FTA RESEARCH

FEDERAL TRANSIT ADMINISTRATION

A Vulnerability and Risk Assessment of SEPTA's Regional Rail

A Transit Climate Change Adaptation Assessment Pilot

AUGUST 2013

FTA Report No. 0071
Federal Transit Administration

PREPARED BY
ICF International

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Metric Conversion Table

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

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This final report for the Federal Transit Administration (FTA) Transit Climate Change Adaptation Assessment Pilot describes the actions taken, information gathered, analyses performed, and lessons learned throughout the pilot project. This report describes the activities conducted for a vulnerability and risk assessment for the Southeastern Pennsylvania Transportation Authority (SEPTA) Regional Rail system. The project focused on SEPTA's Manayunk/Norristown Regional Rail line and began with an analysis of recent weather-related disruptions, tying them to observed weather conditions. The results of this analysis were combined with climate model projections for the area to project future delays, annulments, and costs that may be associated with climate changes. Next, the project team and SEPTA staff held a series of conversations to discuss SEPTA's vulnerabilities to temperature, heavy precipitation, tropical storms, and snowfall to develop adaptation strategies to address these vulnerabilities. The report concludes with recommended adaptation strategies for SEPTA and lessons learned for other transit adaptation efforts nationwide.

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ABSTRACT

This final report for the Federal Transit Administration (FTA) Transit Climate Change Adaptation Assessment Pilot describes the actions taken, information gathered, analyses performed, and lessons learned throughout the pilot project. This report describes the activities conducted for a vulnerability and risk assessment for the Southeastern Pennsylvania Transportation Authority (SEPTA) Regional Rail system. The project focused on SEPTA's Manayunk/Norristown Regional Rail line and began with an analysis of recent weather-related disruptions, tying them to observed weather conditions. The results of this analysis were combined with climate model projections for the area to project future delays, annulments, and costs that may be associated with climate changes. Next, the project team and SEPTA staff held a series of conversations to discuss SEPTA's vulnerabilities to temperature, heavy precipitation, tropical storms, and snowfall to develop adaptation strategies to address these vulnerabilities. The report concludes with recommended adaptation strategies for SEPTA and lessons learned for other transit adaptation efforts nationwide.

EXECUTIVE SUMMARY

Transit agencies in cities around the world are increasingly responding to disruptions in service and damage to assets associated with gradual changes in climate and extreme weather events.[1] In the U.S., the Federal Transit Administration (FTA) initiated a program in 2011 to fund seven pilot projects in transit agencies across the country to build off of research synthesized in FTA's report "Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation" (FTA Report No. 0001). One of these pilot projects—a vulnerability and risk assessment of the Southeastern Pennsylvania Transportation Authority (SEPTA)'s Regional Rail—is the subject of this report.

For this study, ICF partnered with SEPTA and the Delaware Valley Regional Planning Commission (DVRPC) to conduct an analysis of the climate-related risks and vulnerabilities to the Manayunk/Norristown (M/N) line, which has experienced several weather-related disruptions in recent years. The SEPTA pilot was designed to address several barriers to action witnessed in other climate adaptation projects to date and also to begin to develop detailed information on costs, which has also been lacking in many existing vulnerability assessment studies.

In particular, the SEPTA study presents an alternative to the often time-consuming and resource-intensive discussions about "criticality" and climate model selection. Rather than starting with the entire SEPTA system in mind and developing a systematic and quantitative approach to assessing criticality (i.e., what is important), we engaged with key staff in SEPTA to determine the line that would serve as the best case study to socialize and illustrate the impacts climate change may have on a single line.

Because the M/N line has experienced several weather-related disruptions in recent years, we were able to inventory the line, analyze past service disruptions in the context of weather, and develop future climate scenarios to understand its vulnerabilities to projected changes in climate. The study analyzes the risks from extreme weather and climate change in the context of service delays, train annulments, and costs to SEPTA. Projected risks are grounded in historical data on service disruptions and costs from weather events, including labor, materials, and equipment. Finally, we identified, screened, and analyzed adaptation strategies with stakeholder input. This report presents the results of these analyses, including detailed process information and lessons learned for future transit adaptation efforts.

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[1] For example, transit agencies such as New York MTA, Los Angeles MTA, New Jersey Transit, TriMet, Cape Cod Transit, Honolulu Transit, King County Metro, Transport for London, Istanbul, and Taipei are conducting climate change risk assessments and implementing adaptation strategies.

Current Climate Hazards

The first step in the analysis was to understand observed weather events and the impact of those events on the M/N line. The weather events on which we focused in this analysis are extreme heat, heavy rain, snow, and severe storms. An analysis of train delays from 2005 through February 2012 identified the primary weather event types that have affected the line in recent years and provided insight on why those events were disruptive. We paired the dataset of train delays with weather records for that time period to establish connections between meteorological events and delays.

Snow is the most disruptive weather factor affecting the M/N line. However, tropical storms are also major causes of delays and the primary cause of recent train cancellations. The M/N line experiences higher rates of impacts from heavy rain and flooding compared to the entire SEPTA Regional Rail system due to its location along the Schuylkill River. For each weather event type, we determined frequency and duration of delays and annulments and costs for each event type. Costs related to weather-related disruptions were determined based on Federal Emergency Management Agency (FEMA) reimbursement requests and weather-related coded labor costs. Snow was found to be the most costly event, followed by tropical storms.

The next step in the analysis was to identify sensitive locations and assets along the M/N line that may be affected by weather-related events. A list of assets (including bridges, crossings, culverts, and stations) was incorporated into a GIS representation of the line, and SEPTA staff identified locations vulnerable to flooding. Twenty seven vulnerable assets were identified, with a total potential replacement cost of $20 million.

The last step in the analysis was to identify thresholds of extreme weather. Thresholds of extreme weather (i.e., the top 1 and 5 percentile values from the distribution of temperature and precipitation values for the period 1994–2012) were compared against the full dataset of delays to determine how often delays occurred in conjunction with extreme temperatures or rainfall. Results show that SEPTA does not experience disruptions every time these thresholds occur, but they do cause disruptions more frequently and of greater severity than weather conditions below the thresholds. Snow and tropical storms cause the most dramatic increases in delays, but heavy rain and high temperatures also play a major role in causing service disruptions.

To facilitate the comparisons of different types of weather events, two equations were developed to calculate disruption risk for delay minutes and annulments. The risk estimates represent the product of the probability of an event's occurrence and the magnitude of an event's consequence. The risks estimates were monetized by converting the delay risk estimates into a number of major events and combining this estimate with average event costs.

Future Climate Hazards

Based on the climate projections used in this study, the Philadelphia area is projected to experience a future that is warmer and wetter than the past. Average temperatures are projected to warm between 3 to 6°F by mid-century, and hot summers are projected to become more frequent. The Philadelphia area is also expected to experience increased seasonal and annual precipitation levels, with heavy precipitation events expected to become more common.

Climate model projections on snowfall amounts or frequencies in the Philadelphia area were not readily-available in a form usable for this report. However, days with conditions conducive to snow are projected to decrease in frequency from 35 to 12 percent (across climate models and emission scenarios) as temperatures warm. Similarly, existing research does not currently provide definitive insight into the frequency or intensity of storms that might make landfall near Philadelphia in the future. However, given the frequency of storms observed in the region since 1999, they should be considered a weather-related hazard in Philadelphia. Although not specific to the region, studies have projected tropical storms to increase in intensity in North America.

Potential future risk of disruptions, and associated costs, were estimated by combining the projected changes in the frequency of extreme weather events with the known costs and associated service disruptions. Low, Medium, and High estimates are provided, corresponding to the range of model projections for that variable. The results demonstrate that the relatively large increases in the frequency of heat extremes are likely to cause more frequent delays and costs, while increases in temperature could also result in a decline in the risks associated with the chance of a snow delay.

Key Vulnerabilities

Through a series of meetings and interviews, SEPTA staff identified existing vulnerabilities due to extreme weather events. These vulnerabilities were organized by type of weather event and SEPTA department affected. Some identified vulnerabilities are location-specific, while others are not. Areas vulnerable to flooding, and assets located in those areas, are well known within the SEPTA organization, although changes in land use and stormwater run-off patterns may create new areas over time. Vulnerabilities to winter and heat events are less location-specific; rather, they are more sensitive to whether trees and limbs can fall onto the line. Over time, if the growing season is extended, as is anticipated in most climate change scenarios, the tree-trimming cycles may need to be adjusted to keep up with the additional growth.

Currently, SEPTA experiences relatively low disruptions due to temperature compared to other weather events. However, temperatures in the area are projected to increase, with the potential to cause equipment and track stress and harsh working conditions that may make it difficult to assess or repair damages. The M/N line is also highly vulnerable to heavy rain; locations that are currently vulnerable are likely to remain so, while other areas may become prone to flooding due to new stressors from changing urban conditions and climate. Snow events are the largest cause of weather-related disruptions on the M/N line and, despite expected increases in temperature, may continue to be a significant vulnerability for SEPTA. Tropical storms, if continuing to occur at the same rate as in recent years, may also cause significant damage to the SEPTA system.

Adaptation Strategies

The report presents adaptation strategies for the identified vulnerabilities across all weather event types and departments. These strategies represent a range of costs, time frames for implementation, and types of actions (operations, maintenance, or capital planning). These strategies include some actions that SEPTA has already initiated.

The process for identifying these strategies involved research and discussions with SEPTA staff. High-temperature strategies address methods for dealing with sagging wires, track buckling, equipment stress, train speeds, and labor conditions. Rain-event strategies involve methods in dealing with flooding on the M/N line, including increased monitoring and preventing or minimizing flood damage through preventive measures. Snow storm and tropical storm adaptation measures are similar to those for other weather events. SEPTA's response to Hurricane Sandy demonstrates many of the recommended strategies, with one of the most effective being tree trimming.

Several strategies can address vulnerability across a range of weather events: incorporate climate change vulnerability into asset management program; make institutional knowledge more resilient—incorporate climate risk management into SEPTA planning, construction, operations, and maintenance processes; enhance communication systems; create and monitor performance indicators; acquire backup power systems; and incorporate changing climate conditions into planning and budget processes. The feasibility of each adaptation strategy varies based on constraints such as funding, public perception, and jurisdictional boundaries.

Hurricane Sandy

During this study, Hurricane Sandy struck the northeast, including the Philadelphia area. Though the storm happened too late to be included in all analyses, the storm nevertheless showcased not only SEPTA's vulnerabilities to severe storms, but also how it is using lessons learned from previous storms to improve resilience. Philadelphia did not experience the severe storm surge and devastation associated with Sandy in other areas, but the storm nevertheless caused widespread damage to SEPTA. Hurricane Sandy cost SEPTA over $1.3 million, including emergency protective measures before the storm, emergency repairs, and labor. SEPTA's response to the storm demonstrated several adaptation strategies discussed throughout this report, including relocating assets to less vulnerable locations, trimming trees, using a unique code to track storm costs, and frequent communication with customers. SEPTA's response to Sandy is detailed in Section 5, "Adaptation Strategies for Tropical Storms."

Lessons Learned and Appendices

This report concludes with lessons learned by the project team, specifically in the areas of project design, staff engagement, data, and stakeholder engagement. Supplemental appendices are also provided that provide more details on the methods used in analyzing service disruptions, weather-related costs, baseline weather conditions, and climate projections.

SECTION
1

Introduction

Transit agencies in cities around the world are increasingly responding to disruptions in service and damage to assets associated with gradual changes in climate and extreme weather events.[2] In the U.S., the Federal Transit Administration (FTA) initiated a program in 2011 to fund a small number of pilot projects in transit agencies across the country. The purpose of these pilots would be to build off of research synthesized in FTA's "Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation" (FTA Report No. 0001) and lessons learned from a series of Federal Highway Administration (FHWA) pilots focusing on climate adaptation for state and regional highway systems. In all, FTA funded seven adaptation pilots (shown in Figure 1-1), including a vulnerability and risk assessment of the Southeastern Pennsylvania Transportation Authority (SEPTA)'s Regional Rail, the subject of this report.

Figure 1-1

Map of FTA Transit Climate Change Adaptation Assessment Pilots

The FTA pilot projects were chosen to advance the state of the practice for incorporating climate change and extreme weather considerations into existing decision making paradigms and, ultimately, improving the resilience of transit assets and services to the impacts of climate change. These pilots, which focus on climate-related risks, are being conducted in the context of long-term goals to address state-of-good-repair needs and enhance transit safety.

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[2] For example, transit agencies like New York MTA, Los Angeles MTA, New Jersey Transit, TriMet, Cape Cod Transit, Honolulu Transit, King County Metro, Transport for London, Istanbul, and Taipei are conducting climate change risk assessments and implementing adaptation strategies.

For this pilot study, ICF International (ICF) partnered with SEPTA and the Delaware Valley Regional Planning Commission (DVRPC). The SEPTA pilot was designed to address several barriers to action witnessed in other climate adaptation projects to date and also to begin to develop very fine-grained information on costs, which has also been lacking in many of the existing studies.

In particular, the SEPTA study presents an alternative to the often time-consuming and resource-intensive discussions about “criticality” and climate model selection. Rather than starting with the entire SEPTA system in mind and developing a systematic and quantitative approach to assessing criticality (i.e., what is important), we engaged with key staff in SEPTA to determine the line that would serve as the best case study to socialize and illustrate the impacts climate change may have on a single line. This approach leaves open the possibility of conducting vulnerability assessments elsewhere in the system.

Our selection of the study line, the Manayunk/Norristown (M/N) line, was based on ridership and other objective metrics related to criticality, but subjective factors were equally important. Ultimately, the audience for this study, SEPTA management, and our knowledge of current vulnerabilities guided the selection more than any objective ranking of criticality.

With respect to climate model selection, unlike many of the climate change vulnerability studies underway, this study began with historical data and used observed/monitored weather data to drive decisions about which future climate variables to consider. Once the climate variables were chosen, the selection of which model outputs to believe and how fine-grained the model outputs would be became less controversial. Rather than providing a point estimate in time, each climate projection was compared to recent trends to illustrate future scenarios and associated risks.

Because the M/N line has experienced several weather-related disruptions in recent years, we were able to inventory the line, analyze past service disruptions in the context of weather, and develop future climate scenarios to understand the line’s vulnerabilities to projected changes in climate. The study analyzes the risks from extreme weather and climate change in the context of service delays, train annulments, and costs to SEPTA. Projected risks are grounded in historical data on service disruptions and costs from weather events, including labor, materials, and equipment. Finally, we identified, screened, and analyzed adaptation strategies with stakeholder input. This report presents the results of these analyses, including detailed process information and lessons learned for future transit adaptation efforts.

SECTION

2

Current Climate Hazards

Weather events—including extreme heat, snow, and severe storms—affect SEPTA's operations and infrastructure, including the service and assets on the M/N line. An initial step in this project was to understand observed weather events and the impact of those events on the M/N line. We set out to answer the following key questions:

- What types of weather events lead to service disruptions?
- What is the magnitude and duration of disruption for different types of weather events?
- How frequently do disruptive weather events occur?
- What are the costs of different types of disruptive weather events?
- Are there any "thresholds" for temperature or precipitation for which service disruptions consistently occur? If so, how often are such thresholds exceeded?

Several recent disruptive weather events have also demonstrated how weather impacts the SEPTA system. These illustrative examples provide a real-life context for this adaptation analysis, and are shown in below.

Illustrative Examples of Recent Weather-Related Disruptions

July 27, 2005 – Extreme Heat. On July 27, 2005, temperatures in Philadelphia climbed to 104°F. SEPTA operators put speed restrictions into effect system-wide. The extreme temperatures caused catenary wire between the Manayunk station and Green Interlocking to sag excessively, such that trains were unable to proceed through the area. For five hours, SEPTA operated on an alternate plan, switching trains to an unaffected portion of the track. Overall, the hot day resulted in 5.8 hours of cumulative delays on the M/N line and resulted in nearly $13,000 in unplanned labor expenses, according to SEPTA's labor tracking (see Section 2, "Costs of Major Weather-Related Disruption Events" for details).

December 19–21, 2009 – Major Snowstorm. A major snowstorm struck Philadelphia overnight between December 19 and 20, 2009. One and a half inches of snow fell on Saturday, December 19, and 11 more inches fell on December 20. The volume of snow caused several interlocking and switch failures on the M/N line for two days. Overall, the storm caused 9 train annulments, 1 partial annulment, and nearly 30 hours of cumulative train delays on the M/N line from December 19 to 21. The storm was associated with $430,000 in additional labor expenses (see Section 2, "Costs of Major Weather-Related Disruption Events" for details).

August 27–29, 2011 – Hurricane Irene. Hurricane Irene passed over the Philadelphia region on August 27 and 28, 2011, bringing nearly 6 inches of rainfall to the area in 24 hours. The storm caused widespread power outages and major inland flooding. The Schuylkill River rose to 13.6 feet (above its flood level of 11 feet), and the Wissahickon Creek also experienced major flooding, rising to 10.5 feet, well above its flood stage of 5 feet [1]. As the storm came in on the evening of August 27, SEPTA experienced delays on the M/N line and cancelled six trains. SEPTA cancelled all service on August 28. The storm caused catenary damage and downed trees system-wide. In addition, the M/N line experienced high water and flooding, particularly from Conshohocken to Miquon, through August 29. Signal power was also disabled, electric traction was disabled, trees were downed, and switches were broken. Service to the M/N line was finally restored at 1:15 PM on Monday, August 29. In total, Hurricane Irene caused 59 train cancellations on the M/N line alone and nearly 2.5 hours of delays for the trains that did operate. SEPTA requested reimbursements from the Federal Emergency Management Agency (FEMA) totaling $2.5million for storm damage and expenses (see Section 2, "Costs of Major Weather-Related Disruption Events" for details).

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Understanding the current climate hazards to SEPTA's rail lines sets the stage for understanding how those climate hazards and associated risks might change in the future.

Observed Weather Events and Related Disruptions on the Manayunk/Norristown Line

This project analyzed weather-related service disruptions, costs of major weather events, sensitive locations and assets, and thresholds for weather-related disruptions to establish the recently-observed state of SEPTA's climate hazards.

Weather-Related Service Disruptions

SEPTA provided a dataset of all trains on all lines that have experienced delays (greater than 6 minutes) categorized as weather-related from January 2005 through February 2012. We used this dataset to determine which types of weather lead to service disruptions and to compare the magnitude and duration of disruptions associated with different types of weather events. A detailed description of the approach used in analysis is provided in Appendix A. SEPTA's data showed that a subset of "major" events accounted for a disproportionate amount of the total delay minutes and annulments on the M/N line. Ultimately, we identified 28 major event days, representing 20 major weather events (5 events spanned 2 or 3 days). These major events represent a range of weather impacts to the SEPTA system. Together, they account for 63 percent of all weather-related delay minutes in the January 2005 to February 2012 period, 96 percent of the annulments, and 48 percent of all service disruptions on the M/N line.

The analysis showed that snow is the biggest weather factor affecting SEPTA's system overall, including the M/N line, but severe storms—ranging from tropical storms to ice storms—are also dominant causes of major delays. The major events affecting the M/N line are summarized by type of weather event in Table 2-1 and Figure 2-1. Snow events are the largest cause of delays and affect the highest number of trains. The tropical storms and hurricanes impacting Philadelphia over the last six years (Tropical Storm Nicole, Hurricane Irene, and Tropical Storm Lee), however, caused the majority of train cancellations.[3]

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[3] The decisions to cancel trains associated with tropical storms are often made in advance of the storm's arrival. Although the decision may be made in a pre-emptive fashion, we still consider the cancellation to be "caused" by the storm.

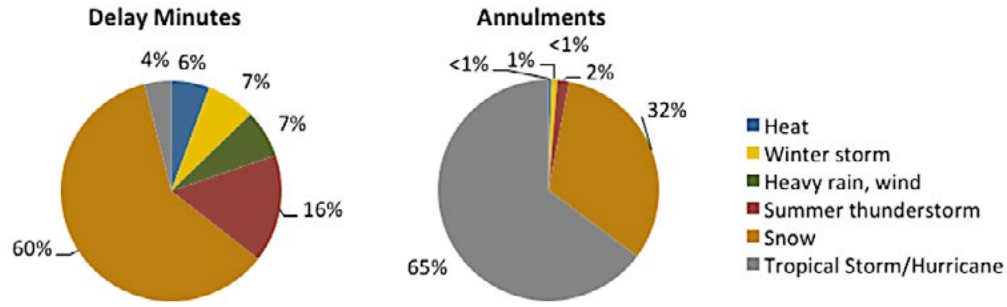
Table 2-1

Summary of Major Disruption Events on Manayunk/Norristown Line by Weather Type (January 2005–February 2012)

Weather Type	Trains Affected	Delay (min)	Annulled Trains	Number of Events
Heat	27	556	1	2
Winter storm (non-snow)	39	708	2	2
Heavy rain, wind	64	694	0	3
Summer thunderstorm	69	1,566	4	4
Snow	328	5,992	75	11
Tropical storm/hurricane	179	390	151	6
Total	*706*	*9,906*	*233*	*28*

Figure 2-1

Percentage of Major Event Delay Minutes and Annulments on Manayunk/Norristown Line by Weather Type (January 2005–February 2012)

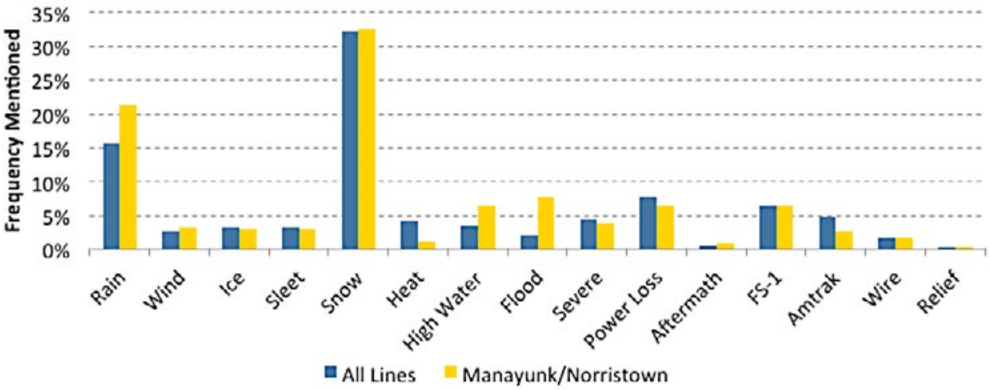


Severe storms impact the M/N line as they occur and often for several days afterwards as the rail system copes with the aftermath. For example, the list of major event delays includes five events spanning multiple days: a bad thunderstorm on July 18, 2006, whose effects lasted through July 19; major snowstorms with multi-day impacts spanning December 19–21, 2009 and February 10–12, 2010; Hurricane Irene, with impacts spanning August 27–29, 2011; and Tropical Storm Lee from September 7–8, 2011.

Compared to the entire SEPTA Regional Rail system, the M/N line experiences higher rates of impacts from heavy rain and flooding in addition to similar rates for all other weather-related delays. We conducted a keyword analysis (described in Appendix A) to compare how often key weather impacts occur in delay descriptions for the M/N line compared to the entire Regional Rail system. The frequency shown is the number of times that key word occurs in delay descriptions as a portion of the total number of delays. The high rates of flooding on the M/N line are shown in Figure 2-2, captured under the key words “rain,” “snow,” “high water”, and “flood.” The M/N line appears to experience fewer heat-related delays compared to the full SEPTA system but similar rates for all other causes.

Figure 2-2

Relative Occurrence of Weather-Related Delay Key Words on Manayunk/Norristown Line Compared to All SEPTA Regional Rail lines (January 2005–February 2012)



Costs of Major Weather-Related Disruption Events

We generated estimates of the costs associated with weather-related disruption events using two sets of information:

- Reimbursement information submitted to FEMA to cover costs associated with weather disasters.[4] SEPTA provided information about recent submittals for five events (see Table 2-2). These events are limited to major snowstorms and tropical storms.
- Weekly labor costs that have been coded as "weather-related" and that correspond to the same dates as the 28 major events days described in Section 2, "Weather-Related Service Disruptions" and in Appendix C. Although the payroll costs are available for the major weather disruption events (as opposed to FEMA reimbursements, which are limited to five events), they are limited to SEPTA labor and do not include costs for equipment, materials, or contracted labor service.

A full description of the data and methodologies is provided in Appendix B.

Table 2-2 shows the total costs of the five events that required FEMA reimbursement. The four recent tropical storms cost SEPTA an average of $3.5 million per storm, and the February 2010 snowstorm cost SEPTA about $1.2 million (unadjusted for inflation). After this analysis was completed, SEPTA submitted reimbursements for Hurricane Sandy totaling $1.325 million.

Table 2-2

Reimbursement Submittals to FEMA for Key Weather Events

Event	Date	Submittal for Reimbursement
Hurricane Floyd	September 16–17, 1999	$1,523,196
Tropical Storm Allison	June 16–17, 2001	$5,755,364
Winter Snowstorm	February 5–10, 2010	$1,274,940
Hurricane Irene	August 26–29, 2011	$2,531,683
Tropical Storm Lee	September 3, 2011	$4,235,009
Five Event Total		*$15,320,191*
Average Cost of Tropical Storm/Hurricane		$3,511,313

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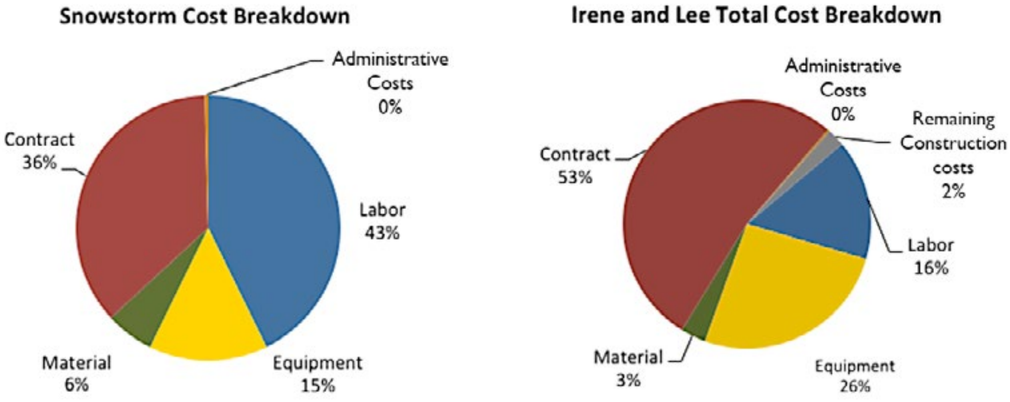
[4] Disasters are defined as events in an area covered by a disaster declaration by the Governor or the President.

Detailed descriptions of the costs are available for the three most recent of these events (the February 2010 Snowstorm, Hurricane Irene, and Tropical Storm Lee; see Figure 2-3). Most of the expenditures incurred were due to labor. For the snowstorm, approximately 80 percent of the costs went to labor (both SEPTA staff and contracted staff). For the tropical storms, around 69 percent of the costs were for labor (both SEPTA staff and contracted staff).

Figure 2-3

Costs to SEPTA of February 2010 Winter Snowstorm and Tropical Storms Irene and Lee



In addition to the costs from FEMA submittals, SEPTA provided labor costs charged to a weather-specific code during the 20 major events (spanning 28 days) identified in Section 2, "Weather-Related Service Disruptions." The average labor costs per weather event type are presented in Table 2-3. Snow is the most costly event type in terms of labor, followed by tropical storms. Heat events appear to have relatively low costs based on the available data, but these costs may be underestimated if they were not consistently coded as "weather-related" within the SEPTA labor system. For example, heat events may lead to equipment problems whose repair is not coded as weather-related. Therefore, the costs of heat events may be higher than reported here.

Table 2-3

Average Labor Costs by Type of Weather Event

Event Type	Number of Events	Average Labor Costs per Event (payroll and benefits)
Heat	2	$53,307
Snow	9	$682,515
Tropical Storm (TS)	6	$164,524
Heavy Rain (Non-TS)	3	$60,249

These costs also account only for the costs of weather-related disruptions to SEPTA, and not the service area at large. Full societal costs of these disruptions are much larger and include, for example, forgone time and earnings of passengers who experience delays or cancellations and lost revenues for local businesses.

Hurricane Sandy

On October 29 and 30, 2012, during the course of this project, Hurricane Sandy passed over the Philadelphia area and caused damage across the mid-Atlantic and Northeast. SEPTA suspended service in advance of the storm and spent the duration of the storm conducting a system-wide assessment of vehicles and infrastructure. While other parts of the SEPTA system were spared significant damage, Regional Rail lines experienced signal power problems, flooded track, downed trees and catenary wires, and track debris. Regional Rail service was suspended from 12:30 AM on Monday, October 29 through 4:30 AM Wednesday, October 31, for a total of 52 hours. SEPTA staff worked throughout the storm and its aftermath to inspect and repair the system.

Cost data for Hurricane Sandy were not able to be incorporated into this analysis, but the storm cost SEPTA $1.325 million in labor costs (internal and third party) related to securing and protecting the system in advance of the storm, emergency activities during and after the storm, and enhanced customer service to communicate to the public. These costs are nearly tenfold the labor costs recorded during previous tropical storms. This reflects, in part, the severity of the storm but also a concerted effort within SEPTA to better track costs associated with weather events. SEPTA developed a labor charge code specifically for Hurricane Sandy that enabled it to capture a fuller picture of the storm's costs then for previous events. Later in this report, we recommend that SEPTA continue to improve tracking of weather event costs as one of several strategies to adaptively manage the system in the face of a changing climate. Better tracking will help SEPTA make more robust decisions and maximize the resilience of the system and the services it provides.

Photos courtesy of SEPTA

Examples of Damage to SEPTA Caused by Hurricane Sandy

Sensitive Locations and Asset Types

To develop a list of sensitive assets on the M/N line, SEPTA first compiled a list of all assets on the line, including bridges, culverts, grade crossings, interlockings, power facilities, stations, and track. This information provides a general overview of the assets that comprise the line and their relative age.

The M/N line's tracks (much of the distance covered by two tracks, with a short portion of the line containing three tracks) run between the North Broad station (2693 N. Broad Street & Lehigh Avenue, Philadelphia) and the Elm Street station (716 Markley Street & W. Elm Street, Norristown), with 10 stations in service between these end points. The track age ranges from 12 to 82 years; its ties were last renewed in 2005. The 18.1 miles covered by the line contain 28.3 miles of track, of which 1.3 miles are beyond their useful life.[5] Two of the stations on the line are near or at the end of their useful life, and most will require work within 15 to 20 years; the four pedestrian tunnels associated with stations will be updated when the adjacent stations are improved.

The line's signal system is currently being upgraded to Positive Train Control (as federally-mandated) and will be completed by the end of 2015. Of the line's 23 switches, 3 are beyond their useful life, and 2 of the line's 16 interlockings and 11 of 17 grade crossings are also beyond their useful life. Although the line's 65 culverts are all in fair to good structural condition, it should be noted that the hydraulic openings for many of the culverts are too small for current (and projected future) heavy precipitation events. This list of assets was incorporated into a GIS representation of the line. SEPTA staff identified areas on the map where flooding has historically occurred, and that information was also incorporated into the line map, which is shown in Figure 2-4.

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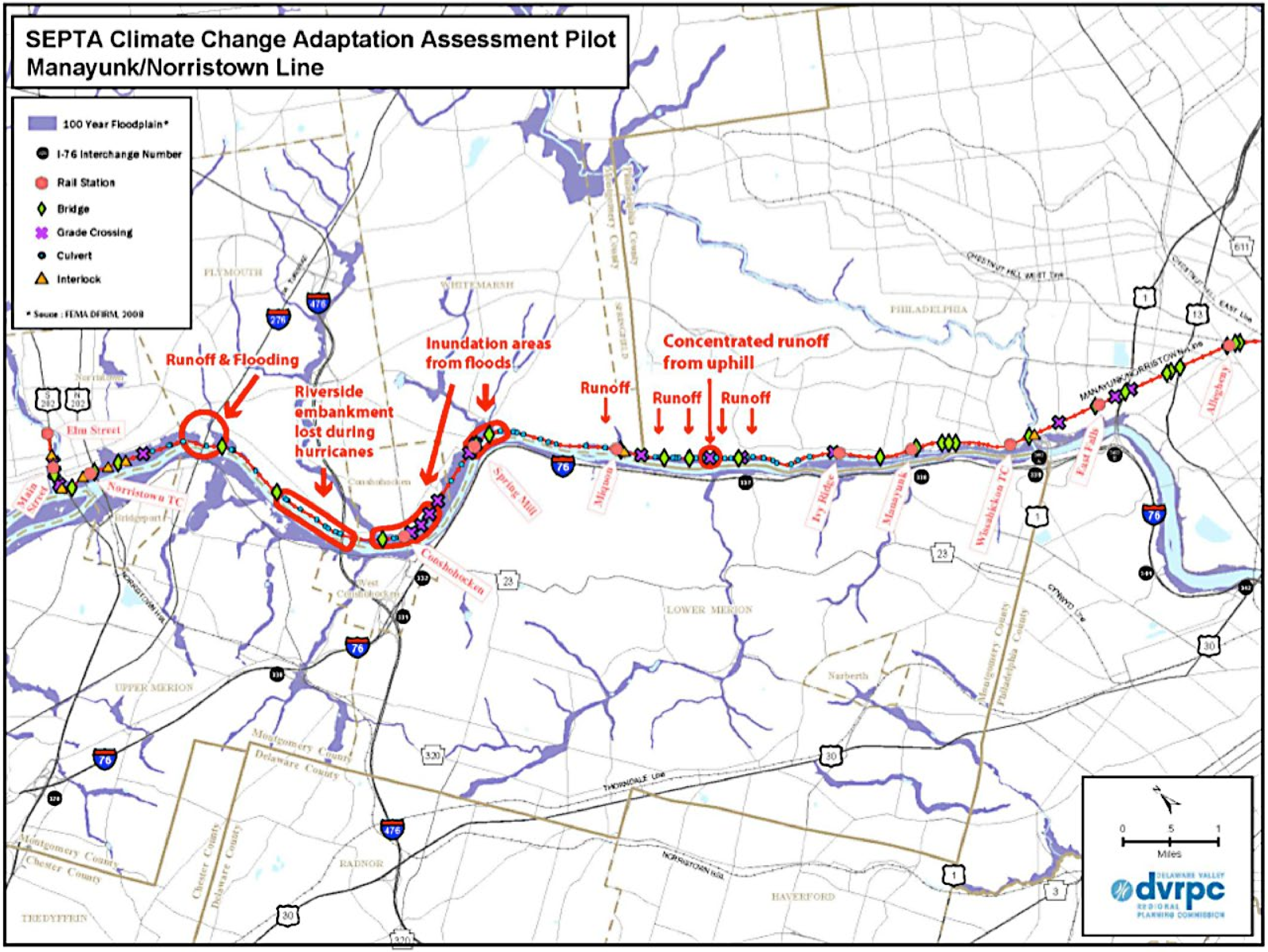
[5] Useful life is the estimated number of years an asset will be able to carry out its intended purpose before being replaced.

Figure 2-4

Assets and Known Vulnerable Areas on Manayunk/ Norristown Line



A list of assets located in the areas known to be vulnerable to historical flooding is provided in Table 2-4. In total, 27 assets with a replacement cost of $20.7 million are located in these vulnerable areas (as shown in Table 2-4), with 2 stations accounting for most of the cost and 18 culverts accounting for most of the count of assets. This does not include track and power assets (including signal huts), which traverse the length of the line. These assets have high replacement costs, but are not typically damaged to the point of replacement during flood events. For track assets, for example, flooding typically causes damage to track beds and slopes, not to the track itself. Thus, the replacement costs listed in Table 2-4 provide a sense, but not the full scope, of the costs associated with flooding on the M/N line.

Table 2-4

Assets Located in Known Flood-Prone Areas (not including Track and Power Assets)

	Asset Type	Asset Name/Description	Location (Milepost)	Budgeted Replacement Cost*
1	Bridge	Spring Mill Creek	12.25	$883,200
2	Bridge	Stream	12.07	$614,400
3	Bridge	Plymouth Creek	13.73	$979,200
4	Bridge	Diamond Run	15.76	$691,200
5	Crossing	Port Royal Avenue – Nixon Street Philadelphia, Philadelphia	9.7	$129,000
6	Crossing	Spring Mill Road – Station Road Whitemarsh, Montgomery	12.25	$90,000
7	Crossing	Harry Street	13.4	$111,000
8	Culvert	Stone Box	9.68	$150,000
9	Culvert	Stone Box	9.7	$150,000
10	Culvert	Cast Iron Pipe	11.94	$150,000
11	Culvert	Concrete Box	13.53	$150,000
12	Culvert	Cast Iron Pipe	13.55	$150,000
13	Culvert	Stone Box	13.59	$150,000
14	Culvert	Cast Iron Pipe	13.69	$150,000
15	Culvert	Cast Iron Pipe	14.17	$150,000
16	Culvert	Cast Iron Pipe	14.19	$150,000
17	Culvert	Stone Box	14.22	$150,000
18	Culvert	Stone Box	14.3	$150,000
19	Culvert	Stone Box	14.34	$150,000
20	Culvert	Stone Box	14.45	$150,000
21	Culvert	Concrete Pipe	14.65	$150,000
22	Culvert	Corrugated Metal Pipe	14.81	$150,000
23	Culvert	Cast Iron Pipe	14.82	$150,000
24	Culvert	Corrugated Metal Pipe	14.85	$150,000
25	Culvert	Corrugated Metal Pipe	15.9	$150,000
26	Station	Spring Mill	12.3	$6,500,000
27	Station	Conshohocken	13.5	$8,000,000

*Replacement costs are for capital planning purposes only and may be revised to reflect actual cost of implementation.

Table 2-5

Summary of Assets Located in Known Flood-Prone Areas

Asset Type	Entire M/N Line		Flood Prone Areas		Percent of M/N Line in Flood Prone Areas	
	Count	*Total Budgeted Replacement Cost*	*Count*	*Total Budgeted Replacement Cost*	*Count*	*Total Budgeted Replacement Cost*
Bridge	27	$210,597,901	4	$3,168,000	15%	2%
Crossing	17	$2,101,500	3	$330,000	18%	16%
Culvert	65	$9,750,000	18	$2,700,000	28%	28%
Station	11	$79,500,000	2	$14,500,000	18%	18%
Total	*120*	*$301,949,401*	*27*	*$20,698,000*	*23%*	*7%*

While this approach is helpful in identifying areas presently vulnerable to flooding, these areas are subject to change. Additional areas may become vulnerable due to changes in impervious surfaces, land use changes, vegetation, or other factors that affect stormwater runoff. Other weather-related risks, particularly affecting the catenary power system, will vary over time. Locations susceptible to falling trees and limbs that threaten the power infrastructure will vary based on the length of time since the most recent tree trimming.

Thresholds for Weather-Related Disruption

We used daily weather data from the Franklin Institute in Philadelphia to establish a connection between the weather-related disturbances observed on the M/N line and the actual weather conditions at the time. Details about this analysis are provided in Appendix C. This analysis paired each of the major events with the weather conditions on that day and also identified the extreme weather conditions in the Philadelphia area (i.e., the top 1 and 5 percentile values from the distribution of temperature and precipitation values for the period 1994–2012). These thresholds of extreme weather were also compared against the full delay dataset, not just the major events, to determine how often delays occurred in conjunction with extreme temperatures or rainfall.

The extreme weather thresholds are shown in Table 2-6. The values are those that are in the top 1st percentile and 5th percentile of daily values over the 18-year data record. The data show that a “very hot” day in Philadelphia (occurring close to 20 times per year) is about 93°F, while an “exceptionally hot” day (occurring 3–4 days per year) is just over 98°F. Similarly, a “very wet” day gets about 1.5 inches of rain (occurring 6–7 days per year), while an “exceptionally wet” day (occurring 1–2 times per year) gets closer to 3 inches of rain. These terms are defined in the textbox in Table 2-7.

Table 2-6

Daily Weather Variables – 1st and 5th Percentile Values

Variable	1st Percentile (1994 2012)	Total Days Exceeding Threshold (2005 2012)	Average Annual Days Exceeding Threshold	5th Percentile (1994 2012)	Total Days Exceeding Threshold (2005 2012)	Average Annual Days Exceeding Threshold
High Temperature	98.1°F	26	4	93.0°F	119	17
Low Temperature	14.0°F	19	3	23.0°F	133	17
Rainfall	2.5 in.	11	2	1.4 in.	47	7
Snowfall	11.5 in.	1	0	7.5 in.	5	1
Snow Depth	24.3 in.	0	0	12.0 in.	2	0

The next step of the analysis was to determine how often delays occurred when these weather thresholds were exceeded. The results show that SEPTA does not experience disruptions every time these rare weather events occur, but that the extreme events cause greater delays than other weather events. We can also use this analysis of how often delays occur when certain temperatures or rainfall amounts occur (based on recent experience) to project how often delays may occur under future climate conditions.

On a given day, there is a 9 percent likelihood of weather-related delays[6] on the M/N line, which we consider the “baseline” frequency for weather-related disruption. In comparison, 44 percent of days with any snowfall exhibit delays, with a median value of 30 minutes per day. Snow events are the most likely to cause delays and also tend to have the largest delays. Tropical storms occur less frequently, but when they do occur, they severely disrupt operations and in the recent past have prompted system-wide service annulments. Non-tropical storm precipitation events cause median delays of 9–18 minutes 47 percent of the time they occur. Extreme heat disruptions occur least frequently, but median delays on heat-related days are still close to two hours of total delays per day. Table 2-7 summarizes these statistics.

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[6] This was calculated by dividing the number of days in the period with weather-related delays over the total number of days in the period (January 1, 2005–February 25, 2012), or 228 days with delays or annulments divided by 2,612 days, which equals 0.09.

Table 2-7

Daily Weather Variables – 1st and 5th Percentile Values

	Threshold Value	% of Days Above Threshold with Delays	Median Delays (min/ day)	Days with Delays	% of Days Above Threshold with Annulments	Median Annulments (trains/	Days with Annulments
Temperature (°F)							
"Exceptionally hot" (1st percentile)	98.1 °F	23%	111	6	4%	1.0	1
"Very hot" (5th percentile)	93.0 °F	15%	35	18	3%	1.0	3
Rain (in.)							
"Exceptionally wet" (1st percentile)	2.5 in.	36%	9	4	0%	-	0
"Very wet" (5th percentile)	1.4 in.	47%	18	22	2%	2.0	1
Snow (in.)	any	44%	30	24	7%	4.5	4
"Exceptionally snowy" (1st percentile)	11.5 in.	100%	448	1	0%	-	2
"Very snowy" (5th percentile)	7.5 in.	60%	598	3	40%	3.0	0
Tropical storms	any	67%	85	4	83%	34.0	5
All weather related delays		9%	17	225	1%	9.3	26

Terminology definitions:
"Very hot" days = days at or above the baseline 5th percentile temperature
"Exceptionally hot" days = days at or above the baseline 1st percentile temperature
"Very wet" days = days with rainfall at or above the baseline 5th percentile precipitation amount
"Exceptionally wet" days = days with rainfall at or above the baseline 1st percentile amount

Figure 2-5 shows these results graphically. The figure shows that all types of extreme weather cause disruptions more frequently than the baseline (9%). Snow and tropical storms cause the most dramatic increases in delays, but heavy rain and high temperatures also play a major role in causing service disruptions. In addition, Figure 2-6 shows that snow events cause the longest delays, followed by heat, tropical storms, and non-tropical precipitation.

Figure 2-5

Percentage of Extreme Weather Days with Service Disruptions on Manayunk/ Norristown line

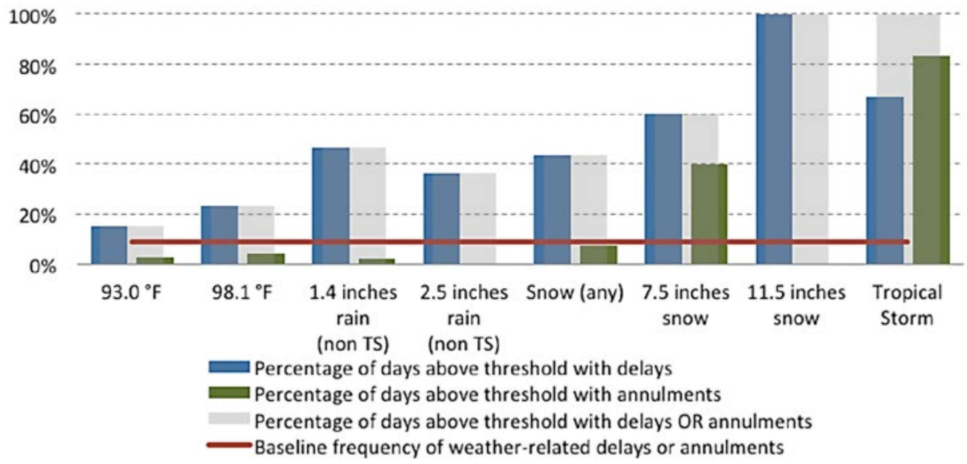
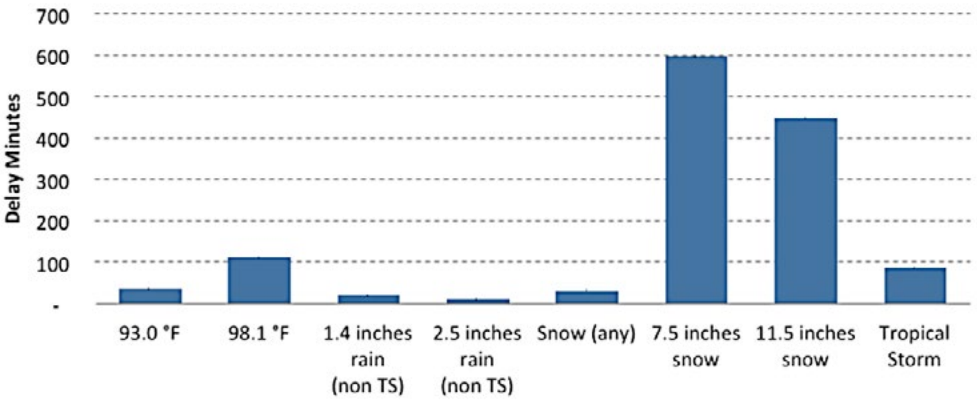


Figure 2-6

Median Delay Minutes per Day above Threshold Values with Delays



In an attempt to facilitate the comparison of different types of weather events, we have developed the following two equations for estimating "disruption risk":

Disruption Risk (in Delay Minutes) = (Probability of a Weather Event) × (Probability of Disruption Associated with that Event) × (Median Delay for that Event)

Disruption Risk (in Annulments) = (Probability of a Weather Event) × (Probability of Annulment Associated with that Event) × (Median Number of Annulments for that Event)

In addition to creating a "level playing field" for comparing the impacts of different types of weather events, this simple conceptualization allows for the straightforward estimation and evaluation of future risks, provided that the future probability of an event can be estimated (see Section 3, "Future Climate Hazards"). Working with a longer time series of observed data could help reduce the uncertainty associated with these risk estimates.

Table 2-8

Current Delay Risk Estimates

	Daily Probability of Occurrence*	Probability of Delays**	Median Delays (minutes)	Current Delay Risk (min/year)
Temperature, 93.0°F (5th percentile)	5%	15%	35	102
Temperature, 98.1°F (1st percentile)	1%	23%	111	116
Heavy rain, 1.4 inches (5th percentile)	1.7%	47%	18	55
Snow (any)	2.3%	44%	30	107
Tropical storms	0.3%	67%	85	56

*Daily probability of occurrence based on observed data from March 1, 1994–April 16, 2012 for temperature, rain, and snow, and from January 1, 1999–April 16, 2012 for tropical storms. For tropical storms, days were noted as experiencing tropical storms based on information from the National Weather Service's Weather Event Archive for the Philadelphia area, which begins in 1999 (http://www.erh.noaa.gov/phi/archives.html). The archive notes 9 tropical storm events impacting the Philadelphia area over that time period, spanning 13 total days.

**See Table 2-7 for probability of delay and median delays.

Table 2-9

Current Annulment Risk Estimates

	Daily probability of Occurrence*	Probability of Annulment**	Median Annulments (trains)	Current Annulment Risk (trains/year)
Temperature, 93.0°F (5th percentile)	5%	3%	1	0.5
Temperature, 98.1°F (1st percentile)	1%	4%	1	0.2
Heavy rain, 1.4 inches (5th percentile)	1.7%	2%	2	0.3
Snow (any)	2.3%	7%	5	2.7
Tropical Storms	0.3%	83%	34	28.3

*Daily probability of occurrence based on observed data from March 1, 1994 – April 16, 2012 for temperature, rain, and snow, and from January 1, 1999 – April 16, 2012 for tropical storms. For tropical storms, days were noted as experiencing tropical storms based on information from the National Weather Service's Weather Event Archive for the Philadelphia area, which begins in 1999 (http://www.erh.noaa.gov/phi/archives.html). The archive shows nine tropical storm events impacting the Philadelphia area over that time period, spanning 13 total days.

**See Table 2-7 for probability of annulment and median annulments.

The risk estimates represent the product of the probability of an event's occurrence and the magnitude of an event's consequences in terms of delays and annulments. The estimates act as a measuring stick to compare the various weather risks. For example, snow and heat currently pose comparable risks to the system, roughly double the disruption risk associated with heavy rainfall.

These results should not be seen as "predictions" of events (e.g., it is not realistic to conclude that 25 trains will be annulled due to tropical storms every year), but they can be used to compare risks between weather event types and across time periods. They are based on a limited sample of events (2005–2012), and the estimates have been made with the assumption that all weather events that exceed the designated threshold have a similar effect on the system (i.e., that the magnitude of the impacts do not scale with the intensity of the event once the threshold is exceeded). While this assumption may hold for some types of events (e.g., the impacts of the 1st and

5th percentile rainfall events are very similar), this is unlikely to be true for all events (e.g., the 1st percentile heat events are more likely to lead to delay and cause greater delays than the 5th percentile events).

Since heat-related impacts did appear to scale with temperature, we have presented separate calculations for both the 1st and 5th percentile heat events. These risks are not additive—the 5th percentile calculations include information on all events that exceed 93°F and already include the 1st percentile events. To employ the risk estimates in future decision making, users can choose a threshold that best fits with their experience and their tolerance for impacts. When considering current risk, the choice of the two thresholds has little influence on the risk of delay and the cost. However, when thinking about future risks (see Section 3, "Potential Future Frequencies and Costs of Service Disruptions"), the large potential increases in 1st percentile events (i.e., the "tail of the tail") generate a more extreme scenario for potential impacts.

The risk estimates can also be monetized by assuming that converting the delay risk estimates into a number of major events. Since we used 170 minutes and/or 5 annulments as the arbitrary cutoff for the definition of a major event, dividing the delay disruption risk (Table 8) by 170 minutes yields the annual number of major events. For tropical storms, all events are considered "major" and so the chance of tropical storms per year, based on the observed period, is used.[7] Combining this estimate with the average payroll costs (Table 2-3) for each event provides an annual monetary estimate for each event, shown in Table 2-10. This table summarizes only payroll costs, because this information was available for all weather events. For all event types, SEPTA experiences additional costs, such as those for materials and equipment.

Table 2-10

Current Risk of Major Events and Associated Payroll Costs

	Risk of Major Events (events/ yr)*	Average Payroll Cost per Major Event**	Risk of Major Events (payroll costs/yr***)
Temperature, 93.0°F (5th percentile)	0.60	$53,307	$36,417
Temperature, 98.1°F (1st percentile)	0.68	$53,307	$31,930
Heavy rain, 1.4 inches (5th percentile)	0.32	$60,249	$19,482
Snow (any)	0.63	$682,515	$428,995
Tropical storms	1.00	$164,524	$164,420***

*Major events are defined as delays greater than 170 minutes or annulments greater than 5 trains. See discussion in text above.

**Payroll cost includes fringe benefits; values shown assume the same cost for both "exceptionally hot" (1st percentile) and "very hot" (5th percentile) heat events.

***Tropical storm events have higher costs than indicated from payroll records. FEMA reimbursements for recent tropical storm events averaged $3.5 million per storm (see Table 2-2).

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[7] Risk of tropical storms per year calculated as daily probability of occurrence (0.3%) multiplied by 365 days per year.

Again, care should be taken when using these estimates for any predictive purposes. We present the following caveats:

- As evidenced by the large differences between payroll costs and FEMA reimbursement costs, payroll costs likely yield an incomplete picture of the actual costs borne by SEPTA for any event.
- There is some degree of inconsistency in simultaneously assuming that a “threshold mechanism” helps drive the physical impacts (i.e., disruption occur when certain weather thresholds are exceeded) and assuming an “additive mechanism” for the cost estimates (i.e., that as the risk of an event grows, its costs will grow proportionally).

The cost estimates do not capture any of the indirect costs associated with delays, such as those associated with lost sales or wages or effects on air pollution [2]. These costs would be borne by riders and businesses coping with the repercussions of disruptions in the transit system.

SECTION
3

Future Climate Hazards

To assess the potential implications of future climate hazards on SEPTA's services and assets, information was collected about projected changes in the climate for Philadelphia and its surrounding region by the mid-21st century.

Climate Change and Projected Changes in the Frequency and Intensity of Extreme Weather

Overall, the Philadelphia area is projected to experience a future that is warmer and wetter than in the past. Average annual temperatures and precipitation levels are projected to increase. Furthermore, temperatures and precipitation amounts that are rare in the observed climate are projected to occur more frequently by the mid-21st century. Changes in temperature are the most pronounced, with several-fold increases in the frequency of extreme heat days. Table 3-1 shows a snapshot of these projections, which are discussed in greater detail throughout this section.

Table 3-1

Projected Changes in Philadelphia Climate, 2046–2065 Compared to 1961–2000 Costs

Climate Variable	Minimum Projected Change*	Maximum Projected Change*	Average Projected Change*
Average annual temperature	4%	9%	7%
Frequency of "very hot" days (5th percentile)	101%	302%	196%
Frequency of "exceptionally hot" days (1st percentile)	215%	1,107%	540%
Average annual precipitation	-6%	17%	7%
Frequency of "very wet" days (5th percentile)	2%	30%	15%
Frequency of "exceptionally wet" days (1st percentile)	-1%	69%	39%
Frequency of "snow chance" days	-12%	-35%	-25%

*Minimum, maximum, and average projected changes across all climate models and emissions scenarios analyzed for 2046–2065 compared to 1961–2000.

This project used two sets of climate projections to study the future climate conditions of the Philadelphia area:

(1) We collected locally-downscaled climate projections for the Philadelphia area from the WRCP CMIP3 Multi-Model Dataset [3]. We considered all nine climate models available in the statistically-downscaled daily

climate dataset, under two emissions scenarios.[8] For each model and emissions scenario (18 data points), we determined the change in frequency of extreme heat and precipitation events, as well as in the number of days that are cold enough for possible snow by mid-century (2046–2065) compared to late 20th century (1961–2000). Results show the range and average of projections across all models and emissions scenarios.

(2) We summarized two reports that draw on regional-scale projections for future climate: an FHWA report that synthesized regional model projections for the Northeast [4] and a Union of Concerned Scientists report that focused on climate change impacts in Pennsylvania [5]. The Union of Concerned Scientists report draws from projections from three different climate models and two different emissions scenarios.[9] The FHWA report draws from 15 models run for a higher emissions scenario and 19 models run for a lower emissions scenario.[10] We used the information in these reports to understand seasonal changes in the region and as a means of doing quality control checks on our downscaled climate data projections.

A detailed discussion of the data and methods used in analyzing climate projections is provided in Appendix D.

Temperature

The projection data consistently point to a warmer future, with a substantial increase in the number of extremely hot days. Across the northeast, average temperatures are projected to warm between 3 to 6°F by mid-century [4]. Our analysis of the locally-downscaled climate model projections shows a similar increase in average annual temperatures of about 4°F by mid-century, with a range of 3 to 6°F across all models and scenarios.

In addition, hot summer days are projected to become more frequent in the Philadelphia area [5] (see Figure 3-1). Our analysis of locally-downscaled climate

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[8] The nine climate models are the Canadian Centre for Climate Modeling & Analysis CGCM3 model (ccma_cgcm3), France's Centre National de Recherches Météorologiques CM3 model (cnrm_cm3), NOAA's Geophysical Fluid Dynamics Laboratory's CM2.0 and CM2.1 models (gfdl_cm2_0 and gfdl_cm2_1), France's Institut Pierre Simon Laplace CM4 model (ipsl_cm4), Japan's National Institute for Environmental Studies and Frontier Research Center for Global Change model (miroc3_2_medres), the Meteorological Institute of the University of Bonn's ECHO model (miub_echo_g), the Max Planck Institute for Meteorology model (mpi_echam5), Japan's Meteorological Research Institute's model (mri_chcm2_3_2a). The two emissions scenarios are A2 and B1 to represent the moderately high and low emissions paths, respectively.

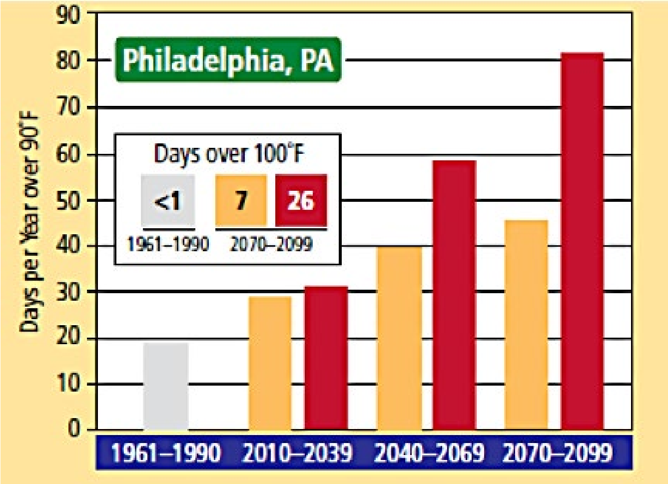
[9] The three models are NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 model, the United Kingdom Meteorological Office's Hadley Centre Climate Model version 3 (HadCM3), and the National Center for Atmospheric Research's Parallel Climate Model (PCM). The two emissions scenarios are A1FI and B1.

[10] The higher emissions scenario used was A2 and the lower emissions scenario was B1. A full list of the models used is available in the FHWA report.

model projections confirms these changes. According to model projections, temperatures at or above the current 5th percentile (in observed conditions, 93°F), or “very hot” days are projected to occur between 2 and 4 times more frequently by mid-century (the range across all models and emissions scenarios). Today’s 1st percentile temperatures (in observed conditions, 98°F), or “exceptionally hot” days are projected to occur anywhere from 3 to 12 times more frequently by mid-century, with an average projected increase of nearly 6.5 times. These projected changes are summarized in Table 3-2. The full spread of climate model projections is illustrated in Figure 3-2, showing that all models show an increase in average annual temperature and extreme temperature frequency. The models show that current extreme temperatures are projected to occur more frequently than they do today, and all models project a greater increase in the frequency of the most extreme, “exceptionally hot” days compared to the “very hot” days.

Figure 3-1

Projected Number of Days per Year over 90°F and 100°F in Philadelphia, PA [5]



Orange bars refer to a low emissions scenario. Red bars refer to a high emissions scenario.

Table 3-2

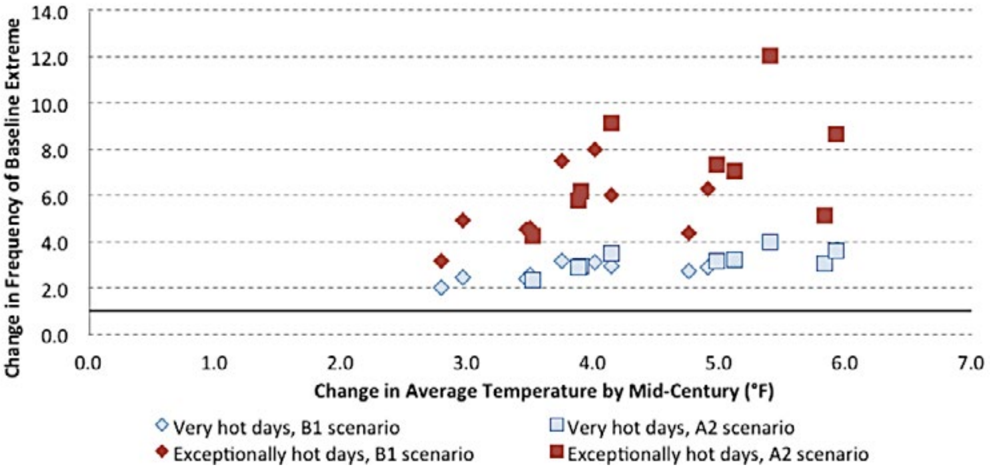
*Projected Change in Frequency of Late 20th Century (1961—2000) Extreme Temperatures by Mid-Century (2046–2065) (Multiplier)**

	Frequency of “Very Hot” Days	Frequency of “Exceptionally Hot” Days
Minimum change	× 2.0	× 3.1
Maximum change	× 4.0	× 12.1
Average change	× 3.0	× 6.4

*Values shown are the minimum, maximum, and average multiplier across the nine climate models and two emissions scenarios (18 data points).

Figure 3-2

Climate Model Projections of Change in Average Daily Temperatures and Frequency of Late 20th Century Extreme Temperatures by Mid-Century

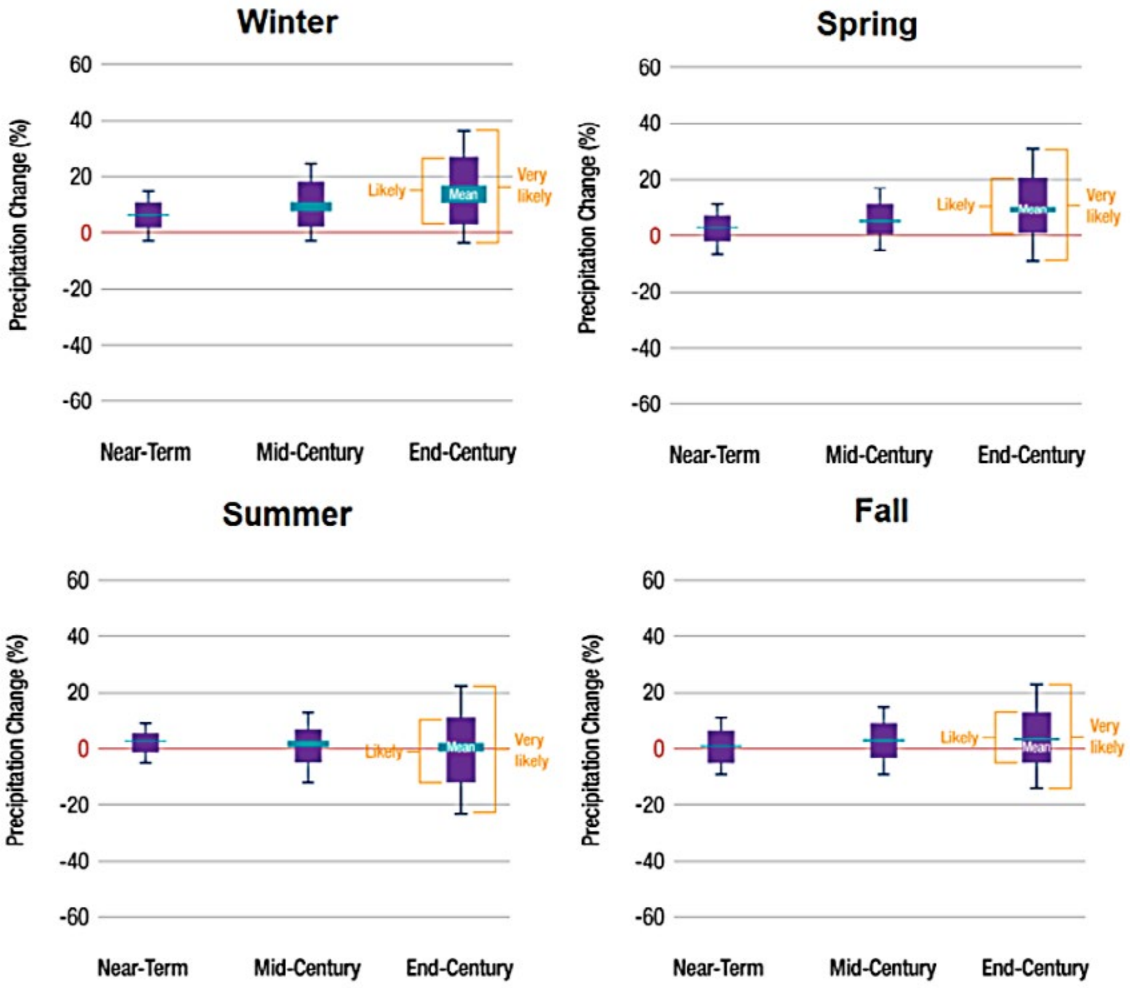


Precipitation

Overall, the Northeast is expected to experience a wetter future compared to historic conditions [4]. Seasonal and annual precipitation levels are expected to increase by mid-century, with the largest increase in the winter (see Figure 3-3). Our analysis of localized projections in Philadelphia corroborates these findings. Nearly all models project an increase in average annual precipitation, with an average increase of 1.9 inches by mid-century across all models and emissions scenarios, or about a 7 percent increase in average annual precipitation.

Figure 3-3

Projected Changes in Precipitation by Season in the Northeast, according to FHWA, 2010 [4]



Heavy precipitation events are also projected to become more common in the future compared to current conditions. In the Northeast, historic heavy precipitation events are projected to become 12 to 13 percent more common by the end of the century, averaging across the models and scenarios studied [4]. Philadelphia-specific climate model projections also show increases in the frequency of heavy 24-hour precipitation events. Under observed conditions, days with rainfall at or above 1.5 inches occurred between 6 and 7 times per year (the 5th percentile precipitation event, or "very wet" days). All models project that by mid-century, these events may become more frequent, with projections ranging from an increase of 2 to 30 percent. On average, models project a 15 percent increase in the number of "very wet" days, or about 1 to 2 additional days per year.

"Exceptionally wet" days (the 1st percentile precipitation event—in observed conditions, at least 2.5 inches in a day) are also projected to occur more frequently. Models are spread on how the magnitude of the increase (ranging from a decrease of 1% to an increase of 70%) but, on average, models project that these "exceptionally wet" days will occur 39 percent more frequently. This translates to nearly 1 additional day per year, on top of the current frequency of 1–2 days per year. Figure 3-4 shows the spread of model projections for the change in frequency of heavy rainfall events from historic conditions to mid-century and the projected change in average annual precipitation. The majority of models project a future that is both wetter overall and includes an increase in the number of days with heavy rainfall.

Figure 3-4

Climate Model Projections of Change in Average Annual Precipitation and Frequency of Late 20th Century Extreme Temperatures by Mid-Century

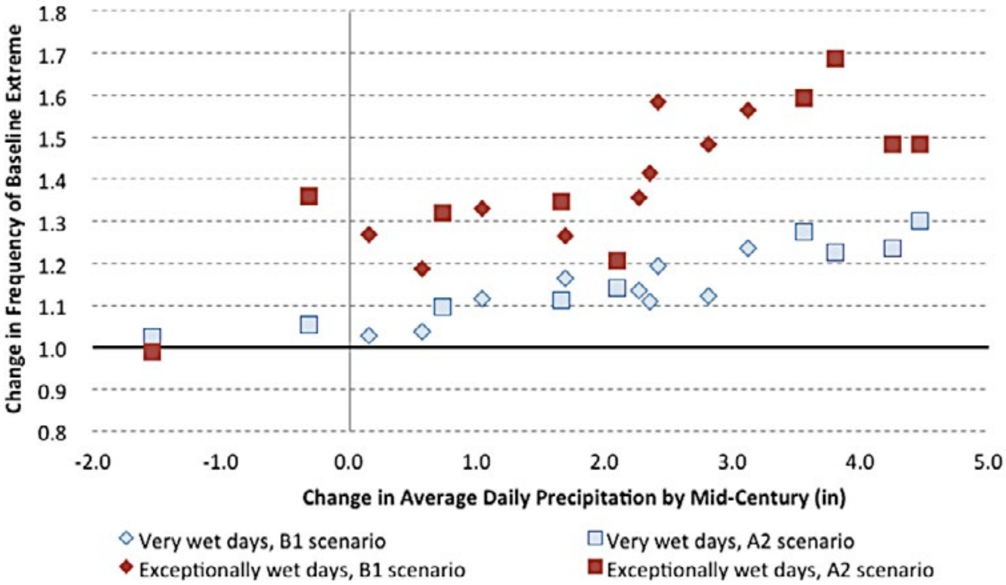


Table 3-3 shows the range of projections for average annual precipitation and the frequency of "very wet" and "exceptionally wet" days. The values shown are the minimum, maximum, and average percent changes across all 18 climate model and emissions scenario projections.

Table 3-3

Projected Percent Change in Average Annual Precipitation and Frequency of Late 20th Century (1961–2000) Extreme Precipitation by Mid-Century (2046–2065)

	Average Annual Precipitation	Frequency of "Very Wet" Days	Frequency of "Exceptionally Wet" Days
Minimum Change	-6%	2%	-1%
Maximum Change	17%	30%	69%
Average Change	7%	15%	39%

Values shown are the minimum, maximum, and average percent change across the nine climate models and two emissions scenarios (18 data points).

Snow

Climate model projections on snowfall amounts or frequencies in the Philadelphia area were not readily available in a form usable in this report. We, therefore, do not have similar projections for snowfall as for temperature and precipitation. However, daily temperatures can provide some indication of how often snow may fall. We defined a "snow chance" day as a day in which the low temperature falls below 2°C above freezing, or 35.6°F. On these days, the temperature theoretically is low enough for snow to occur. This is a rough approximation and does not incorporate several other factors necessary for snow formation, so should not be taken as a direct projection of how often snow will occur. However, it can be used as a rough proxy for how likely snowfall may be in the future.

These approximate "snow chance" days are projected to decrease in frequency by the mid-21st century compared to the late-20th century as temperatures warm. Projected decreases range from 35 to 12 percent across climate models and emissions scenarios, and are summarized in Table 3-4. These results suggest that as temperatures warm, snowfall may become less frequent in the Philadelphia area, but several other factors, including amount of precipitation, can affect the total annual quantity of snow.

Table 3-4

Projected Percent Change in Average Annual Precipitation and Frequency of Late 20th Century (1961–2000) Extreme Precipitation by Mid-Century (2046–2065)

	Frequency of "Snow Chance" Days*
Minimum Change	-35%
Maximum Change	-12%
Average Change	-25%

Values shown are the minimum, maximum, and average percent change across the nine climate models and two emissions scenarios (18 data points).

*"Snow chance" days defined as the number of days per year in which the temperature falls below 36.5°F. This is a rough approximation and does not incorporate several other factors necessary for snow formation.

Tropical Storms

Characterizing the link between climate change and the frequency or magnitude of tropical storms is an active area of research and deals with some of the large-scale factors affecting tropical storm formation and development, including sea surface temperatures. However, existing research does not currently provide definitive insight into the frequency or intensity of storms that might make landfall near Philadelphia in the future. However given the frequency of storms observed in the region over the past decade, tropical storms should be considered a weather-related hazard in Philadelphia.

Current studies considering how tropical storms may change in the future are not specific to Philadelphia nor the Northeast United States, but show the increases in the intensity of North Atlantic hurricanes in recent decades can be attributed to increased sea surface temperatures [6, 7]. Globally, current models and downscaling techniques consistently find that climate change may lead to increases in the globally averaged intensity of tropical cyclones, and decreases or causes little change in the overall global tropical cyclone frequency during the 21st century [7]. A recent downscaling experiment using the average from 18 different climate model simulations projects a 28 percent reduction in the overall frequency of Atlantic storms, and an 80 percent increase in the frequency of major hurricanes[11] in the Atlantic by the end of the century [7].

Despite this knowledge on broader changes in tropical activity, research is not available on how tropical storms may impact the Philadelphia region in the future. However, the recent barrage of tropical storms to hit Philadelphia (10 storms from 1999 through 2012 [8]) indicates that the region is susceptible to these storms and, as a result, SEPTA should be prepared to continue to deal with tropical events.

Potential Future Frequencies and Costs of Service Disruptions

We estimate the future risks of disruption and the costs associated with disruption by combining the projected changes in the frequency of extreme weather events with the known costs and service disruptions associated with these events. These calculations use the daily-event multiplier information developed from the climate projections in Tables 3-2, 3-3, and 3-4 and the observed disruption frequencies in Tables 2-8 and 2-9 (see Section 2, “Thresholds for Weather-Related Disruption”). These projections should not be taken as definite future risks, but provide a sense of the magnitude of potential climate change impacts. The future risks also assume current service levels will continue on the M/N line. Increases in service levels would increase the future risk of disruptions.

Tables 3-5 and 3-6 show the future estimates for delays, annulments, major events, and payroll costs by mid-century (2046–2065). Figure 3-5 shows estimated payroll costs visually. Low, Medium, and High estimates correspond to the range of model projections for the variables: Low estimates represent the model and emissions scenario with the least change for that variable, Medium estimates represent the average of the nine models for that variable across both emissions scenarios,

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[11] Major hurricanes defined as Category 4 and 5 on the Saffir-Simpson scale.

and High estimates represent the model with the most change for that variable. Projections for future snow risk are based on the "snow chance" day calculations described above and carry more uncertainty than the temperature and rainfall projections. Since changes in the frequency and intensity of tropical storms that will affect Philadelphia are not well known, we have not calculated future risk estimates for tropical storms. However, tropical storms will likely continue to affect the region, so the current risk estimates (Tables 2-8, 2-9, and 2-10) could be applied to the future as well.

Table 3-5

*Future Risks of Delays and Annulments**

	Current Risk of Delay (min/yr)	Future Risk of Delay (min/yr)			Current Risk of Annulments (trains/yr)	Risk of Annulments (trains/yr)		
		Low	*Med*	*High*		*Low*	*Med*	*High*
"Very hot" days (5th percentile)	102	205	301	409	0.5	1.0	1.5	2.0
"Exceptionally hot" days (1st percentile)	116	366	743	1,402	0.2	0.5	1.1	2.1
"Very wet" days (5th percentile)	55	56	63	72	0.3	0.3	0.3	0.4
Snow (any)	107	70	80	94	2.7	1.8	2.0	2.4
Tropical Storms**	56	n/a	n/a	n/a	28.3	n/a	n/a	n/a

*Note that these future risks are based on current service levels. Increases in service would increase the future risk of disruptions.

Table 3-6

*Future Risks of Major Disruption Events and Associated Payroll Costs (including Fringe Benefits)**

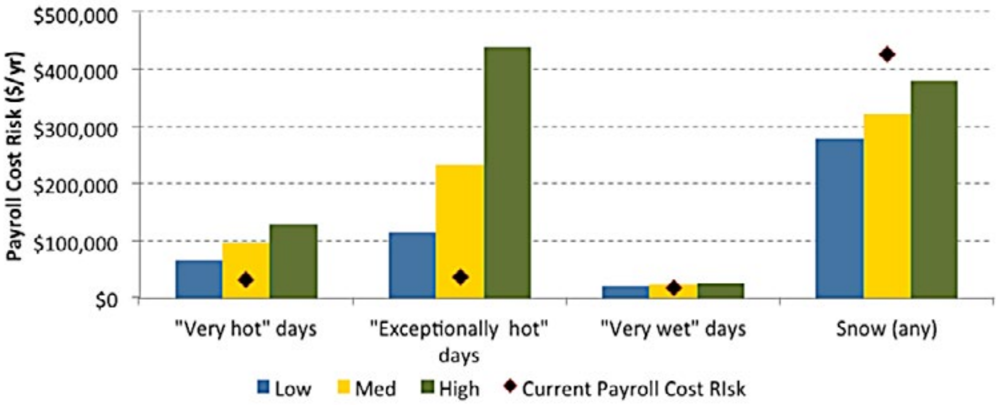
	Current Frequency of Major Events (events/yr)	Future Frequency of Major Events (events/yr)			Current Payroll Costs ($/yr)	Future Payroll Cost Risk ($/yr)		
		Low	*Med*	*High*		*Low*	*Med*	*High*
"Very hot" days (5th percentile)	0.60	1.2	1.8	2.4	$31,930	$64,253	$94,404	$128,331
"Exceptionally hot" days (1st percentile)	0.68	2.2	4.4	8.2	$36,417	$114,659	$232,951	$439,694
"Very wet" days (5th percentile)	0.32	0.3	0.4	0.4	$19,482	$19,947	$22,324	$25,380
Snow (any)	0.6	0.4	0.5	0.6	$428,995	$279,678	$322,179	$378,895
Tropical storms**	1.0	n/a	n/a	n/a	$164,420	n/a	n/a	n/a

*Note that these future risks are based on current risks and all caveats discussed in Section 2, "Thresholds for Weather-Related Disruption" apply, including the assumption of consistent service levels. Increases in service would increase the future risk of disruptions.

**Tropical storms have higher costs than indicated from payroll records. FEMA reimbursements for recent tropical storm events averaged $3.5 million per storm (see Table 2-2).

Figure 3-5

Future Payroll Cost Risks of Extreme Weather (Low, Medium, and High estimates)



The results demonstrate that the relatively large increases in the frequency of heat extremes are likely to translate into more frequent delays and costs. Regardless of the choice of the heat threshold ("very hot" or "exceptionally hot"), nearly all climate models show that the future risk of delay associated with temperature will exceed the current risk of delay associated with snow. Although there is a large range between the high projections for delay (for "exceptionally hot" days, the delay risk is more than 1,100 min/yr; for the "very hot" days, the delay risk is just under 400 min/yr), both estimates are much larger than current snow delay risks. Meanwhile, the risks associated with the chance for snow delay could decline, based solely on the increase in temperatures, although the projections do not provide information about changes in circulation, such as changes in the jet stream that could facilitate more frequent or more severe winter storms.

Potential Changes in Sensitive Locations and Assets

Existing areas vulnerable to flooding and the assets located in those areas were identified in Section 2, and new areas may emerge over time. Whenever a National Weather Service flood warning is in effect, SEPTA staff visually inspect these vulnerable areas. Staff have noted that, over time, new areas may be added to the inspection process, but historical areas have never been removed. Therefore, the areas targeted for inspection can only grow over time. Additional areas may become vulnerable to flooding due to landscape changes such as upstream development, damage from previous storm events, and debris and silt accumulation that affect stream flow. Careful monitoring and coordination of watershed-wide development would help identify and mitigate potential new problems in advance, though that is beyond SEPTA's jurisdiction. On a smaller scale, SEPTA staff visually inspect culverts for blockage from debris, which can create localized flooding.

Vulnerabilities to winter and heat events are less predictably location-specific. Power assets and track are susceptible to winter storm events, but the sensitive locations are a function of whether trees and limbs can fall onto the line. That, in turn, is a function of tree-trimming cycles, where recently-trimmed areas are less vulnerable and areas that have gone several years since the last trimming are more vulnerable. Over time, these areas will switch, and if the growing season is extended, as is anticipated in most climate change scenarios, tree-trimming cycles may need to be shortened to keep up with the additional growth.

SECTION 4

Key Vulnerabilities

SEPTA is already vulnerable to weather-related events. These events cause damage to physical infrastructure, create hazardous conditions, and can prevent SEPTA from providing service to its customers. These existing vulnerabilities will persist into the future and, as discussed in Section 3, many of the events experienced today are likely to become more common in the future.

This section outlines areas the M/N line's current and future vulnerabilities to weather-related events, based on interviews with SEPTA staff and research on general transit vulnerabilities to climate and weather [9]. Understanding these vulnerabilities is a key early step in managing climate risks. This section focuses on vulnerabilities to the M/N line, but many of these vulnerabilities are common to other aspects of the SEPTA system.

Vulnerabilities to High Temperatures

SEPTA currently experiences relatively low disruptions due to temperature compared to other weather events. However, temperatures in the area are projected to increase, causing higher number of days above 90°F (recall Section 3, "Climate Change and Projected Changes in the Frequency and Intensity of Extreme Weather").

In such high temperatures, the M/N line (and other rail lines) would be vulnerable to sagging wires, equipment stress, and track buckling. In addition, these temperatures create harsh working conditions that can make it difficult to assess or repair damages. When temperatures surpass 90°F, SEPTA issues a system-wide FS1 speed restriction, which requires trains to run at 50 mph instead of their typical 60 mph speed. The slow-down can cause schedule delays. In addition, staff are required to visually inspect the track, looking for potential kinks or buckling points. Portions of the track exposed to direct sunlight are most vulnerable to buckling.

High temperatures primarily affect SEPTA's power system. Temperatures affect power lines and wires, and high temperatures can cause wires to sag. Older wires are especially vulnerable. Not only are they more prone to sagging, they are also more likely to break if tightened. The regional power grid may also be stressed and subject to brownouts during periods of high heat. SEPTA's power system is thus further vulnerable to the extent that it is reliant on utility-provided electricity. The vulnerability of power supplied to SEPTA by local utilities is outside the scope of this study but should be considered as a critical factor within SEPTA's efforts to be more resilient to extreme weather.

SEPTA is vulnerable to projected increases in temperature from both an infrastructural and operations standpoint. As discussed, wires and tracks are more susceptible to damage in high temperatures, but SEPTA is vulnerable even from a staffing perspective. As temperatures in Philadelphia surpass 90°F more frequently, more time will be spent under FS1 speed restrictions and with mandatory track inspections. In past heat events, SEPTA has had to cancel or delay capital work in order to monitor the track and power system.

SEPTA's primary vulnerability to projected temperature change is, thus, an added strain on staff time and resources beyond what has been experienced in the past. These stresses will also occur in the context of other changes in weather discussed throughout this report. Adaptive actions to address this vulnerability will likely require incorporating new expectations of heat event frequency in planning processes (see Section 5).

Vulnerabilities to Heavy Rain Events

The M/N line is highly vulnerable to flooding from heavy rain events. When rain falls, it combines with runoff from upstream and can overwhelm culverts and cause severe flooding on the line. Flooding issues are most pronounced at the Spring Mill (see Figure 4-1) and Conshohocken stations on a mile-long stretch of rail just west of Conshohocken and where the Pennsylvania Turnpike (I-276) crosses over the rail. In these places, runoff and direct precipitation combine to flood the rail line, deposit debris along the track, and often wash out the track and the embankment. Heavy rains are often accompanied by high winds, which can lead to downed trees, damage to catenaries, power outages, and damage to signals.

Figure 4-1

Flooding at Spring Mill Station on the M/N Line (photo courtesy of SEPTA)

During heavy rain events, SEPTA is often forced to close sections of track. This, in turn, disrupts service and may require rescue buses for some passengers, single tracking, and changes to service schedules. If sections of the track are washed out and lose embankment, SEPTA must put down new ballast, remove mud slides, and rebuild the track area. In addition to these flood-related damages, SEPTA must also deal with damage to culverts, downed trees, downed wires, debris on track, and damage to equipment such as catenaries, pantographs, signals, interlockings, gates, and other components.

SEPTA has experienced these issues repeatedly in the past and has demonstrated an ability to recover from the damage. SEPTA departments increase their staffing capacity during severe storm warnings, increase track inspections, attempt to maintain a ready supply of ballast and other materials in case of a track washout, and attempt to keep trees trimmed. However, this knowledge of problem areas and how to deal with them is housed primarily in the minds of relatively few senior SEPTA staff. The depth of SEPTA's institutional knowledge provides it with extensive capacity to respond to climate and weather-related threats, but the extremely high concentration of knowledge in a few key senior staff represents a key vulnerability. Rich and useful knowledge, including un-documented protocols for action, is not widely dispersed. Hence, mining, documenting, and disseminating the institutional knowledge that exists at the highest levels in SEPTA is critical for the long-term resiliency strategy.

Further, as extreme weather events are projected to become more frequent, SEPTA's capacity to respond may be stretched without adaptive measures (see Section 5). The locations that are currently vulnerable to flooding are likely to remain vulnerable, and other areas may become prone to flooding as well due to new stressors from changing urban conditions and climate.

Vulnerabilities to Snow and Winter Storms

Snow events are the largest cause of weather-related disruptions on the M/N line. The accumulation or presence of snow is often the primary cause. SEPTA must remove snow from the track and stations, and availability of staff is dependent on roads and other modes of transportation. Snow can also build up over the winter in parking lots and restrict parking availability. Snow removal is both time-intensive and expensive, and third-party workers are often required to clear the snow. Snow removal can also cause injuries to staff.

SEPTA is also vulnerable to snowstorms because of downed power lines and power outages that affect the community at large. In addition, snow and ice can cause interlocking and signal failures.

Extreme cold temperatures, regardless of snowfall, can also cause damage to SEPTA infrastructure. Extreme cold causes equipment failures, switch failures, broken track, wire fatigue, and broken wires.

While temperatures are expected to increase, snow events and major snow events may continue to be significant vulnerabilities for SEPTA. The time and budgetary demands of snow events will interact with other, newer demands from temperature and heavy rainfall.

Vulnerabilities to Tropical Storms

The M/N line is highly vulnerable to damage from the tropical storms that affect the Philadelphia area. Tropical storms combine high winds and high precipitation volumes and, therefore, can cause not only flooding but extensive infrastructural damage. Even more so than heavy precipitation events, tropical storms are likely to cause downed trees, damage to catenaries, power outages, and damage to signals. Some tropical storms can also cause severe flooding, as described in Section 4, "Vulnerabilities to Heavy Rain Events." Tropical storms also cause unsafe travel conditions, making it difficult or dangerous for staff and passengers alike to get to SEPTA facilities. Tropical storms often cause significant service disruptions, with service cancelled and residual delays potentially lasting for multiple days.

SEPTA usually has notice of a tropical storm's approach several days in advance. This notice, combined with the events' magnitude, makes SEPTA's response different than for other weather events. In advance of the storm, SEPTA will, to the extent possible, trim trees, move equipment to strategic locations, pre-screen trouble areas, rent backup power generators, decide whether and when to cancel service, and communicate their decisions to the public. During the storms, SEPTA deploys staff to inspect infrastructure and monitors weather service information on the storm such as wind speed, rainfall, and flood levels. They also keep a wire car available during the storm to make repairs to the catenary if necessary and if conditions allow. Following the storm, SEPTA staff and third-party contractors work to clean up the damage, removing debris and downed trees from the track, repairing equipment, and rebuilding track sections as needed.

SEPTA's processes for dealing with tropical storm events are evolving with their recent experiences. Despite some advanced warning and preemptive measures, however, the storm events still cause severe damage. If these events continue to occur at the same rate as they have in recent years, SEPTA may need to take longer-term adaptive measures to prevent damage from the storms and hasten post-storm recovery (see Section 5).

Overall Vulnerabilities

Overall, the M/N line is currently vulnerable and likely to continue to be vulnerable to flooding from heavy precipitation events and tropical storms. In addition, vulnerabilities from high temperatures are likely to increase in the future. The M/N line is vulnerable to flooding, track washouts, downed trees, power outages, wire damage, and increasingly common speed restrictions. SEPTA's vulnerabilities on the M/N line, current and future, are summarized in Table 4-1 by weather event type and SEPTA department. Collectively, these changes translate to increasing demand on SEPTA's staff and other resources to inspect systems and make repairs in the event of damage while maintaining service levels. Weather-related events may become an increasing burden on SEPTA's labor system, budget, and ability to complete capital projects. In the face of these changes, SEPTA will need to maintain open lines of communication with the public to maintain trust and reliability for customers.

Table 4-1

SEPTA's Vulnerabilities to Weather Events and Projected Climate Changes on the Manayunk/Norristown Line (organized by weather event and SEPTA department)

Department	Heat	Heavy Rain	Snow	Tropical Storm (Heavy Rain + Wind)	Vulnerabilities Common to Multiple Weather Event Types
Power	• Power outages or utility brown-outs • Sagging wires • Inability to run new wire	• High labor demands during severe storm warnings • Catenary damage	• Power outages • Downed power lines • Broken wires (cold temperatures) • Wire fatigue (cold temperatures)	• Power outages • Catenary damage • Increased labor demands during severe storm warnings	• Power outages • Need to cancel capital work to monitor the power system
Bridges & Buildings (B&B)	• HVAC equipment stress	• Flooding and associated damage • Culvert damage • High pumping demands	• Ice on station platforms, sippery conditions • Staff, budgetary demands from snow removal • Loss of parking spaces from snow buildup •	• Flooding and associated damage • Culvert damage • Increased pumping demands • Wind and roof damage to stations	
Track and Civil Engineering	• Track buckling • High labor demands from mandated track inspections •	• Flooding • Track washouts • Potential for lost track embankment • Culvert damage • Flooding, damage to switch machines • Debris on track • Mandated track inspections • Speed restrictions	• Interlocking and switch failures • Downed trees • Staff, budgetary demands from snow removal • High labor demands (incl. third party) • Broken track (cold temperatures) •	• Flooding, damage to assets • Downed trees • Debris on track • Track washouts • Culvert damage • Gate damage •	• Track washouts • Downed trees • High labor demands
Communication and Signals	• Speed restrictions • Jammed switches	• Signal damage	• Signal failures • Power outages	• Signal damage	• Signal damage or failures
Overarching	• Labor demands from visual inspections • Strenuous labor conditions • Potential for utility brown-outs • Speed restrictions • Service disruptions	• Service disruptions • Labor demands from storm preparation and response • Flooding and associated damage to culverts and other assets • Damage from downed trees • Institutional knowledge on vulnerabilities that is deep but narrowly distributed among staff •	• Power outages • Snow removal labor demands and costs • Service disruptions, need to communicate with riders • Equipment failures (snow and cold temperatures)	• High labor demands • Extensive service disruptions, need to communicate with riders • Equipment damage	• Service disruptions, need to communicate with riders • High labor demands • Institutional knowledge on ulnerabilities that is deep but narrowly distributed among staff • Speed restrictions • Equipment damage

SECTION

5

Adaptation Strategies

SEPTA can consider adaptive measures to manage their climate risk and address the vulnerabilities discussed in Section 4. Adaptation refers to a set of adjustments in response to expected changes in climate, and is intended to moderate damage and increase system resilience to climate variability and change. Adaptation options may not be technologically innovative or climate change-specific; the majority are likely to involve well-established technologies and management approaches applied wisely to address climate risks.

This section presents several strategies SEPTA could pursue to reduce their vulnerability to climate risk, organized by weather type: high temperatures, heavy rain, snow, and tropical storms. We also present cross-cutting adaptation strategies. The options range in cost, relevant department, time frame, category (capital planning v. operations v. maintenance), and even feasibility. Recommended options—those that are reasonable for SEPTA to pursue in the near-term due to low costs, strategic timing, or mission importance—are shown in summary tables at the end of each sub-section and recapped in Section 5, Recommendations.

Process for Identifying Adaptation Strategies

ICF developed the adaptation options discussed in this section through a combination of research and a series of meetings and discussions held with four departments within SEPTA's Engineering, Maintenance & Construction Division: Track & Civil Engineering, Building & Bridges, Communications & Signals, and Power. In addition, meetings were held with ranking SEPTA officials in Engineering, Maintenance & Construction, Operations, and Finance & Planning Divisions, which formed a de facto Policy & Administration Committee for the project. First, we conducted research and developed a preliminary list of rail adaptation strategies. The primary sources used included FTA's Flooded Bus Barns and Buckled Rails report on transit adaptation and adaptation-related reports from other northeast transportation and governmental organizations (see Table 5-1). We also supplemented options from these resources with possible strategies we identified through the course of our investigation of the line.

Table 5-1

Main Resources Consulted to Develop Preliminary Adaptation Strategies

Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation – Federal Transit Authority (FTA), 2011 http://www.fta.dot.gov/documents/FTA_0001_-_Flooded_Bus_Barns_and_Buckled_Rails.pdf
Climate Action and Adaptation Plan – Los Angeles County Metropolitan Transportation Authority, 2012 http://www.metro.net/projects_studies/sustainability/images/Climate_Action_Plan.pdf
Metropolitan Transportation Authority (MTA) Adaptations to Climate Change: A Categorical Imperative – Jacob et al., 2008 http://www.mta.info/sustainability/pdf/Jacob_et%20al_MTA_Adaptation_Final_0309.pdf
Massachusetts Climate Adaptation Report – Massachusetts Executive Office of Energy and Environmental Affairs (EEA), 2011 http://www.mass.gov/eea/docs/eea/energy/cca/eea-climate-adaptation-report.pdf
MTA Twenty Year Capital Needs Assessment 2010–2029 (Draft) – Metropolitan Transportation Authority, 2009 http://www.mta.info/mta/capital/pdf/TYN2010-2029.pdf
Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure – North Jersey Transportation Planning Authority (NJTPA), 2010 http://www.njtpa.org/Plan/Element/Climate/documents/CCVR_REPORT_FINAL_4_2_12_ENTIRE.pdf

We then held a series of roundtable meetings with SEPTA staff to discuss the preliminary adaptation options and elicit ideas for other strategies based on their vulnerabilities. Questions used to guide the discussions included: What preparations or actions did you take before, during, and after Hurricane Sandy? What are SEPTA's vulnerabilities when storms like this hit? How can SEPTA better respond to these vulnerabilities? These conversations generated several new ideas and refined others from the preliminary list.

Adaptation Strategies for High Temperatures

SEPTA has several options for responding to the vulnerabilities to heat described in Section 4, "Vulnerabilities to High Temperatures." This section presents an expansive list of adaptation strategies to deal with high temperatures. Not all strategies will make sense for the M/N line specifically, or even for SEPTA generally. Recommended options, those that are "no regrets" options or represent "low hanging fruit" are emphasized in Section 5, "Recommendations."

Catenary wires are more likely to sag in the future given warmer temperatures and cause associated delays. The most effective (and most expensive) way to address this is to modernize the catenary line, upgrading it to a "constant tension" system. A constant tension system typically maintains the wire at the proper tension in a range of wire temperatures from 32°F to about 120°F. Current systems are designed around a fixed-wire temperature of 60°F. Therefore, even if temperatures exceed 90°F in the future, there would be a smaller amount of sag than there would be with the current wires. SEPTA has installed a constant tension system on its Airport Line. Upgrading the wire system elsewhere would reduce maintenance costs but require a significant capital investment (on the order of several million dollars) SEPTA could evaluate which of its Regional Rail lines are candidates for constant tension systems and, for those, conduct a cost-benefit analysis of the upfront costs compared to the maintenance savings to determine if upgrades would be a worthwhile investment. Generally, constant tension systems are less economical on curvy, slower-speed lines like the M/N line but could be economical for long, straight stretches of line. Upgrading to constant tension could be done through the course of meeting SEPTA's State of Good Repair needs. Alternatives to a constant tension system include implementing heat event protocols during and in advance of heat waves that capture heat response best practices, many of which SEPTA already uses, including to check and maintain wire tension and reduce train speeds (as is currently done above 90°F) or responding to sag issues as they arise.

Track buckling is another potential vulnerability from intense heat events, as continuously welded tracks can buckle when rails expand at high temperatures. SEPTA has been taking steps to reduce this risk and, over the past 30 years, has been gradually increasing its "rail-neutral temperatures" for the rail (the temperature up to which the rail can expand before buckling). This is typically done by replacing sections of track with higher rail-neutral temperatures as part of regular maintenance. Several factors complicate determining the appropriate rail-neutral temperatures for an area (see full discussion of these complicating factors in FTA's "Flooded Bus Barns and Buckled Rails" report [9]). SEPTA also activates regular heat patrols on the first five heat events of the year when temperatures are above 90°F, and on every heat event above 95°F thereafter. During these patrols, SEPTA sends out inspectors to continually monitor the system for things like track buckling and other heat effects. Another strategy is to install rail temperature monitoring stations to determine when a section of rail is at risk of buckling, since the risk is driven by the rail temperature, as opposed to ambient temperature.

Heat can also stress equipment, and installing additional ventilation around key electronic equipment can alleviate that stress. Further, electrical equipment is reliant on power from the utility grid, which can also be stressed or experience brownouts during extended heat events. SEPTA could reduce its reliability on the grid during heat events by acquiring temporary or permanent backup power systems. SEPTA can also reduce its reliance by reducing its electricity demand through energy efficiency improvements to buildings and equipment, where possible.

SEPTA is also vulnerable to non-infrastructural issues from heat. These vulnerabilities cover staffing, scheduling, and budgeting. Labor conditions may become difficult or dangerous for crew working outside for extended periods of time during high temperatures. SEPTA may consider shifting summer labor hours to cooler times of the day and educating workers about recognizing signs of heat stress. For example, Mobile, Alabama shifts their construction and maintenance hours from 7:00 AM–3:00 PM to 5:00 AM–1:00 PM during heat events.

Finally, high temperatures can require that SEPTA reduce train speeds, and frequently triggered speed restrictions can cause schedule disruptions if unplanned. Given projections for the Philadelphia area for an increasing number of days above 90°F and 95°F (recall Section 3, "Climate Change and Projected Changes in the Frequency and Intensity of Extreme Weather"), high temperatures may become a more frequent cause of delays. In the near term, SEPTA could track how often speed restrictions occur, how they correlate with temperature, and what delays are associated with speed restrictions. This monitoring may reveal that improved infrastructure conditions mean SEPTA does not need to slow trains at 90°F, and they could increase their speed restriction temperature threshold. Alternatively, the monitoring may show that high temperatures and speed restrictions are causing delays for customers. If that is the case, SEPTA could reduce delays from speed restrictions by setting its summer schedule to incorporate reduced train speeds into the timetable. SEPTA could pilot this approach to determine whether it is effective at avoiding delays and meeting customer demands and to more fully understand the cost and resource impacts of more frequent speed restrictions and track inspections. If needed, this pilot could be useful in developing protocols for the nature and event of slow speed regulations, understanding the tradeoffs between track upgrades versus the impacts of speed reductions, and could allow SEPTA to better budget for increasing resource demands from heat.

SEPTA could achieve many of these adaptation strategies by developing a formal heat event protocol that accounts for these items. The protocol could be triggered when a heat wave is forecast (or even during certain months) and could include renting backup power systems, increasing track inspections with an emphasis on problem areas for buckling, checking wire tension, shifting labor hours, educating staff and customers about heat risks, and creating cooling stations in strategic locations, as necessary.

All of these potential adaptation strategies are summarized in Table 5-2. For each possible solution to heat-related vulnerabilities, the table documents the applicable SEPTA department, the category of the solution (capital planning, maintenance, or operations), and how the solution can integrate within existing SEPTA frameworks and processes. Some adaptation options, including many that fall under capital planning, may be difficult to implement in the near-term because of budget constraints. However, many other strategies represent "low hanging fruit" that could improve SEPTA's resiliency and service and be implemented through tweaks to existing operations, maintenance, or communications protocols. These options are marked as "low" in the "Barriers to Implementation" column below, and are highlighted in Section 5, "Recommendations."

Table 5-2

Potential Adaptation Strategies for Heat Events

Problem	Possible Solution(s)	Department	Category	Barriers to Implementation	Fit within Existing Processes	Other Notes
Sagging wires	Conduct a cost-benefit calculation on fully modernizing the catenary line (high up-front cost, reduced maintenance costs)	Power	Capital planning	High		Typically not economical for curved, slow-speed lines like M/N
	Modernize catenary line to constant tension system (pending cost-benefit analysis)		Capital planning	High	Capital improvement process	Airport Line uses constant tension
	Regularly check and maintain wire tension		Maintenance	Low	Extension of existing maintenance activities	
Equipment stress	Install more ventilation for electrical equipment	Communication and Signals	Capital planning	High	Could occur through regular capital improvement and maintenance processes	
Track buckling	Identify and catalog problem areas	Track and Civil Engineering	Operations	Low	Potential to do through infrastructure maintenance management system	SEPTA will be adopting this strategy
	Replace existing track in vulnerable sections with track that has higher rail-neutral temperatures		Capital planning	High		SEPTA already has adopted this strategy
	Increase track inspections during high temperatures		Operations	Low		SEPTA already has adopted this strategy
	Install rail temperature monitors in key areas		Capital planning	High		
	Improve shading of certain track areas		Capital planning	High		Planting trees or installing shade structures may be at odds with other vulnerabilities and adaptation strategies and therefore may not be appropriate for the M/N line specifically; this strategy is more appropriate where track buckling is a more serious problem than storms

Table 5-2 (cont.)

Potential Adaptation Strategies for Heat Events

Problem	Possible Solution(s)	Department	Category	Barriers to Implementation	Fit within Existing Processes	Other Notes
Harsh working conditions	Shift working schedule to cooler times of day during heat events (or all summer)	Policy and Administration	Operations	High		
	Educate workers about heat stress, hydration		Operations	Low	Fits into existing staff communication systems	
	Have cooling stations available for workers		Capital planning	High		
Increased need for speed restrictions	Track frequency of speed restrictions, how they relate to temperature, delays associated with speed restrictions and high temperatures	Policy and Administration	Operations	Low	Add to existing suite of tracked metrics	Near-term strategy
	Consider increasing FSI temperature threshold (if line can operate successfully at temperatures around 90°F, which can be determined through above tracking)	Policy and Administration	Operations	High	Modification to existing FSI temperature threshold	Longer-term strategy
	Pilot a new "summer schedule" that incorporates FSI speed restrictions daily (pending tracking results)	Policy and Administration	Operations	High		This strategy would apply only if temperatures are consistently passing levels that require trains to reduce speeds
Utility brown-outs	Acquire additional back-up power (purchasing or renting)	Bridges & Buildings	Operations	High		SEPTA is already beginning to adopt this strategy
	Upgrade HVAC units to be more energy efficient	Bridges & Buildings, Rail Vehicle Engineering and Maintenance	Capital planning	High	Could occur through regular equipment upgrade process	
	Use heat-resistant construction materials	Bridges & Buildings	Capital planning	High	Could be integrated into procurement or project planning decisions	

Table 5-2 (cont.)

Potential Adaptation Strategies for Heat Events

Problem	Possible Solution(s)	Department	Category	Barriers to Implementation	Fit within Existing Processes	Other Notes
Increased demand on labor for track inspection, FSI restrictions	Incorporate expectations of FSI restrictions in budgeting and planning. Could use results of pilot summer schedule toward this effort.	Policy and Administration	Operations	High	Incorporate into existing planning and budgeting processes	
Potential for customer discomfort	Maintain HVAC systems	Bridges & Buildings, Rail Vehicle Engineering and Maintenance	Maintenance	Low	Existing maintenance activities	
	Install green roofs on stations	Bridges & Buildings	Capital Planning	High	Could be integrated into project planning decisions	SEPTA evaluates sustainable building practices as appropriate (e.g., the redesigned 69th Street Terminal will have green roofs and green walls)
More frequent heat waves	Develop policies and action plans to be taken when a heat wave is forecast (e.g. worker schedules, cooling stations, equipment readiness, backup power)	Policy and Administration	Operations	Low	Use process similar to formation of internal Hurricane Plan	
	Enhance rider communication	Policy and Administration	Operations	Low	Existing communications framework	SEPTA has already begun to adopt this strategy

Adaptation Strategies for Heavy Rain Events

Flooding has been and is likely to continue to be a problem on the M/N line. This section presents several possible adaptation strategies to reduce service disruptions from flooding and heavy rain events.

SEPTA has decades of experience dealing with heavy rain and flooding on the M/N line. Staff know the "hot spots" along the line and practical ways of dealing with those problem areas. This experience has allowed SEPTA to recover from repeated flood events. A key strategy to increase SEPTA's resiliency to repeated flooding is to develop a way to document and house this institutional knowledge. Means to do this range from creating a document that lists hot spots and responses to incorporating this knowledge into SEPTA's asset management system. Regardless of the specific manner, SEPTA should capture its wealth of knowledge surrounding these issues and ensure it remains part of the institutional knowledge, and in a way consistent with other means of knowledge-sharing within the organization.

SEPTA's current approach to flooding on the M/N line is to clean up and restore service as quickly as possible. Strategies used by the Authority include putting special equipment on standby (such as specialty wire trains, ballast, and rip-rap), moving equipment to strategic (e.g., higher elevation) locations before the storm, pre-screening trouble areas, notifying third party contractors in advance, trimming trees regularly, and renting generators. SEPTA has also installed a new turnback on the M/N line near the Miquon station so that service can at least continue on parts of the line during floods (see text box). Further, SEPTA could improve monitoring of water levels to know when to cancel service and where to target efforts; this could be done by installing new stream gauges or linking to existing ones to either monitor constantly or set up to send alerts when water levels breach key thresholds. Additional strategies to enhance flood recovery include increasing bus service in advance of predicted flood events to service flooded stations; monitoring and tracking problem tree areas, which change regularly; increasing coordination with the local utility, PECO, and other entities that require tree trimming services; and installing debris screens along key sections of track to prevent debris and ease cleanup. Finally, continuing to improve customer communication will be a key strategy across all vulnerabilities, including heavy rain and flooding.

Another class of strategies focuses on preventing or minimizing flooding and flood damage. One such strategy is to elevate assets (track, signal houses, electrical equipment, generators, etc.) to keep them from being flooded. For example, SEPTA is currently raising 19 signal houses along the M/N line as part of its Signal Modernization Project (see Figure 5-1). Other flood avoidance strategies include building flood protection structures like dikes or levees, increasing culvert size, promoting the use of pervious surfaces on SEPTA property and in neighboring jurisdictions, increasing pumping capacity, improving drainage around key assets, and placing sandbags in certain areas.

Adaptation Highlight: New Turnback near Miquon

In early 2013, SEPTA installed a new interlocking near the Miquon station to allow SEPTA to serve some areas of the M/N line even if others were flooded. Prior to the interlocking, service had to be suspended on the entire line if portions (typically areas West of Miquon) were flooded. On August 13, 2013, a severe storm caused flash floods that washed out portions of track near the Spring Mill station. Because of the flooding, SEPTA suspended service to stations west of the interlocking. However, service was able to continue between Miquon and downtown Philadelphia. The interlocking gave SEPTA's Control Center the flexibility to turn around outbound trains at Miquon and send them back into the city. Thus, installing the interlocking allowed SEPTA to maintain partial service on the M/N line, despite severe track washouts.

Figure 5-1

Newly-Raised Signal House Along Manayunk/ Norristown Line

SEPTA is also taking action to redirect runoff away from the track bed, such as tilting platforms away from the track, installing rain gardens, using alternative landscaping, and other drainage strategies. SEPTA has incorporated rain gardens and stormwater retention ponds into some of its station rehab designs, where space is available. SEPTA can further improve stormwater management on its properties through expanding the aforementioned strategies or installing green roofs and using pervious pavement in new projects. Because neighboring runoff contributes to track floods, SEPTA could also increase coordination with neighboring jurisdictions about improving stormwater management across the watershed. To prevent track washouts during flood events, SEPTA could also utilize slope stabilization techniques on the most vulnerable stretches of track, such as the area west of Conshohocken (see Figure 2-4). Such techniques include putting in reinforced soil, installing retaining walls, or planting densely rooting vegetation to hold the slope intact in case of floods.

Some policy strategies can also alleviate disruptions from heavy rain and flooding. For example, elevating all assets may not make sense, but SEPTA could institute a policy to elevate assets if the opportunity arises during business-as-usual maintenance or operations (for example, as happened through the Signal Modernization Project). SEPTA could also increase the frequency of culvert and drainage system inspections and maintenance to ensure these systems are not blocked and can function properly during rain events (SEPTA already inspects all "flood watch" designated bridges after every storm event). SEPTA could also develop flood protocols and plan ahead to adjust services as needed and communicate with riders before, during, and after flood events. Finally, as with heat and other assets, a key strategy is to incorporate projections of flood event frequency and their costs into planning and budgeting process or maintaining an emergency response fund so that SEPTA is equipped to respond as quickly and well as possible to damage.

All of these potential adaptation strategies are summarized in Table 5-3. For each possible solution to heavy rain-related vulnerabilities, the table documents the applicable SEPTA department, the category of the solution (capital planning, maintenance, or operations), and how the solution can integrate within existing SEPTA frameworks and processes. Some adaptation options, including most that fall under capital planning, may be difficult to implement in the near-term because of budget constraints. However, many other strategies represent "low hanging fruit" that could improve SEPTA's resiliency and service and be implemented through tweaks to existing operations, maintenance, or communications protocols. These options are marked as "low" in the "Barriers to Implementation" column below, and are highlighted in Section 5, "Recommendations."

Table 5-3

Potential Adaptation Strategies for Heavy Rain Events

Problem	Possible Solution(s)	Department	Category	Barriers to Implementation	Fit within Existing Processes	Other Notes
Flooding (e.g., Spring Mill, Conshohocken, I-276 overpass, west of Conshohocken)	Move portable equipment (e.g., trains and buses) to higher elevation areas (make sure specific staff are responsible)	All	Operations	Low	Component of existing internal Hurricane Plan	SEPTA is already beginning to adopt this strategy
	Improve monitoring of water levels, set plans based on water levels	All	Operations	Low	Could integrate with existing real-time weather monitoring activities	Near-term strategy
	Increase bus service in advance of predicted flood events to service flooded stations	Policy and Administration	Operations	Low	SEPTA is already adopting this strategy	SEPTA is already adopting this strategy
	Prepare to adjust services as needed and communicate with riders (before, during, and after floods)	Policy and Administration	Operations	Low	Fits within existing communications and control center functions	SEPTA is already adopting this strategy
	Institute policy to elevate assets if opportunity arises through business-as-usual operations	Policy and Administration	Capital planning	High	Could incorporate flood-proneness in infrastructure maintenance management system, use to flag opportunities to raise	SEPTA will have flood watch assets tagged in its asset management system
	Raise assets	Bridges & Buildings, Track and Civil Engineering, Communication and Signals	Capital planning	High		SEPTA has already elevated 19 signal houses on the M/N
	Elevate key portions of track	Track and Civil Engineering	Capital planning	High		
	Increase culvert size	Track and Civil Engineering	Capital planning	High		
	Divert floodwaters	Track and Civil Engineering	Capital planning	High	Would likely involve high-level capital investment decision	

Table 5-3 (cont.)

Potential Adaptation Strategies for Heavy Rain Events

Problem	Possible Solution(s)	Department	Category	Barriers to Implementation	Fit within Existing Processes	Other Notes
Flooding (e.g., Spring Mill, Conshohocken, I-276 overpass, west of Conshohocken)	Build flood protection structures	Bridges & Buildings, Track and Civil Engineering, Communication and Signals	Capital planning	High		
	Increase pumping capacity	Bridges & Buildings, Track and Civil Engineering, Communication and Signals	Capital planning	High		
	Emergency sandbagging	Bridges & Buildings, Track and Civil Engineering, Communication and Signals	Operations	Low	SEPTA is already adopting this strategy	SEPTA is already adopting this strategy
	Increase frequency of culvert and drainage system inspections and maintenance	Bridges & Buildings, Track and Civil Engineering	Maintenance	Low	Expansion of existing maintenance activities; component of internal Hurricane Plan	
	Promote use of pervious surfaces	Bridges & Buildings, Track and Civil Engineering	Capital planning	High	Could be integrated into procurement or project planning decisions	
	Assess need for/feasibility of installing additional turnbacks and install as appropriate	Policy and Administration, Track and Civil Engineering	Capital planning	High		SEPTA has already installed a new turnback on the M/N line
Runoff	Improve drainage capacity	Bridges & Buildings, Track and Civil Engineering	Capital planning, Maintenance	High	Could occur through regular equipment upgrade processes	
	Improve stormwater management on SEPTA property by installing green roofs and rainwater capture systems (e.g., rain barrels)	Bridges & Buildings	Capital planning	High		

Table 5-3 (cont.)

Potential Adaptation Strategies for Heavy Rain Events

Problem	Possible Solution(s)	Department	Category	Barriers to Implementation	Fit within Existing Processes	Other Notes
Runoff	Tilt platforms away from track	Bridges & Buildings	Capital planning	High	Could occur through regular station upgrade processes	SEPTA is already beginning to adopt this strategy
	Improve stormwater management on SEPTA property by creating stormwater retention ponds	Policy and Administration	Capital planning	High		
	Use pervious pavement in new paving projects	Policy and Administration, Bridges & Buildings	Capital planning	High		
	Coordinate with neighboring entities about improving stormwater management in the watershed	Policy and Administration		High		
Debris deposited along track	Place cleanup crews on standby when storm is forecast	Track and Civil Engineering	Maintenance	Low	SEPTA is already adopting this strategy	SEPTA is already adopting this strategy
	Install debris screens alongside key sections of track	Track and Civil Engineering	Capital planning	High		
Track washouts	Put specialty equipment on standby (e.g., high rail excavators, trucks loaded with stone, ballast)	Track and Civil Engineering	Operations	Low	SEPTA is already beginning to adopt this strategy	SEPTA is already beginning to adopt this strategy
	Utilize slope stabilization techniques (e.g., reinforced soil, retaining walls, densely rooting vegetation)	Track and Civil Engineering	Capital planning	High		
Downed trees	Continue and enhance tree trimming program	Power	Maintenance	Low	Continuation or acceleration of existing program	SEPTA is already adopting this strategy
	Monitor and track problem tree areas (these change constantly)	Power	Maintenance	High		
	Increase coordination with PECO and other entities who require tree trimming services	Policy and Administration, Power	Operations	Low		

Table 5-3 (cont.)

Potential Adaptation Strategies for Heavy Rain Events

Problem	Possible Solution(s)	Department	Category	Barriers to Implementation	Fit within Existing Processes	Other Notes
Downed catenary wires	Put specialty equipment on standby	Power	Maintenance	Low	SEPTA is already adopting this strategy	SEPTA is already adopting this strategy
Equipment damage	Keep backup parts, materials, and equipment in stock	All	Maintenance	Low	Enhancement to existing procedures	SEPTA is already beginning to adopt this strategy
	Elevate or otherwise protect key equipment from damage	All	Maintenance	High	Could incorporate flood-proneness in infrastructure maintenance management system, use to flag opportunities to protect	
Potential for power outages	Acquire backup power systems (permanent or temporary)	Power	Capital planning	High		SEPTA is already beginning to adopt this strategy
	Elevate or otherwise protect power supply systems from flooding	Power	Capital planning	High	Could incorporate into asset management system, use to flag opportunities to protect	
Vulnerable institutional knowledge	Implement system for documenting institutional knowledge (e.g., asset management system)	All	Operations	Low	Could incorporate climate and weather-related knowledge into infrastructure maintenance management system	
Repeated events may lead to stressed budgets and resources	Incorporate expectations of flood event costs in planning and budget processes	Policy and Administration	Capital planning	High	Incorporate into existing planning and budgeting processes	
	Set aside emergency response fund	Policy and Administration	Capital planning	High		
Potential for delays	Maintain and improve customer communication	Policy and Administration	Operations	Low	Existing communications framework	SEPTA has already begun to adopt this strategy

Adaptation Strategies for Snow

The Philadelphia area regularly deals with snow (see Figure 5-2) and will likely continue to in the future. SEPTA has experience dealing with snowstorms and snow removal and should build on its best practices moving forward. In addition, SEPTA faces several vulnerabilities from snow storms that are common to other weather events, such as potential for power outages, potential for service disruptions, and increasing resource constraints. Adaptation strategies discussed in other sections, such as acquiring backup power systems, improving tree trimming programs, enhancing customer communication, and planning for the costs of weather-related events apply to snow as well. Further, SEPTA is testing the efficacy of using platform heaters to reduce snow removal and labor costs. If the pilot project is successful, this could prove a useful adaptation strategy across the system.

Table 5-4 summarizes the adaptation strategies related to snow. For each possible solution to snow-related vulnerabilities, the table documents the applicable SEPTA department, the category of the solution (capital planning, maintenance, or operations), and how the solution can integrate within existing SEPTA frameworks and processes. Those strategies that represent “low hanging fruit” are marked as “low” in the “Barriers to Implementation” column below, and are highlighted in Section 5, “Recommendations.”

Figure 5-2

De-Railed Trolley Car during Snow Storm

Table 5-4

Potential Adaptation Strategies for Snow Events

Problem	Solution(s)	Department	Category	Barriers to Implementation	Fit within Existing Processes	Other Notes
Snow on tracks, stations, equipment, etc.	Put third-party contractors on call to facilitate snow removal	All	Maintenance	Low	SEPTA is already adopting this strategy	SEPTA is already adopting this strategy
	Salt rails, stations, and other key areas in advance	Bridges & Buildings, Track and Civil Engineering	Maintenance	Low	SEPTA is already adopting this strategy	SEPTA is already adopting this strategy
	Expand use of platform heaters	Bridges & Buildings	Capital planning	High	Could occur through regular station upgrade processes	SEPTA is currently piloting this strategy
Potential for power outages	Continue and enhance tree trimming program	Power	Maintenance	Low	Continuation or acceleration of existing program	SEPTA is already adopting this strategy
	Acquire backup power systems (permanent or temporary)	Power, others	Capital planning	High		SEPTA is already beginning to adopt this strategy
Dangerous working conditions	Closely monitor staff working on snow removal to prevent or respond to injuries and fatigue	All	Maintenance	Low	Continuation or enhancement of existing staff oversight efforts	SEPTA is already adopting this strategy
Increasing resource constraints from other weather-related events	Continue to plan for snow removal costs in budgets, in addition to other newer stressors	Policy and Administration	Capital planning	High	Incorporate into existing planning and budgeting processes	
Potential for service disruptions	Continue and improve customer communication	Policy and Administration	Operations	Low	Fits within existing communications framework	SEPTA has already begun to adopt this strategy

Adaptation Strategies for Tropical Storms

Tropical storms share many of the same vulnerabilities and adaptation strategies as heavy rain events. All of the strategies discussed in Section 5, "Adaptation Strategies for Heavy Rain Events," can alleviate effects from tropical storms as well. This section discusses adaptation options to address SEPTA's tropical storm vulnerabilities not covered elsewhere.

Because of the higher public awareness of tropical storms and the advanced notice of a storm's arrival, SEPTA has even more ability to prepare in advance compared to more common rainfall events. Renting backup power systems, inspecting track and other equipment, trimming trees, clearing culverts, moving equipment to higher elevations, preparing clean-up materials, and putting staff on standby are among the many activities SEPTA can and does undertake in advance of a storm (see Table 5-5). SEPTA also prepares for the high winds associated with tropical storms that can damage assets (especially gates). When winds above 50 mph are expected, SEPTA chains gate arms in the "up" position or removes particularly long gate arms. SEPTA has also, and should continue to, communicate any service disruptions or cancellations to the public as early as possible. SEPTA's procedures for responding to tropical storms are being documented in their internal Hurricane Standard Readiness Plan, which contains a checklist for pre- and post-storm activities including securing sites, gathering supplies, inspecting infrastructure, setting up water level monitoring, and many other activities discussed throughout this report as best practices for responding to tropical storm and flooding events. This plan is a vehicle for SEPTA to incorporate lessons learned, best practices, and climate change considerations into future storm preparation and response.

Tree trimming is a particularly effective strategy to limit damage from high winds and tropical storms. During storms, trees or tree branches can break off and damage catenary wires or build up debris on tracks. SEPTA has been focusing on its tree-trimming program in recent years and should continue to be vigilant about keeping nearby trees trimmed, particularly as growing seasons may extend with warmer temperatures. During Hurricane Sandy, SEPTA experienced less damage from trees compared to neighboring jurisdictions and can use this "lesson learned" to support future tree trimming efforts.

Table 5-5

Potential Adaptation Strategies for Tropical Storms

Problem	Possible Solution(s)	Department	Category	Barriers to Implementation	Fit within Existing Processes	Other Notes
Wind Damage	Chain gate arms in "up" position in advance of storm	Track and Civil Engineering	Operations	Low		SEPTA is already beginning to adopt this strategy
Flooding (e.g., Spring Mill, Conshohocken, I-276 overpass, west of Conshohocken)	Move portable equipment (e.g., trains and buses) to higher elevation areas (make sure specific staff are responsible)	All	Operations	Low	Component of existing internal Hurricane Plan	SEPTA is already beginning to adopt this strategy
	Improve monitoring of water levels, set plans based on water levels	All	Operations	Low	Could integrate with existing real-time weather monitoring activities	
	Increase bus service in advance of predicted flood events to service flooded stations	Policy and Administration	Operations	Low	SEPTA is already adopting this strategy	SEPTA is already adopting this strategy
	Prepare to adjust services as needed and communicate with riders (before, during, and after floods)	Policy and Administration	Operations	Low	Fits within existing communications and control center functions	
	Institute policy to elevate assets if opportunity arises through business-as-usual operations	Policy and Administration	Capital planning	High	Could incorporate flood-proneness in infrastructure maintenance management system, use to flag opportunities to raise	SEPTA will have flood watch assets tagged in its asset management system
	Raise assets	Bridges & Buildings, Track and Civil Engineering, Communication and Signals	Capital planning	High		SEPTA has already elevated 19 signal houses on the M/N
	Elevate key portions of track	Track and Civil Engineering	Capital planning	High		
	Increase culvert size	Track and Civil Engineering	Capital planning	High		
	Divert floodwaters	Track and Civil Engineering	Capital planning	High	Would likely involve high-level capital investment decision	

Table 5-5 (cont.)

Potential Adaptation Strategies for Tropical Storms

Problem	Possible Solution(s)	Department	Category	Barriers to Implementation	Fit within Existing Processes	Other Notes
Flooding (e.g., Spring Mill, Conshohocken, I-276 overpass, west of Conshohocken)	Build flood protection structures	Bridges & Buildings, Track and Civil Engineering, Communication and Signals	Capital planning	High		
	Increase pumping capacity	Bridges & Buildings, Track and Civil Engineering, Communication and Signals	Capital planning	High		
	Emergency sandbagging	Bridges & Buildings, Track and Civil Engineering, Communication and Signals	Operations	Low	SEPTA is already adopting this strategy	SEPTA is already adopting this strategy
	Increase frequency of culvert and drainage system inspections and maintenance	Bridges & Buildings, Track and Civil Engineering	Maintenance	Low	Expansion of existing maintenance activities; component of internal Hurricane Plan	
	Promote use of pervious surfaces	Bridges & Buildings, Track and Civil Engineering	Capital planning	High	Could be integrated into procurement or project planning decisions	
	Assess need for/feasibility of installing additional turnbacks and install as appropriate	Policy and Administration, Track and Civil Engineering	Capital planning	High		SEPTA has already installed a new turnback on the M/N line
Debris deposited along track	Place cleanup crews on standby	Track and Civil Engineering	Maintenance	Low	SEPTA is already adopting this strategy	SEPTA is already adopting this strategy
	Install debris screens alongside key sections of track	Track and Civil Engineering	Capital planning	High		
Track washouts	Put specialty equipment on standby (e.g., high rail excavators, trucks loaded with stone, ballast)	Track and Civil Engineering	Operations	Low	SEPTA is already beginning to adopt this strategy	SEPTA is already beginning to adopt this strategy
	Utilize slope stabilization techniques (e.g., reinforced soil, retaining walls, densely rooting vegetation)	Track and Civil Engineering	Capital planning	High		

Table 5-5 (cont.)

Potential Adaptation Strategies for Tropical Storms

Problem	Possible Solution(s)	Department	Category	Barriers to Implementation	Fit within Existing Processes	Other Notes
Downed trees	Continue and enhance tree trimming program	Power	Maintenance	Low	Continuation or acceleration of existing program	SEPTA is already adopting this strategy
	Monitor and track problem tree areas (these change constantly)	Power	Maintenance	High		
	Increase coordination with PECO and other entities who require tree trimming services	Policy and Administration, Power				
Downed catenary wires	Put specialty equipment on standby	Power	Maintenance	Low	SEPTA is already adopting this strategy	SEPTA is already adopting this strategy
Equipment damage	Keep backup parts, materials, and equipment in stock	All	Maintenance	Low	Enhancement to existing procedures	SEPTA is already beginning to adopt this strategy
	Elevate or otherwise protect key equipment from damage	All	Maintenance	High	Could incorporate flood-proneness in infrastructure maintenance management system, use to flag opportunities to protect	
Potential for power outages	Acquire backup power systems (permanent or temporary)	Power	Capital planning	High		SEPTA is already beginning to adopt this strategy
	Elevate or otherwise protect power supply systems from flooding	Power	Capital planning	High	Could incorporate into asset management system, use to flag opportunities to protect	
Potential for delays	Maintain and improve customer communication	Policy and Administration	Operations	Low	Existing communications framework	SEPTA has already begun to adopt this strategy
Repeated events may lead to stressed budgets and resources	Set aside emergency response fund	Policy and Administration	Capital planning	High		
Vulnerable institutional knowledge	Implement system for documenting institutional knowledge (e.g., asset management system)	All	Operations	Low	Could incorporate climate and weather-related knowledge into infrastructure maintenance management system	
	Regularly review and update Hurricane Standard Readiness Plan	Policy and Administration	Operations	Low	Existing Hurricane Standard Readiness Plan	SEPTA has already begun to adopt this strategy

Table 5-6

After Action Report: SEPTA's Preparation for and Response to Hurricane Sandy from October 28-November 3, 2013

Date	Time	Comment
Sunday, 10/28	2:00 PM	SEPTA issues press release announcing that all service will be suspended at the end of the day's schedule (approximately 12:30 AM) ahead of the arrival of Hurricane Sandy. Shutdown includes all modes, with the exception of CCT paratransit service, which will be available for reserved dialysis patients only, as long as safe operations are possible.
Monday, 10/29	12:30 AM	The service suspension begins.
	11:00 AM	SEPTA issues press release announcing that early Tuesday (10/30) morning after the storm has passed, SEPTA crews will inspect and assess the conditions of facilities, equipment and infrastructure in order to ascertain when service can be restored for all modes. This system-wide assessment process will take approximately 6 to 8 hours. The final decision to operate will be coordinated with the City's Office of Emergency Management and based on the safety of the public and SEPTA employees.
Tuesday, 10/30	All Day	SEPTA begins system-wide assessment of vehicles and infrastructure
	5:00 AM	SEPTA's Call Center extended its hours of operation, opening up an hour earlier at 5:00 AM and closing two hours later at 10:00 PM. The Center successfully handled more than 18,100 calls, a record for the amount of calls ever recording in the Center for a single day. The previous record was 16,000 recorded on Tuesday, 1/25/00, during a major blizzard.
	10:00 AM	SEPTA circulates an internal status report that finds the following: - All bus and rail equipment were properly stored and no reports of any damage to vehicles or facilities. - SEPTA continues to coordinate with the Mayor's Office and Office of Emergency Management on restoration of service. - Broad Street Line/Market/Frankford Line/Trolley Lines: currently running pilot trains; manpower and equipment available for normal service this afternoon. - City Bus/Trolley Routes: 60% of City Transit Division bus/trolley routes have been surveyed and cleared for service; some routes can operate with minor detours. - Suburban Norristown High Speed Line: currently running pilot trains; manpower and equipment available for normal service this afternoon. - Suburban Media Line: tree damage at Beatty Road that has a six-man crew working to repair by 6:00 PM; can be turned at Woodland for partial service. - Sharon Hill Line: currently running pilot trains; manpower and equipment available for normal service this afternoon. - Suburban Bus Routes: 30% of Suburban Transit Division bus routes have been surveyed and cleared for service; some routes can operate with minor detours. Routes in Bucks and Montgomery counties have been hardest hit. - Frontier Garage is running on a rented emergency generator. - Regional Rail: Amtrak lines currently suspended. A full assessment of Regional Rail lines is currently being performed. Tree removal activities have been ongoing. Further updates will be provided but significant damage has been incurred and it is unlikely that all lines will be fully operational for tomorrow's AM rush.

Table 5-6 (cont.)

After Action Report: SEPTA's Preparation for and Response to Hurricane Sandy from October 28-November 3, 2013

Date	Time	Comment
Tuesday, 10/30	11:30 AM	SEPTA holds press conference with City of Philadelphia Mayor Michael Nutter announcing that the following services would be restored as of noon Tuesday: - Broad Street Line - Market-Frankford Line - City Trolleys: Routes 10, 11, 13, 15, 34 and 36 - Norristown High Speed Line - Sharon Hill Line - 80% of city bus routes (with minor detours) - 60% of suburban bus routes (with minor detours) - Media Line, as far as Woodland Avenue - Regional Rail service is still suspended. Nutter praises SEPTA in the press conference—"SEPTA has exceeded expectations." Says of the Authority's efforts to get buses, trains, and trolleys running in Sandy's aftermath—"SEPTA's operation is critical to this city and this region. It is the way we move people, goods and services around this region, and that's why we're such strong supporters of SEPTA and mass transit."
	3:30 PM	SEPTA circulates an internal status report that finds the following: - Broad Street Line/Market/Frankford Line/Trolley Lines: Currently running normal service. - City Bus/Trolley Routes: All city bus routes are running except the Route 77. Several routes are on detour due to downed trees. - Norristown High Speed Line: Currently running normal service. - Media Line: Tree damage at Beatty Road that has a six man crew working to repair by midnight. The line is being turned at Woodland for partial service. - Sharon Hill Line: Turning the line at North Street due to PECO related signal problems. - Suburban Bus Routes: All suburban bus routes are running except Route 120. - Frontier Garage is running on a rented emergency generator. - Most Regional Rail Lines will resume service on Wednesday morning. Some delays may be encountered due to residual effects. - The following lines are being worked on by SEPTA staff to return to service as soon as possible. - Warminster Line: Signal power problems persist on this line. Delays will result tomorrow if these problems are not resolved, but service will be operated. - Lansdale/Doylestown and Main Line (Glenside to 30th): Signal power problems persist on this territory. Delays will result tomorrow if these problems are not resolved, but service will be operated. - Chestnut Hill West: This is one of the last work locations to be addressed. We are hopeful that service will resume at the start of service tomorrow. Some delays may be encountered due to residual effects.
	5:00 PM	SEPTA announces that Regional Rail service will resume in full on SEPTA to resume on Wednesday (10/31) morning, and that trains on all Regional Rail lines will follow regular weekday schedules, but customers may experience residual delays, and should allow extra time for their commute.
Wednesday, 10/31	4:30 AM	Regional Rail service is restored in full for AM rush hour, with residual delays throughout the system.
Thursday, 11/1	12:00 PM	SEPTA announces that it is offering credits to weekly and monthly pass-holders impacted by the service suspension during Hurricane Sandy. Credits are available on a purchase of a future weekly or monthly pass. The credits will cover the two days service was disrupted—Monday, 10/29, and Tuesday, 1/30.
Saturday, 11/3	12:00 PM	SEPTA announces that it will loan 30 buses to NJ TRANSIT to augment the remaining fleet of NJT's operable vehicles and will support shuttle service for riders traveling from New Jersey into New York City. FTA Administrator Rogoff telephoned GM Casey to express his appreciation of SEPTA's support of its sister agency.
Sunday, 11/4	10:00 AM	Convoy of 31 buses leaves SEPTA Frontier Garage en route to New Brunswick, NJ. The 31st bus transports SEPTA operators back to Philadelphia following the transfer of the 30 loaner buses

Cross-Cutting Adaptation Strategies

Several adaptation strategies can improve SEPTA's resiliency across a range of weather events.

Incorporate climate change vulnerability into the asset management program. SEPTA is developing an asset management program to track information about its assets and inform capital planning decisions. The asset management program has three components: a day-to-day life cycle management system for fleet assets (which tracks things like inspections, routine maintenance, and others); a similar system for fixed assets; and a State of Good Repair capital decision-making tool used for planning and containing information such as an asset's useful life, ridership impact, and replacement value. The asset management program is an opportunity for tracking information about an asset's vulnerability. For example, asset managers could enter information an asset's vulnerability (e.g., whether it is flood-prone, prone to buckling, sensitive to wind, or sensitive to heat). SEPTA, in fact, already has a field built in to its asset management program to house this data. This information would then appear when decision-makers are dealing with an asset, either through maintenance or long-term planning activities. Over time, as more information is added to the system, SEPTA could develop a way to formalize how climate is considered in the engineering and design of assets to make them more resilient as they are being updated through State of Good Repair activities.

Document and disseminate institutional knowledge. SEPTA managers have been responding to weather-related issues for decades, and veteran staff have many best practices in place to manage for these weather events. To ensure this knowledge remains with the organization (e.g., when individuals retire, get promoted), SEPTA must implement strategies to document and update institutional knowledge on specific weather thresholds that trigger action (e.g., at what wind speed do we remove the gates), specific locations or assets that require preparations before an extreme weather event (e.g., upstream side of specific culverts) and other general protocols for responding to various types of weather events. SEPTA's asset management program may be an effective place to store institutional knowledge on which assets are most vulnerable to climate stressors, as described above. SEPTA's internal hurricane plan or other extreme weather protocols may also serve to store and disseminate institutional knowledge on event preparedness and response.

Incorporate climate risk management into SEPTA planning, construction, operations, and maintenance processes. Weather and climate regularly effect SEPTA operations. The risks of damage from weather, however, can be minimized with strategic planning and adaptation-oriented decision-making. All SEPTA staff should be engaged in identifying weather-related risks and contributing ideas to minimize them.

Continue to enhance communication systems. Communication with riders is essential as SEPTA responds to various weather events (and even non-weather-related disruptions). SEPTA is building a robust communications strategy involving press releases, close coordination with city leadership, and social media (especially Twitter), as demonstrated by SEPTA's communication both during and after Hurricane Sandy (Table 5-6). Further enhancements and refinements are possible. For example, sending pictures of damage to explain why a section of track is closed can help customers understand and respond more positively to necessary closures. SEPTA will also need to continue coordination with the city of Philadelphia, large employers, and other key entities as part of weather event preparedness and response protocols. SEPTA has increasingly used these kinds of communications tactics, including during recent extreme weather events; continuing this trend will be important as the system balances continuity of service with passenger safety under extreme weather conditions.

Create and monitor performance indicators. As SEPTA adapts to a changing future, performance indicators can help provide perspective on how the organization is doing and insights on how management can continue to adapt. For example, tracking metrics such as how frequently FS1 speed restrictions occur, customer complaints about disruptions, length of delays, and costs associated with weather events can help SEPTA be responsive to changing conditions and meet customer needs. Key areas to monitor are as follows:

- ***Weather-related costs*** – SEPTA currently has a weather-related code in its billing system, but it may not be consistently or comprehensively used. SEPTA could move toward creating a unique Work Order number for each weather event they experience to track the labor costs of weather events. Material costs could be similarly tracked and tied to relevant weather events. SEPTA has already identified these as needs and has, for example, created a unique Work Order for Hurricane Sandy. SEPTA could continue to improve their tracking of weather-related costs for both major storms and incremental changes such as heat and incorporate that knowledge into planning.
- ***Heat and speed restriction delays*** – As discussed in Section 5, "Adaptation Strategies for High Temperatures," SEPTA could monitor the frequency of speed restrictions and high temperatures. Better understanding the relationship between temperatures, speed restrictions, and train delays will allow SEPTA to adapt to changes underway.
- ***Real-time condition monitoring*** – SEPTA could also improve monitoring of actual conditions throughout their system to inform adaptation planning or

real-time responses. For example, SEPTA could monitor rail temperatures in critical spots to better prepare for track buckling or install remote monitoring systems of water levels to prepare for floods.

Acquire backup power systems. SEPTA's reliance on the utility grid is a key vulnerability to weather events that can disable the grid region-wide. On-site power generation, backup generators, or even pre-established agreements to rent generators in advance of storms or heat waves can improve SEPTA's ability to operate in the event of a power outage.

Incorporate changing climate conditions into planning and budgeting process. Preparing for climate change involves recognizing that the past may no longer be a good guide for the future. Planning, let alone setting budgets, for an uncertain future is challenging. SEPTA should allow for flexibility in their planning processes and, where feasible, incorporate projections or scenarios of future climate conditions. One way to do this is to employ a policy to evaluate whether to replace assets to a higher standard (rather than replacing them exactly as they were) if they are damaged. The asset management system changes discussed earlier can play a key role in implementing this strategy.

Recommendations

All of the adaptation strategies discussed throughout this section have potential to reduce SEPTA's vulnerability to climate risks. These options, however, have a range of feasibilities due to various constraints such as funding, public perception, jurisdictional boundaries, and others. The following strategies address SEPTA's greatest vulnerabilities and carry benefits regardless of whether the climate changes as projected. They each carry costs and have to be evaluated against budgets, service disruptions, maintenance considerations, and other relevant factors, but are recommended for SEPTA's consideration. All were mentioned earlier and are repeated here, organized into Capital Planning, Operations, and Maintenance strategies.

Capital Planning Strategies

- Promote use of pervious surfaces.
- Improve stormwater management on SEPTA property by installing green roofs and rainwater capture systems (e.g., rain barrels).

Operations Strategies

- Record climate- and weather-related vulnerability for assets in transit asset management program, beginning with most critical assets, if necessary.
- Continue efforts to make institutional knowledge more resilient (e.g., through asset management program and other means).

- Create and track performance indicators of resilience (e.g., frequency of FSI restrictions, relationship of delays to weather conditions, labor hours spent on and costs of weather events, customer satisfaction).
- Improve monitoring of water levels and possibly identify key thresholds for planning.
- Continue to enhance customer communication and develop weather event communication protocols.
- Incorporate changing climate conditions into planning and budgeting processes (projected number of heat events, tropical storm risk, etc.).
- Prepare to adjust services as needed and communicate with riders (before, during, and after events).
- Increase bus service in advance of predicted flood events to service flooded stations.
- Develop policies and action plans to be taken when a heat wave is forecast (e.g., worker schedules, cooling stations, equipment readiness, backup power).
- Put specialty equipment and staff on standby when storms or heat waves are forecast (e.g., high rail excavators, trucks loaded with stone and ballast, chain saws).
- Educate workers about heat stress and hydration, especially in advance of summer months.
- Store equipment in higher elevation areas in advance of potential flood events (and ensure it gets done by assigning tasks to specific people).
- Institute policy to consider elevating assets (or otherwise making them more resilient) if opportunity arises through business-as-usual operations
- Place sandbags in flood-prone areas when floods are predicted.
- Increase coordination with PECO and other entities who require tree trimming services.
- Chain gate arms in “up” position in advance of severe, windy storms (such as tropical storms).
- Regularly review and update Hurricane Standard Readiness Plan.

Maintenance Strategies

- Continue tree-trimming program.
- Monitor and track problem tree areas.
- Keep backup parts, materials, and equipment in stock and in good repair.
- Identify and catalog problem areas for track buckling.
- Regularly check and maintain wire tension, especially during heat waves, to avoid sagging wires.

- Maintain HVAC systems to reduce potential for customer discomfort during heat waves.
- Increase frequency of track inspections during heat waves.
- Increase frequency of culvert and drainage system inspections and maintenance.
- Continue to salt rails, stations, and other areas in advance of snow storms.
- Continue to monitor staff working on snow removal to prevent or respond to injuries and fatigue.

SECTION 6

Lessons Learned

Outside of the adaptation strategy lessons learned and documented earlier in this report, the project team learned several lessons throughout the course of completing this pilot project that could inform similar projects in the future. These lessons learned are categorized into four main areas: Project Design, Staff Engagement, Data, and Stakeholder Engagement.

Project Design

The project design, both in approach and in scope, proved to be an effective way to analyze transit vulnerability and adaptation strategies. This project examines climate change vulnerability through the lens of current weather conditions and weather-related disruptions. This proved to be an invaluable aspect of the project. It allowed the project team to immediately engage SEPTA staff about their vulnerabilities without needing to broach more controversial climate change topics and without having to complete a full climate modeling effort beforehand. SEPTA staff from a range of backgrounds could therefore be engaged from the outset of the project. Discussing current vulnerabilities to weather helped staff think about potential vulnerabilities if those conditions were to change and solicited very useful information about future vulnerabilities.

In addition, this project had a very narrow scope with regard to the line considered and data analyzed. Limiting the scope of the data analysis allowed for a time- and cost-effective study, and for the team to deeply consider vulnerabilities on the M/N line and potential adaptation strategies. Further, the outcomes of the study are unexpectedly broadly applicable to SEPTA. Thus, focusing on one line and streamlining the data analysis process actually facilitated an analysis that is relevant across SEPTA's regional rail system.

The project design has limitations in that it would be insufficient if a transit agency were considering a novel climate stressor. The approach relies on data about historical vulnerabilities to stressors that occur in today's climate but are projected to change in the future. For a novel stressor such as sea-level rise, where there are no historical examples of those impacts, this approach cannot quantify projected disruptions, costs, or other damages. The estimation of future risks is also only as strong as the information on current risks, and so is reliant on the quality of underlying data about historical disruptions and costs. For example, the estimates of future costs in this project are limited by what information we could gather about historical costs. These known, quantified costs do not capture the full costs associated with transit disruptions, including labor or materials costs that SEPTA does not track and, more importantly, the much larger societal costs of disruptions.

Staff Engagement

This project was also successful at effectively engaging busy SEPTA staff. The best ways to engage staff may vary by organization, but within SEPTA it was effective to engage them on an as-needed basis. The project team scheduled in-person meetings with staff by department on an as-needed basis at several milestones in the project and provided preliminary materials for staff to react to. Combined with the project design element described above, this enabled productive meetings and generated many ideas from staff. We also held meetings with department-level staff and incorporated their feedback in advance of meetings with SEPTA policy-makers. Being able to point to specific staff suggestions at the policy-maker meetings proved a successful way of getting policy-makers engaged in the project. This project also demonstrated the value of holding these sorts of staff meetings as a way of capturing institutional knowledge and initiating internal conversations about improving the authority's performance. Even outside of a formal project like this one, these conversations could be a useful start for any organization thinking about their vulnerabilities to extreme weather or changes in climate.

Data

The analyses performed under this project were possible because SEPTA provided high-quality datasets on delays and their causes, along with available information on event costs. We examined just a portion of SEPTA's available data, which suggests there may be untapped potential in using the agency's data to inform strategic planning and analysis of critical issues facing the Authority. Focusing on a subset of the data and getting "into the weeds" in the data for this one line showed the potential to do similar analyses on a larger scale.

Stakeholder Engagement

This project also convened a broader group of stakeholders, including representatives from the City of Philadelphia, Amtrak, and other organizations for which SEPTA's decisions hold relevance. For this project, meetings with this group were largely informational, informing them that SEPTA was undertaking this vulnerability assessment and apprising them of our progress along the way. There may be potential to improve the use of such a group in future projects, using it to solicit ideas and get "public" reactions to some of the adaptation strategies suggested. This would be particularly relevant for adaptation strategies that involve coordination with groups outside of SEPTA, such as the strategies on coordinating tree trimming and stormwater management with neighboring jurisdictions. The broader stakeholder group was not used that way for this project, and future projects could learn from this to improve the broader stakeholder engagement process to be more productive for all involved.

APPENDIX

A

Detailed Approach for Analysis of Baseline Service Disruptions

SEPTA's data on weather-related service disruptions was used to better understand and characterize current climate hazards relevant to service and assets on the M/N line. Results of this analysis are discussed in Section 2, "Weather-Related Service Disruptions."

Data

SEPTA provided a dataset of all trains on all lines that have experienced delays (greater than 6 minutes) categorized as weather-related from January 2005 through February 2012. For each delayed train, the dataset included the:

- Date
- Train number
- Route code (this analysis focused on 2N – the Manayunk/Norristown line)
- Whether the delay occurred during rush hour
- Whether the delay was on a weekday, Saturday, or Sunday
- Whether the train was annulled or partially annulled
- Total delay minutes – total delays for the train, occurring on all lines (e.g., prior to the train switching to the given line)
- Delay minutes – delays occurring on that line only
- Delay details – these are notes explaining the delay, and range from very specific (e.g., "Slippery rail on Norristown line [on account of] sleet") to general (e.g., "Weather-related delays")

SEPTA also provided the Railroad Operations Control Center Daily Reports for specific days. These reports contained Unusual Occurrence Reports (UORs), which provided more detailed information on the system-wide delays for each day and how they were resolved.

Analysis Methodology

The goal of this analysis was to identify what types of weather lead to service disruptions and compare the magnitude and duration of disruptions for different types of weather, focusing on the M/N Line. Since there were over 225 days during the January 2005–February 2012 period coded as having weather-related delays (constituting nearly 1,500 delay reports), we developed a method to sort and classify delay reports, and to identify some of the largest delay events.

We took the following steps to identify and analyze major weather-related events on the M/N line:

1. **Narrowed dataset** to focus only on the M/N line. The M/N line was identified in the SEPTA dataset by route code 2N. This subset consisted of 1,235 delay reports.
2. **Ranked dates by total delay minutes and annulments each day**. Each day could have multiple delay reports, so we summed total delay minutes and annulments for each day and ranked the dates from most to least delay minutes and annulments.
3. **From this list, established a threshold for cutoff of "major" events to focus on**. Upon review, it was clear that a subset of "major" events accounted for a disproportionate amount of the total delay minutes and annulments. These events also appeared to cause widespread disruption across the SEPTA system. Based on examination of the distribution of delay minutes across the time period, and given a desire to focus on 20–25 major dates because of resource constraints, we chose 170 delay minutes and/or 5 annulments as the cutoff to define a major event day. These cutoff parameters resulted in a list of 28 major event days, representing 20 events (because 5 events spanned 2–3 days). These major events represent a range of weather impacts to the SEPTA system (as described below).
4. **Categorized major events by event type**. We then categorized each of the delay events into one of six distinct weather-related delay causes: Heat, Tropical Storm/Hurricane, Snow, Summer Thunderstorm, Winter Storm, and Heavy Rain and Wind (which included rain events not already captured under the other categories). We made these assignments by reading the delay descriptions and UORs for each day.

This process resulted in the list of major events shown in Table A-1. These 28 days account for 63 percent of all delay minutes, 96 percent of all train annulments, and 48 percent of all train disruptions on the M/N line from 2005 through early 2012.

Table A-1

Major Weather-Related Disruption Events on Manayunk/Norristown Line

Date	Day	Trains Affected	Delay Minutes	Annulled Trains	Partial Annulments	Weather Type
07/27/2005	Wed	16	348	-	-	Heat
12/09/2005	Fri	14	171	-	-	Snow
02/12/2006	Sun	24	358	10	-	Snow
07/18/2006	Tue	8	271	-	1	Summer thunderstorm
07/19/2006	Wed	21	570	-	-	Summer thunderstorm
03/16/2007	Fri	25	445	-	-	Winter storm
04/16/2007	Mon	22	201	-	-	Heavy rain, wind
06/10/2008	Tue	11	208	1	1	Heat
10/28/2008	Tue	17	254	-	1	Heavy rain, wind
08/02/2009	Sun	23	518	2	3	Summer thunderstorm
12/19/2009	Sat	43	871	3	-	Snow
12/20/2009	Mon	28	598	6	1	Snow
12/21/2009	Mon	25	315	-	-	Snow
02/06/2010	Sat	37	244	29	-	Snow
02/10/2010	Wed	17	415	5	-	Snow
02/11/2010	Thu	44	699	8	-	Snow
02/12/2010	Fri	34	911	12	-	Snow
06/24/2010	Thu	17	207	2	-	Summer thunderstorm
10/01/2010	Fri	51	58	47	-	Tropical storm/hurricane
12/27/2010	Mon	41	962	2	-	Snow
01/27/2011	Thu	21	448	-	-	Snow
02/02/2011	Wed	14	263	2	-	Winter storm
08/27/2011	Sat	15	111	6	-	Tropical storm/hurricane
08/28/2011	Sun	34	1	34	-	Tropical storm/hurricane
08/29/2011	Mon	23	37	19	-	Tropical storm/hurricane
09/07/2011	Wed	11	184	-	-	Tropical storm/hurricane
09/08/2011	Thu	45	-	45	-	Tropical storm/hurricane
09/23/2011	Fri	25	239	-	-	Heavy rain, wind
TOTAL		*706*	*9,906*	*233*	*7*	

Keyword Analysis

We also analyzed all of the delay descriptions to compare the frequency of different weather delays on the M/N line against the entire SEPTA rail system. We read through a sample of the delay descriptions and identified several commonly occurring key words in the description. Then, using Microsoft Excel's "FIND" function, we checked how often each of the key words occurred in the delay logs. The key words were Rain, Wind, Ice, Sleet, Snow, Heat, High Water, Flood, Severe, Power Loss, Aftermath, FS-1 (speed restrictions), Wire, and Amtrak.

APPENDIX

B

Detailed Approach for Analysis of Weather-Related Costs

We estimated the costs of weather disruptions using 1) SEPTA's cost data submitted to FEMA for reimbursement and 2) labor costs associated with weather disruptions from payroll tracking. Results of this analysis are discussed in Section 2, "Costs of Major Weather-Related Disruption Events." The second dataset provided the number of hours and payroll costs spent by each department (Administration, Bridges and Buildings, Capital Construction, Communications and Signals, Power, Revenue Operations, Track, and Vehicle Maintenance) during each event. We used these data to calculate the median and average cost of labor (including benefits) for each event type (see Table B-1).

Table B-1

Labor Cost per Event Type (Payroll and Benefits)

	Median Cost	Average Cost	Range
Heat	$53,307	$53,307	$23,684 – $82,931
Snow	$577,926	$614,264	$279,170 – $1,488,423
Tropical Storm	$105,472	$141,021	$51,496 – $349,654
Heavy Rain	$60,389	$60,249	$48,914 – $60,389

To check data consistency, we compared the labor costs recorded in payroll tracking with those from the FEMA-related data. The labor costs are similar for the February 2010 Snowstorm. However, the labor cost from payroll tracking is significantly lower than that of the FEMA-related dataset for Irene & Lee combined (see Table B-2). This may be due to differences in the dates covered as part of the weather event, or exclusion of overtime and contracted labor hours from the weather-specific billing code.

Table B-2

Comparison of Labor Costs from Payroll Tracking and FEMA Reimbursement Data

	Cost in Weather Labor Code Dataset	Cost in FEMA Submittal	Difference between Weather Labor Code and FEMA Data
Hurricane Irene & Tropical Storm Lee	$574,949	$1,055,900	-84%
Winter Snowstorm (02/2010)	$679,171	$544,933	20%

We also acquired "Unusual Occurrence Reports" from SEPTA for the 28 major event dates to identify the corrective actions taken in each event type (Heat, Snow, Tropical Storm, and Heavy Rain (non-tropical)). The list of corrective actions, presented in Table B-3, was helpful in identifying the vulnerability of the system to climate change as well as adaptation options. Initially, we hoped to quantify the costs associated with each corrective action and thus of each event type, but upon discussion with SEPTA, such quantification was not possible.

Table B-3

Corrective Actions Taken during 28 Major Weather Events from SEPTA's Unusual Occurrence Reports Series

Power-Related
Remove downed trees (from catenary, transmission line, signal line, or track)
Clear downed wire
De-energize catenary
Restore signal power
Restore overhead power
Equipment Repairs
Manually operate switch
Fix signal problems/Track Occupancy Lights
Fix switch failure
Fix motor overload
Repair damaged pantographs
Repair broken gate
Repair interlocking
Repair air-conditioning
Reset HVAC breakers
Repair sagging wire
Send out Maintainers/Mechanics
Scheduling/Passenger Issues
Detour trains
Reverse trains
Transfer passengers and crew to another train
Send rescue buses/vans (for passengers)
Send rescue train (for the stuck train)
Add extra train (when service is resumed)
Express trains operate as local
Local trains operate as express
Single tracking
Equipment swap
Winter Issues
Deicing/salting rails/ platforms
Snow removal
Repair frozen air lines in the interlocking
Repair broken ice breaker
Clear ice from overhead bridge
Open snow desk
Provide medical assistance to passenger(s) who fell on slippery platform
Other
Remove debris
Respond to high water (putting down new ballast, removing mud slides)

APPENDIX

C

Detailed Approach for Analysis of Baseline Weather Conditions

We used daily data from a local weather station to connect weather-related service disruptions with actual weather conditions at the time. Results of this analysis are discussed in Section 2, "Thresholds for Weather-Related Disruptions."

Data

We used the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) Climate Data Online map tool to find daily weather data for the Philadelphia area. Using the map tool filtered for daily data in the Philadelphia area, we compared stations for the length and consistency of their dataset and proximity to the M/N line. Daily weather data used in this analysis came from the Franklin Institute in Philadelphia, which is part of NOAA's Global Historical Climatology Network (GHCN). The Franklin Institute station was selected out of others in the area because it had the longest continuous data record of the stations in the area, extending from March 1, 1994, to the present. The dataset contains daily precipitation totals, high and low temperature, daily snowfall, and snow depth (referring to the accumulation of snow on the ground at the end of each day, which can include snowfall from previous days).

Analysis Methodology

This analysis sought to establish a connection between weather-related disturbances on the M/N line and the actual weather conditions at the time to understand how disruptions may change as climate and associated weather events change in the area. We approached this analysis from two angles: pairing delay events with weather and pairing weather events with delays. The latter approach proved more useful in identifying associations between weather and disruptions that could be applied to climate change projections.

Approach 1. Weather Conditions Associated with Major Disruption Events

First, we examined the recorded weather conditions on the days of the major delay events to see if any key patterns or weather thresholds (e.g., certain temperatures or rainfall amounts) emerged. The weather data for each major delay event are shown in Table C-1. The bold values highlight the weather variable expected to be relevant to the event (e.g., temperature for a heat event or amount of rain for a precipitation event). The "N/A" values mean that the station was unable to record that measurement on that day.

The weather data for rainfall events shows that major disruptions have occurred when there is relatively low rainfall (less than one inch), up to nearly 6 inches of rain in 24 hours. Similarly, major snow-related disruptions have occurred with even small amounts of snowfall (0.2–1.5 inches). These data points may also reflect different local conditions between where measurements were recorded and points along the M/N line.

Overall, comparing the major delay events with weather data from that day did not provide a clear message about what atmospheric conditions caused each event. This is likely due to the difference between local conditions between where measurements were recorded and points along the M/N line, as well as the timing of weather recordings compared to the timing of delays. For example, if a storm occurred overnight, the rainfall totals may be captured on a different day than the delays.

Table C-1

Weather Conditions Associated with Major Disruption Events

Date	Weather Type	Rain (in.)	Snow (in.)	Snow Depth (in.)	High Temperature (°F)
07/27/2005	Heat	0.2	0.0	0.0	**104**
12/09/2005	Snow[1]	0.0	**0.0**	0.0	48.9
02/12/2006	Snow	0.0	**0.2**	**7.0**	32.0
07/18/2006	Summer thunderstorm[2]	**0.2**	0.0	0.0	104
07/19/2006	Summer thunderstorm[3]	**0.0**	0.0	0.0	93.9
03/16/2007	Winter storm[4]	**0.0**	0.0	0.0	39.9
04/16/2007	Heavy rain, wind[5]	**0.1**	0.0	0.0	43.0
06/10/2008	Heat	0.1	0.0	0.0	**99.0**
10/28/2008	Heavy rain, wind[6]	**0.0**	0.0	0.0	46.0
08/02/2009	Summer thunderstorm	**1.4**	0.0	0.0	79.0
12/19/2009	Snow	0.2	**1.5**	**2.0**	34.0
12/20/2009	Snow	0.9	**11.0**	**11.0**	26.1
12/21/2009	Snow	0.0	0.0	**11.0**	34.0
02/06/2010	Snow[7]	N/A	N/A	N/A	39.0
02/10/2010	Snow	N/A	N/A	N/A	39.9
02/11/2010	Snow	N/A	N/A	N/A	33.1
02/12/2010	Snow	N/A	N/A	**16.0**	37.9
06/24/2010	Summer thunderstorm[8]	0.0	0.0	0.0	93.9
10/01/2010	Tropical storm/hurricane	**4.4**	0.0	0.0	80.1
12/27/2010	Snow	0.7	**7.5**	**8.0**	39.9
01/27/2011	Snow	1.7	**11.9**	**12.0**	34.0
02/02/2011	Winter storm	**0.8**	0.0	**6.0**	35.1
08/27/2011	Tropical storm/hurricane	**0.0**	0.0	0.0	89.1
08/28/2011	Tropical storm/hurricane	**5.7**	0.0	0.0	78.1
08/29/2011	Tropical storm/hurricane [9]	**0.0**	0.0	0.0	75.9
09/07/2011	Tropical storm/hurricane	**2.9**	0.0	0.0	68.0
09/08/2011	Tropical storm/hurricane	**3.9**	0.0	0.0	87.1
09/23/2011	Heavy rain, wind	**0.1**	0.0	0.0	80.1

[1] Snowfall for this event was 3.0 inches, measured overnight on 12/08/2005.

[2] This severe storm featured heavy, damaging winds, with gusts up to nearly 70 mph [10].

[3] Delays on this day were due to aftermath from the previous day's storm.

[4] In this sleet storm, Philadelphia received 3 inches of mostly sleet, with peak wind gusts of 40 mph [1].

[5] Total rainfall for the storm was 5.82 inches with peak wind gusts of 47 mph; most rain fell overnight on 4/15/2007 [12].

[6] Heavy winds from storm downed trees.

[7] The severe snowstorms disabled measurements at the Franklin Institute station. National Weather Service reports show that 28.5 inches of snow fell in Philadelphia on February 5-6, and 17 inches fell February 9–10 [13,14].

[8] This storm registered extremely high wind speeds of 75 mph along with quarter-size hail in Philadelphia, causing widespread power outages [15].

[9] Delays on this day are from the aftermath of Hurricane Irene.

Approach 2. Disruptions Associated with Extreme Weather

Next, since this first activity was inconclusive, we used the Franklin Institute data to identify, from a weather perspective, what constitutes an extreme event in the Philadelphia area and then identify what M/N service disruptions were associated with these extremes.

We determined the 1st the 5th percentile values for daily temperature, precipitation, snowfall, and snow depth across the daily data record. The values are those that are in the top 1 and 5 percent of days over the 18-year data record, and are shown in Table 2-6. The temperature percentiles consider all days in the year, and the rain and snow percentiles consider only days with non-zero precipitation.

We then used the 1st and 5th percentile weather values to see how extreme weather has impacted the M/N line. The analysis identified the percentage of days above those thresholds that have experienced any delays or annulments and the extent of those disruptions, summarized in Table 2-7. For heat, we combed through the delays to confirm they were heat-related and ensure there was no double counting with rain events since often, delay-causing precipitation events occur on days when the temperature is also high). We also separated Tropical Storm and Hurricane events from other heavy precipitation events in this analysis, because of the substantially different nature of their impacts on the system.

This approach successfully identified useful associations between weather events and the probability and magnitude of disruptions that can be applied to changes in climate.

APPENDIX

D

Detailed Approach for Analysis of Future Climate Projections

To get a more robust picture of climate change in the area where SEPTA operates, we acquired downscaled daily climate projections for a single cell over Philadelphia (144 sq. km or 55.6 sq. mi) from the WRCP CMIP3 Multi-Model Dataset [3]. A single grid cell was used due to time and resource constraints on the project. This approach could be improved by using aggregated outputs from four or more model grid cells. The daily climate data were available for nine climate models,[12] three emissions scenarios: A1b, A2, and B1, and three time periods: base period (1961–2000), mid-century (2046–2065), and end-of-century (2081–2100). We considered two scenarios, A2 and B1, to represent the moderately high and low emissions paths, respectively. Only the mid-century projections were considered since these are more important to SEPTA in terms of assessing vulnerability and adaptation options.

We downloaded temperature and precipitation from nine climate models for the base period (1961–2000) and mid-century (2046–2065). For each model, we determined the change in average annual temperature and total annual precipitation by mid-century compared to the base period. We then identified what constitutes an extreme, or rare, event in the base period for the Philadelphia area for each model. Extreme heat and precipitation events were calculated as the highest 5th percentile and 1st percentile occurrences of daily maximum temperature and daily precipitation (i.e. such events occur 1 and 5 percent of the time). The percentiles were taken out of all days for temperature and all days with non-zero precipitation for precipitation. Then, we counted how often these percentiles from the base period were surpassed in that model's mid-century projections, to determine the change in frequency between the base period and mid-century.

In addition, we defined a "snow chance" day as a day in which the low temperature fall below 2°C above freezing, or 35.6°F. On these days, the

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[12] The nine climate models are Canadian Centre for Climate Modeling & Analysis CGCM3 model (ccma_cgcm3), France's Centre National de Recherches Météorologiques CM3 model (cnrm_cm3), NOAA's Geophysical Fluid Dynamics Laboratory's CM2.0 and CM2.1 models (gfdl_cm2_0 and gfdl_cm2_1), France's Institut Pierre Simon Laplace CM4 model (ipsl_cm4), Japan's National Institute for Environmental Studies, and Frontier Research Center for Global Change model (miroc3_2_medres), the Meteorological Institute of the University of Bonn's ECHO model (miub_echo_g), The Max Planck Institute for Meteorology model (mpi_echam5), Japan's Meteorological Research Institute's model (mri_chcm2_3_2a).

temperature is low enough for snow to theoretically occur. This is a rough approximation and does not incorporate several other factors necessary for snow formation, so should not be taken as a direct projection of how often snow will occur. However, it can be used as a rough proxy for how likely snowfall may be in the future. We calculated the number of days with daily minimum temperatures below 2°C for each model in the base period and in mid-century to calculate the change in frequency of "snow chance" days.

A summary of the results from this downscaled climate data analysis is provided in Section 3, "Climate Change and Projected Changes in the Frequency and Intensity of Extreme Weather," and the detailed results are presented in Tables D-1, D-2 and D-3.

Table D-1

Change in Average Temperature and Frequency of Extreme Heat Events by Mid-Century for Philadelphia Area, All Models and Emissions Scenarios

Model (scenario)	Average Temp, 1961 2000 (°F)	Average Temp, 2046 2065 (°F)	Change in Average Temp (°F)	1961 2000 5% Tmax (°F)	1961 2000 1% Tmax (°F)	2046 2065 Frequency of 5% Tmax (%)	2046 2065 Frequency of 1% Tmax (%)	Change in Frequency of 5% Tmax*	Change in Frequency of 1% Tmax**
cccma_cgcm3 (B1)	64.3	67.8	3.5	89.74	93.83	13%	5%	2.6	4.6
cnrm_cm3 (B1)	64.3	67.3	3.0	89.37	93.03	12%	5%	2.4	4.9
gfdl_cm2_0 (B1)	64.3	68.4	4.0	89.95	94.12	16%	8%	3.1	8.0
gfdl_cm2_1 (B1)	64.4	68.1	3.8	89.85	93.74	16%	8%	3.2	7.5
ipsl_cm4 (B1)	64.3	69.1	4.8	89.75	93.92	14%	4%	2.7	4.4
miroc3_2_medres (B1)	64.3	69.2	4.9	89.51	93.34	15%	6%	2.9	6.3
miub_echo_g (B1)	64.4	68.5	4.1	89.74	93.64	15%	6%	3.0	6.1
mpi_echam5 (B1)	64.3	67.8	3.5	89.92	94.03	12%	5%	2.4	4.5
mri_chcm2_3_2a (B1)	64.3	67.1	2.8	89.71	93.72	10%	3%	2.0	3.1
cccma_cgcm3 (A2)	64.3	69.4	5.1	89.74	93.83	16%	7%	3.3	7.1
cnrm_cm3 (A2)	64.3	68.2	3.9	89.37	93.03	15%	6%	2.9	6.2
gfdl_cm2_0 (A2)	64.3	69.7	5.4	89.95	94.12	20%	12%	4.0	12.1
gfdl_cm2_1 (A2)	64.4	68.5	4.1	89.85	93.74	18%	9%	3.5	9.1
ipsl_cm4 (A2)	64.3	70.1	5.8	89.75	93.92	15%	5%	3.0	5.2
miroc3_2_medres (A2)	64.3	70.2	5.9	89.51	93.34	18%	9%	3.6	8.7
miub_echo_g (A2)	64.4	69.4	5.0	89.74	93.64	16%	7%	3.2	7.3
mpi_echam5 (A2)	64.3	68.2	3.9	89.92	94.03	14%	6%	2.9	5.8
mri_chcm2_3_2a (A2)	64.3	67.8	3.5	89.71	93.72	12%	4%	2.4	4.3

* Calculated as 2046-2065 frequency/0.05. Temperature at or above the baseline 5-percentile is projected to occur X times more frequently by mid-century, where X is the number reported in this column.

**Calculated as 2046-2065 frequency/0.01. Temperature at or above the baseline 1-percentile is projected to occur X times more frequently by mid-century, where X is the number reported in this column.

Table D-2

Change in Average Annual Precipitation and Frequency of Extreme Precipitation Events by Mid-Century for Philadelphia Area, All Models and Emissions Scenarios

Model (scenario)	Average Annual Precip, 1961 2000 (in)	Average Annual Precip, 2046 2065 (in)	Change in Annual Precip (in)	1961 2000 5% Precip (in)	1961 2000 1% Precip (in)	1961 2000 Freq. of 5% Precip	1961 2000 Freq. of 1% Precip	2046 2065 Freq. of 5% Precip	2046 2065 Freq. of 1% Precip	Change in Frequency of 5% Precip*	Change in Frequency of 1% Precip**
cccma_cgcm3 (B1)	27	31	3.1	0.52	1.01	3.4%	0.7%	4.2%	1.1%	24%	57%
cnrm_cm3 (B1)	26	28	2.3	0.49	1.00	3.5%	0.7%	3.9%	1.0%	11%	42%
gfdl_cm2_0 (B1)	26	29	2.4	0.49	0.93	3.4%	0.7%	4.1%	1.1%	19%	58%
gfdl_cm2_1 (B1)	27	29	2.8	0.50	0.98	3.4%	0.7%	3.9%	1.0%	12%	49%
ipsl_cm4 (B1)	27	27	0.6	0.49	0.92	3.4%	0.7%	3.6%	0.8%	4%	19%
miroc3_2_medres (B1)	27	28	1.0	0.52	1.01	3.4%	0.7%	3.8%	0.9%	12%	33%
miub_echo_g (B1)	28	29	0.1	0.54	1.07	3.4%	0.7%	3.5%	0.9%	3%	27%
mpi_echam5 (B1)	27	29	1.7	0.51	1.03	3.4%	0.7%	4.0%	0.9%	17%	27%
mri_chcm2_3_2a (B1)	28	30	2.3	0.52	1.04	3.4%	0.7%	3.9%	0.9%	14%	36%
cccma_cgcm3 (A2)	27	31	3.5	0.52	1.01	3.4%	0.7%	4.4%	1.1%	28%	59%
cnrm_cm3 (A2)	26	30	3.8	0.49	1.00	3.5%	0.7%	4.3%	1.2%	23%	69%
gfdl_cm2_0 (A2)	26	31	4.2	0.49	0.93	3.4%	0.7%	4.2%	1.0%	24%	49%
gfdl_cm2_1 (A2)	27	31	4.5	0.50	0.98	3.4%	0.7%	4.5%	1.0%	30%	49%
ipsl_cm4 (A2)	27	25	-1.5	0.49	0.92	3.4%	0.7%	3.5%	0.7%	2%	-1%
miroc3_2_medres (A2)	27	27	-0.3	0.52	1.01	3.4%	0.7%	3.6%	0.9%	5%	36%
miub_echo_g (A2)	28	29	0.7	0.54	1.07	3.4%	0.7%	3.8%	0.9%	10%	32%
mpi_echam5 (A2)	27	29	2.1	0.51	1.03	3.4%	0.7%	3.9%	0.8%	14%	21%
mri_chcm2_3_2a (A2)	28	29	1.7	0.52	1.04	3.4%	0.7%	3.8%	0.9%	11%	35%

*Calculated as (2046–2065 frequency-Baseline frequency)/Baseline frequency. Precipitation at or above the baseline 5-percentile is projected to occur X% as often by mid-century, where X is the number reported in this column.

**Calculated as (2046–2065 frequency-Baseline frequency)/Baseline frequency. Precipitation at or above the baseline 1-percentile is projected to occur X% as often by mid-century, where X is the number reported in this column.

Table D-3

Change in Frequency of Days that are Cold Enough for Possible Snow, All Models and Emissions Scenarios

Model (scenario)	1961 2000 Frequency of "Snow Chance" Days (%)	2046 2065 Frequency of "Snow Chance" Days (%)	Change in Frequency of "Snow Chance" Days*	% Change in Frequency of "Snow Chance" Days
cccma_cgcm3 (B1)	29%	23%	0.8	-22%
cnrm_cm3 (B1)	29%	26%	0.9	-12%
gfdl_cm2_0 (B1)	29%	23%	0.8	-22%
gfdl_cm2_1 (B1)	29%	23%	0.8	-21%
ipsl_cm4 (B1)	29%	20%	0.7	-30%
miroc3_2_medres (B1)	29%	21%	0.7	-28%
miub_echo_g (B1)	29%	22%	0.8	-24%
mpi_echam5 (B1)	29%	24%	0.8	-19%
mri_chcm2_3_2a (B1)	29%	24%	0.8	-17%
cccma_cgcm3 (A2)	29%	20%	0.7	-32%
cnrm_cm3 (A2)	29%	23%	0.8	-21%
gfdl_cm2_0 (A2)	29%	19%	0.7	-34%
gfdl_cm2_1 (A2)	29%	23%	0.8	-20%
ipsl_cm4 (A2)	29%	19%	0.7	-35%
miroc3_2_medres (A2)	29%	19%	0.7	-34%
miub_echo_g (A2)	29%	20%	0.7	-32%
mpi_echam5 (A2)	29%	23%	0.8	-23%
mri_chcm2_3_2a (A2)	29%	23%	0.8	-22%

* Calculated as 2046–2065 frequency/1961–2000 frequency. "Snow chance" days are projected to occur X times more frequently by mid-century, where X is the number reported in this column.

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