and wave activities, and poor stormwater drainage in West Seattle and Duwamish Valley. • **Heat stress on moveable bridges** that causes components of bridge structures to malfunction.	• Increased **flooding risk to rail infrastructure in currently affected areas** in West Seattle and Duwamish Valley due to: o River flooding from heavy rainfall. o Coastal flooding from storm surges and sea level rise. o Stormwater-related flooding.
Minor	• **Flooding risk to rail infrastructure** in multiple areas from stormwater-related flooding. • **Heat stress to the auto-tension overhead catenary system** (OCS). • **Heat stress on air-conditioned electrical equipment.** • **Icing** of the OCS and elevated structures from extreme winter storms.	• Increased **flooding risk to electrical equipment** in West Seattle and Duwamish Valley areas due to: o River flooding from heavy rainfall. o Coastal flooding from storm surges and sea level rise. o Stormwater-related flooding. • Increased **rates of corrosion and wear** for rail/track and bridge infrastructure from more frequent and intense flooding and extreme heat events. • **Tunnel seepage from heavy rainfall events.** • Increased activity of **moderate mudslides and landslides** in the West Seattle, Duwamish Valley, and Queen Anne areas.	• **Heat stress on rail/track infrastructure**, especially ballasted tracks, with potential for rail buckling. • **Heat stress to non-tunnel fixed-termination OCS.** • **Heat stress on naturally ventilated electric equipment.** • Increased activity of **small mudslides and landslides** in the West Seattle, Duwamish Valley, and Queen Anne areas.

In addition to assessing the climate impacts to Sound Transit's Link Extensions, it is important to also consider **adaptive capacity**—or the ability for a system to moderate or cope with change. Climate vulnerability is generally defined as the degree to which a system is susceptible to adverse effects of climate change. Vulnerability can be moderated, or reduced, by adaptive capacity. For example, an elderly person who lives in a densely urbanized area is at high risk from extreme heat events. However, if that elderly person has reliable air conditioning in their housing unit, that person also has a moderate to high adaptive capacity for coping with extreme heat events. Therefore, their overall climate vulnerability to extreme heat events may be considered minor to moderate. For the WSBLE project, there are multiple considerations for adaptive capacity, including the siting and design of specific project elements and operational considerations (e.g., regular maintenance). Considering adaptive capacity of the various systems, **Table 1-2** shows the estimated adaptive capacity and climate vulnerability of elements of the WSBLE Project. The remainder of this chapter explores each of these project elements including opportunities to address vulnerabilities and increase resilience to climate change as well as other natural hazards and human impacts.

Table 1-2. Climate Impacts, Adaptive Capacity, and Vulnerability Summary

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Rail/Track			
Rail buckling, fatigue cracking, pavement rutting, and switch failures	Moderate	Moderate	Low
Flooding	Moderate to Major	Moderate	Moderate
Mudslides and landslides	Minor	Moderate	Low
Overhead Catenary System			
Heat stress	Minor to Moderate	High	Low
Severe winter storms	Very Minor	High	Low
Electrical Equipment			
Heat stress	Minor to Moderate	High	Low
Flooding	Moderate to Major	Moderate	Moderate
Tunnels			
Flooding	Moderate to Major	Moderate	Moderate[a]
Extreme events	Moderate to Major	High	Low
Bridges and Elevated Structures			
Extreme heat and air pollution	Moderate	Moderate	Low
Flooding	Minor	High	Low

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Extreme events and winter storms	Minor	Moderate	Low
Rail Service Operations *(cross-cutting)*			
Extreme heat	Minor	Moderate	Low
Flooding	Moderate	Limited	Moderate
Mudslides and landslides	Minor	Moderate	Low
Customer Experience *(cross-cutting)*			
Heavy rains and storms	Moderate	Moderate	Low
Flooding	Moderate	Moderate	Low
Construction *(cross-cutting)*			
Extreme Heat	Minor	Moderate	Low
Flooding	Moderate	Moderate	Low

[a] Likely low to moderate depending on tunnel location.

*Notes: Impacts were assessed as shown in Error! Reference source not found. and **Table 1-1**.. **Adaptive capacity** was assessed on a limited-moderate-high scale, where high adaptive capacity means that there are both proactive and reactive adaptation options available; moderate means that there are proactive or reactive adaptation options available; and limited means that there is not an adaptation option available. **Vulnerability**, which is measured by considering climate impacts less the adaptive capacity, was categorized in a high-moderate-low scale. High vulnerability means that there is potential for major impacts with low adaptive capacity; moderate vulnerability means that adaptive capacity can ameliorate potential climate impacts, but not completely prepare for or adapt to potential climate impacts; and low vulnerability means that there is sufficient adaptive capacity to reduce potential climate impacts and risk.*

1.3 WSBLE Project Area

Sound Transit is advancing the West Seattle and Ballard Link Extensions (WSBLE) Project to provide fast, reliable light rail connections to dense residential and job centers throughout the region and add a new downtown Seattle light rail tunnel to provide efficient operating capacity for the entire regional system. The West Seattle Extension would operate on a 4.7-mile guideway from downtown Seattle to West Seattle's Alaska Junction neighborhood and include a new fixed-span bridge across the Duwamish Waterway. The Ballard Extension would operate 7.1 miles from downtown Seattle to Ballard's Market Street area and include a new 3.3-mile rail tunnel from Chinatown/International District to Seattle Center/Uptown. A map of the WSBLE Project study area is shown in **Figure 1-1**.

Figure 1-1. West Seattle and Ballard Link Extensions Map

2 CLIMATE CHANGE IMPACTS ON WSBLE PROJECT

The following sections synthesizes the results from the climate vulnerability analysis conducted in conjunction with Sound Transit staff.

2.1 Rail and Track

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Rail/Track			
Rail buckling, fatigue cracking, pavement rutting, and switch failures	Moderate	Moderate	Low
Flooding	Moderate to Major	Moderate	Moderate
Mudslides and Landslides	Low to Moderate	Moderate	Low

2.1.1 Extreme Heat Impacts

Future extreme heat will increase the risk for **rail buckling, fatigue cracking, pavement rutting, and switch failures**. This can lead to service slowdowns, interruptions, increased maintenance costs, costly repairs, and in rare cases, train derailments. This impact was one of the **highest priorities** for Sound Transit staff. Specifically, some climate risk considerations for the WSBLE project include:

- **Ballasted tracks**—typically used for at-grade segments, maintenance yards, or for trackwork where tracks converge, diverge, or cross over—are more sensitive to extreme heat than other track types.
- **Older rail structures** that do not have expansion joints are more vulnerable. For example, in June 2019, an older part of the rail system at 4th Avenue South buckled when temperatures surpassed 90 °F.

In addition to typical adaptation options—such as visual monitoring or slow orders—specific adaptation actions to cope with extreme heat impacts on rail structures for the WSBLE project include:

- Provide **shading** whenever possible to cool tracks.
- Install **sensors** or temperature monitoring equipment.
- **Run water to cool switches** and prevent failure.
- Install **rail expansion joints** to relieve heat stress.
- **Map heat island hotspots** and identify potential solutions for specific areas. King County recently conducted a heat mapping study.

2.1.2 Flooding Risks

Flooding risk will likely increase due to a variety of impacts, including: 1) riverine flooding, 2) stormwater-related flooding, and 3) coastal flooding. The confluence of multiple climate impacts will likely lead to substantial flooding events in the future. Flooding events along rail corridors can **damage rail infrastructure**. Additionally, standing water over rail lines can cause **issues with visual monitoring and signaling**. This impact was one of the **highest priorities** to address by Sound Transit staff. Specifically, some climate risk considerations for the WSBLE project include:

- Areas of flooding risk include:
  - **Low-lying areas near the Duwamish River**, which is particularly high risk for flood damage during extreme rainfall events, high tide events, and future sea level rise.
  - **SODO area** which has a shallow groundwater table that fluctuates with heavy precipitation events and tidal cycles. There is already existing issues with standing water near Holgate crossing at 6th Avenue South.
  - Construction projects in the **International District/Chinatown** area is already diverting water onto existing rail structures. More intense rain events and continued development in the area can cause more frequent flooding events.

In addition to typical adaption options—such as installing water pumps, adhering to Design Criteria Manual stormwater and flood standards, and visual monitoring of the rail corridor—other adaptation actions specific to the WSBLE project include:

- **Site and construct rail infrastructure** so that the top rail elevation is above the 500-year floodplain and 3 feet above 100-year floodplain.
- In addition to water pumps, adding **flood gates** to the tunnel portal can mitigate flood risks.

2.1.3 Landslides and Mudslides

The risk for landslides and mudslides will likely increase in the future due to more intense heavy rain events. Landslides and mudslides can **damage rail infrastructure** and **disrupt rail service**. This impact is a high priority concern for Sound Transit staff. Some WSBLE-specific considerations include:

- Hilly areas—such as **Pigeon Point** and **Queen Anne**—are of particular concern.
- Landslides and mudslides can also lead to **tree debris** falling on the guideway or tunnel portals in areas such as **Delridge** and the **Duwamish crossing**.

Adaptation options for the WSBLE project could include:

- Make **slope stability** improvements in landslide-prone areas.
- **Site key facilities** away from landslide-prone areas.
- Build **walls** around the guideway to protect it from landslides.

- Install **camera monitoring** capabilities along the route known to be more sensitive to landslides.

2.2 Overhead Catenary System

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Overhead Catenary System			
Heat stress	Minor to Moderate	High	Low
Severe winter storms	Very Minor	High	Low

2.2.1 Heat Stress and Extreme Heat Impacts

Extreme heat can cause **excessive line sags** in the overhead catenary system (OCS). This can lead to **slower train speeds** or **power loss** if the train loses contact with the OCS. In severe cases, line sags can cause the **OCS wire to snap** or cause **damage to the pantograph, insulators, and other OCS equipment**. This impact was ranked as a **high priority impact** by Sound Transit staff. Some considerations include:

- **Fixed-termination OCS is more susceptible to heat stress** than auto-tension OCS because the system uses fixed poles or support structures to maintain wire tension at pre-set temperatures.
- Future intense heat waves can put **undue stress on the electricity grid**, leading to a mismatch of energy demand and supply, **potentially leading to power loss**.

Sound Transit already employs many strategies to address heat impacts to the OCS, which include:

- Changing the **midpoint for weights** and installing **longer guide rods** in auto-tension OCS to accommodate a broader temperature range.
- Regularly **maintain** the OCS.
- **Raise the set point** for a fixed-termination OCS.
- Increase **visual monitoring** of the OCS and implement slow orders or halt service as needed to re-tension lines.

In addition to these strategies, implementing WSBLE-specific adaptation options could include:

- Build more **robust foundations** to support higher loading and tension from extreme heat for fixed-termination OCS.
- **Map heat island hotspots** and identify potential solutions for specific areas.

2.2.2 Severe Winter Storms

Though **very unlikely** in the Seattle area, **severe winter storms could also impact OCS through continuous exposure to snow and ice**, which can build up and affect OCS functionality (Rossetti, 2002). For Sound Transit, this risk might be a consideration during La Niña years, or other times when the region experiences abnormal winter storms.

To address potential impacts from severe winter storms, Sound Transit can continue to implement existing strategies to address ice accumulation on the OCS, including:

- Run **ice trains with heated pantographs** to melt ice on OCS lines.
- Increase **visual monitoring** of the OCS and implement slow orders or halt service as needed.

2.3 Electrical Equipment

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Electrical Equipment			
Heat stress	Minor to Moderate	High	Low
Flooding	Moderate to Major	Moderate	Moderate

2.3.1 Heat Stress and Extreme Heat Impacts

Electrical equipment—such as traction power substations (TPSS), signal bungalows, and signal boxes—generates substantial heat from normal operations, which can amplify **ambient heat and future extreme heat stress**. This can lead to **loss of power and traffic signal control** for TPSS, signal bungalows, and small signal boxes, leading to **reduced operating speeds** or **service interruptions**. Despite these risks, Sound Transit is already implementing many strategies for electrical equipment to cope and adapt to future heat stress, including:

- Increase **shading** around electrical equipment.
- Adopt design criteria that allows for **natural ventilation and air flow**.
- Provide **HVAC** for new and existing signal bungalows.

Because of these strategies already addressing heat stress impacts, this was a low priority impact for Sound Transit staff. However, there was one particular concern that also emerged—future climate change may create a mismatch of energy supply and demand, potentially leading to **brownouts**, which can affect rail service. Some adaptation options to proactively address this concern include:

- Work with Seattle City Light to have a **dedicated line** for Sound Transit.

- Utilize **renewable energy** (e.g., solar panels) and place them near TPSS. This could be useful since energy reliability concerns will very likely occur during summer months.

2.3.2 Flooding Risks

Electrical equipment, depending on location, can be **exposed and vulnerable to flooding**. This can **damage electrical equipment**, causing cascading effects for light rail operations. This impact was a high priority impact for Sound Transit staff. Some WSBLE-specific considerations include:

- Electrical equipment near the Duwamish River—the **Boeing Access TPSS** and the **South 133rd Street TPSS**—had already been identified as vulnerable areas to **tidally-influenced flooding**.
- Other locations—such as areas near the **Duwamish River, SODO, and Smith Cove**—had already been identified as flood-prone due from **stormwater-related flooding**.
- Potential siting locations for the WSBLE— **areas near Delridge, Duwamish River, Chinatown/International District, and Ballard**—have been flagged as areas that might be sensitive to stormwater-related flooding.

WSBLE-specific adaptation options could include:

- Site electrical equipment in **elevated locations** (e.g., not in tunnels) or **away from flood-prone areas**.
- Design grading around TPSS to **slope away** to divert water away.

2.4 Tunnels

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Tunnels			
Flooding	Moderate to Major	Moderate	Moderate[a]
Extreme events	Moderate to Major	High	Low[a]

[a] Likely low to moderate depending on tunnel location.

2.4.1 Flooding and Groundwater Seepage

Flooding risk will likely increase in the future, **affecting tunnel systems and groundwater seepage**. This can affect **vertical conveyance equipment** (see 2.8 Customer Experience), cause **odor** issues from groundwater seepage, and require **more maintenance**. This impact was **the highest priority** for Sound Transit staff. Some considerations for the WSBLE project include:

- Various tunnels—such as **Beacon Hill Tunnel** and **Downtown Seattle Transit Tunnel**—already experience flooding and groundwater seepage issues.
- WSBLE route alternatives in the **SODO**, **Stadium**, and **Chinatown/International District** areas were identified as vulnerable to flooding because:
  - For SODO:
    - Rising sea levels may **raise the groundwater table** and **back up a major SPU sewer line** that runs east/west between Puget Sound and Sound Transit's Operations and Maintenance Facility.
    - Additional **copper pollution** and **soil/water contamination** from stormwater runoff.
  - For Stadium and Chinatown/International District:
    - **Existing tunnel drains currently drain to the Stadium District** area, likely leading to more frequent or intense flooding events due to future climate. Change.
    - Existing flooding already in **the BNSF tunnel**.
    - Other construction projects **diverting water**, potentially amplifying climate-related flooding risk.

Sound Transit currently designs for the 100-year storm event for tunnels. Additional adaptation options could include:

- **Site locations** of tunnel portals, station entrances, and at-grade ventilation systems in areas that reduces flood risk.
- Construct **water protection structures** to prevent water entry.
- Install **watertight conduits, pipes, and doors**. Watertight doors—which is used by Taipei Metro—can mitigate flood risk by placing them at station entrances, underground connections, and joint developments.
- **Ensure water pumps function** during critical events and provide **back-up pumps or generators** in case of failure.
- **Design for more severe flooding scenarios,** such as designing for the 100-year flood plus 3 additional feet or using the 500-year floodplain as a baseline.

2.4.2 Extreme Events

There is a very low likelihood of an extreme event—**such as earthquakes, tsunamis, or dam failures**—that could lead to catastrophic flooding damage to tunnels. While not expressly a climate impact, future climate impacts—such as sea level rise and shifting groundwater tables—can create conditions more favorable conditions for liquefaction to happen. Hazard preparedness will ensure that Sound Transit's infrastructure will be resilient to these extreme and rare events.

2.5 Bridges and Elevated Structures

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Bridges and Elevated Structures			
Extreme heat and air pollution	Moderate	Moderate	Low
Flooding	Minor	High	Low
Extreme events and winter storms	Minor	Moderate	Low

2.5.1 Extreme Heat and Ambient Air Pollution

Extreme heat impacts can affect bridges and elevated structures in multiple ways. For moveable bridges, extreme heat can cause expansion joint malfunctions. Additionally, heat stress can increase creep rate. Increased ambient air pollution—which is associated with warmer temperatures—can increase carbonation-induced damage for bridge structures. This impact was a high-priority impact for Sound Transit staff. Some specific WSBLE considerations include:

- Bridges will span the **Duwamish River** and the **Queen Anne/Ballard** crossing.
- Elevated structures are being considered to be used at various segments of the WSBLE, including areas in **West Seattle, SODO, and Queen Anne**.

Some specific WSBLE adaptation options include:

- Install sensors to detect high track temperatures.
- Map current urban heat islands to identify potential vulnerable spots.
- Reduce, modify, or relocate new development in vulnerable areas.
- Use special monitoring equipment to protect the bridge's moving parts—including seismic monitoring equipment.
- Use more robust, heat-resilient components, such as nuts and bolts, that are designed for sufficient heat impacts.

2.5.2 Flooding, Hydrology, and Sea Level Rise

Flooding due to hydrological changes, sea level rise, and extreme rainfall can accelerate bridge corrosion and scour. These coupled impacts can aggravate and weaken bridge foundations and substructural supports, potentially leading to bridge failure or decreased lifespans. Additionally, heavy rain events can overwhelm bridge drainage systems and increase hydrostatic pressure building up behind bridge abutments. Specific WSBLE considerations include:

- The WSBLE bridge that spans the **lower Duwamish River** is particularly at risk due to:
  - Increased exposure to saltwater in the tidally influenced river.
  - Increased rains – especially during winter months – can induce bridge scour.

Some specific adaptation options include:

- Reduce, modify, or relocate new development away from vulnerable regions.
- Integrate increased potential for damage under extreme hydraulic loads into design and management procedures.
- Elevate bridges that are vulnerable to deck unseating – even though it is unlikely due to height of planned bridges.
- Reduce scour damage through armoring or measures such as riprap, collars, and scour monitoring devices.

2.5.3 Extreme Events

Extreme events—such as winter storms, windstorms, and earthquakes—can have a variety of impacts on bridges and elevated structures. While there is some uncertainty in the causal connections between these extreme events and climate change, the interaction of extreme events and future climate conditions can create circumstances that can amplify the magnitude of consequences. Specific examples and considerations for the WSBLE include:

- Freeze and thaw cycles and de-icing salt application can **accelerate bridge deterioration**.
- Climate change can create conditions—such as sea level rise affecting groundwater tables—more favorable for **liquefaction** to happen.
- High winds during extreme storms can **increase wind static loading**, which was a primary reason for the 1940 failure of the Tacoma Narrows Bridge.

2.6 Rail Service Operations

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Rail Service Operations *(cross-cutting)*			
Extreme Heat	Moderate	Moderate	Low
Flooding	Moderate	Limited	Moderate
Mudslides and landslides	Minor to Moderate[a]	Moderate	Low

[a] Likely low to moderate depending on location.

2.6.1 Extreme Heat Impacts

Extreme heat events and heat waves can delay or disrupt WSBLE service operations in multiple ways, including:

- Affecting different WSBLE systems, such as causing:
  - **Rail buckling, fatigue cracking, pavement rutting, and switch failures** for rail and trackways.

  - **Line and wire sags** on the OCS.
  - **Overheated electrical equipment**, such as TPSS and signal bungalows.
  - **Malfunction of expansion joints** for moveable bridges.
- Increasing energy demand and stress during summer months, increasing the likelihood of brown outs and power outages.

2.6.2 Flooding Risks

Future flooding risk will likely increase across the WSBLE project area due to sea level rise, heavy rainfall, and changes in hydrological patterns. Increased flooding risks can disrupt rail service operations in multiple ways, such as causing service delays and disruptions due to flooding on the guideways, tunnels, and equipment. Specific WSBLE considerations include:

- Flooding damage to rail corridors that **impede track visibility**, leading to slow orders or delays.
- Flooding **damage to electrical equipment**, such as TPSS and signal bungalows, in flood-prone areas or areas with limited drainage capacity.
- **Tunnel flooding** due to extreme storms, leading to service delays and disruptions.
- **Inundating hi-rail vehicle entry points** on guideways for regular maintenance or emergency services.

2.6.3 Mudslides and Landslides

Mudslides and landslides will likely increase with increased heavy rainfall frequency and can disrupt rail service operations. Specific considerations for the WSBLE project include:

- Slope failures and landslides are most likely to occur in areas with steep slopes – specifically areas of **West Seattle near the Duwamish River** and the hills adjoining **Interbay**.

However, there are multiple potential adaptation options to mitigate and minimize mudslide and landslide risks to WSBLE project. These options include:

- **Locating tracks away** from steep slopes.
- **Containing and diverting moving debris** using walls, berms, ditches, and catchment basins.
- **Stabilizing slopes** by grading unstable slopes to lower gradients, constructing buttresses or retaining walls, or improving drainage systems.
- Continuing to contract with Community Transit, King County Metro, Pierce Transit, and Starline Luxury Coaches to **provide coach service when mudslides affect rail service**.

Figure 2-1. Map of Known Landslide Locations and Potential Landslide Areas within Half Mile Buffer of Proposed WSBLE Alternatives

Notes: Known and potential landslide areas are identified in the City of Seattle's Critical Areas Ordinance. Please see Appendix TBD for downscaled maps of impacts.

2.7 Customer Experience

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Customer Experience *(cross-cutting)*			
Heavy rains, storms, and flooding	Moderate	Moderate	Low
Extreme heat	Moderate	Moderate	Low

2.7.1 Heavy Rains, Storms, and Flooding

Customer experience will likely be affected with increasing intensity of heavy rain events, storms, and flooding in tunnels and low-elevation stations Specific impacts include:

- **Heavy rains and high winds** negatively affecting customer experience, especially at exposed and/or elevated stations.
- **Service delays** and **trip cancellations** when wind intensity exceeds 55 mph on elevated bridges and crossings, such as the Duwamish River crossing and the Ballard-Queen Anne bridge crossing.
- Floods or standing water can **inhibit customer access** to station entrances and exits.
- Inhibit **function** or **damage vertical conveyance equipment**, such as elevators, escalators, and other facility equipment. This will disproportionately affect people with physical disabilities that prevent them from using alternative options, such as stairs.

However, potential adaptation options can help mitigate these impacts. These options include:

- Building **canopy coverage** at stations to shield customers from rain.[1]
- Building in **full continuous canopy coverage** from the station entrance to train cars.
- Providing **wind protection** at elevated stations.
- **Regular maintenance and detailing** to prevent water leaks.
- Install **louvers**, which can prevent water inside hoistway, vertical conveyance equipment, and in the station. However, they do not always protect against wind-driven rain and water leaks.

2.7.2 Extreme Heat Impacts

Extreme heat can affect customer experience in multiple ways. In June 2021, the Northwest region—including the Puget Sound region and the Greater Seattle Metropolitan Area—experienced multiple consecutive days of extreme heat, with temperatures in the Greater Seattle Area reaching multiple consecutive days with temperatures over 100°F. Specific extreme heat impacts on customer service and experience include:

[1] Current DCM is 65% roof coverage; Seattle Municipal Code requires 100% coverage. Sound Transit is currently in discussion on how to address these updates in the DCM.

- **Elevator belts slipping due to overheated o**il, leading to difficulty in levelling units.
- **Overheated escalators**, leading to unplanned shut offs.
- **Overheated hoistways**, leading to delays and malfunctions of elevators.

Some adaptation options include:

- Continue using **oil coolers**.
- **Avoid direct sunlight** on aluminum threshold plates on escalators.
- **Utilize fans or AC** to cool hoistways.

2.8 Construction

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Construction *(cross-cutting)*			
Extreme Heat	Minor	Moderate	Low
Flooding	Moderate	Moderate	Low

2.8.1 Heat Impacts

With more frequent and more intense extreme heat events, there are multiple construction-related impacts that can happen. These include:

- Heat impacts on concrete—such as **distress, rutting, or cracking**—early on in its lifespan that can lead to worsening conditions and other subsequent impacts (e.g., flooding leakage into facilities through cracks).
- **Labor-related extreme heat considerations** for outdoor construction laborers, especially during summer months.

Siting construction sites with **adequate shade** can prevent heat impacts on concrete and provide cooling options for workers. Additionally, **providing additional cooling options**—such as iced water—during extreme heat days can mitigate overheating and heat exhaustion.

2.8.2 Flooding Impacts

While flooding risk will increase in the future, WSBLE construction as well as other non-WSBLE construction projects around the WSBLE project and Sound Transit sites, can amplify flooding risk. For example, other nearby construction project can redirect water onto the WSBLE tracks, causing issues with **signaling** and **damaging rail infrastructure**. One adaptation option available to Sound Transit is to **ensure that construction risks are included and integrated in the WSBLE project plan** to ensure that there are contingency plans to avoid or mitigate flooding risk during heavy rainfall events.

Appendix A: Overview of Climate Change Impacts and Projections

3 CLIMATE CHANGE IN THE PUGET SOUND REGION

The climate of western Washington has been rapidly changing since the 1900s—with warmer air temperatures, reduced mountain snowpack, increasing wildfire risk, sea level rise, and changing water availability affecting the region's communities and infrastructure systems (May, et al., 2018; Mauger, et al., 2015). Understanding the region's climate change is critical to prepare for impacts to Sound Transit's existing and planned infrastructure investments, including the WSBLE Project. Greenhouse gas (GHG) emissions scenarios—known as Representative Concentration Pathways (RCPs)—describe several possible climate futures, ranging from lower (RCP2.6) to higher (RCP8.5) emissions scenarios. In this report, we primarily use a high emissions scenario (RCP8.5) and a low emissions scenario (RCP4.5) when providing a projected range. The following sections provide an overview of projected climate change impacts in the Puget Sound region (Hayhoe, et al., 2017); a separate document provides a more detailed summary of the climate science literature for the region.

3.1 Temperature

Warming is projected to continue in the Puget Sound region for all four emissions scenarios across all seasons, with summer seeing the most substantial temperature increases. Average annual temperature in the region is anticipated to warm 4.3 °F or more after 2040, relative to the 1970–1999 average, and will be accompanied by more frequent and intense heat waves and fewer and less intense cold periods. **Table 3-1** summarizes projected temperature increases.

Table 3-1. Projected Changes in Puget Sound Region Temperature, relative to the 1970–1999 average

Factor	2040–2069	2079–2099
Average annual temperature	**+5.5 °F** +4.3 to +7.1 °F	**+9.1 °F** +7.4 to +12 °F
Summer (June–August) temperature	**+6.8 °F** +4.8 to +9.7 °F	**+11 °F** +8.8 to +15 °F
Winter (December–February) temperature	**+4.9 °F** +3.2 to +6.5 °F	**+8.3 °F** +6.0 to +10 °F
Temperature of hottest days	**+6.5 °F** +4.0 to +10.2 °F	**+9.8 °F** +5.3 to +15.3 °F
Temperature of coolest nights	**+5.4 °F** +1.3 to +10.4 °F	**+8.3 °F** +3.7 to +14.6 °F

Notes: Projections are consistent with the RCP8.5 scenario. Values within the table are the average (first line of each row, in boldface) and range (second line of each row) of projections from 10 climate models.

As of 2019, four of the five hottest years on record in Seattle happened since 2013, with 2015 having a total of 12 days over 90 °F and 2018 seeing a total of 11 days over 90 °F (Baker, 2019; Sundell, 2019). Furthermore, 2019 and 2020 also continued to set heat records in Seattle and Western Washington (Sistek, 2020). **Figure 3-1** shows average annual temperatures in Seattle.

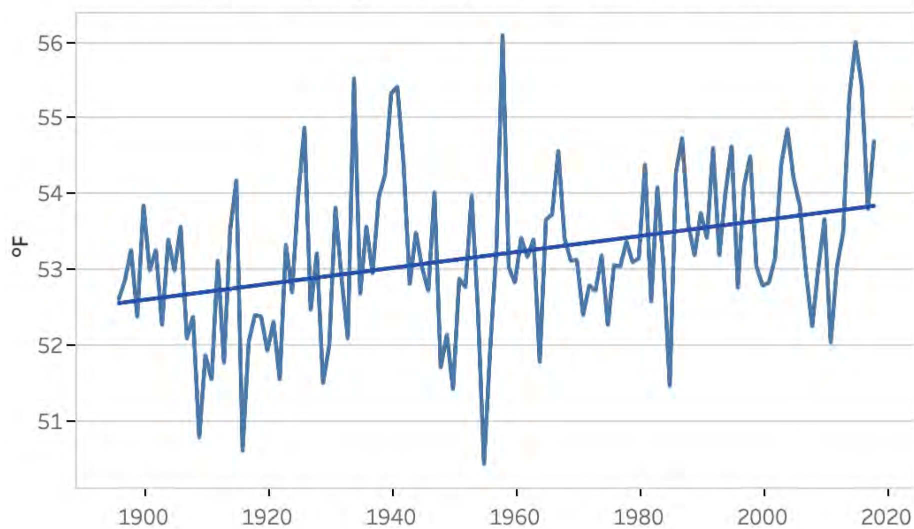


Figure 3-1. Average Annual Temperatures between 1895 to 2018 for Downtown Seattle

Notes: Temperature dataset from the U.S. Historical Climatology Network, version 2.5.5.20190405 (through March 2019) and has been data adjusted for biases and inhomogeneities resulting from changes in the environment or operation of individual observing sites (e.g., urbanization, station moves, instrument upgrades, and time of observation changes). Data visualized by the Office of the Washington State Climatologist.

3.2 Precipitation

Average annual precipitation in the Pacific Northwest is expected to increase slightly in the coming decades. Seasonal precipitation is expected to shift, with summer rainfall declining 22% and winter precipitation increasing 11% by 2050, as shown in **Table 3-3**.

Historical records indicate that the frequency of heavy rainfall events has increased over the 20th century in the Puget Sound region. Climate models suggest that this trend will likely continue into the 21st century. Winter extreme precipitation, including atmospheric rivers, is projected to increase and become more severe (Ralph, Neiman, & Wick, 2004). A recent study of extreme precipitation projections for King County showed the potential for substantial increases in future precipitation intensity. For example, there is a projected 54% increase in the 10-year hourly rainfall event by 2080 (Mauger & Won, Projecting Future High Flows on King County Rivers: Phase 2 Results, 2020).

Table 3-2. Projected Changes in Puget Sound Seasonal Precipitation

Period	2040–2069	2070–2099
Summer (June-August)	**−22%** −50% to −1.6%	**−27%** −53% to +10%
Winter (December-February)	**+11%** +1.8% to +19%	**+15%** +6.2% to +23%

Notes: All changes are relative to the average for 1970–1999. Values in the table are the average (first line of each row) and range (second line of each row) or projections from 10 climate models for RCP8.5.

3.3 Hydrology

Consistent with projected changes in precipitation, climate change is expected to alter the volume and timing of seasonal streamflow in the Green-Duwamish, Cedar, Chehalis, Nisqually, Sammamish, Snohomish, and White rivers. Increased winter flooding and a 15–73% increase in the frequency of 100-year flood events are projected in the Green-Duwamish watershed. In summer, streamflow is expected to decline 7–21% by the 2080s, and the duration of low-flow periods is projected to increase.

Current trends in annual streamflow are mixed, without a statistically meaningful trend in annual average streamflow. Dry years are becoming more prevalent for some rivers. Peak streamflow is shifting earlier in the spring in watersheds historically dominated by snow, and peak flow is shifting later in the spring in watersheds historically dominated by rain (Mauger, et al., 2015).

As the climate warms and precipitation shifts to the winter months, the Pacific Northwest is projected to face decreased snowpack, increases in summer stream temperatures, and changes to streamflow timing, seasonal minimums, and flooding. While total annual streamflow volumes are not projected to change consistently, seasonal streamflow volume and timing are expected to shift based largely on a higher portion of precipitation falling as rain rather than snow (Mauger, et al., 2015).

Heavy rainfall events in Western Washington will intensify by 22% by the 2080s. Heavier rainfall events, coupled with increased 100-year flood events from streamflow, will create more frequent and intense river and inland flooding events. Regional models indicate a 35% increase for 10-year flood events and a 32% increase for 100-year flood events in the Green-Duwamish River (**Table 3-3**).

Table 3-3. Anticipated Changes for Streamflow Timing and Volume for the 2080s

Watershed	Earlier Peak Streamflow Timing	Streamflow 100-Year Flood	Streamflow 10-Year Flood	Summer Minimum Flows
Green-Duwamish	**−38 days** −50 to −31 days	**+32%** +15 to +73%	**+35%** +14 to +73%	**−16%** −21 to −7%

Notes: Projections are for unregulated flows under the A1B (SRES) emissions scenario.

3.4 Sea Level Rise

The rate at which sea level rises in Puget Sound depends on the rate of global absolute sea level rise and regional factors such as ocean currents, wind patterns, location, and elevation. For example, in Neah Bay, the land elevation is rising at a rate of +1 inch per decade, compared to Seattle, which is decreasing at a rate of approximately -0.5 inches per decade (Petersen, et al., 2015). In areas where the land is sinking, the regional *relative* sea level rise will be greater than the *absolute* sea level rise, and in regions where the land is rising, *relative* sea level rise will be less than the *absolute* sea level rise. A large earthquake along the Cascadia subduction zone could result in sudden changes in land elevation and reverse vertical land movement trends, resulting in rapid relative sea level rise. Smaller earthquakes along the Seattle fault can also result in changes in land elevation levels, although the magnitude of changes is dependent on the earthquake epicenter (Miller, et al., 2018).

In the Elliott Bay area, there is a 50% probability of exceedance of sea levels to rise by 0.8 feet by 2050 and 2.3 feet by 2100. In the Ballard area, there is a 50% probability of exceedance of sea levels to rise by 0.9 feet by 2050 and 2.4 feet by 2100 (**Table 3-5**).

Table 3-4. Projected Relative Sea Level Change, in Feet, for Elliott Bay and Ballard, Compared to 1991–2009

Period	2050	2100
Elliott Bay	**0.8 feet** 0.6 to 1.1 feet	**2.3 feet** 1.7 to 3.1 feet
Ballard	**0.9 feet** 0.7 to 1.1 feet	**2.4 feet** 1.8 to 3.1 feet

Notes: This table reports relative sea level rise projections from the Washington Coastal Resilience Project for Seattle near Elliott Bay (47.6 N, 122.4 W) and Ballard (47.7 N, 122.4 W). Projections are centered on 2050 (2040–2069) and 2100 (2090–2109). The boldface number (first line of each row) indicates the probability of exceeding the indicated relative sea level rise is 50%. The range of values (second line of each row) represent the 83% and 17% probability of exceeding the indicated relative sea level rise, respectively. Data were downloaded from www.wacoastalnetwork.com/wcrp-documents.html (updated January 27, 2021).

As sea level rises, studies suggest increased potential for higher tidal and storm surge, leading to coastal inundation, erosion, and flooding. The rate and amount of inundation varies by the projected sea level rise and shoreline characteristics. Compounding events—such as the combined effects of high tide, winter storm surge, and sea level rise—can lead to coastal flooding events (Mauger, et al., 2015).

For coordination and permitting purposes for WSBLE, Sound Transit is aligning with Seattle's draft climate adaptation planning work, which uses the sea levels shown in **Table 3-5**.

Table 3-5. Sea Level Rise Projections for the City of Seattle for 2100, in Feet

Condition	2020 Water Levels	Sea Level Rise by 2100	2100 Water Levels
Daily high tide	0	+3	3
Monthly high tide	1	+3	4
Annual high tide	2	+3	5
100-year storm surge	3	+3	6

Notes: Water levels are relative to the average daily high tide (mean higher high water mark, MHHW) in 2020, which is 9 feet above the official "zero" point of North American Vertical Datum of 1988 (NAVD88). Sea level rise of 3 feet by 2100 corresponds to 17% probability for the high emissions scenario (RCP8.5) (Miller, et al., 2018).

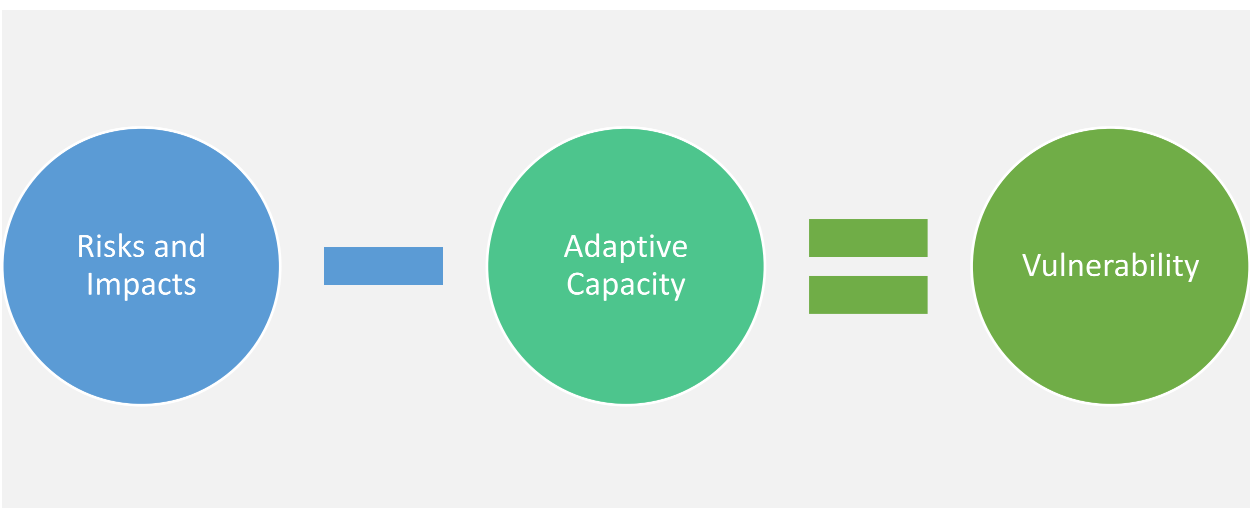
Appendix B. Climate Vulnerability and Adaptation Considerations

4 CLIMATE VULNERABILITY

Generally, climate vulnerability is defined as the climate risks and impacts moderated by the capacity to adapt and cope with those risks and impacts (Figure 2). To assess the vulnerability of the WSBLE project, Sound Transit staff held over four months. Dates and workshop objectives are listed below.

- **March 26, 2021** – Sound Transit staff identified potential climate impacts to the WSBLE and prioritized these climate impacts.
- **April 21, 2021** – Sound Transit staff mapped out prioritized climate impacts and considerations across the WSBLE alternative routes.
- **May 19, 2021** – Sound Transit staff identified key adaptation considerations and opportunities.
- **June 30, 2021** – Sound Transit staff confirmed the final vulnerability rankings of prioritized climate impacts.

Figure 2. Climate Vulnerability Framework



Climate risks and impacts were defined as the product of the likelihood and the severity of impacts from a given scenario (Cardona, et al., 2012; Jones, 2003). For the purposes of this project, a general framework is shown in **Error! Reference source not found.**.

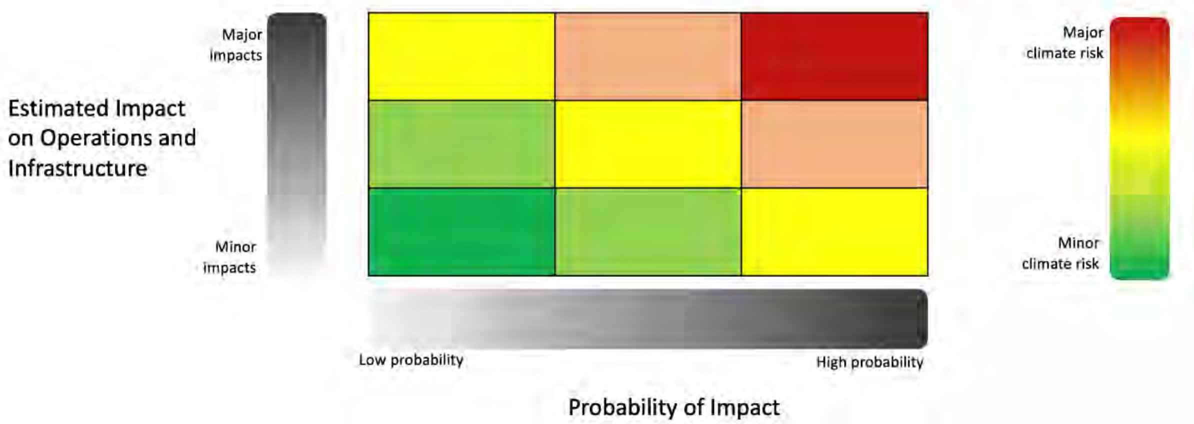


Figure 4-3. Framework to Eval

The 2013 report, *Sound Transit Climate Risk Reduction Project*, used this framework to evaluate climate risks for Sound Transit's infrastructure, systems, and operations. Building on this prior work, climate risks have been evaluated for the WSBLE Project in **Table 1-1.** on the following page. The rating criteria shown in Error! Reference source not found. were applied (note that no ratings were assigned in the "no impact" or "extreme impact" categories). While climate impacts and risks affect different elements of the WSBLE project, they should not be considered in a vacuum. The potential of cascading and compounding impacts should be considered, as a series of low to moderate impacts can combine to produce a major impact or system failure.

Table 4-1. Ratings of Impacts on Sound Transit Infrastructure and Operations

	Impact Rating	Description
	No Impact	No additional action required to maintain service levels.
	Minor Impact *("a blip on the radar")*	Minimal additional action required to maintain service levels.
	Moderate Impact *("a nuisance")*	Some action required to maintain service levels but needed action can be easily accommodated.
	Major Impact[2] *("we've got a problem")*	Substantial and/or costly action required to maintain service levels. Impact affects system beyond a single day.
	Extreme Impact *("a game-changer")*	No service level can be maintained. Operations must be halted for a prolonged period of time or permanently.

[2] Note that this category was renamed from "Significant" in the 2013 *Sound Transit Climate Risk Reduction Project* to distinguish from discussion of significant impacts in the Project's Environmental Impact Statement.

Table 4-2. Summary of Climate Change Probability and Potential WSBLE Project Impacts.

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Rail/Track	**Extreme heat impacts**: • Rail buckling. • Fatigue cracking. • Pavement rutting. • Switch failures.	• Map current heat island effects to identify potential trouble spots and site tracks away from these areas. • *Site in shaded areas to reduce heat impacts.*	• Install sensors to detect high track temperatures in at-risk areas. • Use rail expansion joints to relieve heat stress. • Update DCM to reflect appropriate temperature range. • Use heat resistant materials that are less prone to rail buckling.	• Slow rail traffic during hours or days of extreme heat. • Increase visual monitoring of tracks and issue heat advisories. • Run garden hose to cool switches during hot days. • Adjust temperature monitoring thresholds or policies to pre-empt rail buckling. • *Deploy staff during extreme heat events to identify and mitigate emerging issues.*	**Low**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Rail/Track *(continued)*	**SLR + Heavy Rains + Hydrological Impacts:** • Flooding and corrosion of infrastructure and damage to rail corridors	• Ensure top rail elevation is above 500-year floodplain and 3 feet above 100-year floodplain levels. • Relocate ground-level and underground equipment and structures.	• Partner with jurisdictions on design standards and stormwater management. • Sizing drains on elevated structures to accommodate future flows. • Adhere to design criteria (e.g., not placing tracks at lowest point) to minimize flooding issues. • Design for more severe flooding scenarios, such as designing for the 100-year flood plus 3 additional feet or using the 500-year floodplain as a baseline.	• Increase visual monitoring of riverbanks, bridge supports, and infrastructure. • Maintain infrastructure and equipment with drainage problems. • Adjust policies related to rainfall, wind speed, etc. for when to begin monitoring for rail damage (e.g., extremes in the future will change thresholds, but systems are in place). • Utilize pumps to mitigate flooding issues.	**Moderate**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Rail/Track *(continued)*	**Mudslides and landslides:** • Damage to rail infrastructure at specific sites (e.g., Pigeon Point, Queen Anne)	• Locate tunnel portals away from slide-prone areas. • Explore different siting options. For example, consider risks to at-grade options in West Seattle/Pigeon Point.	• Make slope stability improvements as part of project. • Build walls around column to protect it from slides. • Control groundwater to manage slope stability. • Build retaining walls. • Install slope underdrain to prevent chance of mudslide. • Adopt seismic standards for construction to prepare for erosion impacts and lateral forces. • Design columns of elevated structures for sufficient lateral impact.	• Install CCTV around Pigeon Point and Queen Anne to monitor that there is no mud on rail. For example, Sounder operations and USGS program monitor slope conditions and environmental events.	**Low**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Overhead Catenary System (OCS)	**Extreme heat impacts on:** • Excessive line and wire sags • Possible power loss during extreme heat	• Consider where the most likely locations are to have wire sagging and line impacts and install sensors to monitor. • Map current heat island effects to identify potential trouble spots. • Provide shading to reduce heat impacts.	• Consider OCS design and assumptions using the DCM earlier in the process, such as OCS lifespan and length. Typically, the OCS design comes later in the process civil engineering design. • Use more robust foundations to support higher loading and tension from extreme heat. • Change midpoint for weights and install longer guide rods in auto-tension systems to compensate for line sag from extreme temperatures. • Coordinate new OCS infrastructure with existing OCS structure system.	• Regularly maintain OCS. • Raise set point for a fixed termination system, re-tension for a higher average temp. • Increase visual monitoring of OCS. • Implement slow orders or halt service until lines are re-tensioned.	**Low**
	Extreme winter storms: • Repeated snow and ice could impair OCS functionality	—	• Consider changes to OCS requirements for future projects.	• Run ice trains with heated pantographs to melt ice on power lines. • Regularly monitor OCS and issue slow orders during extreme winter storms.	**Low**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Electrical Equipment & TPSS	**Extreme heat impacts:** • Overheating electrical equipment delays or disrupts service.	• Increase shading around equipment. • Provide redundancy in TPSS infrastructure – especially	• Continue to require HVAC for all signal bungalows. • Update design criteria that allow for natural ventilation and air flow, particularly around signal boxes.	• *Provide regular maintenance checks—especially for vulnerable TPSS locations.*	**Low**
	Brownouts: • Electricity and power demand during summer months can lead to brownouts.	—	• Work with Seattle City Light to install a dedicated SCL line for Sound Transit to meet system power demand during summer months and brownouts. • Investigate the role of wayside power systems. • Install solar panels on top of TPSS.	—	**Low**
	Flooding impacts: • Damage to TPSS in flood-prone areas (e.g., flood risk zones, areas with limited drainage capacity).	• Locate or relocate TPSS and other sensitive equipment above or away from flood-prone areas (e.g., don't place TPSS in tunnels or underground). • Site TPSS and construct them above the floodplain elevation.	• Partner with City of Seattle and Port on reducing flood and erosion risks. • Raise ground-level and underground equipment (i.e., elevate "housekeeping pad") to avoid flooding. • Design grading around TPSS to slope away from the TPSS. • Consider drainage and rain screens around elevators and escalators to avoid damage and service interruptions.	• Inspect and monitor equipment in flood-prone areas more frequently. • Ensure that pumps and drains are working properly to mitigate flooding events. • Ensure that there is easy access to TPSS and heavy equipment for ongoing maintenance.	**Moderate**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Tunnels	**Flooding and Groundwater Seepage:** • Groundwater seepage leading to odor issues and higher maintenance.	• Build outside of hazard-prone areas.	• Design standards avoid direct soil contact, which should help prevent odor. • Design tunnel portals and vent shafts to prevent water intrusion. • Create compartments that can serve as temporary flood barriers where tunnels run under water bodies. • Work with SR-99 tunnel design staff to learn what they did to incorporate SLR and flooding considerations.	• Conduct routine preventative maintenance of drains and sump pumps, such as cleaning and inspections, to ensure they are working and prevent future issues.	**Moderate**
	Heavy Rains and Extreme Events: • Increased risk of extreme flooding. • Low risk of catastrophic events—such as earthquakes, tsunamis, dam failures, or flash floods.	• Consider locations of portals, station entrances, at-grade ventilation systems like grates in the street to protect from water entry.	• Install floodgates at tunnel portals. • Install pumps in tunnel. • Continue to design for the 100-year storm event for tunnels (e.g., site station entranced above the floodplain, provide watertight conduit and pipes, provide watertight doors on station entrances and underground connections). • Consider facility lifespan when designing and installing pumps. • Size drains sufficiently to handle flows.	• Plan for pump failures by installing back-up pump failures. Continue to monitor and maintain pumps so they function during critical events.	**Low to Moderate, depending on location**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Bridges & Elevated Structures	**Extreme heat impacts:** • Malfunction of expansion joints for moveable bridges. • Increased creep rate.	• Map current urban heat islands to identify vulnerable spots. • Reduce, modify, or relocate new development away from vulnerable regions.	• See **Rail & Track** Extreme Heat Adaptive Capacity Options if rail structures are on elevated structures. • Install special monitoring equipment to protect and monitor moveable bridge parts, including seismic monitoring equipment. • Use more robust and heat-resilient components, even nuts and bolts. Mechanical and electrical systems often use off-the-shelf products that meet specs, not a custom design. Are those products designed for sufficient heat impacts? • Learn adaptation option from other transit systems in AZ, TX, NM.	• Spray water on moveable bridges during heat events. However, this might impact service.	**Low**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Bridges & Elevated Structures *(continued)*	**Flooding Impacts:** • Drainage capacity and hydrostatic pressure build-up behind bridge abutments. • Accelerated rates of bridge corrosion and scour.	• Reduce, modify, or relocate new development away from vulnerable regions.	• Integrate increased potential for damage under extreme hydraulic loads into design and management procedures. • Elevate bridges that are vulnerable to deck unseating (unlikely to be an issue given high planned bridge heights).	• Reduce scour damage through armoring or measures such as riprap, collars, and scour-monitoring devices.	**Low**
	Extreme winter storms: • Ice impacts on elevated guideways. • Pipes/standpipes on elevated guideways exposed to freezing temperatures.	—	• Consider types of wind screens and walkway types used elsewhere that don't allow ice to build up. Learn from other transit agencies in cold geographies, such as Minnesota.	—	**Low**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Rail Service Operations *(cross-cutting)*	**Extreme heat impacts on:** • Disruption of service due to extreme heat and increased energy demands.	• See **Rail & Track** Extreme Heat Adaptive Capacity Options.	• See **Rail & Track** Extreme Heat Adaptive Capacity Options.	• See **Rail & Track** Extreme Heat Adaptive Capacity Options.	**Low**
	Flooding impacts: • Disruption of service due to flooding issues. • Limits access to hi-rail vehicle entry points on guideway for regular maintenance or emergency services.	• See **Rail & Track** SLR + Heavy Rains + Hydrological Impacts Adaptive Capacity Options.	• See **Rail & Track** SLR + Heavy Rains + Hydrological Impacts Adaptive Capacity Options.	• See **Rail & Track** SLR + Heavy Rains + Hydrological Impacts Adaptive Capacity Options.	**Moderate**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Rail Service Operations *(continued)*	**Mudslides and landslides:** • Disruption of service at vulnerable locations.	• Locate tracks away from slopes.	• Contain and divert moving debris using walls, berms, ditches, and catchment basins. • Stabilize and grade unstable slopes to lower gradients, construct buttresses or retaining walls, improve drainage systems.	• Continue to contract with Community Transit, KC Metro, Pierce Transit, and Starline Luxury Coaches to provide coach service when mudslides affect rail service (Sounder).	**Low**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Customer Experience *(cross-cutting)*	**Heavy rains, storms, and flooding:** • Impede customer access and experience, especially at elevated stations. • Elevators, escalators, and other facility equipment may be damaged.	—	• Consider heat impacts and HVAC needs when enclosing elevators and escalators in glass boxes. • Provide canopy coverage from rain and accordingly update the DCM. Current DCM requires 65% roof coverage; Seattle Municipal Code require 100% coverage. • Provide full continuous canopy coverage from station entrance to train cars. • Size canopy drainage in response to climate change. • *Caulking glazing panels and roof and envelope details can mitigate leakage into hoistways.* • Provide wind protection at elevated stations. • *Install louvers, which can prevent water inside hoistway, vertical conveyance equipment, and in the station. However, they do not always protect against wind-driven rain and water leaks.*	• Regular maintenance and detailing to prevent water leaks.	**Low**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
	Extreme heat impacts: • Service interruptions of vertical circulation equipment • Overheating or heat exhaustion	—	• *Installing durable elevator cab fans.* • *Mount AC split units in areas away from direct sun exposure.* • *Use opaque or lighter designs and panels.* • *Continue to use oil coolers.* • *Retrofit older light rail vehicles (LRVs) with HVAC systems and implement requirements for HVAC units in new LRVs.*	—	**Low**

WSBLE Project Elements & Effects	Climate Change Impacts	Adaptive Capacity Options			Vulnerability Draft Rating
		Siting/Location	Design	Operations	
Construction *(cross-cutting)*	**Heat impacts on:** • Concrete during construction. • Construction workers and overheating.	• *Site construction sites with adequate shade.*	• *Build temporary canopies to provide shade to construction workers.*	• *Provide cooling options—such as iced water—during extreme heat days.*	**Low**
	Flooding: • Nearby construction redirecting water flow onto guideway, causing issues with signaling. • Retaining wall construction, excavation – *cover in **Construction Risks** section of the project.*	—	• Ensure that planning for construction risks includes considerations for more extreme weather and potential flooding. • Create water and rain diversions to divert water flow away from key construction sites.	—	**Low**

In addition to assessing the climate impacts to Sound Transit's Link Extensions, it is important to also consider **adaptive capacity**—or the ability for a system to moderate or cope with change. There are pre-construction and post-construction adaptation considerations. For the WSBLE project, there are multiple adaptive capacity considerations, including:

- **Siting and location** of key project elements to ensure that they are not located in high-risk areas. For example, not siting rail tracks in landslide-prone areas can prevent damage to the guideway and minimize service disruption. These adaptation options happen pre-construction.

- **Design** of key project elements to ensure that there is the ability of the WSBLE system to cope with future climate impacts. For example, utilizing expansion joints on rail tracks can alleviate heat stress to prevent or mitigate rail buckling risk. These adaptation options happen pre-construction.

- **Operations** can ensure that the WSBLE system can continue to adapt to future climate change during or post-construction. For example, regular maintenance can pre-empt and mitigate flooding events or slow orders during extreme heat days can ensure that the Light Rail continues to safely operate.

4.1 Rail and Track

In 2013, Sound Transit staff rated the risk for rail buckling as **moderate**, given that there was a **low probability** of a rail buckling event that could result in **moderate to major damages and costs**. In particular, the 2013 report found that non-tunneled portions of the Link light rail system were the most susceptible to damage from rail buckling (Whitely Binder, Tohver, Shatzkin, & Snover, 2013).

Since 2013, Seattle has experienced warmer years—with five of the six hottest years on record—and prolonged heat waves (Baker, 2019; Sundell, 2019). A rail buckling event on Link was noted in the summer of 2019 in South Seattle (Adolph, 2019). Sound Transit should consider whether rail buckling risks could lead to increased climate vulnerability in the future and warrant increased scrutiny. For the new Link extensions, Sound Transit can mitigate the risk of rail buckling and operational impacts by incorporating proactive adaptation measures into the construction design.

In 2013, climate impact from flooding was considered **moderate**, with certain rail infrastructure at higher risk for flood damage depending on its proximity to flood-prone areas (e.g., along the Duwamish River). Flood impacts have been relatively minor to date. However, climate change is expected to increase the risk for both river flooding, coastal flooding, and stormwater-related flooding across the Seattle region, making it increasingly likely that future flood events will affect Sound Transit's infrastructure. Sound Transit has adopted more stringent flood-related design criteria and could consider additional adaptation measures to further mitigate climate impacts.

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Rail/Track			
Rail buckling, fatigue cracking,	Moderate	Moderate	Low

pavement rutting, and switch failures			
Flooding	Moderate to Major	Moderate	Moderate
Mudslides and Landslides	Low to Moderate[a]	Moderate	Low

[a] While impacts can be significant, the overall impacts to the WSBLE system is low due to the low likelihood of a severe mudslide or landslide. However, this impact can be moderate depending on the specific location.

4.1.1 Heat Stress and Extreme Heat Impacts

The 2013 *Sound Transit Climate Risk Reduction Project* found that the risk for rail buckling was tied primarily to **extreme heat events and heat stress** (Whitely Binder, Tohver, Shatzkin, & Snover, 2013). Specifically, the report found that **high temperatures and direct sunlight exposure** can cause steel and rail to expand and shift laterally, forcing the rail out of alignment, known as rail buckling (or sun kinks). Rail buckling can lead to service slowdowns, interruptions, costly repairs, and in rare cases, train derailments (Whitely Binder, Tohver, Shatzkin, & Snover, 2013).

The 2013 report explored the differences in these heat impacts by rail type as well as effective mitigation strategies.

- **Ballasted tracks** are used for various at-grade segments, maintenance yards, and for special trackwork where tracks converge, diverge, or cross over. They are generally **more sensitive to extreme heat** than the other track types. **Pre-fabricated concrete ties** reduce the probability of buckling. The Design Criteria Manual now requires concrete ties for all new construction of special trackwork (and Sound Transit plans to replace existing wood ties during regular maintenance).
- **Direct fixation track** is used on elevated structures, tunnels, underpasses, and some at-grade segments, and is **minimally sensitive to extreme heat** and rail buckling. **Pre-fabricated concrete ties and fasteners** that anchor rail directly into supporting concrete structure reduce the probability of buckling.
- **Embedded track** is used where Link shares trackway with rubber-tired vehicles and is the **least sensitive to extreme heat**. These tracks are entirely encased in concrete or other pavement and the only portions of the rail that are exposed are the top and gauge sides, which are just above the adjoining road surface.

As of 2013, Sound Transit had experienced **no rail buckling events on Link light rail**, though Sounder experienced two rail buckling events in 2006 and 2008, both on the Ballard railroad bridge owned by BNSF. Around the time Central Link opened in July 2009, the Seattle region experienced extreme heat events, including a heat wave that brought four consecutive days of temperatures above 92 °F and a record high temperature of 103.5 °F in Seattle on July 29, 2009 (Whitely Binder, Tohver, Shatzkin, & Snover, 2013).

Since 2013, there has been **at least one recorded event of rail buckling**—in June 2019 when a part of the rail at 4th Avenue South buckled when temperatures surpassed 90 °F. However, Sound Transit attributed the event, in part, to older rail structures that did not have expansion joints. The buckling was also part of a series of failures that led to shutdowns across the Link system (Adolph, 2019). During the heat dome event of June 2021, when temperatures exceeded 110 °F, Sound Transit issued slow orders and conducted visual monitoring of tracks.

Since 2013, there has been **new research focused on climate impacts to rail infrastructure**. Heat-related delays for trains and rail systems have been steadily increasing over the past decade (Chinowsky, Helman, Gulati, Neumann, & Martinich, 2019). Research indicates that under projected climate changes, warmer temperatures increase the likelihood for fatigue cracking and pavement rutting, which could affect various track types, resulting in potential infrastructure failures (Gudipudi, Underwood, & Zalghout, 2017). For instance, a train accident in Chicago was partially attributed to abnormally high temperatures during a 1995 heatwave (Björnsson, et al., 2019).

The Northwest region's relatively milder summers compared to other regions in the U.S. may protect Sound Transit's infrastructure from some of these extreme heat-related impacts. However, the moderate climate also means that the Northwest's rail systems are less acclimated to high heat and may be more sensitive to cases of prolonged heat events or unusually high temperatures (Chinowsky, Helman, Gulati, Neumann, & Martinich, 2019). Sound Transit currently manages the potential for rail buckling through advisories, visual monitoring, and slow orders if needed when temperatures reach 94°F or higher (Whitely Binder, Tohver, Shatzkin, & Snover, 2013; Sound Transit, 2021b). These high temperatures are projected to occur more frequently in the future.

Another consequence of extreme heat that Sound Transit faces is the overheating of operational switches. At high air temperatures, these switches can malfunction or become damaged due to heat stress. This causes additional delays to rail service when time is taken to cool the equipment or to make necessary repairs. South Transit currently avoids the overheating of equipment by using garden hoses to cool these switches during extreme heat days (Sound Transit, 2021b).

4.1.2 Flooding Risks

The 2013 *Sound Transit Climate Risk Reduction Project* found that **flooding could damage Sound Transit infrastructure, leading to the loss of key access routes, increased maintenance costs due to corrosion or erosion, and service disruptions**. While flooding is a general risk, planning should consider three different types of flooding scenarios—which can occur independently or in combination: 1) riverine flooding, 2) stormwater-related flooding, and 3) coastal flooding.

Riverine flooding can result from heavy precipitation events and rapid snowmelt. As of 2013, there had been no instances of river flooding events affecting Sound Transit operations or infrastructure. However, the **Duwamish River is at particularly high risk for flood damage** (Mauger & Won, Projecting Future High Flows on King County Rivers: Phase 2 Results., 2020; Lee, Mauger, & Won, 2018). By the early 2020s, the historic 500-year flood may likely become the new 100-year flood in the Green/Duwamish River (Lee, Mauger, & Won, 2018). Riverine flooding from extreme rainfall events can be compounded by high tide events and future sea level rise, which can hinder the river's ability to drain into Puget Sound (Mauger, et al., 2015). Levees and the Howard Hanson Dam help mitigate flooding risks but will not prevent all flood events (Whitely Binder, Tohver, Shatzkin, & Snover, 2013; Mauger G. , et al., 2018).

Climate change is also expected to cause more stormwater-related flooding where heavy precipitation overwhelms the drainage capacity of soils and stormwater systems (Mauger, et al., 2015). Low-lying areas or areas with extensive impervious surfaces are particularly vulnerable to this type of flooding, which can lead to corrosion of rail infrastructure. The SODO area has a shallow groundwater table that fluctuates with heavy precipitation and tides. Heavy precipitation events have caused standing water to collect near Holgate crossing at 6th Avenue South and some instances of groundwater seeping through the tiles at SODO Station. Due to these water impacts, the track ballast in the SODO area requires more regular inspection and maintenance than other areas (Whitely Binder, Tohver, Shatzkin, & Snover, 2013).

By the end of the century, Seattle will likely experience a 54% increase in the 10-year hourly rainfall event, which can worsen stormwater-related flooding (Mauger G. , et al., 2018). To account for predicted heavier rainfall, Sound Transit's current Design Criteria Manual calls for the agency's stormwater systems in parking lots, roadways, and track roadbeds to be designed to handle a 25-year storm. For culvert and drainage facilities crossing rail corridors with potential for flood damage to the rail corridor, facilities must be designed to handle a 100-year storm (Sound Transit, 2021).

Finally, future sea level rise can contribute to coastal flooding. By 2100, there is a 17% probability that sea levels will exceed 3.1 feet and a 1% probability that sea levels will exceed 5.2 feet in the Elliott Bay and Duwamish River area (Miller, et al., 2018). **Coastal flooding can also be amplified by high tide events, winter storms, and heavy rain events.** For example, West Seattle regularly experiences tides 2 feet higher than normal during king tide events, exceptionally high tides that occur several times a year and can result in coastal flooding (Error! Reference source not found.) (Seattle Public Utilities, 2018). King tides show a preview of what future sea levels will look like and can help identify infrastructure prone to coastal flooding (Environmental Protection Agency, n.d.).

Photo credit: Megan Farmer, KUOW

Figure 4-4. King Tide Event at Alki Beach in West Seattle on December 5, 2017

4.1.3 Landslides and Mudslides

Climate projections indicate that there will be more intense rain events in the future (Mauger G. , et al., 2018). As a result, soils can become saturated and are destabilized, resulting in landslide and mudslide conditions. An increase in landslides and mudslides can have significant impacts on rail systems, including **causing damage to rail infrastructure** and **disrupt rail services**, especially in areas with steep slopes that are more susceptible to soil destabilization and sediment transport—such as West Seattle and Queen Anne. While consequences can be significant, these major landslide events are also rare. Damage to rail systems from landslides or mudslides are often caused by debris landing on the tracks, such as fallen branches or tree trunks (Sound Transit, 2021a).

Rail service disruptions can cause negative customer experience when forced to wait longer due to service shutdowns or re-routing. While the entire geographic scope of Sound Transit's work is susceptible to these natural events, Pigeon Point in West Seattle and Queen Anne have both been identified as particularly high-risk areas due to their hilly terrain (Sound Transit, 2021a).

Sound Transit can take many different actions in terms of design and re-enforcement to address mudslide and landslide risk. For current sites, making improvements to slope stability can be done, reducing the risk of a landslide or mudslide causing damage to current infrastructure. Additionally, building walls around rail structures to protect the infrastructure from debris or installing camera monitoring on sensitive or known landslides areas are both methods of preparing for increased intensity of rainfall events. When siting future locations, choosing areas located away from landslide areas can mitigate future landslide risk (Sound Transit, 2021b).

Figure 4-5. Map of Known Landslide Locations and Potential Landslide Areas within Half Mile Buffer of Proposed WSBLE Alternatives

Notes: Known and potential landslide areas are identified in the City of Seattle's Critical Areas Ordinance. Please see Appendix TBD for downscaled maps of impacts.

4.1.4 Climate Adaptation Considerations

Extreme Heat Adaptation

Sound Transit can take a **proactive or reactive** approach to adapting to the climate impacts associated with heat stress and rail buckling, with proactive adaptation resulting in potential short- and long-term cost savings. **Proactive adaptation** options could include **installing sensors to detect when track temperature** exceeds normal operating parameters, **utilizing heat-resistant materials** (such as rail expansion joints) that minimize rail buckling risks, and **mapping out areas that experience heat island effects** and site railways away from at-risk areas or provide shading to reduce heat island effect. King County recently conducted a heat mapping study. Experts project that proactive adaptation can collectively save U.S. rail companies **at least $4 billion and up to $11.5 billion** by the end of the century (Chinowsky, Helman, Gulati, Neumann, & Martinich, 2019).

Reactive adaptation options include **slowing rail traffic** during hours or days of extreme heat, or when temperatures could potentially exceed safe operating conditions. This approach, however, leads to service delays, interruptions, and lost revenue potential (Chinowsky et al., 2019). Other reactive adaptation options include **increasing visual monitoring of tracks**, **issuing more frequent heat advisories**, and **running a garden hose to cool rail switches** during extreme heat days. However, many of these reactive adaptation options could impact service and long-term revenue (Whitely Binder, Tohver, Shatzkin, & Snover, 2013). Additionally, with longer and more intense heat wave events, **adjusting Sound Transit temperature thresholds and policies may be necessary to pre-emptively respond to future extreme heat impacts** (Sound Transit, 2021b). During the 2021 heat dome event, Sound Transit's Power & Track staff were on site throughout the day to identify and mitigate emerging issues. However, this option reduces staff availability to address other issues and poses additional heat risks for staff who are monitoring the tracks.

Flooding Adaptation

Sound Transit can adopt several adaptation measures to reduce flooding impacts. Sound Transit's Design Criteria Manual has **increased the rail elevation requirements**, mandating that the elevation of the top rail is above the 500-year floodplain elevation or 3 feet above the 100-year floodplain elevation, whichever is greater (Sound Transit, 2021). Adjusting future DCM requirements may be needed to adequately adapt and cope with future flooding risk associated with climate change. Furthermore, **building or relocating rail infrastructure outside of the floodplain** can minimize future flooding impacts.

Sizing drains to accommodate future heavy rainfall can minimize risks for certain areas like elevated structures. Adhering to design criteria—such as not placing guideways at the lowest point or considering the design and coordination between the guideway and roadways—can mitigate flooding issues. Sound Transit will also likely need to **increase visual monitoring** of riverbanks, bridge supports, and rail infrastructure. More **frequent maintenance** of equipment and infrastructure and **active intervention to address drainage problems** (e.g., use of temporary or permanent pumps) can reduce flooding damage and impacts (Whitely Binder, Tohver, Shatzkin, & Snover, 2013).

Partnering with other jurisdictions will also be key in preparing for climate change. Local jurisdictions are modifying their design requirements to adapt to climate change. For example, the City of Seattle is incorporating sea level rise considerations into design requirements and infrastructure planning across city departments (Seattle Office of Sustainability & Environment, 2017). For the Elliott Bay Seawall, sea level rise projections of 50 inches were incorporated into the design (Seattle Department of Transportation, 2013). Seattle Public Utilities (SPU) also considers sea level rise projections and flood risk in its approach to infrastructure planning, stormwater design, and stormwater maintenance (Seattle Public Utilities, 2018; Radil, 2018). The SPU Design Standards and Guidelines call for flooding to be considered in a range of design principles, including the size and shape of culverts and in assessing the risk of gutter flow onto roadways or private property. In the case of gutter flow, SPU analyzes flood risk based on a 25-year and 100-year storm design frequency (Seattle Public Utilities, 2020). Seattle, King County, and the Port of Seattle are in discussions regarding sea level rise projections and approaches for incorporating them into project planning; Sound Transit is connecting with these jurisdictions regarding engagement in the sea level rise planning discussions.

Landslide and Mudslide Adaptation

There are multiple adaptation options to prevent and adapt to future landslide and mudslide risk. **Locating tunnel portals away from slide-prone areas** can ensure that tracks are shielded from potential landslide-related damage, especially in slide-prone areas in West Seattle, Queen Anne, and other areas with steep slopes. Additionally, other design options can mitigate landslide impacts, including making **slope stability improvements** in slide-prone areas, **building walls around columns** of elevated structures to protect rail structures from slides, **installing slope underdrains** to prevent mudslides, and **building retaining walls** (Sound Transit, 2021b). In addition to these design standards, **adopting seismic standards** for construction reduces the risk of structural damage from erosion and changing lateral forces. Finally, installing **monitoring videos** in slide-prone areas can allow Sound Transit staff to monitor slope conditions and rail impacts.

4.2 Overhead Catenary System

In 2013, Sound Transit determined that climate change impacts posed a **low risk** to the overhead catenary system (OCS). Though the probability of heat impacts to the OCS ranged from low to high (depending on type of OCS), the severity of the anticipated impacts was minor. The primary risks—line sags caused by extreme heat—have been identified, and Sound Transit has mitigation systems and protocols in place. While this low risk remains largely unchanged today, there is a possibility that **adverse impacts to the OCS could cascade with other impacts and possibility lead to broader problems**.

Overhead Catenary System			
Heat stress	Minor to Moderate	High	Low
Severe winter storms	Very Minor	High	Low

4.2.1 Heat Stress and Extreme Heat Impacts

The 2013 *Sound Transit Climate Risk Reduction Project* found that **heat stress from high temperatures** can cause **excessive line sags in the OCS,** leading to slower train speeds or power loss if the train loses contact with the OCS. If severe enough, line sags can cause the

OCS wire to snap, or can cause damage to the pantograph, insulators, and other OCS equipment (Whitely Binder, Tohver, Shatzkin, & Snover, 2013).

There are two main types of OCS and each has a different temperature sensitivity:

- **Auto-tension OCS** is used in most non-tunneled portions of the Link and **uses counterweights to maintain constant wire tension** over a range of temperatures. The minimum-maximum wire temperature range for this type of OCS is between 5 °F to 130 °F, or roughly equivalent to a maximum air temperature of 107 °F. Because of the counterweights, which move freely between high and low temperatures**, auto-tension OCS sections can automatically adjust to changing temperatures and thus have a low sensitivity to extreme heat**.
- **Fixed-termination OCS** is used in tunnels, maintenance yards, and all of Tacoma Link. This system type uses **fixed poles or support structures such as tunnel walls to maintain wire tension**. Fixed-termination systems are installed for nominal tension at average wire temperatures of 60 °F. The wire sags or contracts as temperatures vary from the average. The Central Link's maximum sag limit is to accommodate a maximum wire temperature of 120 °F. Because of these limits in the system's temperature threshold, **fixed OCS systems are relatively more sensitive to extreme heat**.

Sound Transit has experienced minimal impacts to the OCS from heat stress to date. As of 2013, neither OCS type had experienced line sag extreme enough to cause damage, and mitigation efforts were limited to increasing the monitoring of line wires via wire watch alerts during days with extreme heat (>90°F). Since 2013, there has been at least **one recorded heat-related event**—in June 2019 at the Othello Station. High temperatures caused the turnbuckle—or the component that loosens or tightens the wire—to expand, leading to wire sag and triggering a chain of reactions that affected trains at Othello Station (Adolph, 2019). While there were no major issues to Sound Transit's OCS during the heat dome event of June 2021, comparable jurisdictions—such as Portland TriMet—had to halt transit service because of sagging OCS and melted power cables (Wanek-Libman, 2021).

Figure 6. Melted power cables for Portland Streetcar during the June 2021 Heat Dome Event

Extreme heat days can also put undue stress on the electricity grid through higher **energy loads and demand**, which can have cumulative effects (May, et al., 2018). Wire sag in the OCS coupled with increased energy demands during extreme heat days can have other **energy-related implications, including power loss** (Zimmerman, et al., 2019).

OCS failures on their own are relatively infrequent. However, it is important to consider that **extreme heat events can have cascading snowball effects, with multiple small issues contributing to broader system problems** (Clark et al., 2018). For example, heat waves can increase the likelihood of both rail buckling and OCS line sag. Individually, these failures may not cause widespread issues. However, in aggregate, rail buckling and wire sags can stress the system, contributing to service delays and power outages, such as the one Sound Transit experienced in June 2019.

4.2.2 Severe Winter Storms

Though **very unlikely** in the Seattle area, **severe winter storms could also impact OCS through continuous exposure to snow and ice**, which can build up and affect OCS functionality (Rossetti, 2002). For Sound Transit, this risk might be a consideration during La Niña years, or other times when the region experiences abnormal winter storms.

4.2.3 Climate Adaptation Considerations

As with rail buckling, Sound Transit can take a proactive or reactive approach to adapting to climate impacts threatening the OCS. **Proactive adaptation options** include:

- Regular maintenance of the OCS. Currently, auto-tension OCS is monitored on quarterly basis, and fixed-tension OCS wire tension is adjusted annually as needed.
- Raising the set point for a fixed-termination system and re-tensioning to a higher average temperature to prepare the system to withstand more extreme temperature changes.

- Changing the midpoint for weights and installing longer guide rods in auto-tension systems to provide counterweights with a longer travel range (i.e., more distance between high and low temperatures) to allow the system to compensate for additional line sag caused by extreme temperature changes.
- Developing and implementing a heat operation plan for the WSBLE project.

Reactive adaptation options include continuing Sound Transit's increased visual monitoring of the OCS during extreme heat events; implementing slow orders until crews can re-tension when line sag occurs; provide shading to reduce heat impacts; and in extreme cases halting service until line sags are corrected (Whitely Binder, Tohver, Shatzkin, & Snover, 2013). During the June 2021 heat dome event, Operations staff notified other Sound Transit teams to notify them if OCS counterweights got within 1-foot of the ground. In snow and ice conditions, Sound Transit can run "ice trains" with heated pantographs to melt ice on the power lines and also issue slow orders (Sound Transit, 2021b).

4.3 Electrical Equipment

In 2013, Sound Transit determined that climate impacts posed **a minor to moderate risk** to electrical equipment and infrastructure, including traction power substations (TPSS), signal bungalows, and small signal boxes. Future extreme heat can amplify the natural and ambient heat generated from electrical equipment, which can result in service delays and equipment damage. Flooding could also damage equipment and infrastructure located in flood-prone areas. To date, heat impacts have been relatively moderate, and there have been no recorded incidents of river flooding impacting substations, signal bungalows, or signal boxes. Sound Transit can adopt design measures to reduce the risk of these impacts in the coming years.

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Electrical Equipment			
Heat stress	Minor to Moderate	High	Low
Flooding	Moderate to Major	Moderate	Moderate

4.3.1 Heat Stress and Extreme Heat Impacts

Electrical equipment—such as traction power substations (TPSS), signal bungalows, and signal boxes—generates substantial heat from normal operations, and the 2013 *Sound Transit Climate Risk Reduction Project* found that **heat stress from extreme temperatures and sun exposure can amplify this heat stress and cause loss of power and traffic signal control for TPSS, signal bungalows, and small signal boxes,** leading to reduced operating speeds or service interruptions. Furthermore, lack of cooling options and inadequate ventilation systems in TPSS or signal bungalows can further stress electrical equipment and infrastructure (Whitely Binder, Tohver, Shatzkin, & Snover, 2013).

Heat impacts have been relatively moderate thus far, with most impacts limited to TPSS and signal bungalows built before 2012. These older models have been impacted by heat stress when ambient air temperatures exceed 80 °F, leading internal temperatures to exceed 100 °F. As of 2013, only one TPSS had lost function due to heat stress. This event occurred prior to the Link opening and was attributed to a faulty temperature setting. However, **many signal bungalows in Central Link are frequently affected by heat stress**, especially in the afternoon when there is high sun exposure. Furthermore, HVAC systems in signal bungalows and communication cabinets were unable to keep up with the cooling load and demand during the 2021 heat dome event (Sound Transit, 2021c).

In 2013, heat stress was expected to have a minor to moderate impact on TPSS and other electrical equipment. For aboveground or at-grade TPSS, signal bungalows, and small signal boxes without air conditioning, climate change will increase the potential for heat stress. Using air conditioning to cool units reduces the risk of heat stress but **also increases electricity demand**. Without redundant cooling options, air conditioning units can fail, **especially during extreme heat days when electricity demand is highest** (May, et al., 2018). During the heat dome even in June 2021, utilities experienced load demand issues which led to some minor power outages and equipment failure for vertical conveyance equipment. As Seattle experiences more extreme high temperatures, HVAC systems will require more frequent maintenance and upgrades to avoid system failures, and at times air-conditioning may be insufficient to meet future cooling demands (Whitely Binder, Tohver, Shatzkin, & Snover, 2013).

4.3.2 Flooding Risks

TPSS are also susceptible to flooding, depending on their location. The 2013 *Sound Transit Climate Risk Reduction Project* identified that severe flooding on the Duwamish River could flood two ground-level TPSS: the Boeing Access TPSS and the South 133rd Street TPSS (Whitely Binder, Tohver, Shatzkin, & Snover, 2013), though no incidents of river flooding in either of these high-risk TPSS have been identified. The tidally influenced lower Duwamish River area may be particularly susceptible to flooding—with an intermediate likelihood, or 17% probability, of having sea levels increase by approximately 3.1 feet by 2100 (Error! Reference source not found.) (Miller, et al., 2018; NOAA, n.d.).

Furthermore, with increasing intensity of heavy rainfall events, these events can overwhelm stormwater systems, leading to localized flooding that can affect multiple locations, such as the Duwamish River, SODO, and Smith Cove areas (Mauger, et al., 2015; Rosenberg, et al., 2010). Electrical equipment in flood-prone areas—such as low-lying areas near the Duwamish River, SODO, and Ballard—can be exposed to water, leading to corrosion or damage to electrical equipment and infrastructure.

Figure 4-7. Potential Projected Inundation based on SLR, FEMA Floodplains, and additional Flood-prone Areas within Half Mile Buffer of Proposed WSBLE Alternatives

Notes: SLR data is from the NOAA Coastal Sea Level Rise viewer and FEMA flood maps. Please see Appendix TBD for downscaled map of impacts.

4.3.3 Climate Adaptation Considerations

Extreme Heat Adaptation

Sound Transit can adopt several adaptation measures to mitigate the risks of heat stress to electrical equipment. Tools to reduce heat stress include system design criteria that allows for **improved natural ventilation and air flow**, particularly for signal boxes; **increasing shading** around equipment to maximize passive cooling; and **adding HVAC systems**, which is already required for all signal bungalows. Providing **regular maintenance checks**—especially for electrical equipment sites in vulnerable locations—can mitigate future extreme heat impacts to electrical equipment.

Redundancy built into the Sound Transit system has reduced the risk of heat stress causing major service disruption. If one TPSS shuts down due to overheating, tie switches can link adjacent substations, minimizing service disruption to about 20 minutes in Central Link (Whitely Binder, Tohver, Shatzkin, & Snover, 2013). However, the loss of two or more sequential TPSS necessitates reducing service for approximately two hours while the equipment cools.

Finally, power outages during extreme heat events can be mitigated by **working with Seattle City Light** to install a dedicated line for Sound Transit systems trains to continuously run during extreme heat days. While expensive to do, **installing solar panels on top of electrical equipment** can allow for allow for electrical equipment to continue to function during summer months and brownouts. During the heat dome event in June 2021, various electrical equipment—such as vertical conveyance equipment—failed due to energy load demand.

Flooding Adaptation

To reduce the impact from flooding, Sound Transit can **locate TPSS, signal bungalows, and small signal boxes in less flood-prone areas**—such as areas along the Duwamish River, SODO, or in Ballard—or **raise the equipment higher above ground** (Whitely Binder, Tohver, Shatzkin, & Snover, 2013). Sound Transit can also **design grading around TPSS to slope away** to prevent flooding impacts or **install drainage and rain screens around equipment** to avoid damage and service interruption. Additionally, Sound Transit can also partner with the City of Seattle and Port of Seattle on reducing flood and erosion risks around equipment located in sensitive areas through **coordinated stormwater management**.

Additionally, Sound Transit operations staff can **regularly inspect and monitor equipment** in flood-prone areas more frequently and **ensure that pumps and drains are properly working**.

4.4 Tunnels

Overall, climate change impacts for tunnels are considered **minor**. In 2013, tunnel seepage was considered a minor impact because it had limited effect on customer service and operations. While Sound Transit has some infrastructure in place to accommodate increases in seepage rates, changes in design standards can mitigate the impact. However, considering the increased intensity of precipitation and storm events, extreme flooding Additionally, tunnels may experience rare extreme events, such as earthquakes, tsunamis, or dam failures. Even though these events are extremely unlikely to happen, they can result in catastrophic damage; accordingly, risks of these extreme events are considered **moderate**. While climate change is not a direct driver of these events, future climate conditions can create situations that increase the likelihood of flooding damage, tunnel failure, and poor post-event recovery.

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Tunnels			
Flooding	Moderate to Major	Moderate	Moderate[a]
Extreme events	Moderate to Major	High	Low

[a] Likely low to moderate depending on tunnel location.

4.4.1 Flooding and Groundwater Seepage

The 2013 *Sound Transit Climate Risk Reduction Project* identified that **heavy precipitation and flooding from stormwater is likely to increase groundwater seepage into tunnels**, leading to increased maintenance costs and odor issues. As of 2013, both the Beacon Hill Tunnel and the Downtown Seattle Transit Tunnel had experienced groundwater seepage. Beacon Hill had also experienced minor odor-related impacts associated with bacteria that produce foul-smelling hydrogen sulfide gas.

In addition to tunnel seepage, the confluence of multiple climate impacts such as sea level rise, high tide events and higher groundwater tables, and heavy precipitation events could cause **extreme flooding or flash flooding of tunnel stations or at-grade or below-ground station facilities** (Jacobs, et al., 2018; Mauger G. , et al., 2018). The Northgate Light Rail Station has already experienced water intrusion, affecting vertical conveyance systems and customer access to the tunnel (Morrison, 2021). While major flooding events in tunnels are unlikely, **other transit systems across the world experienced major tunnel flooding in 2021 due to heavy rains**. The NYC Metro has experienced three major flooding events in 2021—first in July 2021 following heavy rains, second in August 2021 following Hurricane Henri, and third in September 2021 following Hurricane Ida (Shanahan & Wong, 2021; Meyer & Beeferman, 2021). Additionally, heavy rains in the city of Zhengzhou in China's Henan province in July 2021 damaged the region's rail system and led to the deaths of 25 people (Woo & Qiu, 2021).

4.4.2 Extreme Events

There is a very low likelihood of an extreme event—such as earthquakes, tsunamis, or dam failures—that could lead to catastrophic flooding damage to tunnels. While no correlation between climate change and earthquakes is known, climate change impacts—such as sea level rise and shifting groundwater tables—can create conditions more favorable conditions for liquefaction to happen (Nath, et al., 2018; Risken, Fraser, Rutter, & Gadsby, 2015). While it is rare for Seattle to experience a tsunami or tsunami-like waves, strong currents or a strong earthquake along the Seattle Fault can trigger tsunamis and flood low-lying areas in short timeframes (City of Seattle, n.d.). Particularly, the Duwamish Valley, SODO, and Smith Cove areas are subject to liquefaction and tsunami hazards (**Error! Reference source not found.**).

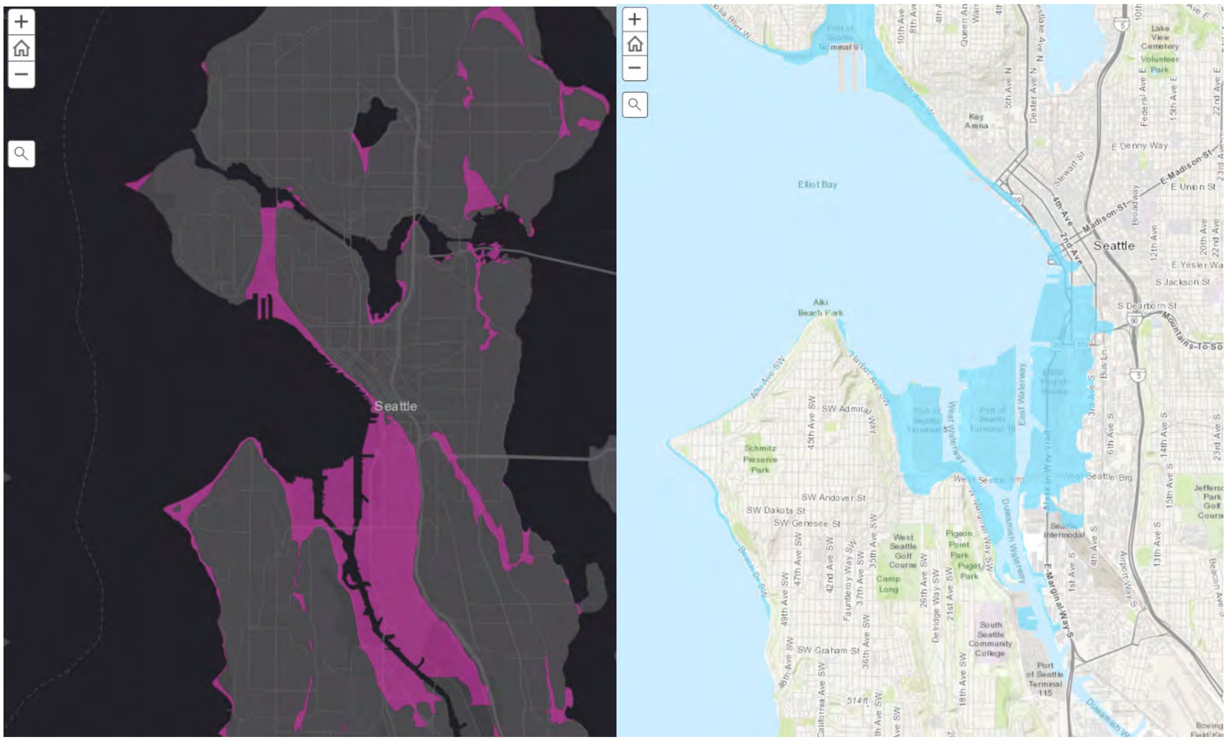


Figure 4-8. Liquefaction-prone Areas *(left)* and Tsunami Inundation Area *(right)*

Source: Seattle Hazard Explorer, accessed February 19, 2021.
Notes: The tsunami inundation area is based on a scenario of a 7.3 magnitude Seattle Fault Earthquake.

Finally, while not a direct climate-related risk, failure of the Howard Hanson Dam could lead to major flooding events along the Duwamish River. Structural deficiencies were discovered in Howard Hanson Dam in 2008–2009 following heavy rains and rapid snowmelt (Federal Emergency Management Agency, 2012). While the structural deficiencies were not attributed to the heavy rains or rapid snowmelt, more intense heavy rain events coupled with a dam failure event could lead to major flooding along the Duwamish River.

4.4.3 Climate Adaptation Considerations

Many transit systems—such as Boston's rail rapid transit network—are **implementing frameworks to evaluate engineering resilience** within the current lifecycle of their rail infrastructure investments (Martello, Whittle, Keenan, & Salvucci, 2021). Additionally, Sound Transit can adapt to the risk of tunnel seepage by **increasing the maintenance and replacement of pumps** used to manage seepage and continuing to adopt design standards that make tunnels more resistant to groundwater seepage. Though increased seepage could occur in any tunnel or underground station, tunnel drainage systems—which are sized to handle large water volumes for fire suppression—should be sufficient to handle seepage easily. Current design standards mandate that **pump stations are installed in all tunnels where gravity drainage is not possible**; that in tunneled sections below the water table, **rubber sealing gaskets are designed for the maximum expected groundwater head**; and that systems and measures used to prevent corrosion of facilities from groundwater be based on achieving a **minimum 50-year design life** (Sound Transit, 2021). Updated tunnel design standards **avoid**

direct soil contact, which should help prevent odor issues (Whitely Binder, Tohver, Shatzkin, & Snover, 2013).

Sound Transit can learn from other City metro and transit agencies to identify best practices. For example, following major typhoon-related flooding in 2001, Taipei Metro updated its design criteria to prevent any future major flooding (Taipei Metro, 2021). To protect infrastructure from the effects of future extreme events, **building tunnels outside of hazard-prone areas** or with minimal hazards can help avoid impacts and damage, though substantial portions of the WSBLE Project corridor could be affected. For example, Taipei Metro build all station entrances **50cm above the 200-year floodplain**. Where tunnels run under bodies of water, creating **tunnel compartments** that can serve as temporary flood barriers can contain flooding damage to a smaller section of the tunnel (Sosa, Thompson, Holter, & Fortune, 2020). **Tunnel portals, floodgates, and vent shafts** can be designed and located to prevent water intrusion from stormwater runoff, flooding, and sea level rise.

4.5 Bridges and Elevated Structures

It is particularly important to consider climate change impacts and vulnerabilities for bridges because they have a **long service life** that can extend beyond 100 years. Climate impacts for bridges are considered **minor** for the WSBLE Project. Increased air pollution and heavy rain events can increase the rate of corrosion and wear on bridges and other elevated structures. Sounder has experienced minor service disruptions due to two rail buckling incidents on a bridge during heat waves. While highly unlikely, an extreme event such as an earthquake could prove to be catastrophic for bridges. Uncertainty remains regarding how climate change will affect wind intensity, but high winds can cause wind-induced loading and potential damage.

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Bridges and Elevated Structures			
Extreme heat and air pollution	Moderate	Moderate	Low
Flooding	Minor	High	Low
Extreme events and winter storms	Minor	Moderate	Low

4.5.1 Extreme Heat and Ambient Air Pollution

There are several different types of extreme heat and air quality impacts for bridges and elevated structures. For WSBLE, there will be multiple elevated structures that will be higher than existing structures, such as the Ballard guideway and Delridge Station in West Seattle. **Warmer temperatures are likely to advance the expansion of joints that connect two bridge spans on moveable bridges.** While expansion joints are a small component of bridge structures, malfunctions to these joints can create major structural problems when coupled with thermal stress. Existing bridges in the Pacific Northwest are particularly vulnerable to expansion joint issues (Palu & Mahmoud, 2019). As noted in the rail buckling section, Sounder experienced rail buckling events on the Ballard railroad bridge owned by BNSF in 2006 and 2008. Since that time, BNSF removed a piece of track on the bridge and cools the rail with water during heat waves to prevent buckling. For example, the DuSable Bridge in Chicago could not open its navigation decks due to the heat-induced closure of its joints during a heatwave in

July 2018. Locally, Seattle Department of Transportation has experienced several incidences of moveable steel bridges over the Lake Washington Ship Canal becoming jammed due to extreme heat, including the Ballard Bridge in 2018 (Lindblom, 2018).

Heat stress and relative low humidity can increase creep rate, which can lead to serious consequences. For example, heat stress combined with aging infrastructure led to the 1996 collapse of the Koror–Babeldaob Bridge in Palau (Bažant, Hubler, & Yu, 2011). The projected temperature warming may place an increased demand on the deformation capacity of bridges and increase the thermal stresses (Nasr et al., 2019).

Bridges are also susceptible to more pronounced and localized air pollution. For example, a study found that increased atmospheric carbon dioxide can lead to a 400% increase carbonation-induced damage for structures by 2100 in Australia (Stewart, Wang, & Nguyen, 2011).

4.5.2 Flooding, Hydrology, and Sea Level Rise

Flooding from heavy precipitation events and sea level rise are likely to accelerate bridge corrosion. A study in Finland found that precipitation and air pollution can accelerate active corrosion by almost twice the current rate from 1980–2009. When flooding and sea level rise is coupled with nutrient runoff, bridge foundations and substructures can be further aggravated. Examples of bridge failures partially attributed to corrosion include Ohio's Silver Bridge and Connecticut's Mianus River Bridge (Nasr, et al., 2019). Exposure to saltwater, such as in the tidally influenced lower Duwamish River can present additional challenges.

Bridge scour, occurring when swiftly moving water removes sediment from around bridge structural supports, weakening or destroying their foundations, proves to be one of the most common causes of bridge failure for New York's Department of Transportation (Cook, Barr, & Halling, 2015). **Projected increases in the intensity and duration of precipitation events may likely exacerbate bridge scour due to higher flow depths and speeds, and lower kinematic viscosity.** The projected increase in winter precipitation may induce some bridge scour along the Duwamish River.

Heavy rain events will also likely affect drainage capacity. Heavy rain events can overwhelm bridge drainage systems and can increase hydrostatic pressure building up behind bridge abutments.

4.5.3 Extreme Events

Extreme events will likely affect bridges, though there is uncertainty in the connections between climate change and these extreme events as well as their impacts on bridges. Potential extreme events include winter storms and blizzards, earthquakes, and windstorms.

Freeze/thaw cycles and de-icing salt application after blizzards and winter storms have had varying impacts on bridge deterioration (Nasr et al. 2019). While this is highly unlikely in Seattle, exposure to **de-icing salt and other de-icing solutions could accelerate bridge deterioration** over its lifespan.

Although no correlation between climate change and earthquakes is known, climate change can create conditions more favorable for **liquefaction** to happen (Nath, et al., 2018).

While the correlation between increased wind intensity and climate change remains uncertain and inconclusive, high winds associated with extreme storms can simultaneously **increase wave height and wind static loading** (Mauger, et al., 2015; Nasr, et al., 2019; Collins, et al., 2019). High winds and wind-induced loading were the primary reasons for the 1940 failure of the Tacoma Narrows Bridge (Nasr, et al., 2019).

4.5.4 Climate Adaptation Considerations

Extreme Heat Adaptation

There is a lot of best practices that Sound Transit can **learn from transit systems** that routinely experience extreme heat—such as those in Arizona, Texas, and New Mexico. Sound Transit can take both **proactive and reactive approaches to adapting to climate impacts that can affect bridges**. Preventative measures to limit sea level rise-induced bridge damage include **reevaluating design standards and construction locations** to reduce, modify, or relocate new development in vulnerable regions. Like extreme heat adaptation options for rail and track systems, **having monitoring equipment** at at-risk areas can help identify and prevent potential bridge malfunctions. While more expensive, **using heat-resistant components** (i.e., nuts and bolts) rather than off-the-shelf products can help mitigate future extreme heat impacts across a structure's lifespan.

To reduce heat expansion issues, cooling methods can be used; for example, SDOT now cools movable bridges by spraying water when Seattle has three consecutive days of >85°F or weather (Seattle Department of Transportation, 2018).

Flooding and Extreme Event Adaptation

Preventative measures can also be taken to adapt to increased precipitation, such as ensuring design and management procedures **integrate the increased potential for damage under extreme hydraulic loads** (Mondoro, Frangopol, & Liu, 2018). Furthermore, considering different types of **wind screens and walkways that don't allow ice to accumulate** can prevent potential extreme winter and cold impacts.

Reactive measures **include retrofitting bridges that are vulnerable to deck unseating** by elevating bridges well above the limit of potential storm surge inundation; a high bridge will already avoid this risk. Reactive measures can also be implemented to reduce bridge substructure failure due to scour. **Scour damage may be reduced through armoring measures or flow-alerting measures** such as riprap, collars, and scour-monitoring devices. Collars may be applied to bridge piers to reduce the magnitude of scour damage, and scour-monitoring devices can provide an indication of the current performance of a bridge (Mondoro, Frangopol, & Liu, 2018).

4.6 Rail Service Operations

Rail service operations are a cross-cutting system-wide consideration. Generally, there is a **minor to moderate risk** that climate change will affect light rail service operations. Impacts to rail and track bed, the OCS, and electrical equipment can delay or disrupt rail services—and in rare cases can lead to larger service disruptions such as the 2019 event where multiple smaller impacts and delays due to extreme heat coalesced into a system-wide service shutdown

(Adolph, 2019). Depending on location, landslides and mudslides can also cause service disruptions, though this has primarily been a concern along the BNSF rail corridor where the Sound operates. Slope failure can be triggered by heavy rainfall events, which are projected to increase in intensity in the future. While unlikely, there may be a future scenario where energy demand exceeds energy capacity, leading to power shortfalls and outages for Sound Transit's operational energy needs.

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Rail Service Operations *(cross-cutting)*			
Extreme Heat	Moderate	Moderate	Low
Flooding	Moderate	Limited	Moderate
Mudslides and landslides	Minor to Moderate[a]	Moderate	Low

[a] Likely low to moderate depending on location.

4.6.1 Extreme Heat Impacts

In 2020, Sound Transit announced that its light rail train are running on carbon-free energy, aligning with its long-term goals of electrifying and reducing carbon emissions in its operations to mitigate climate change (Sound Transit, Sound Transit light rail trains are now running on clean energy, 2020; Sound Transit, 2019 Sustainability Progress Report, 2020). Because Sound Transit's system is dependent on electricity, there is a **minor risk of experiencing future power shortages and disruptions during summer months**, when energy demand increases and could overwhelm electrical systems and grids (May, et al., 2018).

4.6.2 Flooding Risks

While the 2013 *Sound Transit Climate Risk Reduction Project* did not explicitly study disruptions to rail service, **it is important to consider rail service disruptions as extreme weather events increase in frequency**. The 2013 report did indicate, however, that service disruptions could occur from rail buckling or cascading events, as seen with the shutdown of Light Rail operations due to extreme heat in June 2019 (Adolph, 2019). Though major service disruptions are rare, extreme heat days or heavy rainfall events are expected to become more frequent and could result in minor service disruptions, such as the slowing or delaying of trains.

4.6.3 Mudslides and Landslides

Landslides and mudslides are likely to occur and could cause service disruptions depending on locations. Slope failure and landslides can be triggered by intense rainfall events (Mauger, et al., 2015; Sobie, 2020). With rainfall projected to increase, landslides are predicted to increase in frequency—especially considering Seattle's steep hills—which could disrupt rail service if nearby (Nasr, et al., 2019). Sound Transit annually tracks the number of service disruptions due to mudslides. Since 2015, over 20,000 Sounder riders have had their trip disrupted due to mudslides (Sound Transit, Fare Revenue Report, 2019). Areas of West Seattle near the

Duwamish River and the hills adjoining Interbay are prone to landslides (2-1), though the light rail alignment can be located to avoid them.

Figure 4-9. Map of Known Landslide Locations and Potential Landslide Areas within Half Mile Buffer of Proposed WSBLE Alternatives

Notes: Known and potential landslide areas are identified in the City of Seattle's Critical Areas Ordinance. Please see Appendix TBD for downscaled maps of impacts.

4.6.4 Climate Adaptation Considerations

By implementing climate adaptation measures for other parts of the WSBLE system, Sound Transit can mitigate extreme heat and flooding impacts on rail service operations.[3] Additionally, there are several ways that Sound Transit can reduce the risk of landslides disrupting rail services. Options for mitigating landslide risks fall into three categories: landslide avoidance, protection, and stabilization. Avoidance measures include **locating tracks away from slopes** (Sound Transit, Fare Revenue Report, 2019). Protection measures include **containing and diverting moving debris** in the form of walls, berms, ditches, and catchment basins. Stabilization includes **grading unstable portions** of hillside slopes to lower gradients, constructing **rock buttresses and retaining walls**, and **improving drainage systems** to reduce water pressure in the immediate vicinity of hillsides. For Sounder service continuity, Sound Transit contracts with Community Transit, King County Metro, Pierce Transit, and Starline Luxury Coaches to **provide coach service when mudslides affect rail service** (Sound Transit, Fare Revenue Report, 2019).

4.7 Customer Experience

Customer experience impacts are a cross-cutting system-wide consideration. Generally, there is a **moderate risk** that climate change will affect customer experience. Heavy rains, storms, and intense winds can negatively affect customer experience, especially at elevated stations. Flooding associated with heavy rains can impede customer access to station entrances, especially for tunnel and elevated stations. Additionally, vertical circulation equipment, such as elevators and escalators, can malfunction due to heavy rains or extreme heat. Passengers in light rail vehicles without HVAC systems can experience overheating or heat exhaustion, especially during extreme heat days.

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Customer Experience ***(cross-cutting)***			
Heavy rains, storms, and flooding	Moderate	Moderate	Low
Extreme heat	Moderate	Moderate	Low

4.7.1 Heavy Rains, Storms, and Flooding

Future climate change will likely impact the intensity of heavy rain events. Seattle will likely experience **a 54% increase in the 10-year hourly rainfall event by the end of the century** (Mauger G. , et al., 2018). Heavy wind impacts resulting from intense storms can also impact customer experience. This is particularly likely at elevated stations and structures due to an increase in wind speed at higher elevations. As wind intensity increases due to climate change and exceeds the current 55 mph safety threshold more often, **more service delays and trip cancellations are likely to occur**. Areas that are likely to be highly impacted by heavy wind impacts include the elevated bridge that crosses the Duwamish River and the elevated bridge

[3] See 4.1.4 Climate Adaptation Considerations in the Rail and Track section for extreme heat and flooding adaptation considerations.

crossing over ship canal between Ballard and Queen Anne area. Currently, Sound Transit has adapted to heavy wind events by constructing canopy coverage and wind protection for certain stations.

As heavy rains increase in intensity and frequency, stormwater flooding will increase comparatively leading to significant impacts on **customer access to station entrances** to elevated and tunnel station entrances. Specific stations of concern due to location and design include Ballard and Delridge stations, where heavy rains can impede station access.

Flooding and heavy rains may also **impact vertical mobility functions of elevators and escalators**, resulting in bottlenecks for customer traffic, causing increased wait times and customer dissatisfaction. For example, Sound Transit has experienced water leakage and flooding in elevator hoistways, which causes service interruptions. These flood events **prevent access for those who may need physical access** to elevated structures.

4.7.2 Extreme Heat

The heat dome event in June 2021 caused **multiple service interruptions of vertical circulation equipment** that affect customer experience. In the Mukilteo station, elevator belts continued to slip due to overheating, making it difficult for elevator units to level correctly and causing a 12–24-hour service outage. Additionally, an escalator at the SeaTac Airport Station overheated and shut-off during the heat dome event due to multiple consecutive days of >100°F and direct exposure of the aluminum threshold plates to sunlight. Additionally, elevator hoistways overheated across the Sound Transit service area, interrupting or halting service.

Additionally, there are some older light rail vehicles that do not have HVAC systems. Extreme heat days can amplify negative experiences – such as **overheating or heat exhaustion** – for Sound Transit passengers.

4.7.3 Climate Adaptation Considerations

Heavy Rains, Storms, and Flooding Adaptation

Sound Transit has multiple proactive design options available to them. **Canopy coverage, especially at elevated stations,** can provide rain and wind protection for customers. The current DCM requires 65% roof coverage—however, this may be updated to be consistent with Seattle Municipal Code, which requires 100% coverage. The use of glass canopies and clerestory layers for aesthetic purposes can be expensive to construct and maintain.

There are also multiple ways to prevent or adapt to future flooding related to heavy rain. Installing **louvers** can prevent rain and water from entering hoistways. However, they do not always protect against wind-driven rain and water leaks. **Caulking glazing panels**, **roof and envelope details**, and **trench drains** can also mitigate flooding, leakage, and water damage. Regular **maintenance and detailing** can also preempt water damage and leakage issues.

Extreme Heat Adaptation

There are multiple options for Sound Transit to adapt to extreme heat to maintain and improve customer experience. Installing and maintaining **durable elevator cab fans**, mounting **AC split units in areas away from direct sun exposure** or in well ventilated areas, using **more opaque or lighter designs and panels**, and continuing to use **oil coolers** can ensure that vertical circulation equipment service is uninterrupted during extreme heat events.

Retrofitting older light rail vehicles with HVAC systems or implementing **purchasing requirements for HVAC units** on all future light rail vehicles can ensure that there are cooling and ventilation options for customers during extreme heat days.

4.8 Construction

Climate impacts to construction design and process are a cross-cutting system-wide consideration. Generally, there is **minor to moderate impacts** to construction sites and workers can experience due to extreme heat and flooding. However, providing shading and cooling options can mitigate extreme heat impacts and diverting water away from guideways can mitigate flooding impacts.

WSBLE Project Elements & Effects	Impacts	Adaptive Capacity	Vulnerability
Construction *(cross-cutting)*			
Extreme Heat	Minor	Moderate	Low
Flooding	Moderate	Moderate	Low

4.8.1 Heat Impacts

As climate change continues longer and hotter extreme heat events, construction of new infrastructure will have to adapt to a changing environment. One of the largest heat impacts to consider when constructing new stations or other infrastructure is the impact on concrete. This is especially important to consider because concrete serves as the beginning of the rail infrastructure's lifecycle. When pouring concrete, **high temperatures can affect the material's compressive strength**, as the material cannot properly hydrate and therefore will lose some of its compressive strength. Additionally, pouring concrete during an extreme heat event can lead to cracking and shrinkage of the material, making it unstable.

Additionally, we know **concrete can create heat island effects**, leading to warmer temperatures for construction workers at sites. To keep workers safe during construction processes, considering the impact of the heat island effect on worker health and safety is crucial. This also affects Sound Transit staff who respond to events during extreme heat days, such as June 2021 heat dome event.

4.8.2 Flooding Impacts

Flooding can cause additional issues during construction, in situations where other nearby construction projects redirecting water onto the guideway, **causing issues with signaling**. Flooding during construction can be catastrophic to certain projects, **ruining materials, or causing delays** where the land must dry and stabilize before proceeding.

4.8.3 Climate Adaptation Considerations

To prevent extreme heat impacts on construction processes, **adequate shade**—whether natural or built—during summer months can alleviate extreme heat impacts and heat island effects during construction. Additionally, creating **water and rain diversions** and **planning for**

flooding risks during construction design and siting can prevent flooding of guideways during construction.

Finally, ensuring that construction workers and Sound Transit staff have a**dequate shading and cooling options**—such as ice water—can prevent overheating and heat exhaustion during extreme heat days.

5 SUMMARY

The climate in western Washington has been rapidly changing since the 1900s—with warmer air temperatures, reduced mountain snowpack, sea level rise, winter storms, and changing water availability. Climate change in the region will continue to affect infrastructure, including the WSBLE Project, over the next century and beyond. This report updates Sound Transit's 2013 *Climate Risk Reduction Project* with new research from the scientific literature, other agencies, and Sound Transit's experience.

This report identifies projected climate change impacts that may create infrastructure, access, or operational vulnerabilities for the WSBLE Project. Potential climate change impacts to the WSBLE Project include the following:

- **Rail and track systems** can experience rail buckling in extreme heat and flood damage from river flooding, coastal flooding, and stormwater-related flooding.
- **Overhead catenary systems** can have line sags during extreme heat, though risks to Sound Transit's OCS are considered low.
- **Traction power substations (TPSS), signal bungalows, signal boxes, and other electrical equipment minor to moderate risk to electrical equipment and infrastructure** can face heat stress and equipment damage from heat waves or water damage if located in areas where they can be inundated by stormwater, flooding, or sea level rise.
- **Tunnels** can experience seepage, though existing drainage systems are ample to handle these flows. Rare extreme events, such as earthquakes, tsunamis, or dam failures are unlikely but could result in severe damage.
- **Bridges** that are moveable can experience issues with extreme heat. Stormwater, flooding, air pollution, and wind can also increase corrosion and wear on bridges. Rare extreme events such as a major earthquake can damage structures.
- **Rail operations** can be affected by climate change impacts to the infrastructure elements outlined above, including heat stress, flooding, or landslides. Impacts on the overall electricity grid, such as during severe storms or heat waves, could also result in power shortfalls and outages for Sound Transit's operations.
- **Customer experience** can be affected in a variety of ways. Heavy rains, storms, and flooding can affect access to station entrances and negatively affect customer experience, especially at elevated stations. Extreme heat can also cause service issues for vertical circulation equipment, affecting accessibility to tunnel and elevated stations.
- **Construction** projects can be by extreme heat by damaging concrete and overheating workers. Heavy rain events can flood construction sites, especially in areas where other construction projects or impervious surfaces divert water into construction sites.

In addition to the individual impacts summarized above, the potential of cascading and compounding impacts should be considered, as a series of low to moderate effects can combine to produce major climate change-related impacts. By assessing climate-related impacts and vulnerabilities in the planning stages for the WSBLE Project and other infrastructure, Sound Transit can prepare for climate changes and include adaptation measures to support resilient infrastructure and operations over the next century.

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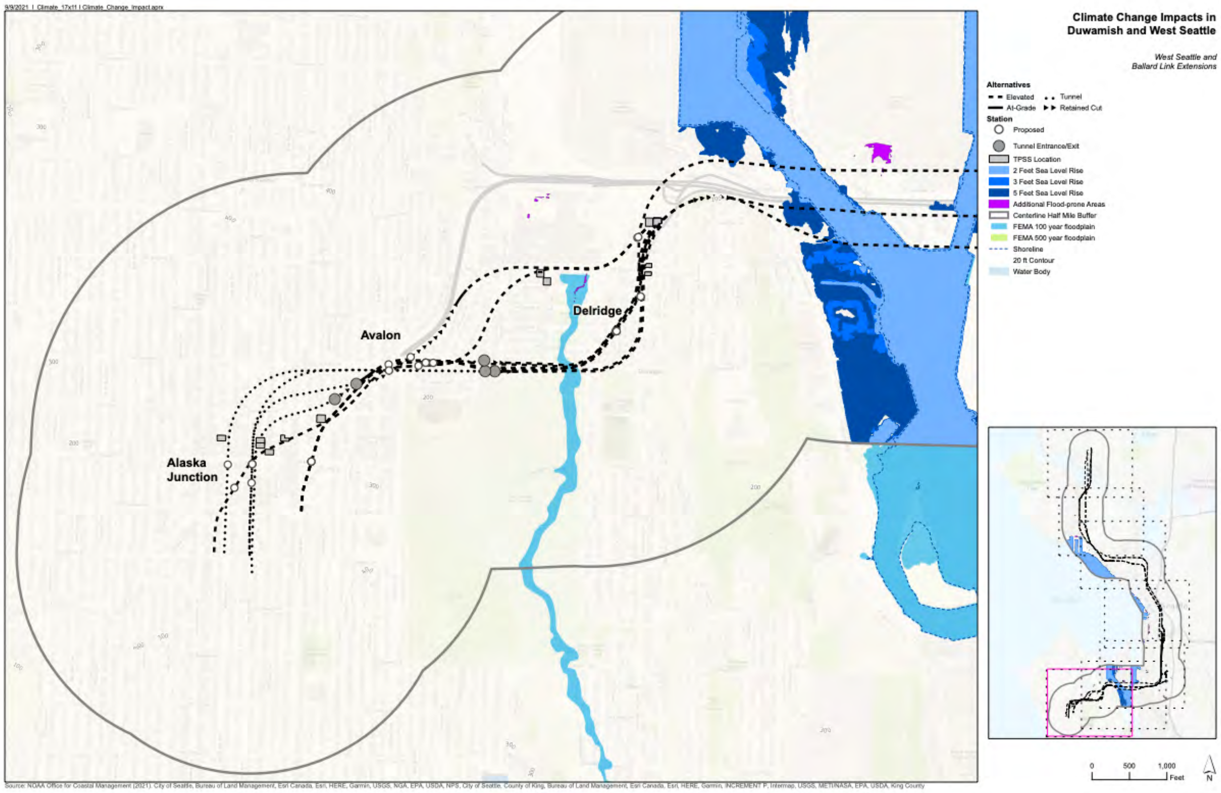
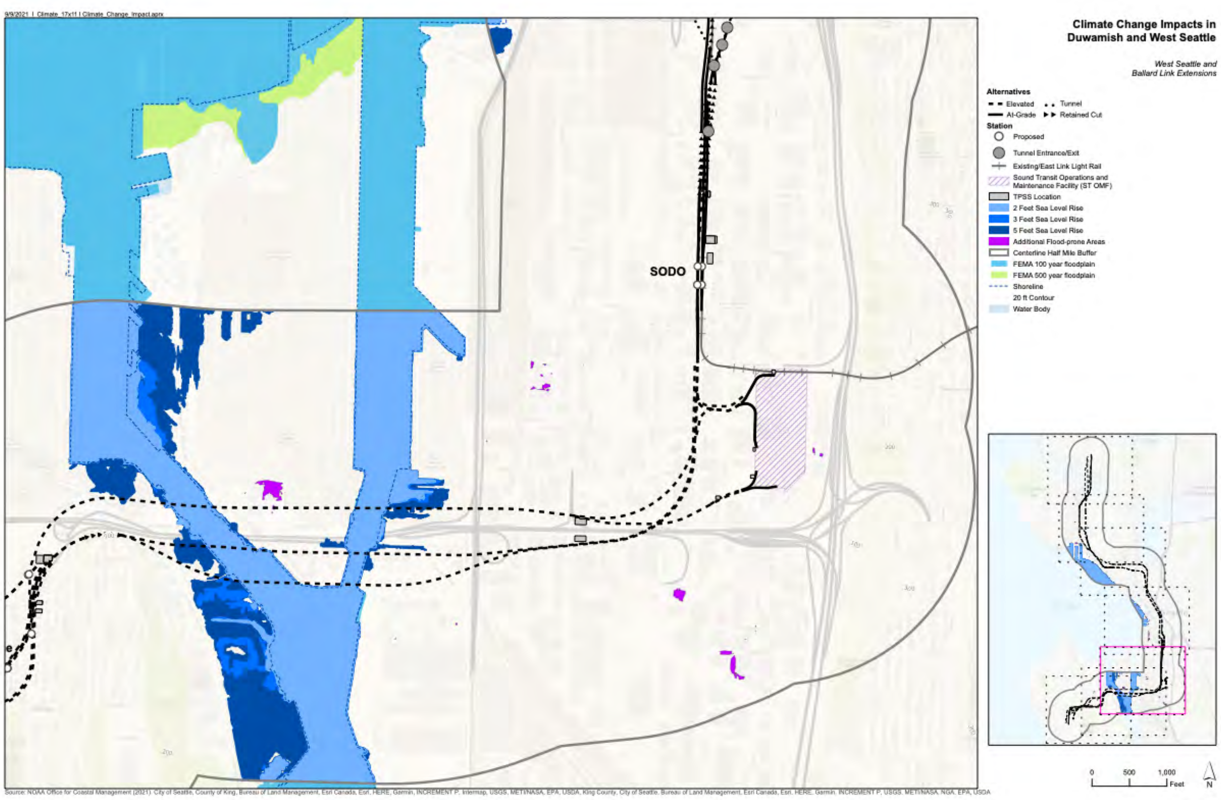
7 CLIMATE IMPACT MAPS

The maps below provide an overview of flooding and landslide impacts with a half mile buffer of WSBLE route alternatives. These maps have been downscaled for each section of the WSBLE. We have also included extreme heat maps developed by King County.

7.1 Flooding and Sea Level Rise Maps


9/9/2021 | Climate_17x11 | Climate_Change_Impact.aprx
Climate Change Impacts in Duwamish and West Seattle
West Seattle and Ballard Link Extensions
Alternatives
Elevated
Tunnel
At-Grade
Retained Cut
Station
Proposed
Tunnel Entrance/Exit
TPSS Location
2 Feet Sea Level Rise
3 Feet Sea Level Rise
5 Feet Sea Level Rise
Additional Flood-prone Areas
Centerline Half Mile Buffer
FEMA 100 year floodplain
FEMA 500 year floodplain
Shoreline
20 ft Contour
Water Body
Delridge
Avalon
Alaska Junction
0
500
1,000
Feet
N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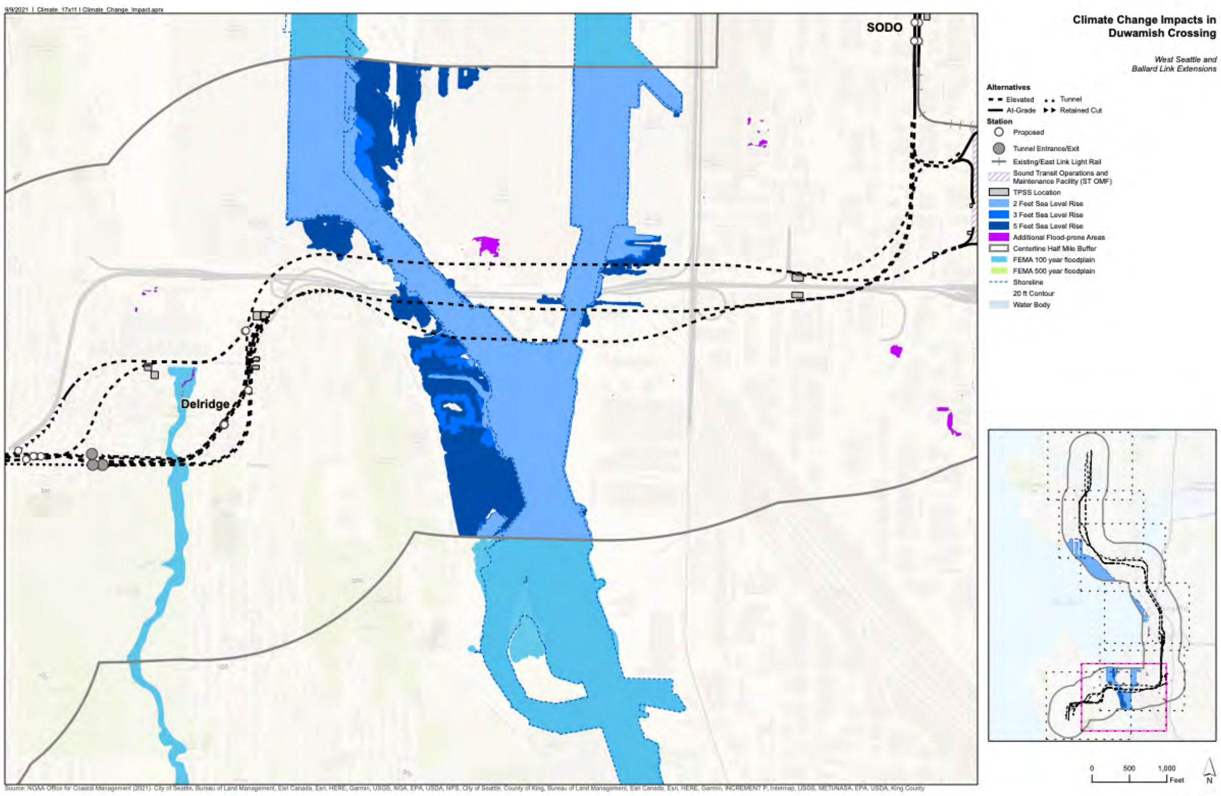
Climate Change Impacts in Duwamish and West Seattle
West Seattle and Ballard Link Extensions
Alternatives
Elevated
Tunnel
At-Grade
Retained Cut
Station
Proposed
Tunnel Entrance/Exit
Existing/East Link Light Rail
Sound Transit Operations and Maintenance Facility (ST OMF)
TPSS Location
2 Feet Sea Level Rise
3 Feet Sea Level Rise
5 Feet Sea Level Rise
Additional Flood-prone Areas
Centerline Half Mile Buffer
FEMA 100 year floodplain
FEMA 500 year floodplain
Shoreline
20 ft Contour
Water Body
SODO
0
500
1,000
Feet
N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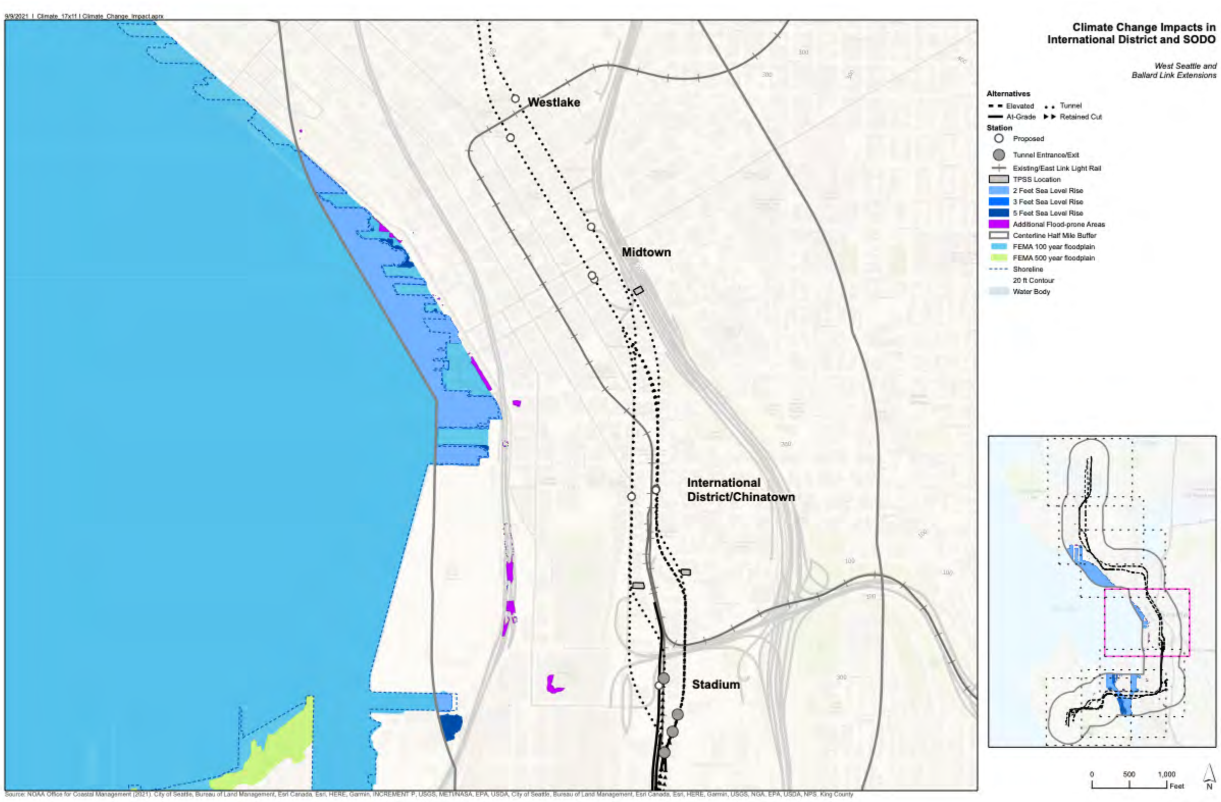
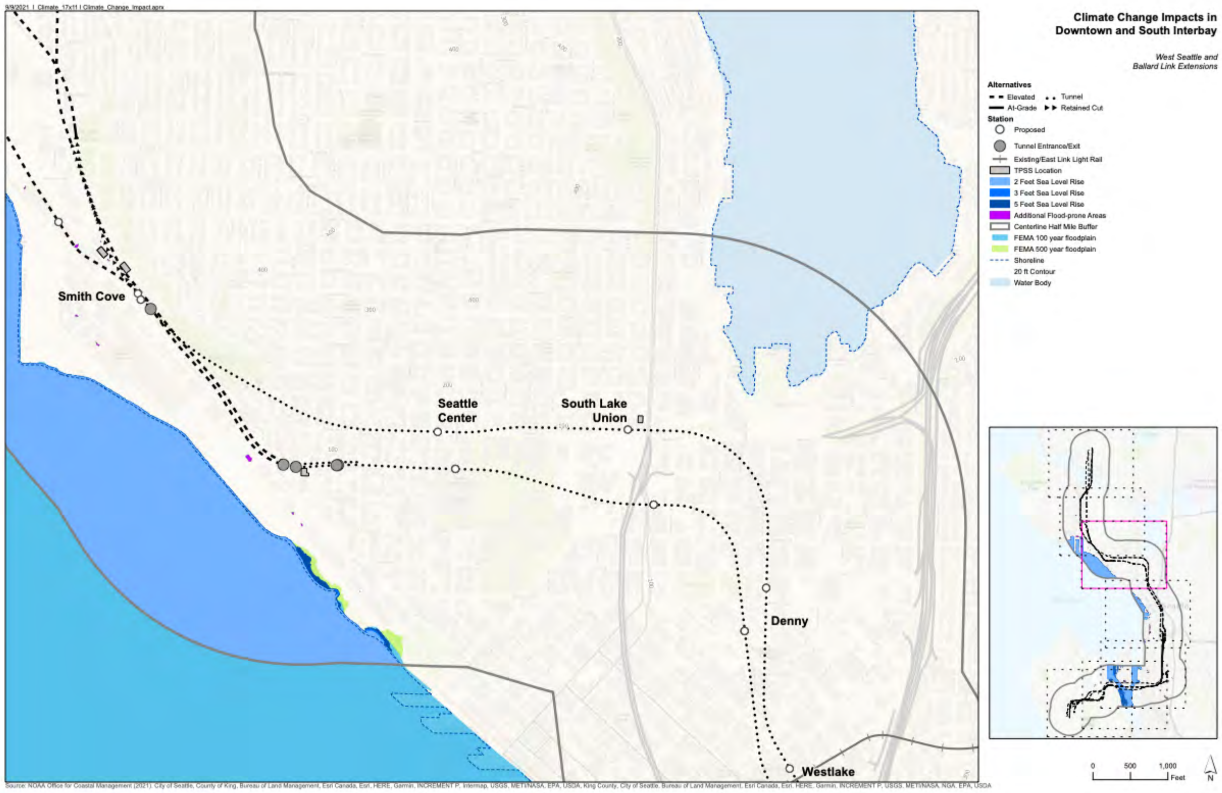
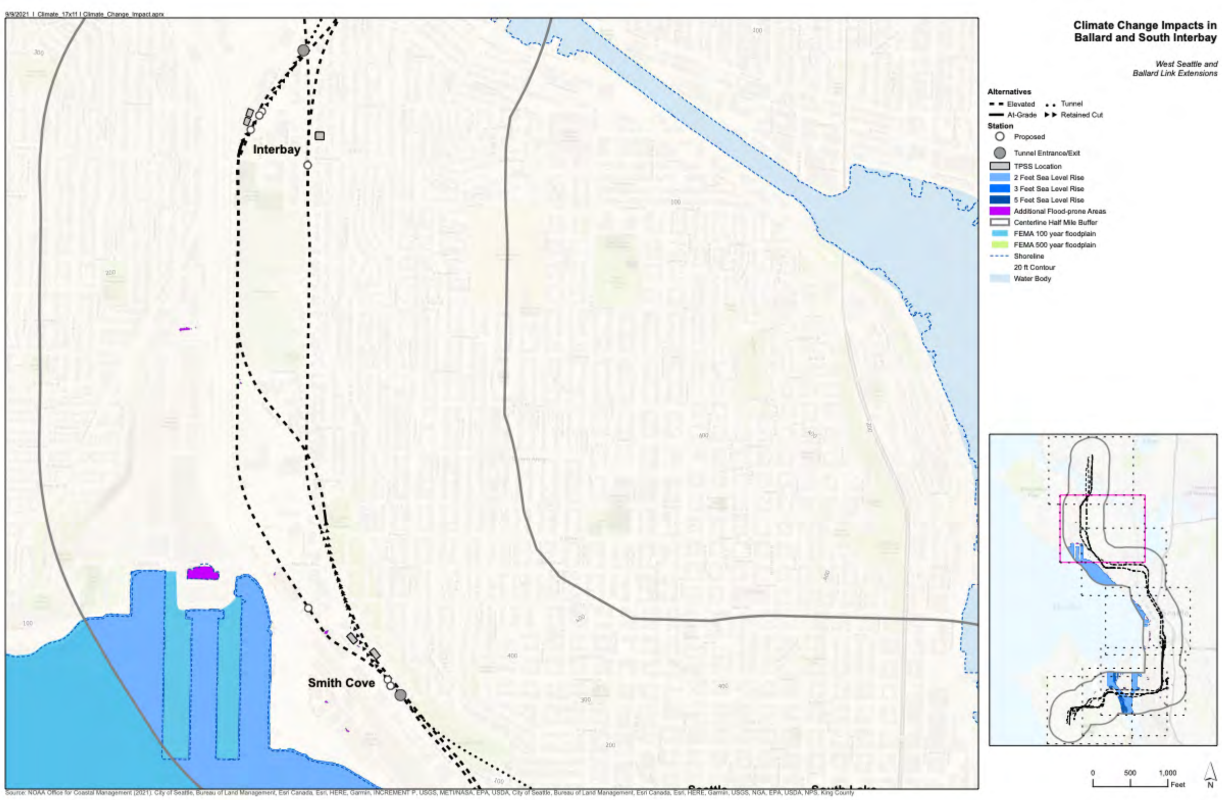
Climate Change Impacts in Duwamish Crossing
West Seattle and Ballard Link Extensions
Alternatives
Elevated
Tunnel
At-Grade
Retained Cut
Station
Proposed
Tunnel Entrance/Exit
Existing/East Link Light Rail
Sound Transit Operations and Maintenance Facility (ST OMF)
TPSS Location
2 Feet Sea Level Rise
3 Feet Sea Level Rise
5 Feet Sea Level Rise
Additional Flood-prone Areas
Centerline Half Mile Buffer
FEMA 100 year floodplain
FEMA 500 year floodplain
Shoreline
20 ft Contour
Water Body
SODO
Delridge
0
500
1,000
Feet
N

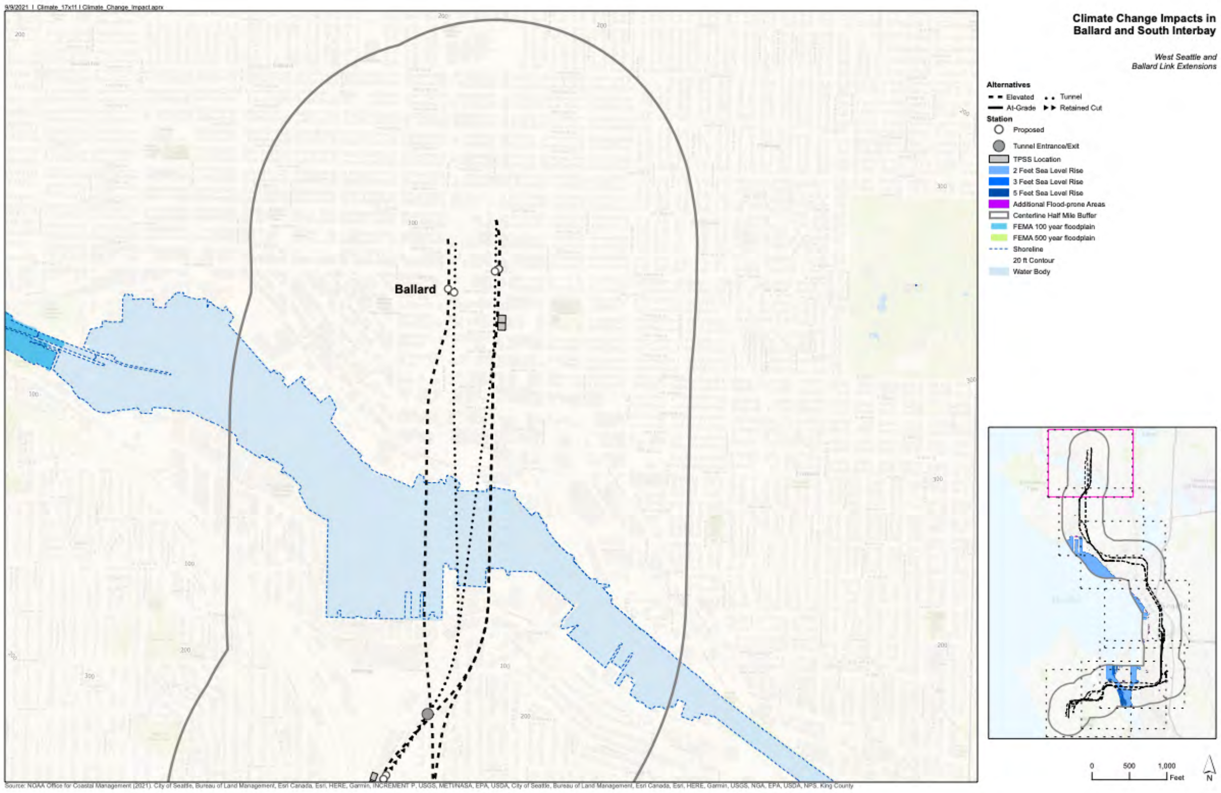

9/9/2021 | Climate_17x11 | Climate_Change_Impact.aprx
Climate Change Impacts in International District and SODO
West Seattle and Ballard Link Extensions
Alternatives
Elevated
Tunnel
At-Grade
Retained Cut
Station
Proposed
Tunnel Entrance/Exit
Existing/East Link Light Rail
TPSS Location
2 Feet Sea Level Rise
3 Feet Sea Level Rise
5 Feet Sea Level Rise
Additional Flood-prone Areas
Centerline Half Mile Buffer
FEMA 100 year floodplain
FEMA 500 year floodplain
Shoreline
20 ft Contour
Water Body
Westlake
Midtown
International District/Chinatown
Stadium
0
500
1,000
Feet
N



Climate Change Impacts in Downtown and South Interbay
West Seattle and Ballard Link Extensions
Alternatives
Elevated
Tunnel
At-Grade
Retained Cut
Station
Proposed
Tunnel Entrance/Exit
Existing/East Link Light Rail
TPSS Location
2 Feet Sea Level Rise
3 Feet Sea Level Rise
5 Feet Sea Level Rise
Additional Flood-prone Areas
Centerline Half Mile Buffer
FEMA 100 year floodplain
FEMA 500 year floodplain
Shoreline
20 ft Contour
Water Body
Smith Cove
Seattle Center
South Lake Union
Denny
Westlake
0
500
1,000
Feet
N



Climate Change Impacts in Ballard and South Interbay
West Seattle and Ballard Link Extensions
Alternatives
Elevated
Tunnel
At-Grade
Retained Cut
Station
Proposed
Tunnel Entrance/Exit
TPSS Location
2 Feet Sea Level Rise
3 Feet Sea Level Rise
5 Feet Sea Level Rise
Additional Flood-prone Areas
Centerline Half Mile Buffer
FEMA 100 year floodplain
FEMA 500 year floodplain
Shoreline
20 ft Contour
Water Body
Interbay
Smith Cove
0
500
1,000
Feet
N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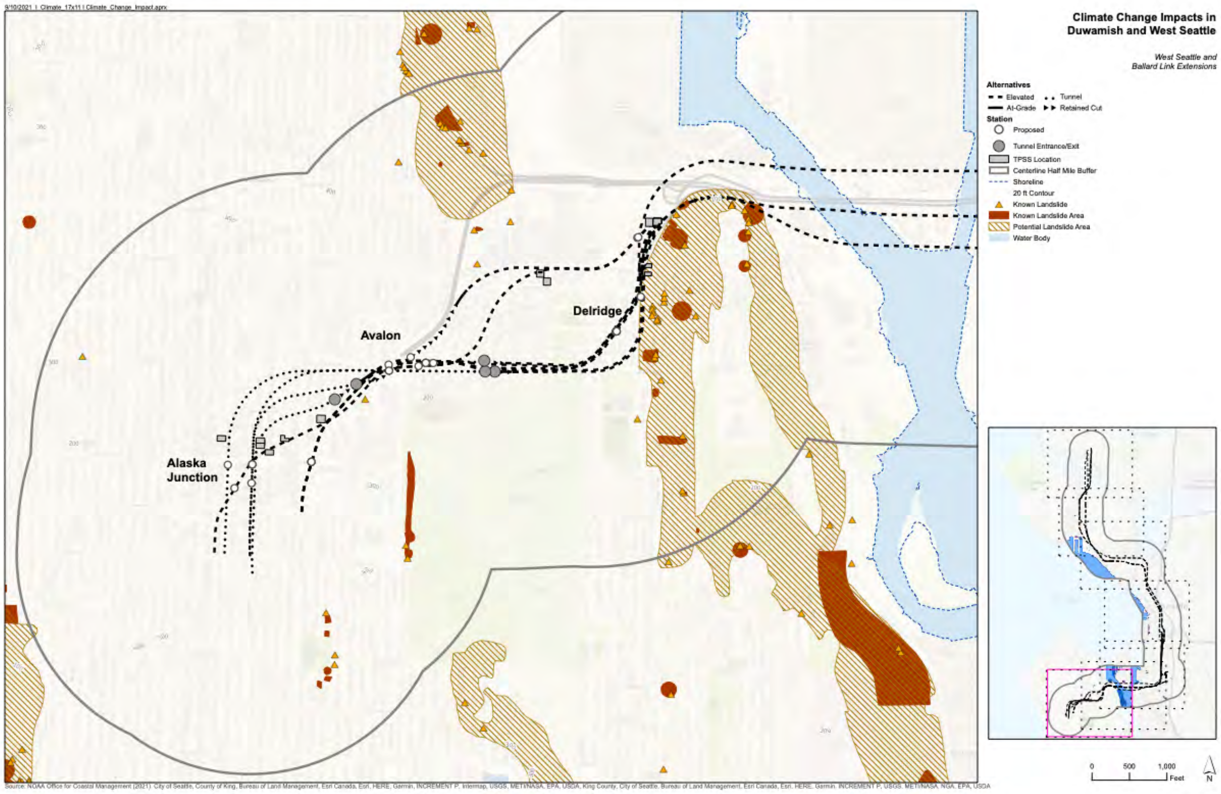
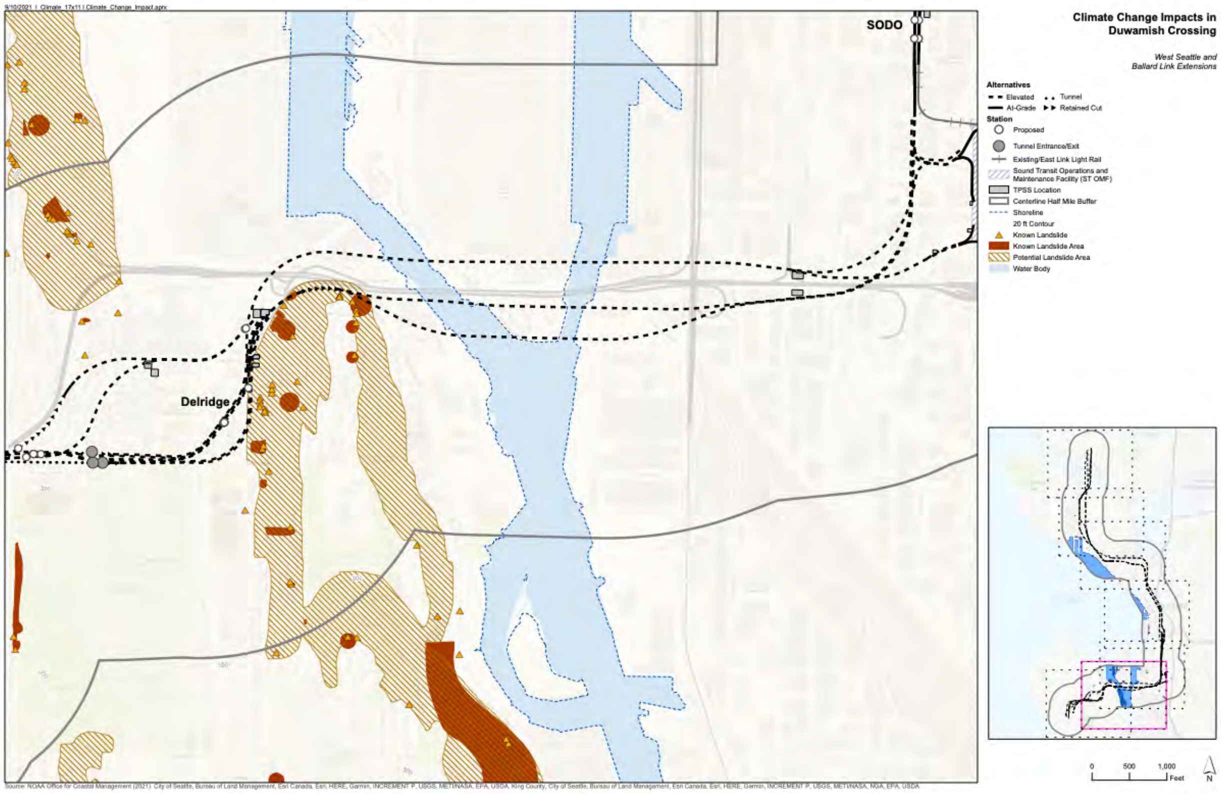
Climate Change Impacts in Ballard and South Interbay
West Seattle and Ballard Link Extensions
Alternatives
Elevated
Tunnel
At-Grade
Retained Cut
Station
Proposed
Tunnel Entrance/Exit
TPSS Location
2 Feet Sea Level Rise
3 Feet Sea Level Rise
5 Feet Sea Level Rise
Additional Flood-prone Areas
Centerline Half Mile Buffer
FEMA 100 year floodplain
FEMA 500 year floodplain
Shoreline
20 ft Contour
Water Body
Ballard
0
500
1,000
Feet
N

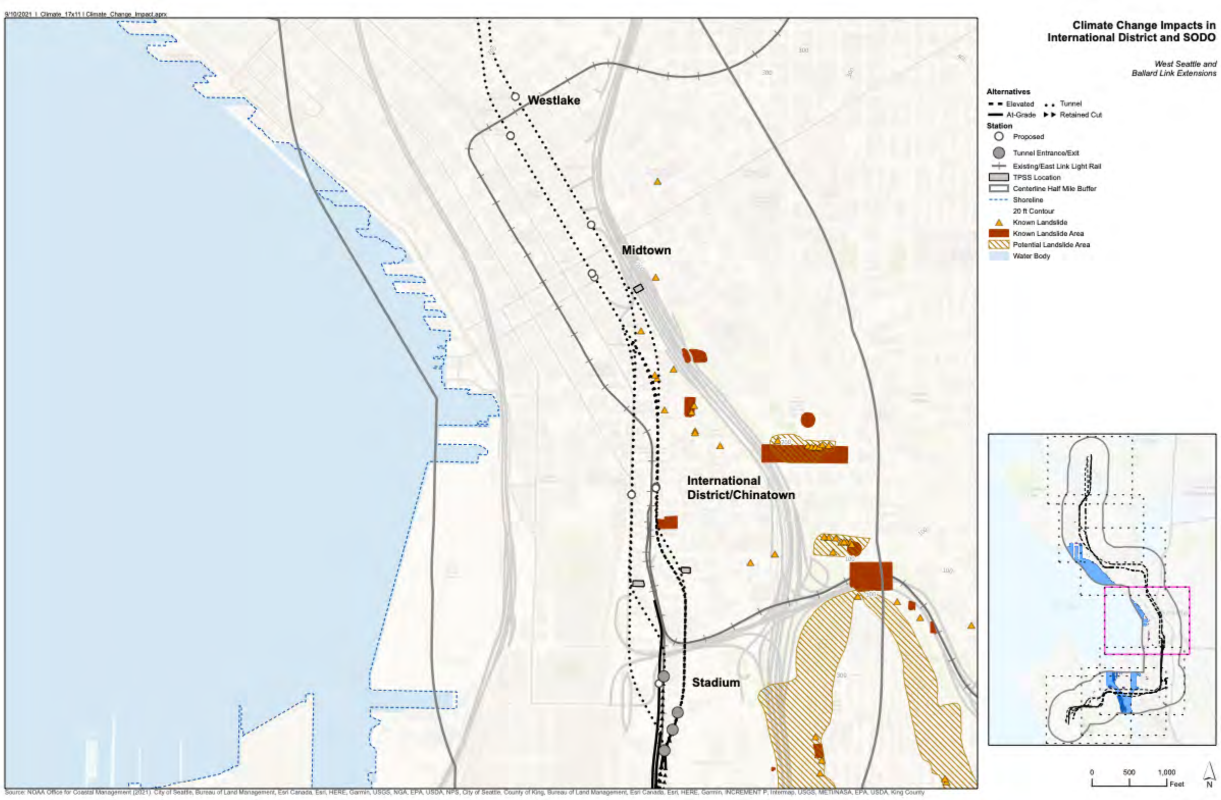
7.2 Landslide Maps


Climate Change Impacts in Duwamish and West Seattle
West Seattle and Ballard Link Extensions
Alternatives
Elevated
Tunnel
At-Grade
Retained Cut
Station
Proposed
Tunnel Entrance/Exit
TPSS Location
Centerline Half Mile Buffer
Shoreline
20 ft Contour
Known Landslide
Known Landslide Area
Potential Landslide Area
Water Body
Delridge
Avalon
Alaska Junction
0
500
1,000
Feet
N

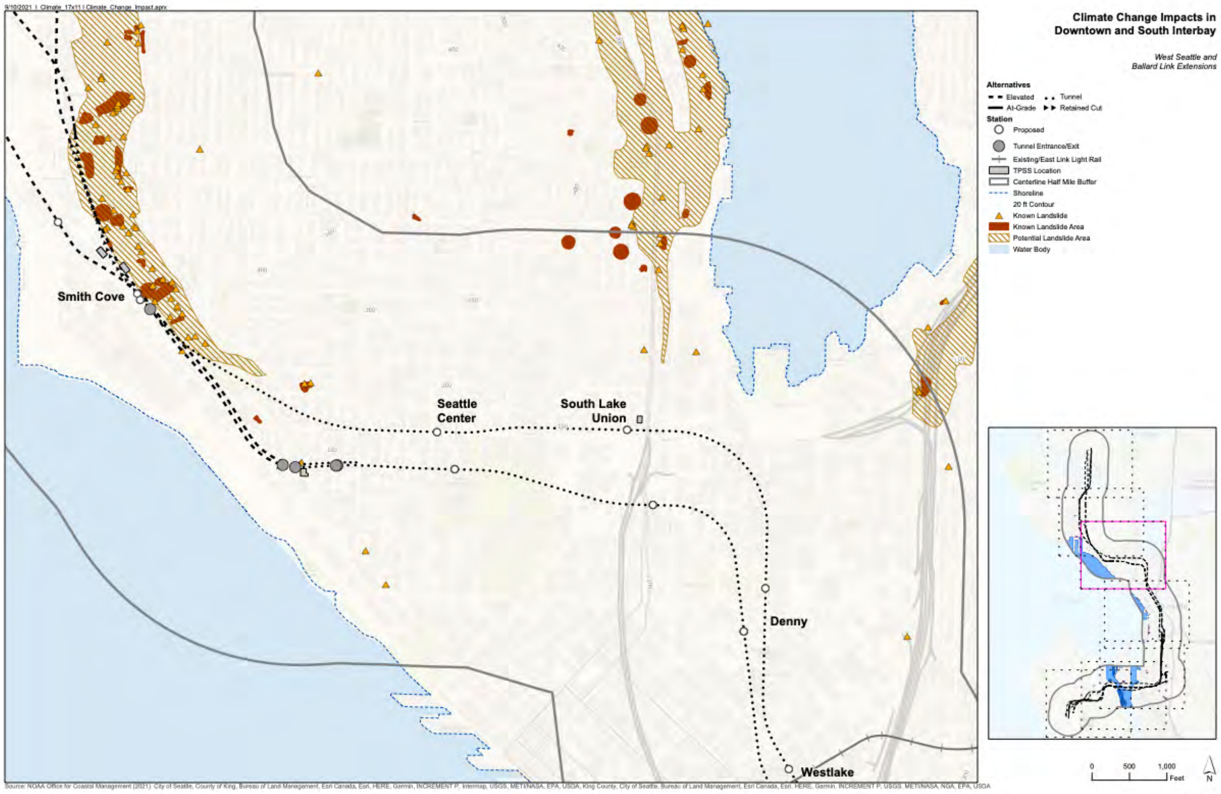

Climate Change Impacts in Duwamish and West Seattle
West Seattle and Ballard Link Extensions
Alternatives
Elevated
Tunnel
At-Grade
Retained Cut
Station
Proposed
Tunnel Entrance/Exit
Existing/East Link Light Rail
Sound Transit Operations and Maintenance Facility (ST OMF)
TPSS Location
Centerline Half Mile Buffer
Shoreline
20 ft Contour
Known Landslide
Known Landslide Area
Potential Landslide Area
Water Body
SODO
0
500
1,000
Feet
N

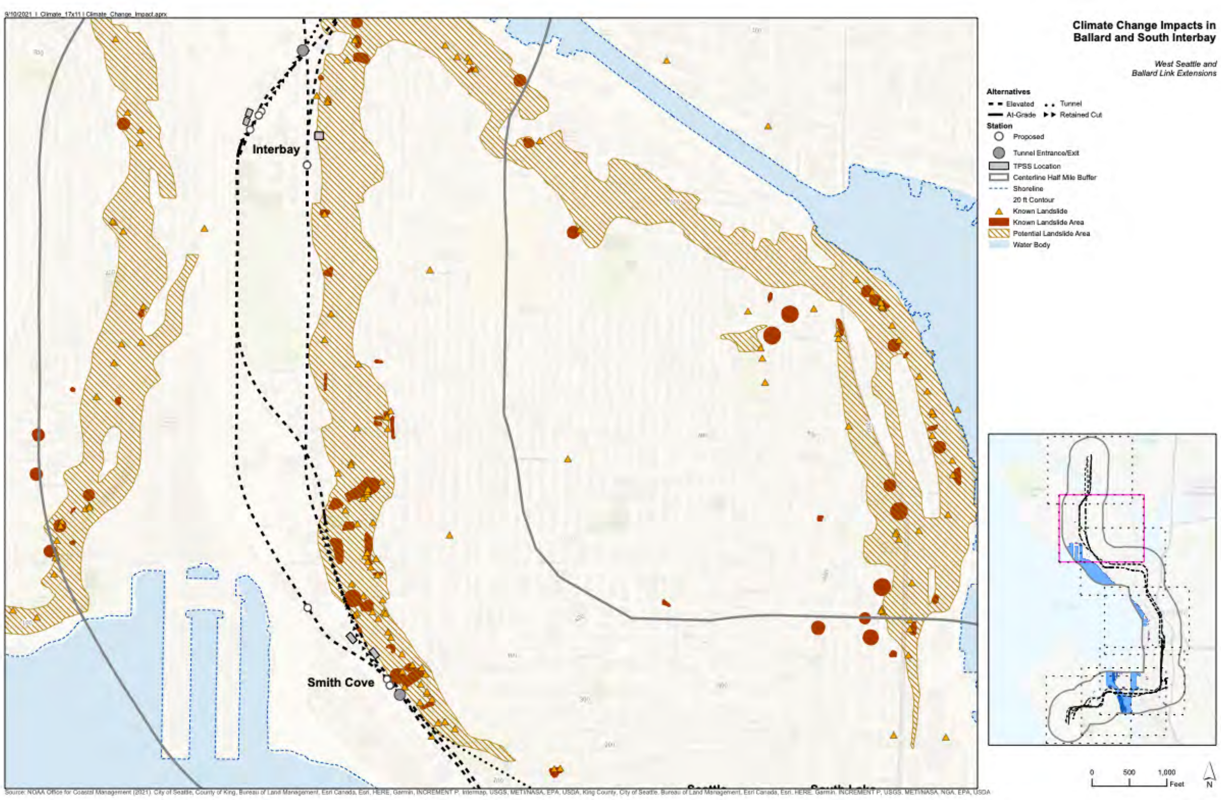


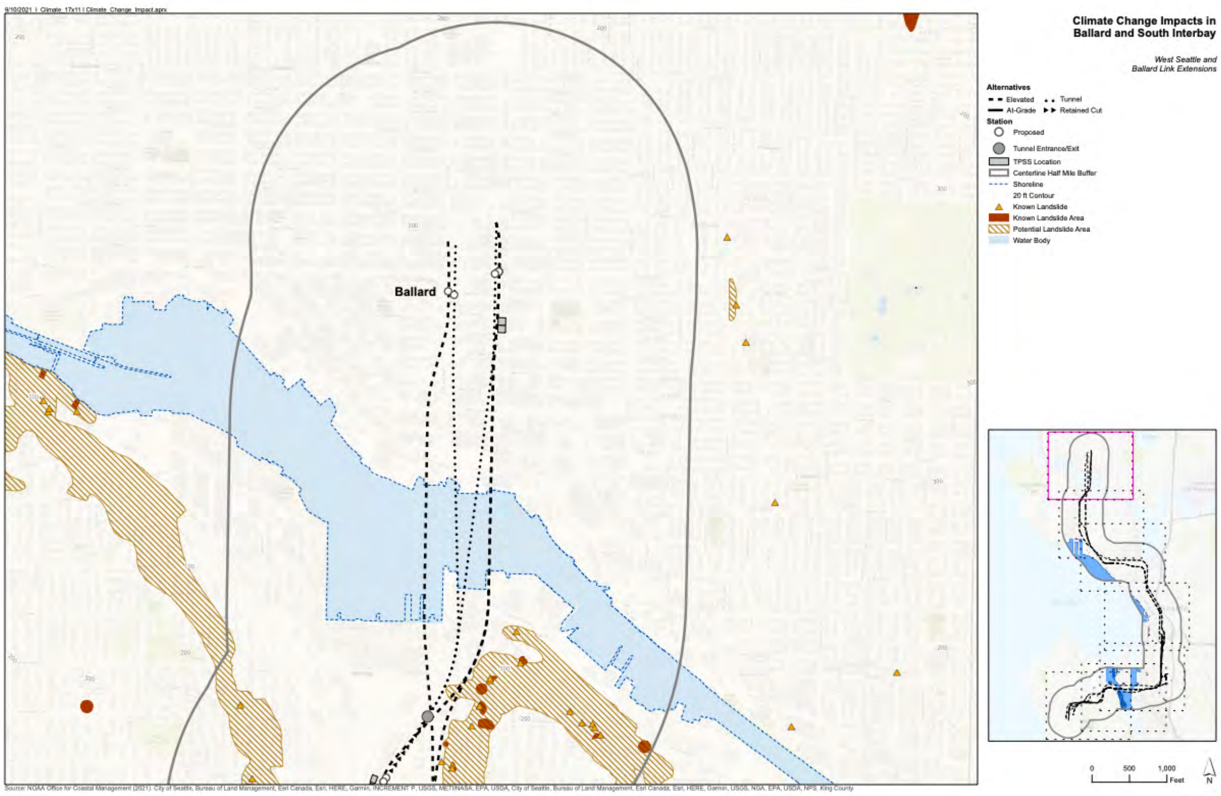
Climate Change Impacts in Duwamish Crossing
West Seattle and Ballard Link Extensions
Alternatives
Elevated
Tunnel
At-Grade
Retained Cut
Station
Proposed
Tunnel Entrance/Exit
Existing/East Link Light Rail
Sound Transit Operations and Maintenance Facility (ST OMF)
TPSS Location
Centerline Half Mile Buffer
Shoreline
20 ft Contour
Known Landslide
Known Landslide Area
Potential Landslide Area
Water Body
SODO
Delridge
0
500
1,000
Feet
N



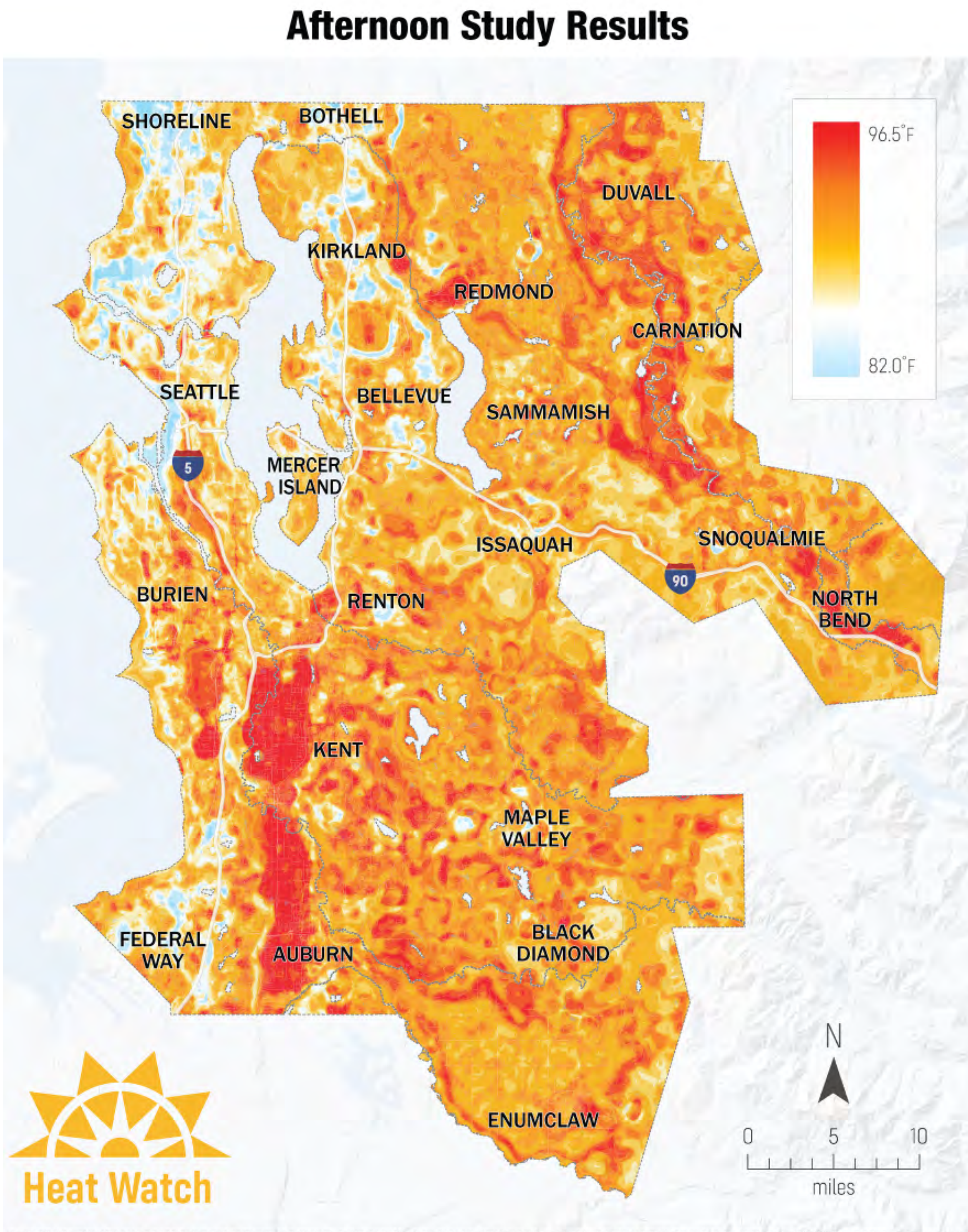
Climate Change Impacts in International District and SODO
West Seattle and Ballard Link Extensions
Alternatives
Elevated
Tunnel
At-Grade
Retained Cut
Station
Proposed
Tunnel Entrance/Exit
Existing/East Link Light Rail
TPSS Location
Centerline Half Mile Buffer
Shoreline
20 ft Contour
Known Landslide
Known Landslide Area
Potential Landslide Area
Water Body
Westlake
Midtown
International District/Chinatown
Stadium
0
500
1,000
Feet
N


Climate Change Impacts in
Downtown and South Interbay
West Seattle and
Ballard Link Extensions
Alternatives
Elevated
Tunnel
At-Grade
Retained Cut
Station
Proposed
Tunnel Entrance/Exit
Existing/East Link Light Rail
TPSS Location
Centerline Half Mile Buffer
Shoreline
20 ft Contour
Known Landslide
Known Landslide Area
Potential Landslide Area
Water Body
Smith Cove
Seattle
Center
South Lake
Union
Denny
Westlake
0
500
1,000
Feet
N

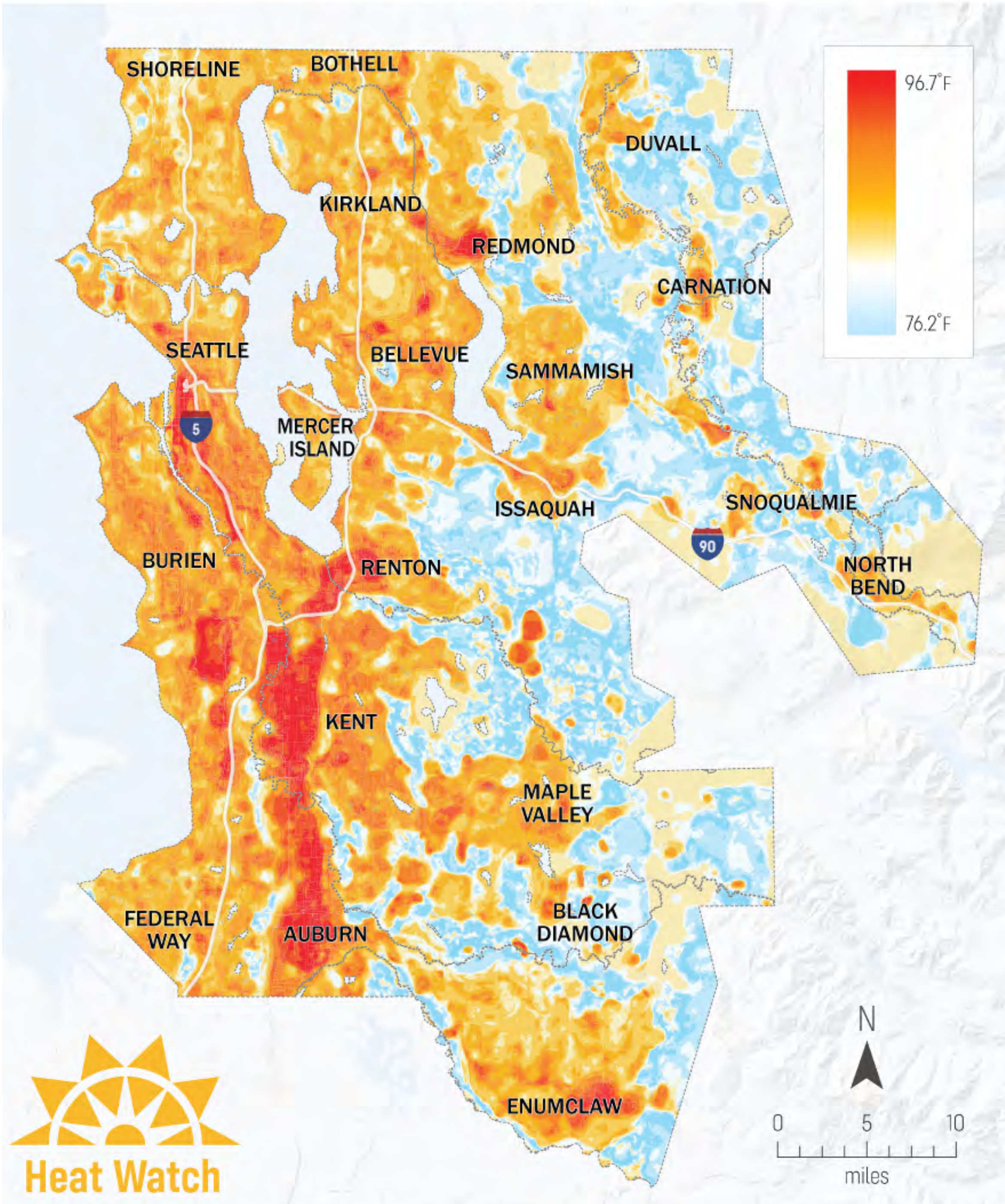

Climate Change Impacts in
Ballard and South Interbay
West Seattle and
Ballard Link Extensions
Alternatives
Elevated
Tunnel
At-Grade
Retained Cut
Station
Proposed
Tunnel Entrance/Exit
TPSS Location
Centerline Half Mile Buffer
Shoreline
20 ft Contour
Known Landslide
Known Landslide Area
Potential Landslide Area
Water Body
Interbay
Smith Cove
0
500
1,000
Feet
N


Climate Change Impacts in
Ballard and South Interbay
West Seattle and
Ballard Link Extensions
Alternatives
Elevated
Tunnel
At-Grade
Retained Cut
Station
Proposed
Tunnel Entrance/Exit
TPSS Location
Centerline Half Mile Buffer
Shoreline
20 ft Contour
Known Landslide
Known Landslide Area
Potential Landslide Area
Water Body
Ballard
0
500
1,000
Feet
N

7.3 Extreme Heat Maps



Evening Study Results



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