Worcester Polytechnic Institute

Supporting Winter Climate Adaptation in Worcester, Massachusetts

by

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and

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A thesis submitted in partial fulfillment of the degree of

Master of Science in
Community Climate Adaptation

December 2024

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Abstract

Our study explored the impacts of climate change on Worcester, MA, during the winter season, focusing on the vulnerability of critical infrastructure and populations. We analyzed historical and projected weather trends, conducted 38 interviews with stakeholders that included city officials, residents, climate experts, and utility providers, and surveyed 565 residents. Anticipated winter climate change risks include winter flooding, freezing rain, and shifting precipitation patterns from snow to rain. Vulnerabilities identified are disruptions to internet connectivity, school closures, and overflowed drainage systems. At-risk populations include the elderly, homeless, disabled, and non-English speaking residents. This research was conducted in collaboration with the city of Worcester's Department of Sustainability and Resilience We conclude the study by proposing short and long-term adaptation strategies to enhance Worcester's resilience against increasingly severe winter events.

Acknowledgments

We want to extend our heartfelt gratitude to all our stakeholders who contributed to this research with valuable insights and expertise. We are incredibly thankful to our advisors, Professor Sarah Strauss and Professor Stephen McCauley, and our collaborators from the city of Worcester's Department of Sustainability and Resilience, John Odell Chief Sustainability Officer and Luba Zhaurova, Director of Projects, Sustainability and Resilience.

Our sincere thanks also go to the climate experts who provided critical information on winter climate in our region: Dr. Colin Zarzycki, Assistant Professor of Meteorology and Climate Dynamics at Pennsylvania State University; Dr Mathew Barlow, Professor of Climate science at the University of Massachusetts Lowell; and Dr. Elizabeth Burakowski, Research Assistant Professor at the University of New Hampshire.

We are equally grateful to community organizations, National Grid, and city officials who shared their important perspectives with us. Most importantly, we sincerely appreciate the 565 Worcester residents who completed our survey and those who took the time to share their personal experiences of winter storms. We are extremely grateful to the residents who answered our questions so thoughtfully, especially those who connected us with further relevant stakeholders and peers they thought would answer the questions with even more clarity.

Executive Summary

Background

Climate change is reshaping winter seasons, particularly in the Northeastern United States, with Massachusetts experiencing a 3.5°F increase since 1990 and projections indicating a further rise up to 9°F by the end of the century. Warming temperatures are causing shifts in precipitation and snowfall patterns and increasing the intensity of winter storms. These changes disrupt ecosystems, infrastructure, and communities. Warmer winters result in more precipitation falling as rain, increasing flooding risks. Other impacts due to these changes may include power outages and transportation and telecommunication disruptions. Vulnerable populations, including low-income individuals, people with disabilities, older people, and the unhoused, are disproportionately impacted, with more significant risks of accessibility challenges, exposure to extreme cold leading to hypothermia, and disruption to essential services. Addressing these challenges requires adaptation measures, including resilient infrastructure upgrades and stakeholder coordination to promote long-term resilience. By understanding localized impacts and implementing targeted interventions, Worcester can better prepare for and adapt to the evolving challenges of winter climate change.

Methodology

This project addressed the gaps regarding climate hazards identified in Worcester's Municipal Vulnerability Plan. The city of Worcester identified winter/ice storms as one of the climate hazards that the city needs to prepare for to increase its resiliency. This project contributed to a better understanding of the challenges faced by the city of Worcester due to winter storms to ensure Worcester becomes one of the most resilient mid-sized cities in the United States. The methodology for this project incorporated archival research to understand the winter storms that the city has experienced. It also included a survey of residents' perceptions of winter storms, which had 565 respondents, and 38 semi-structured interviews with various stakeholders, including city officials, National Grid representatives, climate experts, representatives from community organizations and residents. We accomplished four objectives (Figure 1) for the completion of the project.

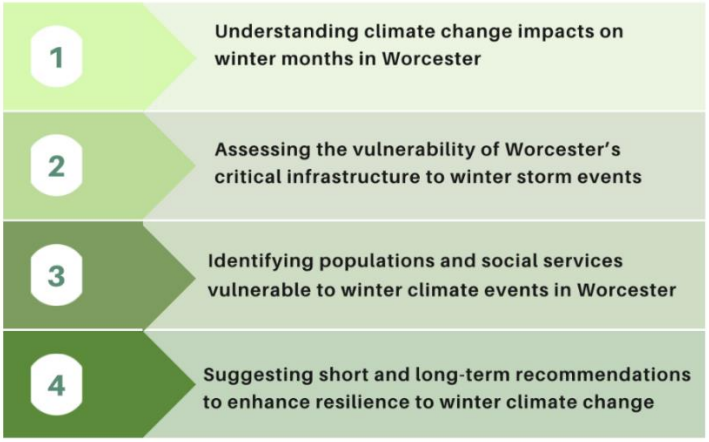

Figure 1: *Project objectives*

Results and Discussion

In this section we give an overview of how climate change is transforming Worcester's winters, impacting infrastructure, and disproportionately affecting vulnerable populations. It analyses past trends, future projections, and risk while presenting targeted adaptation strategies to enhance the city's resilience.

Objective 1: Climate change impacts on winter months in Worcester

The analysis of past trends (2000-2024) and projections (2030-2090) shows that Worcester's winters are warming due to climate change, with average winter average temperatures increasing from 28.6°F in 2000 to 33.5°F in 2024. Projections under RCP 4.5 and RCP 8.5 scenarios indicate further warming, with fewer days below freezing by 2090. Warmer air holds more moisture, leading to increased precipitation, primarily rain or freezing rain rather than snow. Total winter precipitation rose from 8.01 inches in 2000 to 16.92 inches in 2024, and this trend is expected to continue, resulting in wetter winters. Snowfall is declining overall, but warming temperatures could lead to more intense snowstorms when snow does occur. The variability and intensity of winter storms, influenced by phenomena like the polar vortex and El Niño-Southern Oscillation, create challenges for forecasting and preparedness.

Objective 2: Vulnerable infrastructure

Winter storms in Worcester significantly impact critical infrastructure, including stormwater systems, roads, vegetation, electric utilities, and telecommunications. Increased winter rainfall and frozen ground heightened flood risks, straining drainage systems and increasing basement flooding. Roads are damaged by freeze-thaw cycles, leading to cracks and potholes. Heavy snow and ice accumulation on trees threaten power lines and properties. Internet disruptions are also a communication challenge widely experienced during storms. While undergrounding power lines could enhance grid resilience, high installation costs remain a barrier.

Objective 3: Vulnerable populations

Winter climate events in Worcester disproportionately affect vulnerable populations, including non-English speakers, newcomers, the elderly, disabled, and unhoused individuals. Language barriers and limited knowledge of winter preparedness place non-native speakers and newcomers at greater risk during severe weather. The elderly and disabled face challenges with snow removal, increasing their risk of isolation. The unhoused population experiences exposure to extreme cold, with shelters often operating at capacity, stressing the need for additional resources. School closures due to winter storms affect low-income families, disrupting school meals and childcare, which exacerbate social inequalities. Mobility challenges during winter storms impact resident's access to essential services, particularly for those with disabilities. The city's snow-clearing efforts prioritize main roads, but resource constraints hinder timely and effective operations, including a shortage of snowplow drivers and equipment.

Objective 4: Adaptation strategies

This objective presents the recommendations for the city. Our archival research, semi-structured interviews, and surveys informed these recommendations. We also reviewed ten climate action plans across different North American cities, finding cities with similar profiles as Worcester and the adaptations they are implementing to complement our recommendations. Our recommendations are divided into two categories: infrastructure vulnerability and social vulnerability. A snapshot of them can be reviewed in the table below.

Recommendations

Recommendations for Infrastructure Vulnerabilities

Drainage systems

- Review the stormwater and combined sewer systems to manage the expected increased winter rainfall
- Investigate incorporating permeable surfaces in areas prone to flooding
- Evaluate incorporating bioretention systems for stormwater flooding

Roads

- Assess the incorporation of eco-friendly de-icing agents
- Determine the possibility of implementing permeable pavement design in future infrastructure projects
- Consider employing roadway materials that can support rapid temperature fluctuations

Telecommunication Networks

- Evaluate expanding broadband internet options
- Explore the feasibility of having a backup satellite internet service

Electrical Infrastructure

- Conduct a cost-benefit analysis of targeted modernizations in areas at high risk

Trees

- Select tree species that are resistant to ice and heavy snow
- Continue existing coordination on tree trimming with National Grid

Recommendations for Social Vulnerabilities

Non-English Speaker and Newcomers

- Make multilingual emergency information for winter storms more accessible
- Update the Emergency Communications website for disaster preparedness

- Develop and implement education programs on emergency preparedness before, during, and after winter storms

Elderly and Disabled

- Build partnerships with college campuses and organizations to increase the number of available volunteers
- Leverage multi-channel communication strategies to share services

Unhoused

- Expanding warming centers

School Closures

- Evaluate students' food insecurity and partner with community organizations for short-term relief during extended closures
- Partner with local daycares for temporary childcare

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1. Introduction

Climate change is a serious challenge, with its growing impact visible worldwide. While much attention has been directed toward the effects of rising temperatures, droughts, and extreme heat (AghaKouchak et al., 2020), the implications of climate change on the winter season, particularly in mid-latitude regions, remain underexplored (Templer et al., 2017). In the Northeastern United States, specifically Worcester, Massachusetts, winters are undergoing significant transformations. Rising temperatures in the winter months are shifting precipitation patterns, intensifying storm events, and altering the fundamental characteristics of the season. These changes threaten not only the city's physical infrastructure but also its social systems, disproportionately affecting vulnerable populations such as the elderly, disabled, non-English speakers, and unhoused residents.

Worcester's winters are traditionally marked by cold temperatures, snow, and ice storms. Climate change alters these patterns, leading to a rise in winter temperatures, shifts in precipitation from snow to rain, intensified storm events, and changing freeze-thaw cycles.

Worcester has made strides in advancing sustainability and resiliency in response to these challenges. Initiatives like the Municipal Vulnerability Preparedness (MVP) program and the Green Worcester Plan have identified the city's primary climate risks: flooding, extreme heat, and severe storms. However, winter-specific climate risks remain an underexplored area within urban resilience planning in Worcester.

This study aims to fill that gap. It was undertaken in partnership with the city of Worcester's Department of Sustainability and Resilience to assess the impacts of climate change on Worcester's winters and to identify strategies for adaptation. Focusing on the vulnerabilities of critical infrastructure such as stormwater systems, roads, telecommunications, and electrical infrastructure and on populations most at risk, this research aims to provide actionable recommendations to enhance the city's resilience to winter storms and evolving climate conditions. The study draws on an interdisciplinary approach, combining archival research, community surveys, and semi-structured interviews with climate experts, city officials, utility providers, and residents. The project captures a comprehensive understanding of historical trends, projected climate changes, and localized challenges through these methods.

This research highlights the necessity of proactive adaptation measures to mitigate the risks of shifting winter climates. The findings point to increased flooding due to winter rainfall, damage to roadways from freeze-thaw cycles, and disruptions to power and telecommunications networks. Social vulnerabilities are also emphasized, with language barriers, limited mobility, and insufficient shelter resources compounding the risks for at-risk populations. By addressing these challenges and implementing targeted interventions, Worcester can safeguard its residents and infrastructure and position itself as a leader in climate adaptation for mid-sized cities. This study aims to bridge knowledge gaps and support the city in building a sustainable and equitable future amid a changing winter climate.

2. Background

2.1 Impact of Climate Change on Winter

Climate change is reshaping winter weather across the Northeastern United States, bringing warmer temperatures that alter traditional snowfall patterns and contribute to extreme winter events. These shifts disrupt seasonal norms, impacting the region's ecosystems, infrastructure, and communities. By the end of the century, temperatures in the Northeastern region are projected to increase by~5.4 °F under RCP 4.5 and ~9 °F under RCP 8.5 (Burakowski et al., 2022). The hazard and mitigation plan for the Commonwealth of Massachusetts, *Resilient Massachusetts* (2023), indicates that an increase of 3.5 °F has already been observed since 1990. Researchers from the Northeast Climate Science Center at the University of Massachusetts Amherst report that the average winter temperature in the state will increase by 15 to 40% by 2090, compared to the 1971-2000 baseline of 26.6 °F. Temperatures are expected to rise at 0.5 °F per decade (Massachusetts Environmental Policy Act Office, 2018). Similarly, The Green Worcester Sustainability and Resilience Strategic Plan (GWP) points towards similar trends in Worcester regarding increasing temperatures.

The increase in temperature results in warmer air. This warmer air can hold more moisture, which means the propensity for precipitation is higher (Pendergrass et al., 2017). According to Hoell et al. (2021), the atmosphere holding more moisture means that when extreme winter events do happen, they tend to be much stronger in intensity, resulting in storms that can cause much more damage.

Warmer winters will result in a shift from snow to rainfall (Burakowski et al., 2022); this raises the risk of flooding as impervious soil becomes saturated, limiting its capacity to absorb water, leading to higher runoff and making the evaluation of winter flood risks more challenging (Jaffe & Woloszyn, 2013). By the end of the century for the Northeastern region, most of the precipitation in the winter months will fall as rain instead of snow due to the warmer winter climate (Executive Office of Energy and Environmental Affairs & Resilient Mass, 2023).

Climate trends indicate that Worcester is projected to experience higher temperatures and shifts in precipitation patterns to more rainfall and freezing rain (City of Worcester & Green Worcester Working Group, 2021).

2.2 Impacts of Winter Climate Change on Critical Infrastructure

Climate change-induced shifts in winter conditions have significant consequences for Worcester’s critical infrastructure. Critical infrastructure consists of fundamental systems and assets that are essential for the operation of a city or region. Such components include power systems, transportation networks, water and sewer systems, communication networks, and important buildings and facilities (Barrage, 2023). As winter climate change began to impact some

regions in the United States, components of critical infrastructure became more exposed to the altering conditions (Hummel et al., 2020).

Critical infrastructure consists of physical and digital systems necessary for a city or region's functionality. They are the basis of everyday life, economy, and public wellbeing. Critical infrastructure particularly exposed to winter climate change includes power grids, road and railway systems, stormwater management, communication towers, and a range of buildings serving important purposes such as hospitals and emergency response (Casey et al., 2024). These systems are interconnected and a malfunction or other type of disruption in one can lead to a chain of malfunctions in another. Based on that, we can say that the interconnected nature of critical infrastructure makes it especially vulnerable to winter climate change.

Power systems tend to be at risk from the impact of extreme winter weather. In particular, ice storms and heavy snow can destroy power lines and transformers, causing power outages. Climate change alters winter weather patterns, leading to more severe winter storms and extended periods of mild winter weather. Unfortunately, power infrastructure is not always equipped to handle these new challenges of extended mild weather followed by severe storms (Perera et al., 2020).

The rapidly changing winter climate has a significant impact on road and transportation infrastructure. Extreme winter storms often disrupt transportation networks, causing delays and hazards. Additionally, continuous freeze-thaw cycles in some areas exacerbate road damage, leading to increased maintenance costs (Wang et al., 2020). These cycles accelerate pothole formation and degrade roadway infrastructure, posing challenges for long-term sustainability and requiring more frequent repairs to ensure safety and functionality.

Winter rainfall events place additional stress on stormwater systems. During freezing conditions, impervious soil surfaces increase runoff, making these systems more susceptible to overflow. Stormwater management systems are designed to handle particular precipitation scenarios. As Hathaway et al. (2024) noted, with more precipitation expected during the winter season, and particularly if precipitation occurs when soils are frozen and impervious, existing systems may no longer be sufficient to handle the increased volume and intensity of water.

2.3 Impacts of Winter Climate Change on Social Infrastructure

Social vulnerability refers to the increased likelihood that certain social groups will be disproportionately impacted by natural hazards, facing higher rates of mortality, injury, loss, or disruption to their livelihoods (Mah et al., 2023).

The term "social infrastructure" encompasses the various institutions, networks, and facilities that foster social connections and interactions (Layton & Latham, 2021). It includes essential services that shape daily life, such as healthcare, education, and cultural activities.

A recent EPA study indicated that low-income, minorities, the elderly, and those with limited education are most at risk of the impacts of climate change (EPA, 2021). Low-income neighborhoods have higher rates of temperature-related mortalities, and individuals who are 65

years and older are especially susceptible to extreme weather events as they exacerbate their pre-existing health conditions.

As climate change intensifies, the vulnerability of these populations and essential services increases as well. Climate-related events, especially severe winter weather, pose increased risks for communities already struggling with disparities (Islam & Winkel, 2017). Many built environments were not designed to withstand winter climate hazards. When such hazards occur, they interact with existing social infrastructure systems, amplifying the vulnerability of both people and infrastructure. Where winter climate hazards meet human systems, we find social infrastructure vulnerability (Birkmann et al., 2021).

The impacts of winter climate change are especially severe for communities already facing challenges. These communities are at heightened risk due to existing vulnerabilities and system inequities in service delivery. These inequities often become more pronounced during extreme events, such as winter storms, cyclones, and floods, as resource access and service delivery gaps widen (Ebi et al., 2021). Understanding the full impact of winter climate change requires considering the demographic makeup, socio-economic factors, and pre-existing inequities within affected communities. These elements interact to determine the future burdens and health outcomes for these communities as they face climate-related challenges (Ebi & Hess, 2020).

The winter climate presents a significant challenge for vulnerable populations, especially the unhoused, as extensive exposure to cold weather increases health risks such as hypothermia (EPA, 2024). Mobility and accessibility worsen during winter. Key obstacles to winter accessibility are icy sidewalks and slushy street crossings, disproportionately affecting older adults (Bergen et al., 2022)

2.4 Winter Climate Change Adaptation

In addition to reducing greenhouse gas emissions and mitigating rising temperatures, it is crucial to focus on adapting to the impacts of climate change (J. Zhang et al., 2022). This includes addressing extreme weather events that we are already experiencing in order to protect our communities (Field et al., 2012). Adaptation to climate change requires local and large-scale efforts (Shi & Moser, 2021). The particular adaptation measures that are appropriate in any setting depend on the context as the type of hazards, and the unique topography of each region, adaptation to climate change must be done urgently; delaying winter climate adaptation would increase the vulnerability of communities already at risk (Parsons et al., 2024).

Adaptation is defined as the adjustments made to processes, methods, and structures in order to lessen possible harm or take advantage of opportunities associated with climate change (Dale, 2022). Effective adaptation measures rely not only on government responsibility and action but also on active stakeholder engagement. By sharing knowledge, challenges, and experiences, stakeholders can collaborate to reach consensus and create more comprehensive, resilient solutions.

The Chicago Action Plan 2008 (Hayhoe & Wuebbles., 2008) forecast an increase in precipitation during winter and spring. The precipitation intensity is also likely to increase in the coming years, which could lead to an increased frequency of floods.

With the highlighted impacts of projected winter changes on people's lives and infrastructure, various interventions are in place to mitigate the effects of such climate changes. Some adaptation measures and policies include pitched roofs to make them sturdy against the snow load (Jafe & Woloszyn, 2013). Likewise, to minimize the effects of climate changes on highways, they are crowned with a tighter radius to improve drainage. The adaptations should include solutions on how winter climate changes affect economic activities. The city can monitor stormwater flows and mitigate basement flooding risks. Backup power generation can also be an essential adaptation to help in the continuous operations in case of power blackouts. Likewise, the city can install more resilient traffic controllers and ensure the installation of more resilient infrastructure to cater for the damage resulting from freezing rain and winter precipitation.

3. Methodology

The goal of this project was to support the winter adaptation plan for the city of Worcester by assessing vulnerabilities and proposing recommendations, to improve the city's readiness to face winter storms and safeguard critical infrastructure and the community. This approach was essential for building resilience and ensuring the continuity of essential services for the community, in the face of potential impacts of winter storms related to climate change. This study was approved by the Worcester Polytechnic Institute's Institutional Review Board (IRB) and was exempt from further IRB review. Below, we identify the methods used to gather and analyze the various types of data used in our research efforts. This project had four objectives (Figure 1).

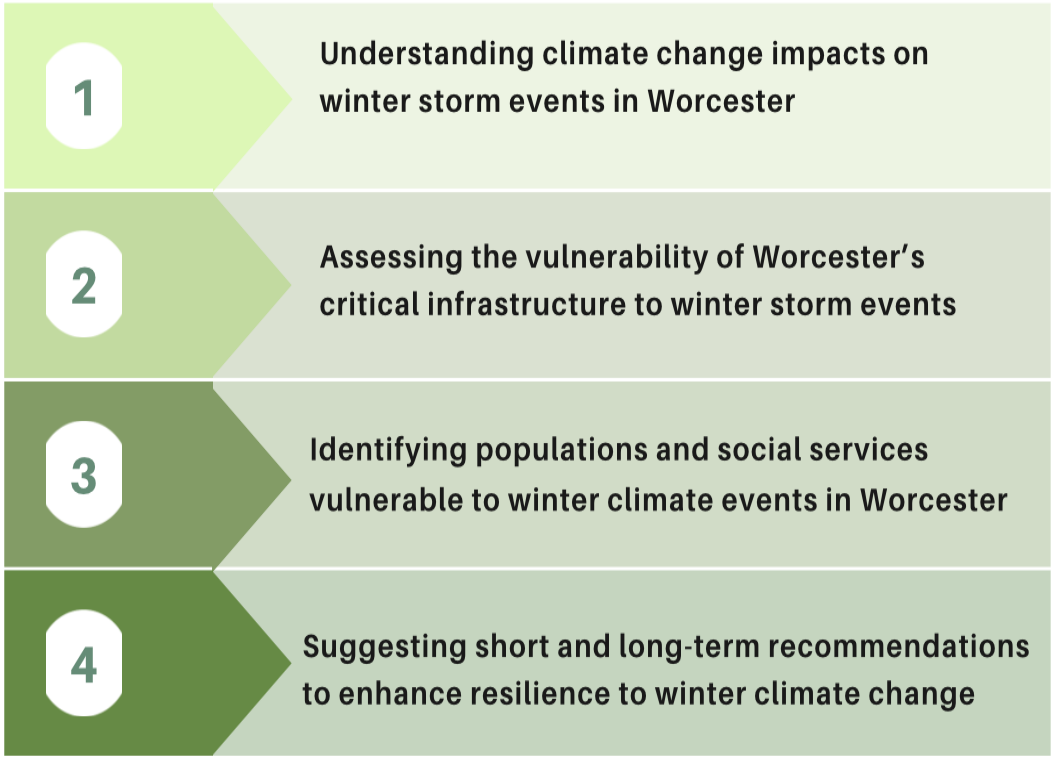


***Figure 1**: Project objectives*

To meet the project objectives, we used three methods for data collection: archival research (Ventresca & Mohr, 2017); a survey of residents (Abrami et al., 2021); and semi-structured interviews (Adeoye-Olatunde & Olenik, 2021).

Archival research: The study of these documents would provide us with information that organizations and individuals may not have of the earlier time. There are two primary questions that are asked. Firstly what type of material would be used for analysis, and secondly how will that

material be analyzed (Ventresca & Mohr, 2017)? We applied this method to achieve our first objective.

Survey: We use this method in our qualitative research because it provides experiences, perceptions, and needs of the residents. Additionally, surveys allow us to get a wide range of individuals with different geographic and demographic needs. Our research survey was conducted through Qualtrics, a cloud-based software platform used to create, distribute, and analyze surveys. We received 565 responses. We applied this method to achieve our second, third and fourth objectives.

Semi-structured interviews: Semi-structured interviews combine structured questioning with the flexibility to discuss more ideas that appear during the interview (Adeoye-Olatunde & Olenik, 2021). We used the semi structured interview method in our qualitative research because it allowed us to gather diverse perspectives, experiences and insights from different stakeholder groups. This method provided the flexibility to adapt our questions based on the flow of the conversation, ensuring that we were asking the right questions and uncovering any key issues that we might have missed. We conducted 38 semi-structured interviews with different stakeholders (Figure 2)**.** Analysis of the semi-structured interviews was completed using ATLAS.ti, a web-based software for coding that helped us to analyze qualitative data from the interview's transcripts and field notes. We applied this method to achieve all of our objectives.

For the semi-structured interviews and surveys, participants were invited to contribute voluntarily, with the assurance that their responses would remain confidential and anonymous. However, some interviewees, particularly climate experts, were asked for consent to include their names in the report.

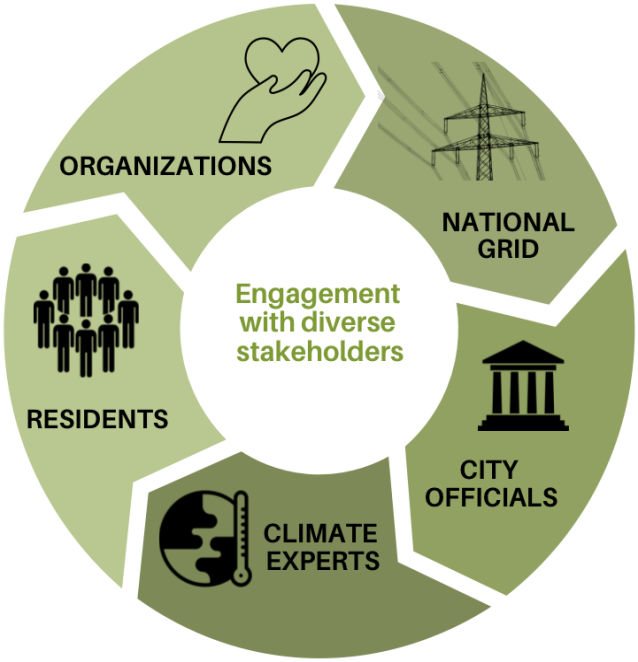


Figure 2: *Visual of stakeholder groups included in the semi-structured interviews*

Objective 1: Understanding climate change impacts during winter months in Worcester

For this objective, we analyzed historical data (2000 - 2024) and project trends (2030 - 2090) to determine how climate change is influencing winter storm patterns. We also identified specific changes in Earth system factors driving these conditions. The methods we used to complete this objective were archival research and semi-structured interviews.

Archival research: This method was implemented to answer two of our research questions. The first question was: What patterns and trends emerge in the data regarding seasonal changes in winter precipitation, including the likelihood of more frequent heavy snow or rain events in Worcester? and the second question was: Are there identifiable correlations among the major winter storms that have impacted Worcester, such as patterns in frequency, intensity, or associated weather conditions?

In order to answer these questions, we collected winter weather data specific to Worcester by reviewing historical archives and documentation of major winter storms that have affected the city. Our research included examining microfilms, books, newspapers, almanacs and weather data sourced from various institutions such as the WPI library and archives, the American Antiquarian Society, the Worcester Historical Museum, and the Worcester Public Library.

From the historical materials and data, we identified dates of significant winter storms in Worcester. To further analyze these events, we conducted a detailed review of archival data at the Worcester Public Library (WPL). The library houses a collection of microfilm data from the Worcester Telegram and Worcester Gazette, accessible through a dedicated device for viewing newspapers from specific dates. Using this resource, we examined the newspaper coverage for all identified storm dates, extracting relevant details about each event.

We systematically gather data on the year, specific days, type of storm, and precipitation (measured in inches of snow or ice). This process involved identifying the necessary information, finalizing the relevant data, reviewing archival materials, and analyzing the data to identify recurring themes and patterns. By synthesizing this information, we assessed the impact of winter storms on the city of Worcester and created a detailed table (see Results section) that outlines key storm characteristics and helped us to identify if there were any emerging correlations or trends across winter storms.

We also gathered data on both historical and projected climate trends for Worcester. For historical data (2000-2024), we accessed snowfall, precipitation, and temperature trends through the NOAA Regional Climate Center using the xmACIS[1] (Applied Climate Information System) interface. For projected data (2030-2090), we utilized the Climate Change Projections Dashboard[2] at Resilient Mass, this resource provided data on expected changes in temperature, precipitation, and the number of days below 0°F and 32°F. These combined datasets allowed us to investigate

[1] https://xmacis.rcc-acis.org/

[2] https://mass-eoeea.maps.arcgis.com/apps/dashboards/2e8534bc2a7849b0aa6f64d0f79a8937

both past and future climate trends, supporting an analysis of winter weather impacts and patterns in Worcester.

Semi-structured Interviews: We interviewed four climate experts: Dr. Colin Zarzycki, Assistant Professor of Meteorology and Climate Dynamics at Pennsylvania State University; Dr. Matthew Barlow, Professor of Climate Science at the University of Massachusetts Lowell; Dr. Elizabeth Burakowski, Research Assistant Professor at the University of New Hampshire and a meteorologist. Those with knowledge and experience regarding the impact of climate change on the Northeastern United States shared how climate change affects winter in the region. Interview questions are included in (Appendix A). Through these semi-structured interviews, we explored two key research questions: What recurring themes indicate significant impacts on winter storms, and What specific patterns are changing climate conditions in the Northeastern United States?

Research limitations

One limitation of this objective was the variability and inconsistency in the historical data sources and the inherent uncertainty of past winter storms, making interpretation challenging. For example, news reports may detail snowfall and impacts in specific Worcester areas but do not provide a comprehensive view of impacts across the city. The primary weather station is located at Worcester Regional Airport, which sits at a higher elevation and may record different data compared to lower areas of the city. Additionally, precipitation measurement techniques have evolved, resulting in potential inconsistencies across the data range we analyzed. These factors introduce challenges in creating a unified, accurate analysis and mean that future projections may not fully capture the complexities of winter storm patterns in Worcester.

Objective 2: Assessing the vulnerability of Worcester's critical infrastructure to winter storm events

This objective aimed to understand Worcester's infrastructure's vulnerabilities, such as power grids, roads, transportation systems, buildings, communication networks, and drainage systems. Knowledge gained from this analysis will inform strategies for enhancing the resilience of these essential systems. For this objective, we implemented two methods: first, semi-structured interviews with city offices, National Grid representatives, and residents, and second, a survey on residents' perceptions of climate change and winter storms. The interviews and surveys helped us collect data on infrastructure challenges, past impacts, and resilience needs in severe winter conditions.

Semi-structured interviews with experts: We interviewed nine stakeholders, including city officials and representatives from National Grid, Worcester's primary electricity provider, across different departments.

We interviewed three city officials from the Department of Public Works Streets, Parks & Recreation, and Worcester Regional Transit Authority (WRTA). We identified staff from those departments through the city's website and the Department of Sustainability and Resilience. Through the interviews, we explored infrastructure such as sewer systems, roads, trees, and communication networks and how they are impacted by ice or heavy snow accumulation (Appendix B).

We interviewed six National Grid officials from electric operations, engineering, community engagement, and emergency planning departments. Our research question was how the city's utility provider is affected during winter storms and what their preparation and coordination process is. We also looked at the city's infrastructure, which includes substations, main feeders, overhead lines, and distribution poles. We sought to determine if ice/heavy snow accumulation was impacting them in any way (Appendix C). We first identified interviewees from National Grid through a search on LinkedIn. We connected with one utility provider leader who had mutual connections with WPI and National Grid, who in turn connected us with an executive leader at National Grid who oversaw operations during the 2008 ice storm. The executive leader had recently retired and connected us with the current leadership team, who helped us connect with officials from the Engineering, Operations, Planning, and Community Engagement streams at National Grid.

We obtained informed consent verbally. Confidentiality and anonymity were ensured, with participants given the option to remain anonymous. The interviews were recorded and transcribed; detailed notes were also taken. Recordings were used solely to aid the analysis, and quotations were incorporated to inform our findings.

Semi-structured interviews with residents: We interviewed 14 residents. We examined how residents were impacted by transportation disruptions, significant home challenges such as power outages, loss of internet connectivity, and property damage. Interview questions for residents are included in (Appendix D). We connected with participants who expressed interest in further discussion through the survey. At the end of the survey, we provided an optional section for residents to share their contact information if they were open to an in-depth conversation on this topic. For those who shared their details, we reached out via text and email to arrange a follow-up meeting, offering them the choice of an in-person or online format to suit their preference. This same method was used for the objective below on social vulnerabilities.

Research limitations

We were unable to connect with the broadband internet provider for the city of Worcester, Spectrum which is the trade name of Charter Communication. We were also unable to connect with the Water and Sewer Operations Department. Some of the electrical infrastructure data is proprietary information that is not publicly available. We are basing our understanding of the challenges based on the available data, the perception of the residents, and the resources and plans

put in place by the city. The increased risk of flooding due to impervious surfaces during the cold winter months is a limitation in this study that could be looked up in a follow-up study.

Objective 3: Identifying populations and social services vulnerable to winter climate events in Worcester

The third objective was to identify the populations in Worcester most vulnerable to winter storm impacts. To achieve this, we used two methods: first, we conducted semi-structured interviews with residents, and representatives from various Worcester city departments and community organizations; and second, we conducted a citywide survey from February to June 2024. These methods allowed us to gather detailed insights into which populations are particularly at risk, the specific challenges they face, the city's current efforts to enhance preparedness for these groups, and existing gaps that need further attention.

Survey: We conducted a community-wide survey, receiving responses from 565 residents across various Worcester zip codes (Appendix E). The survey was available in both English and Spanish.

We ran a pilot to test the survey and incorporated feedback before launching the final version. The ultimate survey was distributed both online (via QR codes on digital flyers) and in print. For outreach, we visited locations across Worcester, including the Worcester Public Library, Printers Building Elevator (WCPC office), Mount Audubon, Worcester Common Ground, Worcester Senior Center (where we set up a table with printed surveys), Islamic Society of Greater Worcester, St. John's Catholic Church, and Clark University. At each location, we posted flyers in visible areas where residents could easily access the QR code.

In addition to physical outreach, we used digital platforms, including the Central MA Reddit Community, Nextdoor Worcester, and Facebook groups (MA Latinos en Worcester, Mexicanos en Worcester, Colombianos en Worcester, Anuncios en Worcester Massachusetts, and What's Happening in Worcester). We also employed a snowball sampling method to reach additional residents through community referrals.

Semi-structured interviews with city officials and community organizations: We conducted semi-structured interviews with 12 stakeholders, including city officials and representatives from community organizations, to gain insights into the challenges faced by various vulnerable populations during winter storms.

We interviewed five officials from Worcester Public Schools, the Department of Health & Human Services, and Emergency Communications & Management. Our questions focused on school closures and school challenges during winter storms. Additionally, we inquired about the unhoused population, discussing their needs, available shelter options, and the city's emergency response efforts (Appendix F). To connect with them, we located staff contacts via department websites and arranged meetings through email outreach.

We interviewed seven representatives from community organizations, including Worcester Common Ground, Center for Living and Working, Food for the Poor, the Southeast Asian Coalition, the Accessibility Advisory Commission, Worcester Senior Center, and Halo (an organization advocating for the unhoused population). These interviews focused on vulnerable groups such as individuals with disabilities, the unhoused, and older people, exploring how they are impacted during winter storms and what specific challenges they face (Appendix G).

We conducted semi-structured interviews with 14 Worcester residents, focusing on their perspectives regarding winter storm resilience. Residents were asked to identify vulnerable populations they observed in Worcester, describe the challenges these groups face during winter storms, share their experiences with past storms, and bring out priorities they believe the city should address to enhance resilience (Appendix D).

Research limitations

During the survey process, we encountered over 800 bot-generated responses. This necessitated the implementation of increased security measures to protect the integrity of the survey data. These bot responses were characterized by peculiar submission patterns, such as being submitted at unusual hours, like 3 a.m. and consisting of similar looking answers. Notably, these responses failed to provide input for questions that asked for explanatory, personalized answers. When we identified this pattern, we reached out to the Academic Technology Center (ATC) at WPI to address it. We put in place stricter data control protocols. This enabled us to successfully identify and remove bot generated data. This ensured that the survey results were safe, secure and representative of the residents.

In addition to the bot-related challenges, we faced difficulties in collecting responses from non-English speaking residents. Despite our efforts, only four Spanish-speaking residents filled the survey specifically designed for them, highlighting a limitation in representing the linguistic diversity of Worcester's population. This language barrier underscores a potential gap in capturing the full spectrum of experiences among Worcester residents.

Consequently, the limited number of residents surveyed (14) may not fully reflect the diverse perspectives within the community. While the findings provide valuable insights, the representatives of our results may be constrained because of these challenges.

Objective 4: Suggesting short and long-term recommendations to enhance resilience to winter climate change

The final objective of this study was to leverage its findings, along with an analysis of winter adaptation strategies from comparable cities across North America, to develop actionable recommendations. These recommendations were designed to address the identified gaps and provide both short- and long-term solutions.

To achieve this, we conducted a thorough review of climate adaptation plans with similar climatic challenges, including Albany, New York; Alexandria, Virginia; Aspen, Colorado; Buffalo, New York; Burlington, Vermont; and Cherry Hill, New Jersey; Keene, New Hampshire; Chicago, Illinois; Hartford, Connecticut; Montréal, Québec and Anchorage, Alaska.

Additionally, semi-structured interviews with stakeholders engaged in the previous objectives provided important insights into existing gaps and offered valuable feedback on the proposed recommendations. This process was completed by extensive online research to identify relevant adaptation strategies.

Research limitations

The study faced the limitation that few comparable cities have undertaken planning for winter climate change impacts. We have identified several cities with climate adaptation plans; however they have adaptation for summer; only a few of them mentioned adaptation measures for the winter season such as Keene, New Hampshire; Chicago, Illinois; Hartford, Connecticut; Montréal, Québec and Anchorage, Alaska, as well some of them were dated for more than 10 years (Keene, 2007; Chicago, 2013; Hartford, 2017; Montréal, 2015). Given that this is a new domain for city planning, it may be difficult to identify extensive details about winter planning interventions from case study cities. Nevertheless, any information we found was useful, as the city of Worcester recognizes this is an emergent area of planning. The approach might miss quantitative measures that could better inform cost-benefit analyses for proposed actions.

4. Results

This section presents the findings for each objective of the study, along with a discussion on the implications of those findings. The first part describes past trends and projections for Worcester's winter climate. The second part reports on the challenges and vulnerabilities related to Worcester's critical infrastructure, and the third part examines the populations most vulnerable to the negative impacts of winter storms and the issues they face.

Objective 1: Climate change impacts during winter months in Worcester

The analysis of past (2000 - 2024) and projected (2030 - 2090) climate trends for the City of Worcester and discussions with climate experts revealed that winters will become warmer as the planet warms, causing snowfall to decrease and the atmosphere to retain more moisture. This moisture will fall as precipitation in the form of snow when temperatures are at or below 32°F or rain when temperatures are above 32°F. Climate change has also made these storms more intense and somewhat uncertain to predict.

We analyzed the transcripts from interviews with climate experts by individually identifying recurring themes and developing initial codes. Through deliberation and discussion, we refined these codes, addressing overlaps and ensuring clarity. The codes we identified were: *decrease in snow, freezing rain/ice, increase in rainfall, more water vapor in the atmosphere, past winter storm events, polar vortex, and storm variability.* This analysis revealed the assertions presented below.

1. **Winter months are experiencing an increase in temperature.**

To identify the potential impacts of climate change, we analyzed past temperature trends and projections for the city (Figure 3). The temperature data gathered for the winter months (Dec - Feb) from 2000 to 2024 demonstrates a rise in the average winter temperatures across the city. The red regression line shows a clear ascending trend in the mean average temperature over the 24-year period, starting at 25.9°F in 2000 and increasing to 30.4°F in 2024**.** The blue dots indicate fluctuations in mean average temperatures through the years; the lower dots indicate colder winters, as in 2003 and 2015, while the higher dots indicate warmer winters, such as 2002 and 2023. Despite the temperature fluctuations, the overall trend shows an increase.

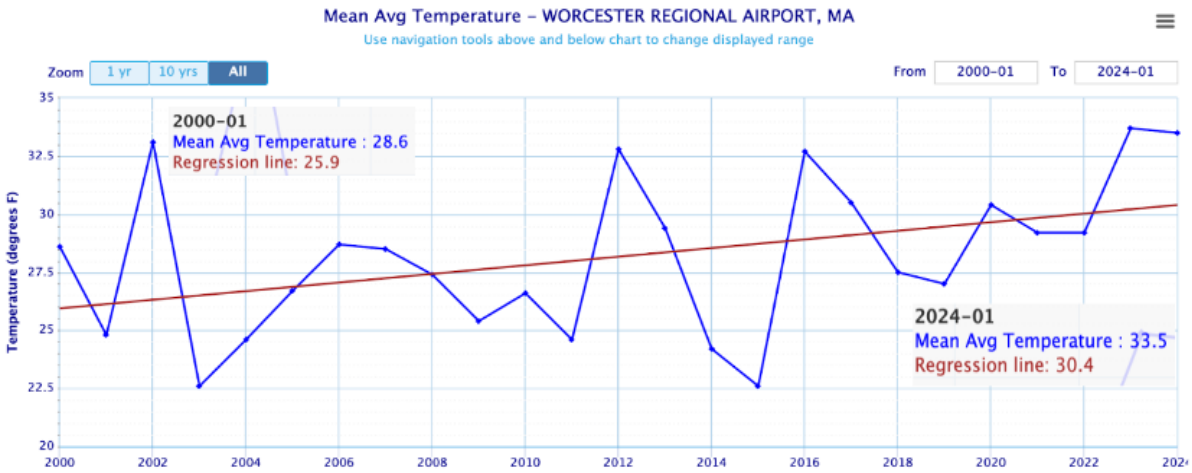


Figure 3: *Average temperature (°F) from 2000 to 2024 for Worcester, MA*
Source: NOAA Regional Climate Center.

We also analyzed projected data for temperature, days below 0°F, and days below 32°F for the winter months (Dec - Feb) for the years 2030, 2050, 2070, and 2090, provided at the watershed scale. The projections are based on two representative concentration pathways (RCP) scenarios: 4.5 and 8.5.

Under lower-emissions scenario RCP4.5 (Table 1), the average winter temperature will increase from 32.16 °F in 2030 to 33.96 °F by 2070 and 2090. The number of days with temperatures below 0 °F is projected to decline relative to the baseline from 2.32 days in 2030 to 1.47 by 2070 and 2090. At the same time, the number of days below 32 °F during the winter months will decrease from 72.9 days in 2030 to 66.56 days by 2070 and 2090.

Projections RCP 4.5	Temperature (°F)	Days below 0°F (Baseline 4.7)	Days below 32°F (Baseline 81.14)
2030	32.16 °F	2.32	72.29
2050	33.06 °F	1.84	69.95
2070	33.96 °F	1.47	66.56
2090	33.96 °F	1.47	66.56

Table 1: *Temperature projections for Worcester, MA under the RCP 4.5 scenario*
Source: MA Executive Office of Energy and Environmental Affairs (EEA)

Under the higher-emissions RCP8.5 scenario (Table 2), the average winter temperature will increase to 38.46 °F by 2090. The number of days below 0 °F and 32 °F will decrease in the target decades (2030, 2050, 2070, 2090). Under both climate scenarios, winters remain warm with

fewer days below 0°F and 32°F. These models suggest that winters are getting warmer and will continue this trend, resulting in less snow.

Projections RCP 8.5	Temperature (°F)	Days below 0°F (Baseline 4.7)	Days below 32°F (Baseline 81.14)
2030	32.16. °F	2.32	72.29
2050	34.86 °F	1.84	63.68
2070	36.66 °F	1.06	57.97
2090	38.46 °F	0.49	52.34

Table 2: *Temperature projections for Worcester, MA under the RCP 8.5 scenario*
Source: MA Executive Office of Energy and Environmental Affairs (EEA)

This increase in temperature might shift the precipitation from snow to rain, resulting in an overall increase in rainfall and freezing rain events during the winter months.

2. Increased atmospheric water vapor is changing winter precipitation patterns.

In Worcester, climate trends indicate an increase in overall precipitation. The increase in atmospheric water vapor due to climate change is one such trend that is transforming winter precipitation patterns in ways that significantly affect the city. With warmer temperatures and more moisture in the air, precipitation that would have fallen as snow is now more likely to come down as rain or freezing rain. This shift means fewer snowy winter days and more instances of rain or ice. The graph (Figure 4) shows the total precipitation (in inches) during the winter months (Dec - Feb) from 2000 to 2024. In 2000, the total precipitation was 8.01 inches and in 2024, it was 16.92 inches. The regression line shows a significant upward slope trend over time. The increase in mean winter precipitation suggests wetter winters (Akinsanola et al., 2024).

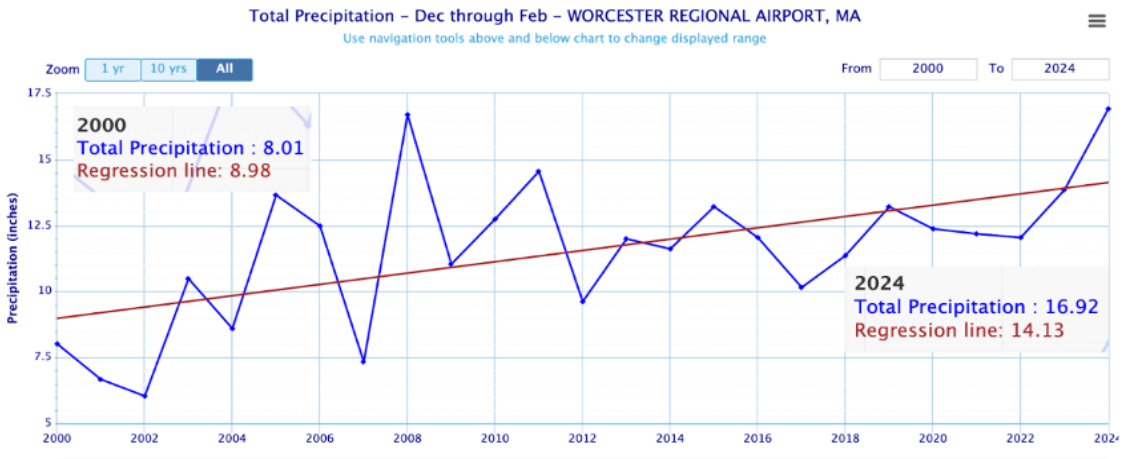


Figure 4: *Total precipitation (inches) from 2000 to 2024 for Worcester, MA*
Source: NOAA Regional Climate Center

The projections under both RCP climate scenarios showed the same increasing trend. Under RCP4.5 (Table 3), the data shows an increase in precipitation from 12.47 inches in 2030 to 13.55 inches in 2090. Under RCP 8.5 (Table 4), precipitation will rise from 12.53 inches in 2030 to 14.08 inches by 2090.

Projections RCP 4.5	Precipitation (Baselines 11.7 In)
2030	12.47
2050	12.74
2070	12.93
2090	13.55

Table 3: *Precipitation projections for Worcester, MA under the RCP 4.5 scenario*
Source: MA Executive Office of Energy and Environmental Affairs (EEA)

Projections RCP 8.5	Precipitation (Baseline 11.7 In)
2030	12.53
2050	13.11
2070	13.51
2090	14.08

Table 4: *Precipitation projections for Worcester, MA under the RCP 8.5 scenario*
Source: MA Executive Office of Energy and Environmental Affairs (EEA)

The projections indicate that Worcester is expected to experience higher amounts of winter precipitation. Different types of winter precipitation fall during a winter storm based on the temperature conditions between the atmosphere and the ground (Figure 5). The air temperature affects the precipitation type at all temperature conditions at or below 32 °F or above 32 °F (Shi & Hu, 2023). These can be snow, sleet, freezing rain, or rain.

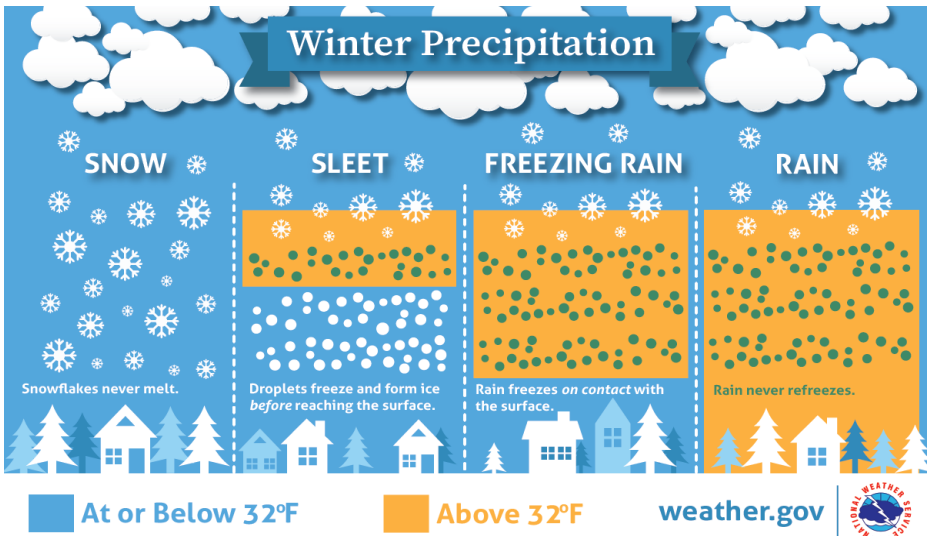


Figure 5: *Types of winter precipitation*
Source: NOAA's National Weather Service

When the temperatures are at or below 32°F, precipitation falls as snow. Sleet occurs when the snowflakes melt when they touch a warm layer, and then the droplets freeze when the ground is at or below 32°F. Freezing rain occurs when snowflakes melt while passing through a warmer layer. Upon contact with surfaces at or below 32 °F, it freezes, creating hazardous quantities of ice. Rain occurs when the snowflakes melt and do not freeze again because the temperature is above 32 °F on the ground.

The recent historical data shows that the number of days at or below 32 °F is decreasing, and those above 32 °F are increasing. This shift suggests that we are seeing and will continue to see less snowfall and more sleet, freezing rain, and rain. This change has begun to be noticeable in the city, emerging in conversations with residents and climate experts. A resident pointed out: "I think this year, we had a lot more like freezing rain or regular rain, and we had a lot of flooding this winter rather than full-on snow." A climate expert explained: "Temperatures are increasing, and overall, a warmer atmosphere holds on to more water. So, therefore, we can potentially have more rainfall." A second climate expert, Dr. Barlow, noted: "In general, with the warmer climate, you can evaporate more water from the ocean, and warmer air can hold more water vapor. When the water vapor condenses, it releases a lot of energy. So, globally, the warmer the climate, the more intense the rainfall."

Building upon that, we examined past snowfall trends, warming impacts snowfall in Worcester. The graph (Figure 6) shows the total snowfall (in inches) during the winter months (Dec - Feb) from 2000 to 2024. The red regression line represents the overall trend from 2000–2024, which shows a decline over time. In 2000, the total snowfall was 60.7 inches; by 2024, it had decreased to 46 inches. The blue dots represent the recorded snowfall for each year, highlighting the variability in snowfall from winter to winter. For example, the total snowfall in 2000 was 24.1 inches, whereas in 2024, it increased to 34 inches. This demonstrates how some winters receive significantly more snow than others. This variability is further influenced by factors such as El Niño and La Niña, which are explored in depth later in this section.

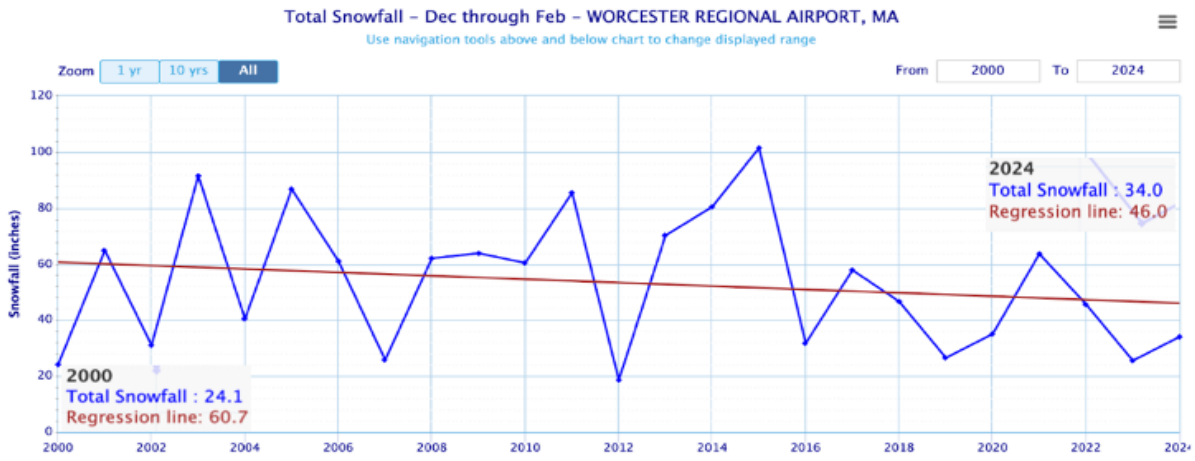


Figure 6: *Total snowfall (inches) from 2000 to 2024 for Worcester, MA*
Source: NOAA Regional Climate Center

Dr Zarzycki explained how climate warming impacts snowfall patterns in complex ways. While rising temperatures reduce the likelihood of snowfall, they also enable the atmosphere to hold more moisture, potentially leading to more intense snowstorms when snow does occur. He stated: “The first competing factor is that the temperature is warming, so the probability of having air temperatures that can support snowfall decreases in the future.” However, having less snow does not mean that the region will expect less intense snowstorms, as the other competing fact of warmer temperatures is that the atmosphere holds more moisture. He noted: “So, the way to think about the fact that there will still be big snowstorms in the future is that, even though the probability of having a snowstorm or the likelihood of days with snowfall decreases, when it does snow, it snows harder because there is more water vapor in the atmosphere that can be converted to snow.” This will increase the likelihood of heavier snow.

3. Winter storms have significant variability in impact, intensity, and frequency.

A review of data from 1921 to 2023 showed that Worcester had experienced significant winter storm events. We recorded 22 major winter storms over this period, including blizzards, ice storms, cyclones, and Nor'easters (Table 5). The events were spread out during the following months: January four storms (1956, 2005, 2015, 2018); February six storms (1969, 1978, 1983, 2003, 2006, 2013); March two storms (1993, 1997); April two storms (1925, 1987); October one storm in (2011); November one storm (1921); December six storms 1947, 1961, 1992, 1994, 2008, 2010), the trend demonstrated that the occurrence of winter storms is variable. An example of this variability is that in 1921, there was an ice storm in November, while in 1925, an ice storm happened in April. Another example of this variability is that in January 2018, Worcester experienced a bomb cyclone with an impact of 17 inches of snow on the city, while in January 2015, Worcester came under a blizzard that left 34.5 inches of snow. These examples point toward the variability of winter storms affecting Worcester, as these two storms happened in the same month but were different types of storms and brought different amounts of snow.

Climate experts, utility providers, and residents acknowledged Worcester's snowfall variability. A climate expert noted: "Over the past 70 years, there has been no clear increase or decrease in winter weather threats. Winter storms vary year to year due to factors like El Niño, which often reduces snowfall in Southern New England. For instance, this year's strong El Niño is similar to 1997-1998, bringing different snowfall levels. Each year differs, as large weather patterns heavily influence winter conditions and precipitation."

Dr. Zarzycki pointed out: "The difference between heavy snow and light snow can occur over 10 miles, so you could get a situation where, in a 20 or 30-minute drive down the Mass Pike, could go from being like a foot of snow to no snow very, very quickly". An official from the National Grid Engineering Department also noted: "Storms are usually different, so what one storm brings the other does not, and there are multiple factors that play a role into it, mainly it is the type of precipitation, wind speed, the direction of the wind." A resident shared: "I do not see a

big change in storms because they have always varied. We have had mild winters; we have had significant winters, and I feel like I have experienced all of them on a somewhat regular basis."

Date	Year	Type	Details
November 25-29	1921	Ice Storm	4 inches
April 19	1925	Ice Storm	14 inches
December 26-27	1947	Blizzard	16.9 inches
December 24	1961	Blizzard	24 inches
February 25-29	1969	“The 100 Hour Storm”	26.3 inches
February 5-7	1978	Blizzard	20.2 inches
February 11	1983	Blizzard	21 inches
April 28	1987	Snowstorm	17 inches
December 10-12	1992	Nor’easter	27 inches
Mar 13-14	1993	Winter storm	20.1 inches
December 22-26	1994	Cyclone	Intense cyclone
January 6-10	1996	Blizzard Juno	33.5 inches
March 30 - April 1	1997	April Fool’s Blizzard	33 inches
February 14-19	2003	Blizzard	27.5 inches
January 20-23	2005	Blizzard	40 inches
February 11-13	2006	Blizzard	22 inches
December 11-12	2008	Ice storm	1 inch
December 22-29	2010	Blizzard	24 inches
October 29-30	2011	Snowstorm	14 inches
February 7-18	2013	North American Blizzard	28.8 inches
January 26-27	2015	Blizzard	34.5 inches
January 4	2018	Bomb cyclone	17 inches

Table 5: *Major winter storms in Worcester*
Source: Microfilms at Worcester Public Library

The variability of winter storms is driven by the El Niño - Southern Oscillation (ENSO) (Zhang & Jiang, 2023). It is a climate phenomenon characterized by shifts in the temperature in the Pacific Ocean. ENSO comprises two phenomena known as El Niño and La Niña. In El Niño, warm Pacific air moves east, pushing the jet stream south. This shift brings warmer temperatures in the Northeast, leading to milder winters with fewer storms and less snow (NOAA, 2024). In La

Niña, cool air from the west pushes the jet stream north. This shift causes colder, wetter conditions in the Northeast, leading to more frequent winter storms and increased snowfall in the region (Noyes, 2024).

According to NOAA, the occurrence of ENSO, on average, takes place between 2-7 years for 9 to 12 months. Wang et al. (2023) found that there has been an increase in ENSO events since 1970. They attribute this to the continued warming in the Pacific Ocean.

4. Warmer winters may intensify the unpredictability of winter storms.

Warmer winters are making winter storms more unpredictable. The reason for this is the warming of the Arctic, which causes the temperature difference between the Arctic and mid-latitudes to decrease. This condition makes the jet streams slower and weaker (Cohen et al., 2018). Two factors play a role here: polar vortex and polar jet stream.

Dr. Barlow explained that as climate change subtly shifts the jet stream's position, there is uncertainty about whether the primary zones of winter storm activity will also move, affecting storm frequency and intensity; he shared: "As the jet stream slowly changes position with climate change, are we changing the main area of activity for these winter storms?... There is also this kind of uncertainty in whether the main areas of activity will shift slightly, so there's this uncertainty about whether the frequency of these storms will change."

The polar jet stream lies in the lower layer of the atmosphere. In stable conditions, it is strong when there is a significant temperature difference between the Arctic and mid-latitudes. Due to this, the coldest temperature remains within the stable polar jet stream ring, and the northeast comes under this region. However, the warming trend is leading to a weaker polar jet stream. The weaker jet stream creates a wavy pattern between the cold Arctic air and the warm mid-latitude air.

The other factor is the polar vortex. The polar vortex lies above the polar jet stream. The polar vortex is a large, low-pressure, cold air zone around the Earth's poles (Waugh et al., 2017). When the polar vortex is stable, it keeps cold air contained near the poles; due to this, the polar jet stream flows strongly from west to east, staying farther north. However, if the polar vortex weakens or becomes disrupted, cold air can move further south on one side while warmer air pushes further north, bringing unpredictable storms. Cohen et al. (2021) pointed out that this disruption in the polar vortex is due to an increase in temperature in the Arctic. These two events are some of the reasons that add to the unpredictability of winter storms in Worcester. Despite the Earth's system having natural cycles, climate experts and scientists have expressed that climate change is causing the weakness of the jet stream.

The unpredictability of winter storms also pressures city officials to manage resources, preparation, and public safety amidst varying forecasts. A National Grid official described the challenge: "So there are times when we plan and staging and everything ready, and nothing happens, and then if something was not forecasted, occasionally we are not ready, but planning for the forecast is what we always say."

A city official from Worcester Public Schools further emphasized the problematic balance in decision-making: "It is almost a liability issue at this point now as we become more cognizant of the liability. You may have a day where today's forecast is for a foot of snow, you cancel school because of that projection, and then you do not have it, so it is a double-edged sword."

Winter climate change is expected to impact infrastructure, and cities must invest in resilient infrastructure upgrades and adaptive strategies to mitigate these impacts. In the next objective, we discuss these impacts and how they might be affected by the changing climate.

Objective 2: Vulnerability of Worcester's critical infrastructure to winter storm events.

The second objective discusses how changes in weather patterns affect the city's critical infrastructure. We interviewed five National Grid officials from the areas of electric operations, engineering, community management, emergency planning, and executive leadership. We also interviewed two city officials within the Department of Public Works and Parks. For the qualitative coding, we individually reviewed and read the transcripts to identify recurring themes. We then met to discuss overlapping and unique codes before finalizing them in Atlas.ti. The codes were: *stormwater system, roads, vegetation (trees), electric system, communication networks, and damage to property.* Furthermore, climate experts and resident interviews made contributions to this objective as well.

1. **Increased winter rainfall will lead to more runoff on frozen ground which can overflow drainage systems, heightening the risk of flooding.**

Climate experts and residents expressed that increasing winter rainfall instead of snowfall increases the risk of winter flooding. This issue becomes particularly concerning when the ground is frozen, as it limits the soil's ability to absorb water, increasing surface runoff and reducing infiltration. Consequently, higher volumes of water may overflow drainage systems in Worcester, leading to potential flooding. Dr. Burakowski expressed: "We are getting a lot of winter rain ... looking into culverts and making sure of the runoff is something to be aware of." Another climate expert, Dr. Barlow, noted: "In the cold season, be prepared for more stormwater flooding. It has a really high impact, is local, and involves stormwater flooding, which probably goes more into the winter season. I do not know what kind of drainage and sewer system Worcester has, but hopefully, they are thinking about stormwater management.

Additionally, a resident was asked about the potential risks associated with winter climate change. The resident noted: "Winter flooding, the ground tends to be colder, you do not have the vegetative uptake that you have in the summer, so you do not have as much storage for the water if it is somewhat frozen…We are less equipped to deal with flooding than we are with snow. So, I think as far as infrastructure priorities, we have to think about better drainage systems."

In the cold months, the ground is usually entirely or at least partially frozen, so it is even less capable of absorbing water (Andersson et al., 2020). The reduction in permeability encourages

more surface runoff and adds pressure on urban drainage systems. This fact is particularly problematic in urban areas, which often have more impervious surfaces (Salimi & Al-Ghamdi, 2020).

Stormwater management systems in many cities are designed to handle particular precipitation scenarios (Hathaway et al., 2024). With more rainfall in the winter season, these systems may be upgraded to accommodate the increased volume of water. Warmer conditions also mean a greater risk of storms exceeding the capacity of liquid water management systems (Lawrence et al., 2020). This is a critical challenge that Worcester must proactively address to ensure reliance against future weather extremes.

Winter flooding can cause damage to property in the city. This threat could become more common and intense as global temperatures rise. Dr. Zarzycki pointed towards the increased risk of flooding in urban areas, highlighting the vulnerability of city infrastructure and property damage. As storms intensify, non-porous surfaces, like streets and sidewalks, limit water absorption, heightening the likelihood of street and basement flooding; he stated: "You have the potential for storms to stress liquid water and infrastructure. So, think about things like sewers and city cityscapes where maybe you are not very porous, so it is very easy to get kind of like street level flooding or flooding and buildings; basement flooding is a really common nuisance problem that we expect to increase with warming."

In conversation with residents, two of them mentioned that they are facing this challenge. One expressed: "Temperatures are warmer, but it is more rain, less snow, which causes a problem because a few years back, my basement flooded." A second resident said: "I get water in my basement all the time." Heavy rainfall, drainage systems that cannot cope with the volume of rain, and frozen ground create conditions for water to find its way into lower buildings.

We did not have the opportunity to interview the Water and Sewer Department operations staff responsible for maintaining the drainage systems for the city of Worcester. However, the Department of Sustainability and Resilience informed us that the city is actively developing a Stormwater System and Green Infrastructure Master Plan. The primary objective of this plan is to develop a clearer understanding of the municipal drainage system, identify its constraints, and prioritize the city's areas most vulnerable to flooding. Combining nature-based solutions with gray infrastructure improvements, the plan seeks to bolster Worcester's flood resilience and effectively manage stormwater.

Despite these goals, the current plan does not consider the unique challenges of winter stormwater loads. During the winter, the drainage system might face an influx of water from snowmelt and ice combined with the increased rainfall. These factors can cause sudden water discharge peaks that overload infrastructure and increase the risk of localized flooding.

2. **Worcester's roads are susceptible to damage during the winter season due to freeze-thaw cycles.**

Worcester's roadway infrastructure is bearing the impact of winter climate change, resulting in further road deterioration. The risks to infrastructure were identified during discussions with residents and the Street operations team under DPW&P.

Freeze-thaw cycles are one of the identified risks. Rapidly changing winter weather substantially impacts road infrastructure. In some areas, continuous winter freezes and thaws not only further destroy roads and increase their maintenance cost (Wang et al., 2020). These freeze-thaw cycles hurt roads because the Water from heavy rains and melting snow penetrates cracks; when the temperature drops below freezing, the Water freezes and expands within the material's pores (Ud Din et al., 2020).

A city official noted this issue: "Water is impacting the subbase of the road and creating what are called sinkholes. Potentially, Water gets in a little bit, and then you have seasonal changes, such as fr. It-thawing, becoming brittle, and breaking. Water gets in it, expands when it is ice, and then it contracts again and disappears when it is Water, creating a void, creating the pothole."

The freeze-thaw cycle can cause considerable damage over time. In conversations with residents and survey comments, some residents highlighted that they have seen this in the city. One resident noted, "After a couple of storms, the streets get bumps and holes." The city has been proactive in maintaining the roads; one city official stated: "I send folks out to do pothole patching where they are out filling potholes now. Some of it will survive through the winter, and we will return and fix those again in the spring." Worcester's roadways will be more susceptible to cracking and potholes due to the rainfall in the winter season. These freeze-thaw cycle events might result in increased resurfacing and maintenance projects in the city.

In the survey of residents' perception of winter storms, we asked respondents to rank the following improvements that they would like to see in the way the city responds to winter storms: improved access to transportation after winter storms, tree trimming, and management, community workshops on winter storm preparedness, winter treatment of roads before winter storms, improving the electricity system. In Figure 7, 63% of the respondents ranked winter treatment of roads before winter storms (gray) as a high priority. The second priority was improved access to transportation after storms for a complete analysis of the survey results (Appendix H)**.** This reflects a strong public desire for safe and accessible roads during winter storms. One resident emphasized that "road management would be beneficial to all winter storms in Worcester."

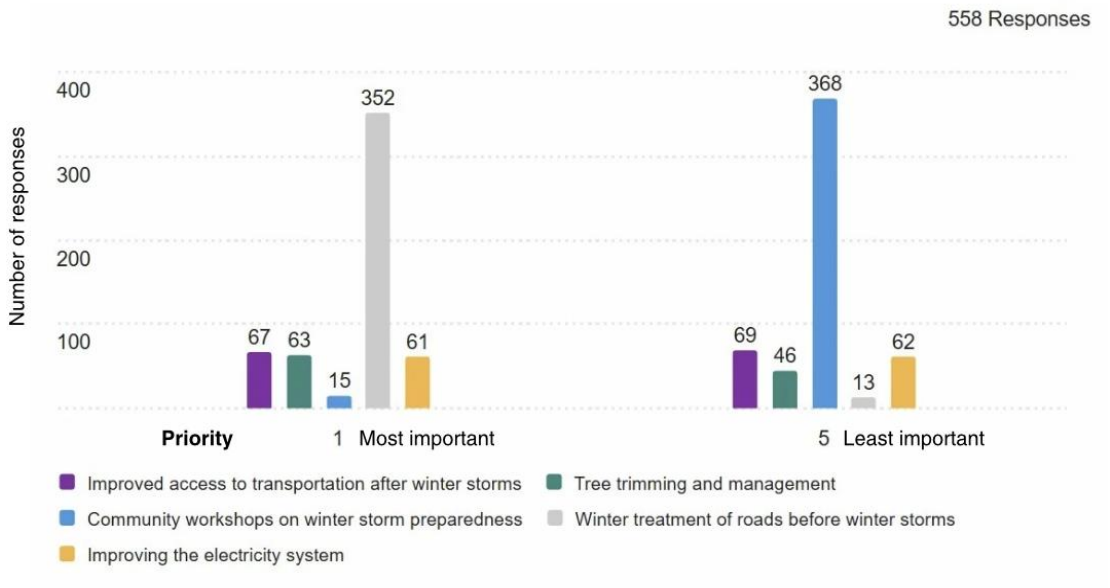


Figure 7: *Community priorities in response to winter storms*
Source: Communities' Perception of Winter Storm - Resident Survey

3. **Heavy snow and ice accumulation on branches often causes breakage, increasing the risk of power outages and property damage.**

Tree management plays a crucial role in reducing the risk of power outages and property damage caused by winter storms. In our conversations with residents, city officials, and National Grid, we focused on the adverse impact of winter storms on trees, which can lead to ice accumulation on branches, causing them to fall onto power lines and properties. With the changing winter climate bringing more heavy snow and freezing rain, we may face an increased risk of damage to power lines and property from these falling branches.

Some trees are susceptible to the impacts of winter as when it gets cold, the sap that is present inside the tree might freeze. The sap is made up of water. When it freezes it leads to pressure inside the tree (Moore, 2024). This pressure pushes back against the tree, which leads to cracks and breakages.

In conversations with residents and National Grid, we found that over time, the duration of power outages in the city has decreased significantly, and in the survey, residents highlighted that power outages are not a concern. We attribute this improvement to two main factors. First, National Grid has been proactive in restoring service, and reducing downtime during outages. Second, the city has implemented a proactive tree maintenance program and established close coordination with National Grid to trim trees near power lines, effectively reducing the risk of outages caused by falling branches and ensuring safer, more reliable power infrastructure.

National Grid communicates to the city if they intend to do any tree maintenance and management and the route, they would need authorization on. National Grid works closely with the DPW and communicates tree clearing and pruning of the branches that are over the power lines

(Figure 8) in advance as one National Grid official shared: “We have a working group with the city, specifically with the DPW, where we get together once a month and talk about our projects”

Additionally, the city conducts coordinated tabletop functional exercises once a year with National Grid and Eversource to prepare for emergencies that may arise. One city official expressed: “We typically do at least one coordinated tabletop or functional exercise a year with National Grid and Eversource.” This proactive planning, decision-making, and coordination between the city, National Grid have significantly decreased the risk of power outages for the city during winter storms. The existing tree maintenance and pruning mechanism should be sustained and further enhanced to ensure timely trimming, minimizing potential disruptions and safeguarding power lines effectively.

Figure 8: *Tree branches intertwined with power lines, Worcester MA*
Source: Author photo

The city is developing the Urban Forest Master Plan[3] to guide its green infrastructure investments and enhance urban resilience. This comprehensive plan outlines strategies for utilizing and managing trees to improve environmental quality, public health and quality of life throughout Worcester.

The city conducted an inventory of tree species within its boundaries and identified the 10 most common species. Using the findings from Hauer et al. (2006), we evaluated these species for the susceptibility to heavy snow and ice, categorizing them into three groups: sensitive, intermediate, and resistant (Table 6). This classification helps assess the resilience of the urban forest and informs targeted strategies.

[3] https://www.worcesterma.gov/uploads/e7/53/e753cc773b32911dc1c56267b9c37400/worcester-urban-forest-master-plan-draft.pdf

Sensitive	Intermediate	Resistant
Cherry (Prunus spp)	Pin Oak (Quercus palustris)	Norway Maple (Acer platanoides)
Honeylocust (Gleditsia triacanthos)	Red Maple (Acer rubrum)	Littleleaf Linden (Tilia cordata)
Callery Pear (Pyrus calleryana)	Red Oak (Quercus rubra)	Northern White Cedar (Thuja occidentalis)
Silver Maple (Acer saccharinum)		

***Table 6**:* Ice/heavy snow Susceptibility of common tree species in Worcester
Source: Worcester Urban Forest Master Plan and (Hauer et. al, 2006)

National Grid is taking a proactive approach by developing its Vegetation Management Optimization Plan (VMO), a digital solution designed to optimize the effectiveness and value of National Grid's vegetation management programs. This initiative prioritizes the removal of hazardous trees, particularly those near power lines, which pose a significant risk of causing power outages during winter storms. This strategy is a crucial approach to minimizing the risks associated with tree-related disruptions, ensuring greater reliability and resilience in the power grid.

4. Loss of internet connectivity during winter storms is a concern among the residents.

The number of households in Worcester that have a broadband internet subscription amount to 87.5% according to the United States Census Bureau's American Community Survey (US Census Bureau, 2023).

Telecommunication services are disrupted during a winter storm. Out of the 565 respondents to our survey of resident perceptions of winter storms, 392 (70%) indicated a loss of internet connectivity due to the storms (Figure 9).

In the interviews conducted with the residents we observed an emerging trend of recurring internet and connectivity challenges during winter storms. One resident shared that "my residential unit has had Spectrum issues". The sole fiber optic broadband internet provider in Worcester is Spectrum. Attempts to connect with Spectrum representatives for their perspective on service disruptions were unsuccessful.

A city official shared the following with us regarding telecommunication disruptions in the city: "We have worked with Spectrum in the past on some emergency connectivity, but it's been difficult because they are a larger company and they do not necessarily have direct representatives always available during emergencies".

We compare and contrast this situation with the situation regarding the tree maintenance and management. That mechanism has an active and proactive collaboration between the city and

National Grid which has resulted in challenges being sorted in time and without much damage. The situation with the telecommunication provider Spectrum provides a contrasting image where we see the lack of such planning and decision making has resulted in residents feeling challenged with the lack of success. A city official shared “this lack of coordination negatively affects service reliability and could pose significant risks for the city during emergencies.”

According to Jakubek (2015), who studied the amount of calls and messages sent before, during and after a winter storm. They saw an increase of 23.7% in the usage of voice minutes during a winter storm. They came to this conclusion by looking at 398 cell sites and reviewing 2,388 measurements. They had two groups, one being control and the other being treatment. The treatment group being the one within the winter storm and the control group outside of it. Through the data analysis they came to the conclusion that an increase of usage was experienced. There was also an increase of 31.5% in text messaging. The increased usage might cause network congestion which can cause communication challenges. This also points towards that winter storms have a widespread moderate impact on telecommunication networks.

Gupta et al. (2024) investigated how weather events impact internet connectivity. They found a strong correlation between the severity of weather events and the level of internet disruption. Low-income communities experienced more significant internet disruptions, exacerbating existing inequalities. Power outages and loss of internet connectivity co-occurred, highlighting infrastructure interdependencies.

During discussions with the Emergency Management and Communications Office at the city of Worcester, we learned about the city’s emergency response mechanisms. Worcester has established a centralized hub for coordinated decision-making, bringing together representatives from key stakeholder groups. This facility is equipped with backup power and internet, ensuring continuous operation and communication during crises. These provisions strengthen the city’s capacity to respond effectively to the challenge of winter storms. However, the fact remains that residents continue to see disruptions and challenges.

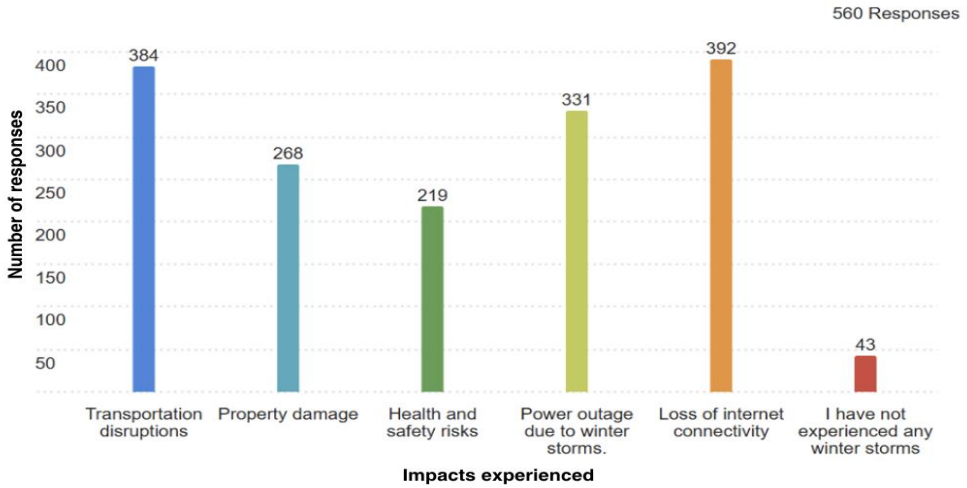


Figure 9: *Impacts experienced due to winter storms*
Source: Communities' Perception of Winter Storm - Resident Survey

5. **Undergrounding power lines improves grid resilience but it is cost-prohibitive due to high costs of installation and maintenance.**

We have seen that the impact of ice and power storms materializes in the most impactful form through power outages and challenges to the grid. One such challenge is seen on the power lines that carry and transmit the power within the city of Worcester. The city passed an ordinance to chapter 372 of the Acts of 1902 that became legislation in January 1903. It stated that in an area of 2 miles from the city center all the power lines have to be underground (Chamberlayne, 2018). What ended up happening was that power lines in the city either ended up being put underground or put in the backyards of houses, as putting power lines on front street-facing areas was not allowed.

Due to this ordinance, the city of Worcester could not have road-facing power lines within those 2 miles of the City Hall; the power lines that were around the downtown area were put underground while the remaining power lines went to the backyard.

We analyzed the impact of this legislation on the current power transmission system in Worcester. One glaring impact we see is that these backyard power lines are susceptible to winter storms. They are at heightened risk of breakage from tree branches. In the case of severe winter storms in which ice might accumulate on the tree branches, the branches may not be able to sustain the additional load and fall on the power lines causing power outages.

We asked National Grid what they thought about this and they shared "We're going to be also looking at potential undergrounding our infrastructure. One of the benefits of undergrounding is that you don't expose your infrastructure to bad weather and everything else, but at the same time, we have to balance the underground distribution infrastructure because the cost to underground is probably anywhere between depending on the area 10 to 20 times more than overhead."

The solution to enhance the city's resilience to winter storms could be to bury the power lines; however, that is cost-prohibitive. According to the Edison Electric Institute, burying overhead power lines can cost about 10 times more than installing overhead lines (Johnson 2018). Another National Grid official pointed out "I would love to build everything underground. I think the last time we did a cost estimate, it was eight times the cost to build underground, and then to build overhead." In a May 2011 report titled "Underground Electric Transmission Lines" by the Public Service Commission of Wisconsin, it was estimated that building underground transmission lines can be 4 to 14 times more expensive than constructing overhead lines of the same voltage and distance. For example, a new 69 kV single-circuit overhead transmission line costs around $285,000 per mile, while an underground line would cost about $1.5 million per mile (excluding terminal costs) (Public Service Commission of Wisconsin, 2011).

Putting the power lines underground might be cost-prohibitive in the short term, but in the long term, this investment would cover the costs that may arise due to the winter storms experienced. For example, winter storm Uri in 2021 led to 69% of Texans losing power, causing 210 deaths and resulting in economic losses in the range of $80 - 130 billion dollars (Donal, 2021).

Larsen (2016) estimates the societal costs and benefits of undergrounding electricity transmission and distribution lines. He acknowledges the high installation costs and contrasts these costs to those of overhead lines which are cheaper but more vulnerable to weather-related challenges. He stresses that the benefits of undergrounding include reduced power outages, the potential increase in property values, and improved aesthetics.

Objective 3: Vulnerability of Worcester's populations and social services vulnerable to winter climate events

The third objective identified the social services and populations vulnerable to winter climate events in Worcester. We interviewed six city officials across Worcester Public Schools and Transportation Department, Emergency Communications & Management, Worcester Regional Transit Authority (WRTA), and Health & Human Services. The key themes were around the communication mechanisms used during an emergency, the existing snow routes, proactive decisions for school closure, availability of shelter and warming centers and collaborative decision-making that protects the most vulnerable populations. We also interviewed 14 residents across different zip codes. We recorded the conversations, transcribed them, and created codes based on vulnerable populations the residents mentioned such as: *disabled, elderly community, homeless, non-native speakers, and people new to NE weather*. We also created codes to find the challenges in the social services such as: *school closures, snow removal, mobility, and accessibility.*

Additionally, we incorporated input from residents through the community's perception of winter storms survey.

1. **Non-English speakers and newcomers are vulnerable during New England winters due to limited knowledge and resources of local conditions and preparedness measures.**

The changing climate in winter in Worcester might disproportionately impact specific populations, particularly non-English speakers and newcomers. One reason is that individuals relocating from different climates may face significant challenges in understanding local winter-related issues and being adequately prepared for severe winter weather events.

Language barriers pose an additional challenge in disseminating critical information, especially among immigrants who may not speak English fluently. This barrier makes it difficult for these communities to understand and act on safety instructions. As one city official from the Department of Health and Human Services explained: "Immigrant communities are folks who don't speak the language. To whom we try to send messages, and there are so many different languages here that we can't reach them." Similarly, a resident was asked about the population that might be vulnerable to the changing climate during winter. The resident noted: "The city deals with immigrants and refugees, right? They barely speak any English, so no matter how much the

city wants to educate their residents, you're not touching this population of people…because, number one, it's in English, these people don't speak English… If they do, it's minor, like a little bit, but they won't understand what they're saying."

Newcomers may lack even basic winter safety knowledge, such as how to walk safely on ice, dress appropriately for winter, respond when a severe winter storm is happening, or what to do in the aftermath. This knowledge gap can place them at heightened risk. A resident emphasized this point, asking: "What does it mean to be ready for a storm? It's one thing to communicate to people, you know, the storm is coming, but for people who are genuinely new to this kind of climate, what does it mean to be ready?"

To newcomers, winter storm warnings mean something severe or that being fully prepared for a winter storm is more complex than having your winter coat and boots are not always understood. Such inexperience and lack of knowledge may lead to inadequate preparation, thus placing them at higher risk during severe weather conditions (Ebi et al., 2021). Therefore, these groups are particularly susceptible to extreme winter weather effects.

2. **Elderly and disabled populations face challenges with snow clearing on private properties, increasing the risk of isolation, injury, and restricted access to essential services.**

Winter climate change would bring storms with heavy snow and freezing rain that can significantly impact elderly and disabled communities in various ways, amplifying their vulnerability during severe winter weather. Feedback garnered from surveys and interviews with area residents highlighted the challenges that elderly and disabled groups experience in winter weather conditions, specifically snow removal mandates. A resident said: “Until the last five years, we've had a very elderly neighborhood and, you know, it was very hard for them to clear their snow and to take care of their parking spots or their sidewalks.”

Clearing driveways, sidewalks, or steps is a strenuous task, and for elderly or disabled individuals, it is often feasible, this fact makes the emergency evacuation challenging. Other residents expressed: “Disabled people can't maintain their properties. I feel like there should be some sort of resource for people that are disabled or elderly." Elderly and disabled people are often reliant on family, friends, or community services for snow removal. As one resident noted: “I just think they need a way to, and not that everyone can't work, but I feel like people that are disabled or elderly there should be some resource for them."

Survey comments show repeatedly that there should be enhanced efforts for the elderly and disabled. Following the trend, a resident suggested to "Enforce the cleaning of snow in front of your house and have volunteers help the elderly and or disabled." We searched all the resources and services available in the city and found that the city has a List of Seasonal Assistance Referrals for the Elderly and Disabled[4]. The city of Worcester’s list of referrals for the disabled and elderly provides year-round assistance with snow shoveling. Some groups and clubs at universities, such

[4] https://www.worcesterma.gov/senior-center/document-center/seasonal-assistance-referrals.pdf

as WPI, Holy Cross, Worcester State University, North High School JROTC, provide these services as well as the Hector Reyes House, which is a rehabilitation center. The Worcester Senior center appears on the list but provides referral services only, which means it doesn't offer direct assistance but connects residents to services and organizations from the list. Most of the services are provided free of charge, which benefits the elderly or disabled who might struggle with additional expenses.

We reached out each of the organizations from the list to confirm if they are still offering the services for the 2024-2025 year-round. The Alpha Phi Omega-WPI chapter, Hector Reyes, Holy Cross Gov & Comm Relations are still offering the services. Worcester State University shared that they do not have students available on a regular basis. However, when a request comes in, they share it with the student's service group. As winter storms become more intense with climate change, bringing heavier snow and ice, the elderly and disabled population in Worcester might require even greater assistance. Although the city provides the list of referrals on the website, a resident commented on the survey: "Help seniors or disabled with shoveling, shopping. If help is already available, make information more available not just by internet or phone (cell)," emphasizing a growing demand for additional communication channels to ensure all residents can easily access and benefit from the support available, especially as winter conditions become more challenging.

3. **Homeless populations are particularly vulnerable, as exposure to severe cold and ice conditions impacts their health due to the lack of warm places.**

Worcester provides shelters and warming spaces for individuals experiencing homelessness, including the Worcester Public Library and the YWCA as warming places. However, the current shelter capacity appears inadequate to meet the growing needs of this population. As one city official noted: "I think we have a shelter that can't hold the number of people that are there, and people are sleeping all over the place and sleeping on mats all over the floor." The limited availability of shelters and warming spaces and the steady increase in the homeless population in recent years exacerbate this challenge.

When asked about the homeless population in Worcester, one city official shared: "Well, in August 2024, there were 366 in shelters, just adult shelters. But then, if you're counting the outreach, it's another 140. So, 366 + 140. That was in August, but it's going up. You can see the chart. It's up over the next few months. So that's their projection here."

We visited the Food for the Poor program at St. John's Catholic Church, a volunteer service providing meals to the unhoused from Monday to Saturday. We also spoke with the head of HALO, an organization that advocates for individuals experiencing homelessness. In these spaces, we engaged directly with homeless community members to understand their concerns and needs. One unhoused individual demanded additional resources: "We need potential warming stations, another emergency shelter."

For people experiencing homelessness, climate change represents a continuous crisis. Extreme weather events have an immediate impact on those living unsheltered. For individuals already exposed to these harsh conditions, such events can pose life-or-death risks (Mello, 2023). Worcester's expectations of heavy snow and ice events due to winter climate change exacerbate these vulnerabilities and strain emergency shelter capacities.

4. **Winter storms elevate the likelihood of school closures, disproportionately affecting people with limited financial resources.**

Winter storms increase the likelihood of schools being closed. During the academic year, such an unplanned school closure is called an unplanned school closure (USC). School closures due to winter storms have three underlying impacts on the community members: first, the closure of schools leaves the students without access to the school breakfast and lunch. Secondly, parents who work away from home have to look for daycare options at short notice. Thirdly, parents who cannot find daycare and cannot work remotely would have to skip work.

Firstly on the question regarding Worcester public schools, their buses rely on the roads being clear for them to provide their services to the students. One city official shared that "The most important variable of whether we have school or not is the condition of the city, streets, and sidewalks for students to be able to access buses to get to and from school." To ensure safety and accessibility in the event of a winter storm, adequate pre-treatment of roads and post-storm cleaning are needed. The pretreatment includes using salt and sand to ensure heavy snow or ice is cleaned easily using a snowblower after the storm passes. If the storm was severe and the roads were not safe to walk or drive on, an unplanned school closure announcement was made.

For example, the school buses have to leave early in the day to get all the students to school by the time school starts. If the buses leave the depot at 4 am in the morning, and the roads are not cleared the school system will not operate. City officials overseeing this try to be proactive in their decision-making regarding school closures so that parents and caregivers have more time to prepare. We noted one city official as saying that: "We actually canceled school when the snow hadn't even happened yet, but it was projected to." In Worcester, 12,000 students rely on school buses to go from their homes to schools. Another 12,000 either walk to school or are dropped off. Winter storms make the roads and sidewalks difficult to walk and commute on. In the case of a storm, the priority is the safety of students and staff. One city official stated "The ability of students to safely get to school, whether on a bus, a car or walking has a significant impact on our decision making."

These closures disproportionately impact low-income communities, as they are forced to make a decision regarding what to do with their children at home. They face a predicament of whether to seek alternative daycare facilities, skip work for the day, or work remotely. Some families may not have the option to work remotely, others may not have daycare opportunities available to them. Hence the school closures add another layer of vulnerability to those with limited means. A resident shared with us that "In lower to middle-income families when school is closed, they have daycare, so you have to stay home because the kids are home from school, and you can't

pay for daycare". Marcotte and Hemelt (2008) pointed out how school closures due to extreme weather events impact student performance. The socio-economic impacts on those students who rely on school-provided lunches was discussed. It was found that students and their families who are socio-economically disadvantaged face a greater challenge from school closures as the lack of education and the unavailability of school lunch due to winter storm closure exacerbates their existence.

Objective 4: Suggesting short and long-term recommendations to enhance resilience to winter climate change.

The fourth objective focused on establishing winter climate adaptation measures for the city of Worcester. A literature review of adaptation and climate action plans across North America revealed that only a few cities (Table 7) have addressed winter-specific adaptation. We reviewed climate adaptation plans from various cities such as : Albany, New York; Alexandria, Virginia; Aspen, Colorado; Buffalo, New York; Burlington, Vermont; Cherry Hill, New Jersey. However, we only found five cities that talked about adapting to climate change in the Winter. These five cities were Keene, New Hampshire; Chicago, Illinois; Hartford, Connecticut; Montreal, Quebec and Anchorage, Alaska. While some cities acknowledge warmer winters as a consequence of climate change, most plans lack detailed adaptation measures tailored to address these impacts. This highlights a significant gap in actionable strategies for winter climate resilience in existing plans.

City	Name of the plan	Details
Keene, New Hampshire.	Adapting to Climate Change: Planning a Climate Resilient Community **(2007)**	The plan has a comprehensive section about Northeast climate change impacts in winter. Those impacts are: decreased natural snowfall cover, increase in winter precipitation in the form of rain or mixed precipitation and decrease in the length of the winter season. They identified the sectors that will be most impacted. Some of the adaptation strategies they have are: Encourage pitched roofs, identify alternate routes for evacuation efforts during emergency situations, use permeable surfaces to effectively remove water from the roadway, explore roadway materials that are more tolerant to quick changes in

		cold weather in order to decrease repair costs.
Chicago, Illinois.	Winter Adaptation Measures for the Chicago Climate Action Plan **(2013)**	Warmer winters due to increased temperatures can also have unintended consequences on Chicago. Heavier snow storms will be expected due to higher winter temperature, as well as more intense rainfall events. The plan shows the projection trends for some weather patterns. It also shows specifically adaptation strategies for extreme winter events in Chicago. Some of the adaptation measures highlighted in this plan included: modification of Chicago's flood risk model, establishing emergency heating centers, increased schedule of tree trimming around overhead power lines, alternative paving material among others.
Hartford, Connecticut	Hartford Climate Action Plan **(2017)**	The plan mentions warmer and wetter winters as one of the impacts of climate change in the city. The city has seen an increase in severe winter storms, less precipitation falling as snow and more falling as rain, sometimes increased precipitation will come in the form of damaging blizzards and specter of flooding due to peak river flows.

Montréal, Québec.	Climate Change Adaptation Plan for the Montréal urban agglomeration **(2015-2020)**	The plan has a section "Destructive Storms" which includes heavy snowfalls, hailstorms, freezing rain, and windstorms. An analysis revealed that the city has experienced an increase of 26% in freezing rain events as well as the number of heavy snowfalls. The plan identified potential impacts on the built environment, socio-economic issues, natural environment, and municipal operations. They also conducted a vulnerability analysis of the tree species, buildings, roads, and populations.
Anchorage, Alaska.	Anchorage Climate Action Plan **(2020)**	The plan states that average winter temperatures in Anchorage have warmed 4.2°F since 1970, bringing more rain-on-snow events. However, The adaptation measures they mention are in general to the climate hazard and do not specify for winter.

***Table 7**: Winter Climate Action plans in North American cities.*

5. Recommendations

The recommendations for this study were informed primarily by our field study and research methods, which included archival research, semi-structured interviews, and surveys. The winter climate adaptation measures were complemented with a few examples from the winter adaptation plans of comparable cities as: Chicago, Illinois; Montreal, Canada and Keene, New Hampshire. These plans were selected because of the similarity in changes in the winter climate and geographical location. We have divided our recommendations into two sections: one is the recommendations for infrastructure vulnerabilities and the second is the recommendations for social vulnerabilities.

5.1 Recommendations for Infrastructure Vulnerabilities

Drainage systems

- **Review the stormwater and combined sewer systems to manage the expected increased winter rainfall.** The city of Worcester is currently developing its Stormwater System and Green Infrastructure Master Plan. We recommend the city incorporate the impact of increased runoff from impervious surfaces and the increased precipitation in the form of rain on the stormwater management system during the winter months. The current planning looks at designing the system for 100-year storms. The additional analysis could be reviewing the increased runoff coefficient in the winter and identifying which areas might be most affected to modify the capacity to handle high volumes if necessary. Successful adaptation requires assessing the drainage system's capacity to handle winter storm runoff. If runoff exceeds design limits, additional measures like permeable surfaces or infrastructure upgrades would be needed to prevent flooding.
- **Investigate incorporating permeable surfaces in areas prone to flooding.** Incorporating permeable surfaces in Worcester in surfaces like parking lots can significantly reduce runoff from increased winter rainfall. Permeable materials, such as porous asphalt and pervious concrete, allow water to infiltrate directly into the ground rather than overflowing the stormwater system. These materials facilitate water absorption, decreasing the runoff volume and reducing the risk of flooding. Successful adaptation requires running a pilot program comparing the frequency of flooding events before and after in piloted areas where these materials were utilized.
- **Evaluate incorporating bioretention systems for stormwater flooding.** These are vegetated basins to treat and control stormwater runoff. Bioretention systems consist of bioswales and rain gardens. They can protect low-lying vulnerable areas from flooding. The design of these systems reduces peak flows and the velocity of water from intense rain during storm events. They can be implemented in urban areas, roadways, and parking lots. The city has developed a Sustainable Yard Design initiative in four properties to mitigate

flooding. This initiative is one such example of nature-based solutions to mitigate the risk of flooding and we recommend incorporating these initiatives in more places around the city.

Roads

- **Assess the incorporation of eco-friendly de-icing agents.** The city's current road pretreatment and snow-clearing process involves using salt, pretreated salt, and sand to treat roads during storms, followed by deploying city resources and hiring plowers to clear routes afterward. Priority is given to main arteries, with pretreated salts used on roadways with steep slopes. Winter climate change is expected to result in more ice, so incorporating a mixture of salt brine and beet juice as an environmentally friendly deicing agent could be a solution, it would be effective, because the sugar content in the beet juice and salt brine reduces the freezing point of water, enabling ice to melt at lower temperatures. Additionally, it would reduce the amount of salt required for de-icing, minimizing environmental harm. Further benefits include reduced corrosiveness to roads and vehicles and eco-friendly runoff that does not harm water bodies.
- **Determine the feasibility of implementing permeable pavement design in future infrastructure projects.** We recommend that the city assess the feasibility of permeable pavement designs for roads in future infrastructure projects. Building such pavements would help rainwater infiltrate into the ground and reduce its impact on roadways. The freeze-thaw cycles could result in the creation of cracks and potholes that might be harmful to the roadway infrastructure. Developing permeable pavement designs would be a proactive long-term adaptation strategy for enhancing the city's resilience.
- **Consider employing roadway materials that can support rapid temperature fluctuations.** To proactively reduce the risk of the formation of cracks and potholes, we recommend using materials such as cold-weather-resistant asphalt that can withstand rapid temperature fluctuations. Using such materials would decrease repair costs and increase the durability of road surfaces.

Trees

- **Select tree species that are resistant to ice and heavy snow.** The city of Worcester is currently working on its Urban Forest Master Plan. We recommend incorporating species that are resistant to the effects of ice/snowstorms. Of the top 10 types of trees in the city, 17% of trees are sensitive to the impacts of heavy snow and ice (Cherry, Honey Locust, Callery Pear, and Silver Maple), while 36% of trees are resistant to ice and heavy snow (Norway Maple, Littleleaf Linden, Northern White Cedar). Incorporating more resistant species will reduce the risk of storm-related tree damage. However, it is important to note that maples, particularly Norway Maple, may not be ideal due to their susceptibility as

hosts to the Asian long-horned beetle, which has caused significant damage in Worcester. To mitigate this risk, the city should consider alternative species that are both resistant to storm impacts and less vulnerable to pest infestations. Hauer et al. (2006) [l]ist down tree species resistant to ice/snowstorms.

- **Continue existing coordination on tree trimming with National Grid.** The city of Worcester has an established coordination mechanism with National Grid in which they trim and prune branches that are five feet around the power lines. This coordination and communication have effectively minimized power outages caused by tree branch breakage, resulting in fewer disruptions than initially anticipated. We made this assessment based on a qualitative analysis of our conversation with residents and their power outage experience over the past years. We recommend maintaining this effective coordination to conduct regular tree maintenance and implementing biannual tabletop exercises between the city and National Grid. These exercises should include one session at the beginning of the winter season to proactively plan and prepare, and another at the end of the season to assess the performance and find ways to continuously improve service delivery for the residents.

Telecommunication Networks

- **Evaluate expanding broadband internet options.** Broadband internet in Worcester is provided by a single service provider, Spectrum. There are alternative mobile options available, but the established broadband infrastructure is only available through Spectrum. Expanding broadband infrastructure to include additional providers would enhance the city's resilience, especially for those who only rely on broadband connectivity.
- **Explore the feasibility of having a backup satellite internet service.** Explore the feasibility of having a backup satellite internet service. The city could consider acquiring a satellite-based internet service like Starlink, which could serve as a reliable backup during winter storms. This service could support critical operations, ensure uninterrupted connectivity, and facilitate life-saving services during emergencies.

Electrical infrastructure

- **Conduct a cost-benefit analysis of targeted modernizations in areas at high risk.** We recommend conducting a cost-benefit analysis to evaluate the possibility of undergrounding power lines in areas highly prone to winter storm impacts. A phased approach could be implemented, prioritizing the most vulnerable areas. While the initial investment may be significant, the long-term benefits such as fewer outages and improved resilience are likely to outweigh the upfront costs. National Grid is working on its Future

Grid Plan[5], ensuring that Worcester's electrical infrastructure is made more resilient to winter storms through this intervention should be one focus for the city.

5.2 Recommendations for Social Vulnerabilities

Non-English speakers and Newcomers

- **Make multilingual emergency information for winter storms more accessible (ALERTWorcester).** The city of Worcester has ALERTWorcester[6], which is an automated emergency communication system app, available in 23 different languages, where the city shares critical information such as severe weather. However, many residents might not be aware of this app. We recommend that campaigns be created to promote the use of this application so that newcomers and non-English speaking community members have access to the information disclosed through the app. According to the Worcester Almanac 2023, the languages spoken in the city that are not included in the ALERTWorcester app are: Twi, Vietnamese, Arabic, and Albanian, these languages. We recommend incorporating these languages into the app.
- **Update the Emergency Communications website with seasonal risks.** The city of Worcester's Emergency & Communications Management Department currently features disaster preparedness resources under the "Ready.gov - Plan ahead for Disasters" section. While this provides valuable general guidance, we recommend adjusting the content to focus on the specific hazards the city is most likely to experience. According to the MVP Plan, ice/snow storms, floods, and extreme heat are among the most pressing local climate hazards. Updating the website to prioritize these risks will better support resident's preparedness efforts, align with the city's climate resilience goals, and provide timely actionable information that reflects the seasonal nature of these hazards.

[5] https://www.nationalgridus.com/media/pdfs/our-company/massachusetts-grid-modernization/future-grid-executive-summary.pdf

[6] https://www.worcesterma.gov/emergency-communications/alertworcester

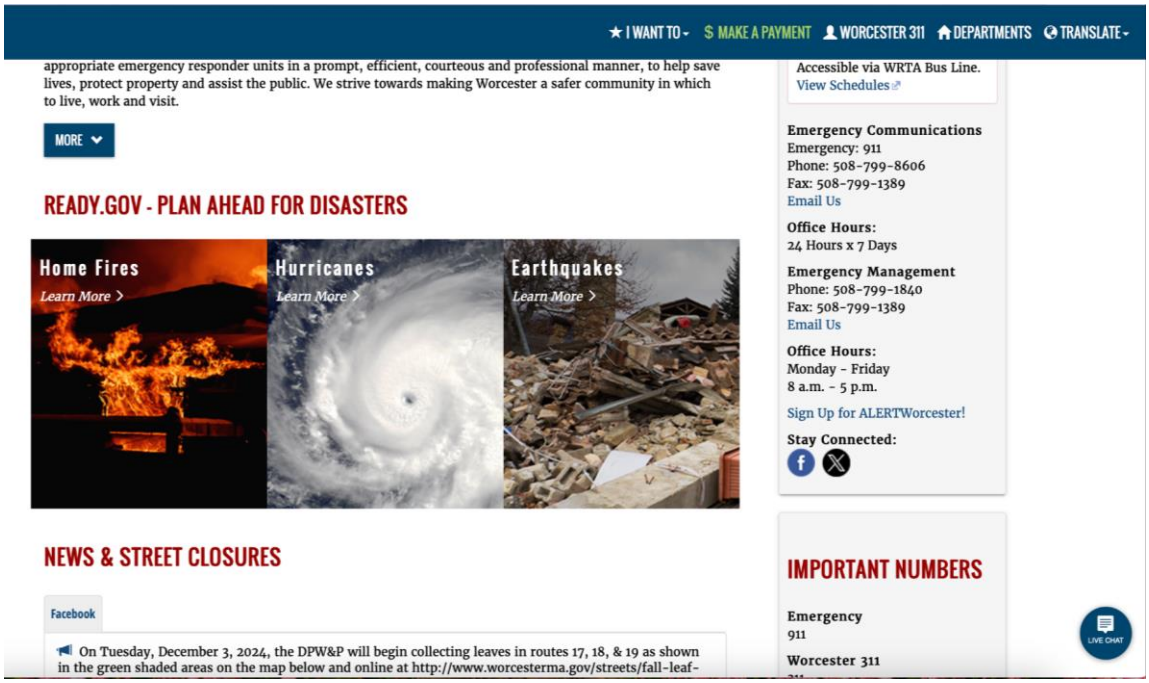


Figure 10: *Emergency Communications & Management website*
Source: Worcesterma.gov

- **Provide education programs and guides on emergency preparedness.** Develop and implement education programs on emergency preparedness before, during, and after winter storms. This is crucial for individuals with limited prior experience of winter storm impacts. Key topics could include safe driving practices on icy roads, remaining safe during extended power outages, and utilizing reliable communication channels, apps, and other tools, for timely updates. This information could be disseminated through accessible guides and community workshops. The city's Snow Emergency Guideline provides essential details on winter preparedness, however it is only available in English. Expanding these resources to include translations into multiple languages and incorporating visual aids would ensure inclusivity.

Elderly and Disabled

- **Build partnerships with college campuses and organizations to boost volunteer participation.** Elderly and disabled residents would be better equipped to tackle the challenge arising from winter storms if there were resources available to assist them, both before storms, in terms of preparing for their needs, and afterward to clear their sidewalks and pathways to ensure their mobility and accessibility. One approach we recommend is that the city can tap into the colleges and universities in the Worcester area. Additionally, we recommend building upon the existing partnerships the city has with the colleges and

organizations mentioned in the results section, as there are some limitations regarding geographical accessibility and human resources. By reaching out to other institutions more resources could be mobilized that assist the elderly and the disabled in times of need during winter storms, increasing the resilience of these community members to winter storms.

- **Leverage multi-channel communication strategies to share services.** The city shares information about the services to help the elderly and disabled population only through its website and many of them appear to have limited access to such information available digitally. If the same information uses a multi-channel approach that includes but is not limited to radio, newspapers, libraries, and stores, it would increase the likelihood of the information reaching the right audience at the right time and will be beneficial to these communities who are in need.

Unhoused

- **Review opportunities to expand warming centers.** The unhoused population would benefit significantly from increased access to warm places during the winter storms. We recommend designating additional spaces as warming centers across the city to provide refuge during extreme weather events. These centers should offer a warm environment where individuals can protect themselves from harsh winter conditions. To maximize their effectiveness, accessible communication strategies should be implemented to inform the unhoused population about the availability and location of these resources. During the development of this project, on November 26, 2024, the city of Worcester announced a partnership with the Central Massachusetts Housing Alliance to establish a day resource center. This center, is aligned with the goals outlined in the Municipal Strategic Plan. The resource center is scheduled to open in 2026 and it will provide essential services to individuals experiencing homelessness.

School closures

- **Evaluate the food insecurity of students and partner with community organizations for short-term relief during extended closures.** Evaluate students' food insecurity and partner with community organizations for short-term relief during extended closures. One way to manage this proactively is to coordinate with school officials to identify food-insecure students and let their caregivers know what services and resources they can utilize in their time of need.
- **Partner with local daycares for temporary childcare.** When schools close during winter storms, working parents often face the difficult decision of choosing between caring for their children or fulfilling work responsibilities. Establishing temporary or subsidized daycare services during such times could provide support allowing parents to manage their responsibilities effectively.

6. Conclusion

The city of Worcester, Massachusetts, is expected to face warmer winters with increased precipitation, predominantly as rain, and more variable and unpredictable winter storms. These shifts will transition from traditional snowfall to freezing rain, sleet, and rain, amplifying challenges like winter flooding due to increased runoff on impervious surfaces. Additionally, disruptions to internet connectivity are straining the city's infrastructure. Vulnerable populations, including non-English speakers, newcomers, the elderly, disabled, and unhoused individuals, are at heightened risk and require targeted support. School closures during winter storms disrupt education and burden working families.

The city has demonstrated proactive leadership through initiatives such as the Green Worcester Sustainability and Resilience Plan, the Stormwater and Green Infrastructure Master Plan, and the Urban Forest Master Plan. Ultimately, the city must adapt to an already-planned physical infrastructure with new weather patterns while also coming up with coping systems for its less privileged residents. Top of the list adaptation interventions are better drainage and road repair, formulating communications strategies for non-native speakers and newcomers alike, assisting elderly and disabled residents dealing with snow and ice, and expanding efforts to help people experiencing homelessness. Further resilience can be achieved by investing in roadway infrastructure improvements as reparations or implementation of material resistant to the changing climatic conditions, adopting environmentally effective deicing agents, and mobilizing enhanced snow and ice-clearing operations. It requires an all-inclusive and iterative strategy for community planning and development that will make Worcester more resilient, keeping every person well-protected against the impacts of climate change.

Worcester has the knowledge, plan, and commitment needed to adapt to the challenges of a changing winter climate. By transforming its strategies into action, the city can emerge as a leader in climate resilience among mid-sized U.S. cities, ensuring its residents' safer, more sustainable future.

References

Abbass, K., Qasim, M. Z., Song, H., Murshed, M., Mahmood, H., & Younis, I. (2022). A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environmental Science and Pollution Research, 29(28), 42539–42559. https://doi.org/10.1007/s11356-022-19718-6

Adeoye-Olatunde, O. A., & Olenik, N. L. (2021). Research and scholarly methods: Semi-structured interviews. JACCP: JOURNAL OF THE AMERICAN COLLEGE OF CLINICAL PHARMACY, 4(10), 1358–1367. https://doi.org/10.1002/jac5.1441

AghaKouchak, A., Chiang, F., Huning, L. S., Love, C. A., Mallakpour, I., Mazdiyasni, O., Moftakhari, H., Papalexiou, S. M., Ragno, E., & Sadegh, M. (2020). Climate Extremes and Compound Hazards in a Warming World. Annual Review of Earth and Planetary Sciences, 48(1), 519–548. https://doi.org/10.1146/annurev-earth-071719-055228

Akinsanola, A. A., Chen, Z., Kooperman, G. J., & Bobde, V. (2024). Robust future intensification of winter precipitation over the United States. Npj Climate and Atmospheric Science, 7(1), 1–11. https://doi.org/10.1038/s41612-024-00761-8

Andersson, M., Baccianti, C., & Morgan, J. (2020). Climate change and the macro economy (Research Report No. 243). ECB Occasional Paper. https://doi.org/10.2866/83282

Barrage, L. (2023). Fiscal Costs of Climate Change in the United States. 60 p. https://doi.org/10.3929/ETHZ-B-000605514

Bergen, K., Jubenvill, M., Shaw, K., Steen, E., Loewen, H., Mbabaali, S., & Barclay, R. (2023). Factors Associated with Outdoor Winter Walking in Older Adults: A Scoping Review. Canadian Journal on Aging / La Revue Canadienne Du Vieillissement, 42(2), 316–327. https://doi.org/10.1017/S0714980822000460

Biggs, R., Preiser, R., De Vos, A., Schlüter, M., Maciejewski, K., & Clements, H. (2021). The Routledge Handbook of Research Methods for Social-Ecological Systems (1st ed.). Routledge. https://doi.org/10.4324/9781003021339

Birkmann, J., Jamshed, A., McMillan, J. M., Feldmeyer, D., Totin, E., Solecki, W., Ibrahim, Z. Z., Roberts, D., Kerr, R. B., Poertner, H.-O., Pelling, M., Djalante, R., Garschagen, M., Leal Filho, W., Guha-Sapir, D., & Alegría, A. (2022). Understanding human vulnerability to climate change: A global perspective on index validation for adaptation planning. Science of The Total Environment, 803, 150065. https://doi.org/10.1016/j.scitotenv.2021.150065

Burakowski, E. A., Contosta, A. R., Grogan, D., Nelson, S. J., Garlick, S., & Casson, N. (2022). Future of Winter in Northeastern North America: Climate Indicators Portray Warming and Snow Loss That Will Impact Ecosystems and Communities. Northeastern Naturalist, 28(sp11). https://doi.org/10.1656/045.028.s1112

Casey, G., Fried, S., & Gibson, M. (2024). Understanding climate damages: Consumption versus investment. European Economic Review, 167, 104799. https://doi.org/10.1016/j.euroecorev.2024.104799

Chamberlayne, D. (2018). Worcester Goes Wireless. http://www.worcesterthen.com/Shorts/Wires/GoingWireless.htm

City of Worcester, & Green Worcester Working Group. (2020). the Green Worcester Sustainability and Resilience Strategic Plan. https://www.worcesterma.gov/uploads/32/47/3247f56d4bf2cafa84be33a9f71592c5/green-worcester-plan.pdf

Cohen, J., Agel, L., Barlow, M., Garfinkel, C. I., & White, I. (2021). Linking Arctic variability and change with extreme winter weather in the United States. Science, 373(6559), 1116–1121. https://doi.org/10.1126/science.abi9167

Cohen, J., Pfeiffer, K., & Francis, J. A. (2018). Warm Arctic episodes linked with increased frequency of extreme winter weather in the United States. Nature Communications, 9(1), 869. https://doi.org/10.1038/s41467-018-02992-9

Dale, L. (2022). Climate Change Adaptation. Columbia University Press. https://cup.columbia.edu/book/climate-change-adaptation/9780231199179

Donald, J. (2021). Winter Storm Uri 2021. https://comptroller.texas.gov/economy/fiscal-notes/archive/2021/oct/winter-storm-impact.php

Eastern Research Group, Inc. (ERG). (2023). 2023 Massachusetts State Hazard Mitigation and Climate Adaptation Plan (p. 362). https://www.mass.gov/doc/resilientmass-plan-2023/download

Ebi, K. L., & Hess, J. J. (2020). Health Risks Due To Climate Change: Inequity In Causes And Consequences: Study examines health risks due to climate change. Health Affairs, 39(12), 2056–2062. https://doi.org/10.1377/hlthaff.2020.01125

Ebi, K. L., Vanos, J., Baldwin, J. W., Bell, J. E., Hondula, D. M., Errett, N. A., Hayes, K., Reid, C. E., Saha, S., Spector, J., & Berry, P. (2021). Extreme Weather and Climate Change: Population Health and Health System Implications. Annual Review of Public Health, 42(1), 293–315. https://doi.org/10.1146/annurev-publhealth-012420-105026

EPA. (2021). Climate Change and Social Vulnerability in the United States : A Focus on Six Impacts, U.S. Environmental Protection Agency (EPA 430-R-21-003). https://www.epa.gov/system/files/documents/2021-09/climate-vulnerability_september-2021_508.pdf

Field, C. B., Barros, V., Stocker, T. F., & Dahe. (2012). Managing the risks of extreme events and disasters to advance climate change adaptation: Special Report of the Intergovernmental Panel

on Climate Change. Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/03/SREX_Full_Report-1.pdf

Hathaway, J. M., Bean, E. Z., Bernagros, J. T., Christian, D. P., Davani, H., Ebrahimian, A., Fairbaugh, C. M., Gulliver, J. S., McPhillips, L. E., Palino, G., Strecker, E. W., Tirpak, R. A., Van Duin, B., Weinstein, N., & Winston, R. J. (2024). A Synthesis of Climate Change Impacts on Stormwater Management Systems: Designing for Resiliency and Future Challenges. Journal of Sustainable Water in the Built Environment, 10(2), 04023014. https://doi.org/10.1061/JSWBAY.SWENG-533

Hauer, R., Dawson, J., & Werner, L. (2006). Trees and Ice Storms: The Development of Ice Storm–Resistant Urban Tree Populations (Second Edition). United States Department of Agriculture, Forest Service / University of Nebraska-Lincoln: Faculty Publications. https://digitalcommons.unl.edu/usdafsfacpub/295

Hayhoe, K., & Wuebbles, D. (2008). Chicago Climate Action Plan. City of Chicago. https://www.chicago.gov/content/dam/city/progs/env/CCAP/CCAP.pdf

Hoell, A., Hoerling, M., Eischeid, J., & Barsugli, J. (2021). Preconditions for extreme wet winters over the contiguous United States. Weather and Climate Extremes, 33, 100333. https://doi.org/10.1016/j.wace.2021.100333

Hummel, M. A., Tcheukam Siwe, A., Chow, A., Stacey, M. T., & Madanat, S. M. (2020). Interacting Infrastructure Disruptions Due to Environmental Events and Long-Term Climate Change. Earth's Future, 8(10), e2020EF001652. https://doi.org/10.1029/2020EF001652

Islam, S. N., & Winkel, J. (2017). Climate Change and Social Inequality (DESA Working Paper No. 152/ESA/2017/DWP/152). Department of Economic & Social Affairs. https://www.un.org/esa/desa/papers/2017/wp152_2017.pdf

Jaffe, M., & Woloszyn, M. E. (2013). Development of an Indicator Suite and Winter Adaptation Measures for the Chicago Climate Action Plan. https://glisa.umich.edu/media/files/projectreports/GLISA_ProjRep_Chicago_Winter_Adaptation.pdf

Jakubek, R. R. (2015). Nonequivalent Quasi-Experimental Study of Wireless Telecommunication Traffic During Severe Winter Storms. IEEE Access, 3, 1036–1041. https://doi.org/10.1109/ACCESS.2015.2450675

Johnson, B. (2018). Out of Sight, Out of Mind? Edison Electric Institute. https://pdi2.org/wp-content/uploads/2021/03/51-EdisonElectInst1.pdf

Kim, Y.-K., & Kim, D. (2024). Role of Social Infrastructure in Social Isolation within Urban Communities. Land, 13(8), 1260. https://doi.org/10.3390/land13081260

Larsen, P. H. (2016). A method to estimate the costs and benefits of undergrounding electricity transmission and distribution lines. Energy Economics, 60, 47–61. https://doi.org/10.1016/j.eneco.2016.09.011

Lawrence, J., Blackett, P., & Cradock-Henry, N. A. (2020). Cascading climate change impacts and implications. Climate Risk Management, 29, 100234. https://doi.org/10.1016/j.crm.2020.100234

Layton, J., & Latham, A. (2022). Social infrastructure and public life – notes on Finsbury Park, London. Urban Geography, 43(5), 755–776. https://doi.org/10.1080/02723638.2021.1934631

Li, Y., Hsu, J. A., & Fernie, G. (2013). Aging and the Use of Pedestrian Facilities in Winter—The Need for Improved Design and Better Technology. Journal of Urban Health, 90(4), 602–617. https://doi.org/10.1007/s11524-012-9779-2

Mah, J. C., Penwarden, J. L., Pott, H., Theou, O., & Andrew, M. K. (2023). Social vulnerability indices: a scoping review. BMC Public Health, 23(1), 1253. https://doi.org/10.1186/s12889-023-16097-6

Mello, C. (2023, April 24). How Climate Change Impacts Homelessness. National Alliance to End Homelessness. https://endhomelessness.org/blog/how-climate-change-impacts-homelessness/

Moore, A. (2024, February 15). How Trees Survive in Winter. College of Natural Resources News. https://cnr.ncsu.edu/news/2024/02/how-trees-survive-in-winter/

NOAA, N. (n.d.). What is the Polar Vortex? Retrieved November 22, 2024, from https://www.weather.gov/safety/cold-polar-vortex

Northeast Climate Science Center at the University of Massachusetts Amherst. (2018). Massachusetts Climate Change Projections. Massachusetts Environmental Policy Act Office. https://www.mass.gov/doc/climate-change-projections-for-major-drainage-basins-in-massachusetts/download

Noyes, D. (2024, October 2). What a potential La Niña winter means for New England. https://www.wbur.org/news/2024/10/02/la-nina-boston-massachusetts-weather-effects

Parsons, E. S., Jowell, A., Veidis, E., Barry, M., & Israni, S. T. (2024). Climate change and inequality. Pediatric Research. https://doi.org/10.1038/s41390-024-03153-z

Pendergrass, A. G., Knutti, R., Lehner, F., Deser, C., & Sanderson, B. M. (2017). Precipitation variability increases in a warmer climate. Scientific Reports, 7(1), 17966. https://doi.org/10.1038/s41598-017-17966-y

Perera, A. T. D., Nik, V. M., Chen, D., Scartezzini, J.-L., & Hong, T. (2020). Quantifying the impacts of climate change and extreme climate events on energy systems. Nature Energy, 5(2), 150–159. https://doi.org/10.1038/s41560-020-0558-0

Salimi, M., & Al-Ghamdi, S. G. (2020). Climate change impacts on critical urban infrastructure and urban resiliency strategies for the Middle East. Sustainable Cities and Society, 54, 101948. https://doi.org/10.1016/j.scs.2019.101948

Shi, L., & Moser, S. (2021). Transformative climate adaptation in the United States: Trends and prospects. Science, 372(6549), eabc8054. https://doi.org/10.1126/science.abc8054

Shi, W., & Hu, Y. (2023). A study on the forecast model of winter precipitation type in Liaocheng based on physical parameters. Meteorological Applications, 30(2), e2126. https://doi.org/10.1002/met.2126

Stagrum, A. E., Andenæs, E., Kvande, T., & Lohne, J. (2020). Climate Change Adaptation Measures for Buildings—A Scoping Review. Sustainability, 12(5), 1721. https://doi.org/10.3390/su12051721

Templer, P. H., Reinmann, A. B., Sanders-DeMott, R., Sorensen, P. O., Juice, S. M., Bowles, F., Sofen, L. E., Harrison, J. L., Halm, I., Rustad, L., Martin, M. E., & Grant, N. (2017). Climate Change Across Seasons Experiment (CCASE): A new method for simulating future climate in seasonally snow-covered ecosystems. PLOS ONE, 12(2), e0171928. https://doi.org/10.1371/journal.pone.0171928

Ud Din, I. M., Mir, M. S., & Farooq, M. A. (2020). Effect of Freeze-Thaw Cycles on the Properties of Asphalt Pavements in Cold Regions: A Review. Transportation Research Procedia, 48, 3634–3641. https://doi.org/10.1016/j.trpro.2020.08.087

US Department of Commerce, N. (n.d.). Social Media: Winter Science. Retrieved November 22, 2024, from https://www.weather.gov/wrn/winter-science-sm

US Department of Commerce, N. O. and A. A. (n.d.). What are El Nino and La Nina? Retrieved November 22, 2024, from https://oceanservice.noaa.gov/facts/ninonina.html#:~:text=But%20in%20the%20U.S.%20Gulf,drier%20conditions%20in%20the%20North.

US EPA, O. (2022, March 21). Climate Change and the Health of Socially Vulnerable People [Overviews and Factsheets]. https://www.epa.gov/climateimpacts/climate-change-and-health-socially-vulnerable-people

Ventresca, M. J., & Mohr, J. W. (2017). Archival Research Methods. In J. A. C. Baum (Ed.), The Blackwell Companion to Organizations (1st ed., pp. 805–828). Wiley. https://doi.org/10.1002/9781405164061.ch35

Wang, B., Sun, W., Jin, C., Luo, X., Yang, Y.-M., Li, T., Xiang, B., McPhaden, M. J., Cane, M. A., Jin, F., Liu, F., & Liu, J. (2023). Understanding the recent increase in multiyear La Niñas. Nature Climate Change, 13(10), 1075–1081. https://doi.org/10.1038/s41558-023-01801-6

Wang, T., Qu, Z., Yang, Z., Nichol, T., Clarke, G., & Ge, Y.-E. (2020). Climate change research on transportation systems: Climate risks, adaptation and planning. Transportation Research Part D: Transport and Environment, 88, 102553. https://doi.org/10.1016/j.trd.2020.102553

Waugh, D. W., Sobel, A. H., & Polvani, L. M. (2017). What Is the Polar Vortex and How Does It Influence Weather? Bulletin of the American Meteorological Society, 98(1), 37–44. https://www.jstor.org/stable/26243661

Zhang, J., Zhang, K., Zhang, M., Jiang, J. H., Rosen, P. E., & Fahy, K. A. (2022). Avoiding the "Great Filter": An Assessment of Climate Change Solutions and Combinations for Effective Implementation. https://doi.org/10.48550/ARXIV.2205.00133

Zhang, W., & Jiang, F. (2023). Subseasonal Variation in the Winter ENSO-NAO Relationship and the Modulation of Tropical North Atlantic SST Variability. Climate, 11(2), 47. https://doi.org/10.3390/cli11020047

Appendices

Appendix A - Interview Questions for Climate Experts

1. Can you tell us a bit more about your work and current role at (add organization or university)?
2. How do you see the future of winter in the Northeast based on your research findings? and what are the particular weather patterns and trends that contribute to the occurrence of winter storms in Northeastern? In terms of blizzards, ice storms, and snowstorms how will they be in the future?
3. How can cities like Worcester, New Hampshire, and other cities around Northeastern enhance their readiness to face winter storms and safeguard critical infrastructure, ecosystems, and society based on the projections?
4. Have you conducted any research on the geographical distribution of storms in Northeastern?
5. In mid-February, National Grid and Eversource sent out emails to their customers that there would be a storm that could disrupt normal operations, closing most of the state. Still, the storm was not of the intensity it was expected. Where did we go wrong with predictions and over-preparing in this case? What can we learn from it?
6. As a climate scientist, what are some key considerations for developing a winter climate adaptation plan for Worcester, considering both the current climate trends and future projections? We need to guide the city to the relevant and accurate guidelines from the experts, what can they expect and should they be aware of while making plans for the future?
7. Are there any city-level climate projection models that you might have come across or used in your work or research? That will help us to understand projections for Worcester. What might be the uncertainties involved in its projections?
8. Is there anything else would you like to share with us that we might have missed and that is relevant to our research? If you were to provide recommendations to the city to improve its resiliency, what would you recommend?

Appendix B - Interview Questions for City Officials (Infrastructure Vulnerability)

Department of Public Works (Streets)

1. Can you tell us more about your day-to-day role, what are the things that you overlook, your responsibilities, and how long have you been in your role?
2. How do the city operations respond to winter storms and how are the streets plowed and cleared? What are the areas that you prioritize? Where do you put the snow?
3. Do you use the same mechanism for the removal of snow and ice before the storm and after? Is Ice being a challenge you have faced recently?
4. Who enforces the sidewalk clearing on private property (business and residential) and who defines the penalties?
5. What is the current process and mechanism of hiring snow plow drivers, how many are permanent city resources, how many are seasonal, and how are they trained and informed?
6. Has the city experienced any challenges related to snowplow driver shortages in recent years? If so, how has this impacted snow removal operations? And what strategies are being considered to address these challenges moving forward?
7. What are the trends that you have seen in the last 20 years (Climate change), what are the changes, have you seen an increase in rain, a decrease in snow, increase in ice, how has that impacted your decision-making process?
8. How are you preparing for projected increases in winter storm intensity and rainfall due to climate change? Are you planning to upgrade snow removal equipment?
9. What do you think are the areas or factors in which the city needs to improve in terms of its response to winter storm preparation that you would like to see in the Winter Climate Adaptation plan?
10. What are the problematic areas when it comes to snow/ice clearing (uphills, curbs etc.), and also are there specific locations within the city?
11. How does the communication with residents take place, how do the residents know what routes have been plowed? Do you have a snow plow route and do you communicate to the residents?
12. How are roads vulnerable to the impacts of winter storms, and what factors contribute to these vulnerabilities? How does DPW handle post-storm road maintenance, are these potholes caused by freeze-thaw cycles or snow removal methods such as plowing? Are there any proactive measures being considered to minimize damage to road infrastructure?
13. Do you have plans to adopt new materials, equipment, or techniques based on changing climate conditions?

Parks & Recreation

1. Can you tell us more about your day-to-day role, what are the things that you overlook, your responsibilities, and how long have you been in your role?

2. Can you tell us more about the Urban Forest Master Plan and the consideration of winter on trees? Are these plants resistant to ice and dense snow accumulation?
3. Are you aware that the new planted trees won't be close to power lines or not represent a risk?
4. What is the tree management mechanism with regards to power lines? Do you have coordination with National Grid?
5. What is the Maintenance and management of the city trees? What specific measures or initiatives has the parks department already taken to adapt to winter climate challenges?
6. Are there any ongoing projects or initiatives related to winter climate adaptation with regards to parks and forests?
7. What are the primary winter climate challenges that Worcester's parks face currently, and what are the anticipated challenges in the future?
8. Has the department conducted any assessments or studies to understand the vulnerabilities of the vegetation to winter weather extremes, specifically heavy rain, heavy snow/ice storms and high wind speeds?
9. What infrastructure improvements or changes are being considered to better withstand winter weather conditions in the parks?
10. How does the department prioritize maintenance tasks during the winter months to ensure park safety and usability?
11. Are there any partnerships or collaborations with other city departments, organizations, or stakeholders to address winter climate challenges in parks?

Worcester Regional Transit Authority (WRTA)

1. Can you tell us more about your role at the WRTA?
2. How are the WRTA services impacted by winter storms?
3. What are the emergency response plans you have in place for winter storms? Are there any winter storm preparedness plans in place for the WRTA, what do those plans look like?
4. How do you communicate with the public during winter storms, to provide information about service disruptions and alternative transportation options?
5. What are the challenges WRTA faces during winter storms?
6. How does WRTA coordinate with the city government or emergency services, during winter storms?
7. Do you have any adaptation strategies in place to enhance resilience to winter storms?
8. Does the WRTA keep track of the socially vulnerable populations in Worcester based on ridership?
9. WRTA is currently fare-free, what is the reasoning behind that?
10. How does WRTA prioritize routes and services during winter storms, particularly in areas prone to severe weather conditions?

Appendix C - Interview Questions for National Grid Officials

Electric Operations

1. Can you tell us a bit more about your role at National Grid?
2. What are the current coordination systems and mechanisms in place between National Grid and the city of Worcester in terms of response to winter storms and tree trimming?
3. There was a pilot smart grid city project between Worcester and National Grid. Can you tell us more about that?
4. There is a Climate Adaptation Plan under development that will be done by the end of 2024 at National Grid about extreme weather events. Can you share more details about this, what things are National Grid considering in this plan?
5. How does NG conduct the response to major storms and emergencies?
6. Are you aware of the Vegetation Management Optimisation (VMO) plan, can you tell us more about that?
7. Is there a way for us to visit the National Grid operations and see how it works?
8. What are the areas in which enhanced cooperation with the city and its residents would result in better services to the residents? What do you think the city is missing in order to enhance its resilience to winter storms?
9. Can you tell us about the Future Grid Plan of NG?
10. Storms could be West-East or East-West. E-W are more problematic. Can you share more about why this might be the case, and how that impacts the infrastructure of National Grid?
11. Is there anything else you might feel we are missing in our research or anyone else you would recommend that we reach out to?

Engineering

1. Can you tell us a bit more about your role at National Grid?
2. As a power utility provider can you tell us the impact of winter storms on critical infrastructure, what are the challenges the utility faced during it? What other risks are in your infrastructure besides tree falling?
3. When a storm is predicted to occur do you know which areas are expected to be the most affected to respond quickly? If so, are these always the same areas?
4. During the restoration process, what challenges have the utilities faced? Do you use a model to assess the time needed for restoration? How are emergency requests for power restoration addressed, such as needs at the hospital, etc? Which customers do you prioritize? How do you communicate the restoration times?
5. Do you have maps of the overhead lines, substations, and main feeders? With these maps, we want to understand which areas need more attention?
6. How to use and understand the National Grid Data Portal.

7. Can you share with us the historical power outage data of National Grid for the major winters storms we have identified?
8. What are the challenges facing the Grid Modernization Plan?
9. Is there anything else would you like to share with us that we might have missed and that is relevant to our research? Do you know someone else we can talk to who would be helpful for our research?

Community Engagement

1. Can you describe your role at National Grid?
2. Do you know who can share with us the information with regards to the main feeders, substations, and overhead lines location/ distribution in Worcester?
3. What measures are you taking to enhance preparedness and resilience to winter storms?
4. How does National Grid prioritize efforts to restore power during and after winter storms, particularly in areas with vulnerable critical infrastructure or populations?
5. How does National Grid engage with the city of Worcester to prepare for and respond to winter storms? Are there any specific initiatives or programs where the company is involved to support community resilience to winter storms
6. In your role at National Grid, what recurring needs shared by the residents to winter storms have you identified? What is centric information that might help you in the work that you do?
7. What outcome of our research would be beneficial for the National Grid in terms of community resilience to winter storms?
8. Has National Grid identified socially vulnerable areas in Worcester? What are the social economic indicators that you take into account? Are you aware of communities and areas that might be more socially vulnerable to winter storms?
9. Has National Grid identified what are the areas in Worcester that are most impacted due to winter storms? Do you differentiate between the impacts of winter storms on different areas, if so what and how does that differentiation look like?
10. Is there anything else you would like to share with us that we might have missed and that is relevant to our research?
11. Do you know someone else we can talk to who would be helpful for our research?

Emergency planning

1. Can you tell us about your role and day to day functions at National Grid?
2. What is National Grid's plan of action if a winter storm is predicted to happen?
3. People were not expecting the impact of the 2008 ice storm, many residents were affected by power outages for many days. Since that event how has National Grid historically prepared for and responded to the ice storm in Worcester?

4. According to the literature review, conversations with climate experts, and the perception of the Worcester residents. Winter trends and projections show us a shift from less snowfall to more rain and ice. Are you more prepared for more ice instead of snow? And to restore the service in fewer days? How has National Grid adapted its approach?
5. What are the challenges National Grid faces during winter storms? And what during ice storms? What are your priority areas for improvement in winter storm preparedness?
6. Does National Grid have some plans or new technologies aiming to enhance winter storm resilience? What do you think would be the challenges for National Grid ensuring reliable service during winter storms?
7. Can you tell us about the planning process for the recent winter storm due to which our meeting was rescheduled and emergency? In the National Grid emergency response operations during winter storms have you faced difficulty in accessing the side streets?
8. What are the ways in which cooperation with the city could help improve winter climate adaptation for NG?
9. Which of your infrastructure is impacted primarily during the extreme winter climate events? Have you observed a pattern of impact of such infrastructure on specific areas in Worcester?
10. During the restoration process, what challenges have the utilities faced? Do you use a model to assess the time needed for restoration? How are emergency requests for power restoration addressed, such as needs at the hospital, etc? Which customers do you prioritize? How do you communicate the restoration times?
11. What measures are you taking to enhance preparedness and resilience to extreme winter climate events?
12. What does your community engagement and communication plan look like? Has your company done any brainstorming sessions after extreme winter climate events to improve your processes?
13. Is there anything else would you like to share with us that we might have missed and that is relevant to our research? Do you know someone else we can talk to who would be helpful for our research?

Appendix D - Interview Questions for Residents

1. How long have you been a resident of Worcester? What is your zip code?
2. In your time as a Worcester resident, have you noticed any changes in the intensity and frequency of winter storms in the city?
3. Can you share your experiences with winter storms in Worcester? What impacts have you seen on yourself and your neighborhood? Ice storm 2008?
4. In your opinion, what should be the priority areas that need close attention to adapt the city to winter storms? (e.g., infrastructure, preparedness, grid modernization, minority groups)
5. Have you observed any initiatives or efforts in the city aimed at enhancing resilience to winter storms? If not, do you have any suggestions or ideas for initiatives that the city should implement to improve residents' readiness for future winter storms?
6. Have you ever provided your input as a resident to the city? How was the experience? Did you feel heard? What more can the city do to engage residents' voices in decision-making?
7. How can the city collaborate and engage with residents to better support them during winter storms?

Appendix E - Survey

Welcome to the Winter Storm Experience Survey

We are conducting a study with support from the City of Worcester's Department of Sustainability and Resilience and Worcester Polytechnic Institute (WPI) on winter storms. This survey aims to gather valuable insights into Worcester resident's experiences with winter storms.

Your participation is voluntary, and your responses will be kept anonymous. The results will be presented in a summarized form. Your input is crucial, and we appreciate any information you are willing to share. This survey should take approximately 5 minutes to complete.
If you have any questions about this survey, please contact the study leads: Camila Gomez (cgutierrez@wpi.edu) or Hassan Dajana (mdajana@wpi.edu)

Note: There is a chance to win a $20 Amazon card if you submit your contact details on a separate piece of paper.

1. Could you please provide the ZIP code for the area where you currently reside? This information will help us understand which areas of Worcester have been exposed to winter storms: _____

2. How long have you lived at your current address? (Circle the option)
    a. Less than 5 years
    b. 5 - 10 years
    c. 10 - 15 years
    d. 20 years or more

3. Since you have lived at your current address in Worcester, have you experienced any of the following? (Circle all that apply)

    a. Snowstorm: more than 6 inches of snowfall
    b. Blizzard: strong winds and heavy snow
    c. Ice Storm/Freezing rain: rain that freezes upon impact with cold surfaces
    d. Heavy rain and wind
    e. I have not experienced any winter storms

4. Since you have lived at your current address have you experienced any of the following impacts due to winter storms? (Circle all that apply)

a. Transportation disruptions (delayed public transport, blocked roads)

b. Property damage (roof damage, fallen trees)
c. Health and safety risks (slip and fall injuries)
d. Power outage due to winter storms, If yes, please indicate the longest duration of the power outage in days and the year. _____
e. Loss of internet connectivity
f. I have not experienced any impacts due to winter storms

5. Which of these improvements in the way the community responds to winter storms would you most like to see? Please indicate your preferences by rank ordering these interventions, giving a 1 to the most important and 5 to the least important intervention.

- Improved access to transportation after winter storms
- Tree trimming and management
- Community workshops on winter storm preparedness
- Winter treatment of roads before winter storms
- Improving the electricity system

6. How much would you be willing to spend monthly in dollars (between 0$ to 30$) to support the following activities?

- Improving the electricity system ($_____)
- Management of trees and vegetation (tree trimming) ($_____)
- Winter treatment of roads before and after winter storms($_____)

7. Do you have any other recommendations to improve Worcester's resilience to winter storms? Please provide details.

_____

THANK YOU SO MUCH FOR COMPLETING THE SURVEY

Appendix F - Interview Questions for City Officials (Social Vulnerability)

Worcester Public Schools & Transportation

1. Can you tell us about your role? How long have you served in these roles?
2. How are the Worcester Public Schools preparing for winter climate change, especially winter storms?
3. What are the impacts and the main challenges your facilities and systems face during winter storms? Power outages, roof collapse, trees falling on power lines, safety of students?
4. The MVP report in their Infrastructure Vulnerability part specifically mentioned Worcester Technical High School being vulnerable, we wanted your input on why that was the case?
5. How do the school systems communicate with the city to ensure an effective response to winter storms? What do you think the city could do in terms of efforts, initiatives or partnerships to improve these issues and enhance the city's resilience to winter storms in schools?
6. We saw that 12000 students use transportation services and 12000 walk to school, that means you have 24000 students in total?
7. How do winter storms and the resulting road conditions affect the decision to close schools? What is the amount of snow you consider to cancel schools?
8. How do you think the city manages the plowing activities in the city, around schools and making them accessible for residents and the 12000 students who walk to school?
9. Have you identified specific areas or routes that are more prone to accessibility issues during winter storms?
10. In your time during your current role, what lessons has Worcester Public Schools learned about winter storm preparedness and how are these lessons applied for future planning?

Emergency Management and Communications

1. Can you tell us a bit more about your role in the city?
2. What is the city of Worcester's emergency response plan for winter storms? Is this a public document? How often do you update your emergency response plans due to the changing weather and climate?
3. How have you and your team experienced the current trends in winter storms, do you see a trend, an increase or a decrease, how are you preparing for it?
4. Worcester is a hilly area, there is different topography across the city, does that have an impact on the winter storm preparedness?
5. How does the city manage and coordinate communication during an emergency? What is a community engagement and conversation mechanism? Have you done workshops for residents winter storm preparedness?

6. What are the challenges for the city during winter weather events in terms of infrastructure and social vulnerabilities?
7. How do you define critical facilities? What are the critical facilities within the city?
8. What are the ways in which utility companies and the city can enhance their co-operation for winter storm preparedness?
9. During emergency management do you have any social vulnerability considerations, specific areas and population that should be prioritized.?
10. Is there anyone who works with the Telecommunication utility for the city of Worcester that you can connect us with?
11. Can you tell us more about the comprehensive, risk-based, multi-hazard emergency management and training program by the Emergency Management Division?

Health and Human Services

1. We are aware that your office plays a crucial role in ensuring the health and safety of all residents. Could you share a bit more about your role and some of the key responsibilities you manage?
2. Are there specific health and emergency protocols in place for extreme winter storms, particularly those that impact vulnerable populations such as the homeless?
3. Could you describe some of the challenges the homeless population faces in Worcester, especially during winter regarding their access to warm space, and have these challenges evolved in recent years? How has the city adapted to address these?
4. What initiatives or resources has the city implemented to support the homeless population during winter, and how effective have these been in the past?
5. Could you provide an overview of the shelters and warming centers available in Worcester, including any new or planned facilities? Are there enough spaces to accommodate the homeless population, especially during peak cold days?
6. Are there particular health issues that the elderly and differently-abled populations face during the winter, and how does your department support them during this time?
7. How does your department communicate health-related information to Worcester residents, particularly during emergencies?
8. In addition to the Winter Climate Adaptation plan we are working on, what would you recommend be included that benefits these vulnerable populations that you work and interact with?

Appendix G - Interview Questions for Organizations

1. Can you tell us more about your role at (Name of the organization) and what is the mission of the organization?
2. How did your organization come into being? How many members do you have?
3. What kind of projects does the organization have in place regarding community resiliency?
4. Has the organization thought about programs related to community preparedness for winter storms?
5. From your perspective, what are the top 3 immediate areas of focus that need close attention to adapt the city to winter storms?
6. What are the social and infrastructure vulnerabilities in this area with regards to natural hazards?
7. How many residents do you serve and what is their composition?
8. What are the demographics of the community that you serve?
9. We are conducting a residents survey regarding their perception of winter storms, can you help us share the survey with the residents of the (organization name)?
10. Is it possible to connect us with residents whom we can interview to hear about their concerns for community preparedness for winter storms?
11. Challenges faced by people with disabilities due to winter storms
12. Current work that is being done for people with disabilities and what should be the improvements.
13. Accessibility for people with mobility issues as pedestrians.
14. Accessibility to public transportation during winter storms?
15. What are the challenges your community members face during winter storms?
16. What kind of support are they getting from the city currently?
17. What could the city do more, to support the homeless population?

Appendix H - Complete Report of the Survey Findings

Residents Perception about Winter Storm on Worcester Results.

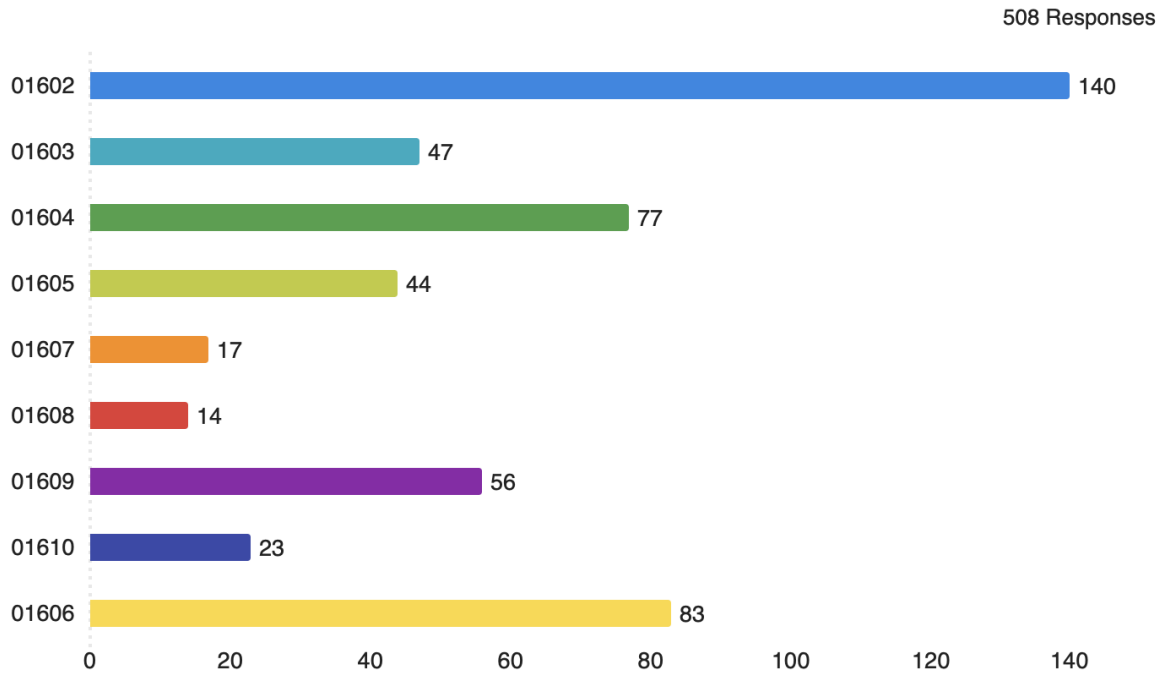
This report presents the results of the *"Residents Perception about Winter Storm on Worcester"* survey, conducted over a period of time between March - July 2024. During this time, the survey was widely distributed through social media, visits to the Friends of Worcester Senior Center, Saint John's Food for the Poor Program, and Worcester Public Library, among other venues, in order to disseminate it to Worcester residents. The study was conducted with the support of the City of Worcester's Department of Sustainability and Resilience and Worcester Polytechnic Institute (WPI). The survey was conducted to gather feedback from Worcester residents regarding their experiences with winter storms, the impacts they face, and priorities for preparedness and resilience to these events by implementing adaptation strategies.

Winter storms are a significant concern for the city of Worcester, causing disruptions to infrastructure and transportation and putting at risk residents' well-being. The results were also accompanied by interviews with a number of residents who expressed interest in providing further input into this project. Participation was completely voluntary, and respondents were assured of anonymity in their responses.

The survey included closed-ended, multi-choice questions about the impacts on their daily lives, the types of storms experienced, and the priority areas that the city should consider when implementing the strategies. In addition, open-ended questions were included where respondents could give information on how long a power outage caused by winter storms impacted them. We appreciate the time and effort each respondent put into providing their feedback.

The information and results collected in this survey are essential to inform the City of Worcester on how to prepare for and adapt to winter storms that have become more extreme due to anthropogenic-induced climate change. By analyzing the survey responses, this report seeks to provide a comprehensive overview of resident's experiences, areas of prioritization, and major challenges. This will help create the final report with recommendations for winter storm response, ensuring that all stakeholders are well-informed and aware of the report's purpose.

1. Could you please provide the ZIP code for the area where you currently reside? This information will help us understand which areas of Worcester have been exposed to winter storms.

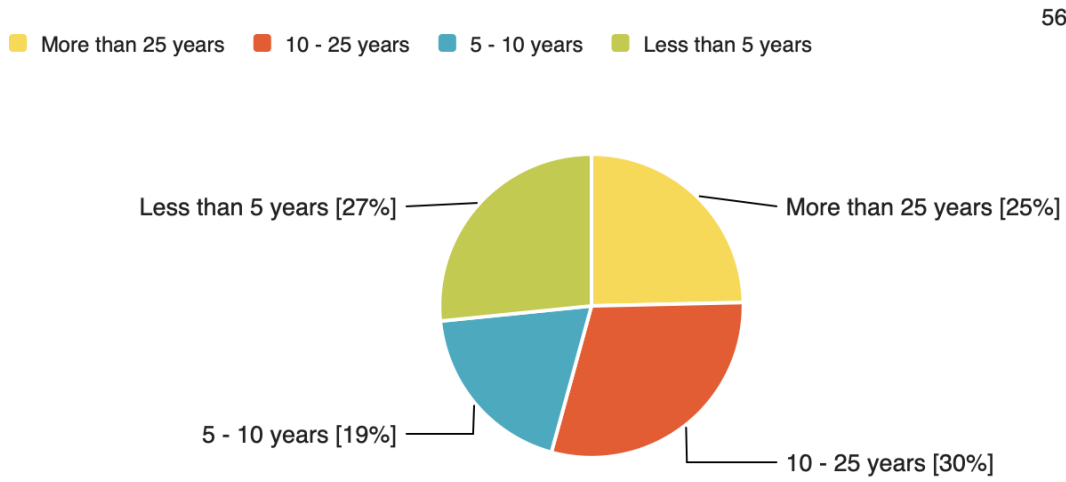


We got responses from each of the residential zip codes from the city, offering a diverse representation of resident experiences across the city. The graph shows the distribution of survey respondents by zip code within Worcester. Most of the respondents live in the zip codes 01602 (27.6%) and 01606 (16.3%). Only 508 respondents shared their zip codes out of 565. According to the United States Zip codes[7], the majority of the people living in this zip code are white (80%), there are a large number of people in their late 20s to early 40s. The population density is 22.819 which represents higher population density and the median household income is 62.832. The neighborhood is Tatnuck.

The people living in the zip code 01606 are primarily white (82.3%). The number of people in their late 20s to early 40s is extremely large. The population density is 19.077 and the median household income is 66.912. The neighborhood is Greendale.

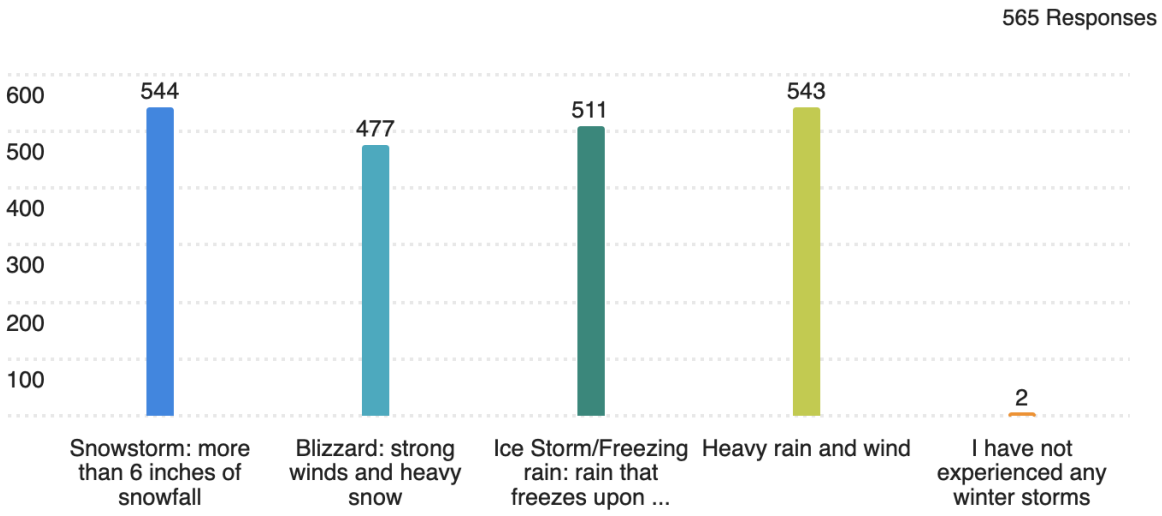
[7] https://www.unitedstateszipcodes.org/01602/

2.How long have you lived at your current address?



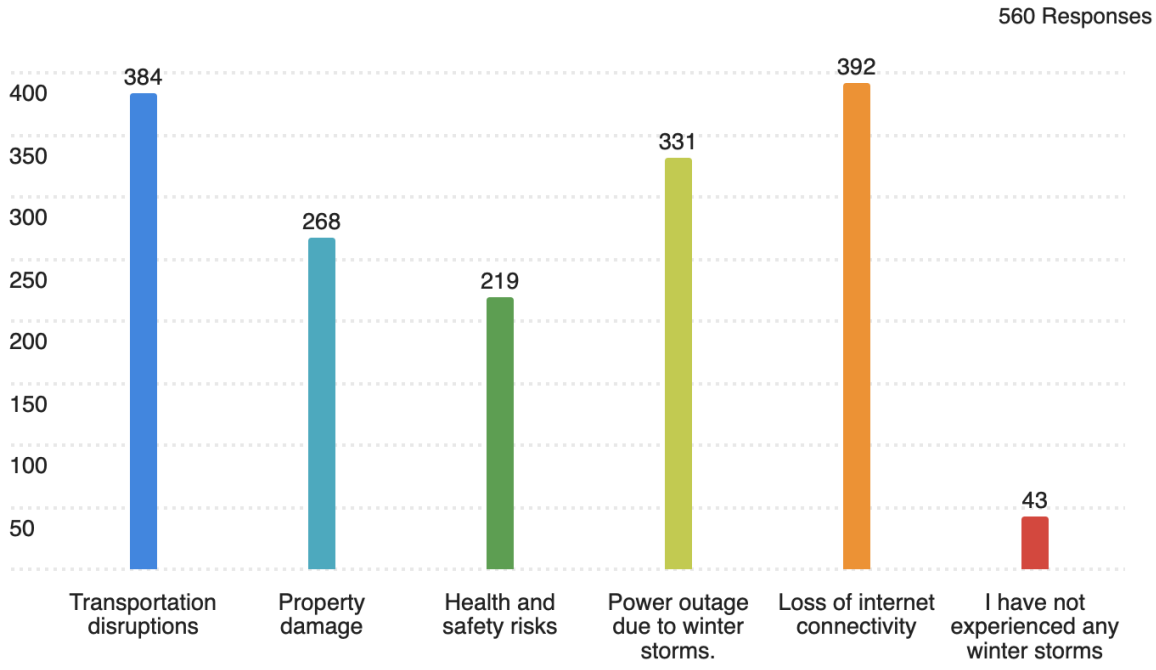
We got responses from residents who have lived in Worcester for various lengths of time at their current address in Worcester. The largest group of respondents (30%) have lived at their current address for 10-25 years and (25%) have lived more than 25 years; these two groups represent the 55% of the respondents as a significant portion of long-term residents . The responses from the residents helped us better understand the challenges faced by residents who have spent considerable time in the city.

3. - Since you have lived at your current address in Worcester, have you experienced any of the following?



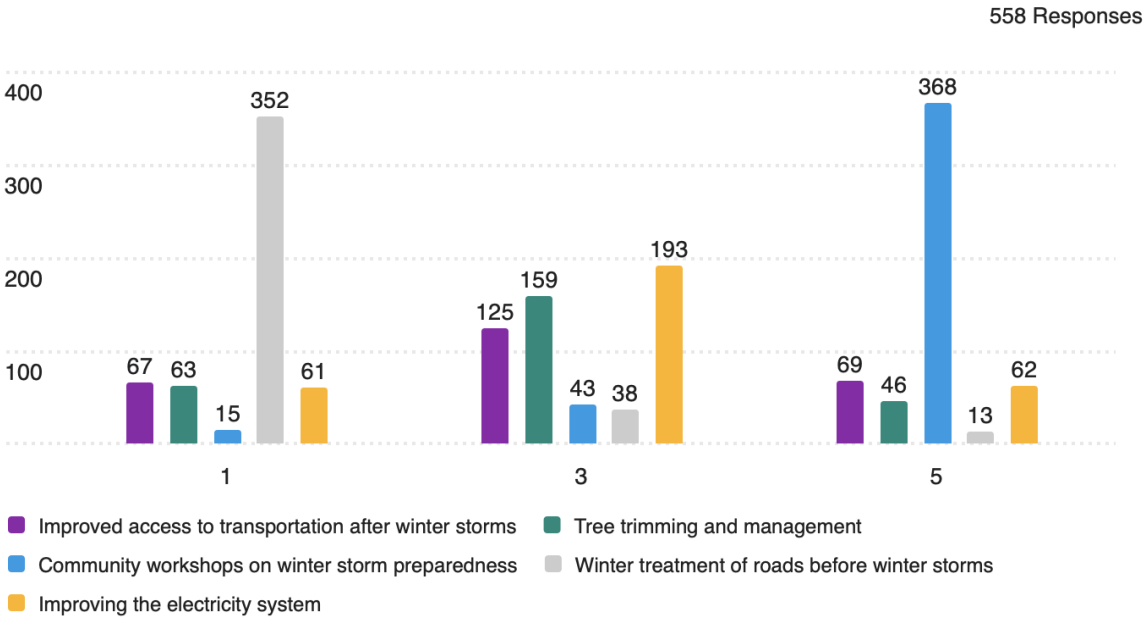
This graph indicates the types of winter weather events that the residents of Worcester have experienced. All the 565 respondents of the survey shared their experience in this question. The key takeaways here are that a majority of residents have been impacted by all types of winter weather events and might have experienced any impact in some way from the storms. Snowstorms (96.2%) and heavy rain and wind (96.1%) are the most commonly reported winter events. (90.4%) of the respondents have experienced ice storms or freezing rain, showing the prevalence of icy conditions.

4.Since you have lived at your current address have you experienced any of the following impacts due to winter storms?



This graph represents the impacts of winter storms that residents have experienced at their current address; of the 565 respondents, 560 shared their experiences for this question, representing an excellent participation rate. The key takeaway here is that loss of internet connectivity (70%) and transportation disruptions (68.6%) are two of the biggest impacts faced by the residents. Internet connectivity increases the vulnerability faced by the residents, decreasing their access to information. Transportation disruption results in mobility and access to services challenges, especially detrimental to those with accessibility needs. (59.1%) of the respondents highlight that power outages are also experienced during extreme winter weather events. This question shows the need for improvements in the telecommunication network infrastructure to ensure uninterrupted operation during these events. Additionally, the mobility challenges highlight the importance of more efficient snow and ice removal operations.

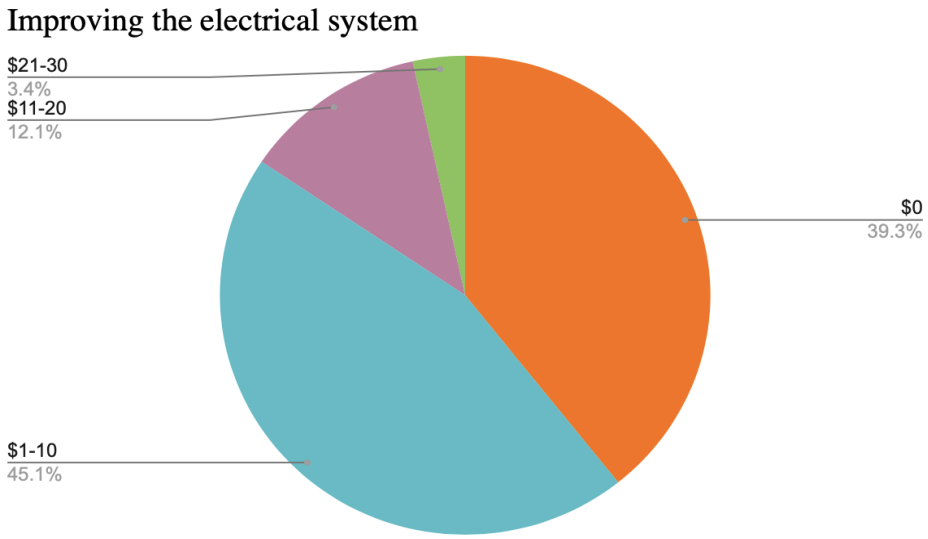
5. Please drag and drop the following improvements you would like to see in the way the community responds to winter storms by dragging the points between 1 - 5, with 1 being the most important and 5 being the least important.



This graph represents the priorities of 558 respondents for improvements in the community's response to winter storms. We only highlighted three priorities as 1 being the (most important), 5 being the (least important) and 3 being something that is necessary but not urgent. The key takeaway here is that winter treatment of roads before winter storms (63%) was ranked as the most important priority, this priority represents the importance of ensuring accessible roads after storms. Community workshops on winter storm preparedness (66%) was ranked as the least important need as communicated by the residents.

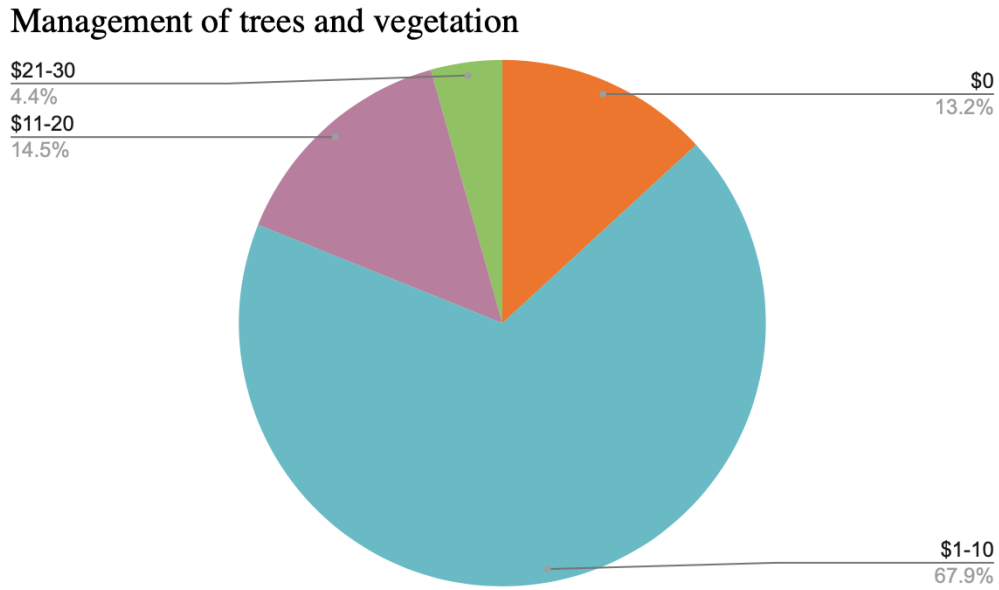
6. How much would you be willing to spend monthly in dollars to support the following activities?

a) Improving the electrical system.



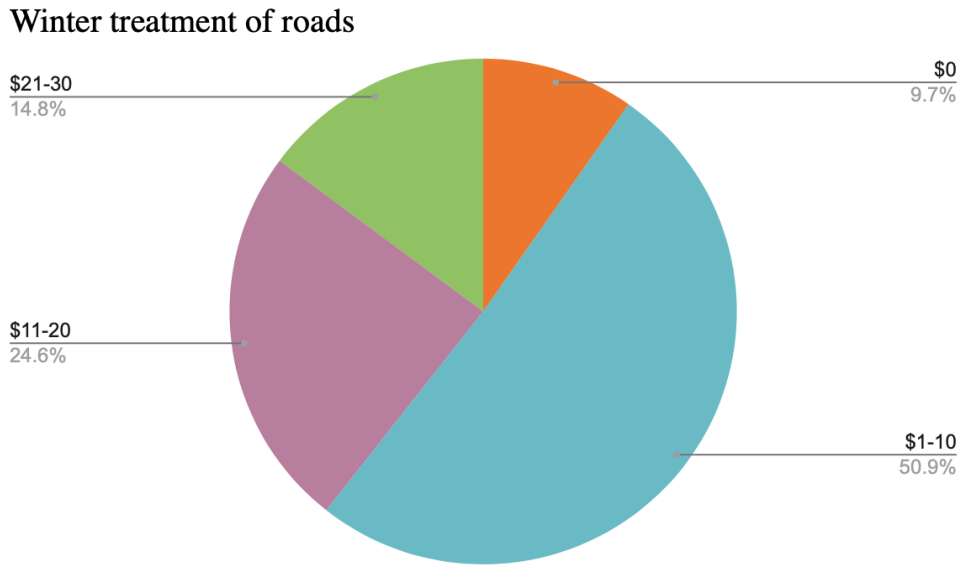
This pie chart represents the willingness of 494 respondents to contribute financially toward the management of trees and vegetation.The key takeaway is that the mean indicated that they would be willing to pay $5.8 per month to improve the electrical system. (60.6%) of the respondents expressed a willingness to contribute to this activity with more than $1. However, (39.3%) of the respondents indicated that they are not willing to contribute anything.

b) Management of trees and vegetation.



This pie chart represents the willingness of 365 respondents to contribute financially toward the management of trees and vegetation. (67.9%) of residents indicated that they would be willing to pay between $1-10 per month to improve the management of trees and vegetation. This represents a strong preference for lower investment in activities related to vegetation management with a mean of $7.5 per month.

c) Winter treatment of roads.



This pie chart represents the willingness of 391 respondents to contribute financially toward investments in the winter treatment of roads. The key takeaway is that the mean of 391 residents indicated that they would be willing to pay $11.5 per month for winter treatment of roads before and after winter storms. (50.9%) of the respondents are willing to contribute $1-10, (24.6%) of the respondents are willing to contribute $11-20, and (14.8%) are willing to contribute $21-30. (90.3%) of the respondents are willing to contribute more than $1 for winter road treatment and only (9.7%) of the respondents indicated that they are not willing to contribute anything.

This chart reflects the preference for contributions toward these improvements, as it has the highest mean rating compared to contributions in improving the electrical system and vegetation management activities. However, many residents believe these activities should be funded by the city through existing tax revenues.

Q7 - Do you have any other recommendations to improve Worcester's resilience to winter storms? Please provide details.

no, I believe the city done an excellent job
Cut trees down that are growing through the wires that provide electricity to my home
We already have debt in the city of Worcester responsible for these activities. I take buses, I am not driving now, so I want the city to make sure residents can still get where they need to after/during some storms. I am 66 years old, but I want to be able to get there OK!
have shelters
more shelters for homeless
More plow trucks, better roads
After a couple of storms, the streets get bumps, holes. The city needs to take care of that.
Some streets in the area do not get clean after the storm until night time or the next day
The city should pass bags of salt before the storms. As some families cannot afford to buy salt and sand.
Volunteers to shovel walkways + driveways for seniors
Ticket those who don't shovel their walks
I feel that the snow plowing could be slightly better- come back for another plowing of the St + additional salting
Perhaps hiring more plowers.
Possibly, looking into different city infrastructure to help promote safer processes.
Help seniors or disabled with shoveling, shopping, if help is already available, make information more available not just by internet or phone (cell)
Re: taxes, make sure storm drains are cleared.
What about staggered schedules for the non essential personnel to be released before and early into major storms?
Stop plowing trucks blocking driveways with road snow (they can avoid it)
Have priority on the roads
Better Communication of the storms so people can be prepared
Enforce the owner's responsibility for shoveling sidewalks.
Qualify and monitor private plow drivers. The guy doing my neighborhood (Quinapoxet near E Mountain) regularly sleeps on Winston Rd
Teach plow drivers how to plow city streets, not just one swipe in the middle of the road 17 times a night. Be nice and widen the snow path to the sidewalk.
My driveway was constantly blocked after plowing. The driveways on either side of my house were minimally blocked but mine always had more snow
I think that the city is usually well prepared, but the condition of roads is so bad that

potholes form after plowing and those can be very bad. I've damaged my vehicle after storms due to potholes. Keeping roads in better condition would help.
Consistency. Some storms our road is cleared well and others barely touched. After storm treatment. Since the street is not done well it melts in the day and freezes at night. Once I had to call 911 and the fire truck slid down the street.
Prioritize plowing to ensure schools can open. Put more sidewalks into residential neighborhoods so kids can safely walk to school on snowy days.
They should be more aware of elderly people who they force to clean their sidewalks and end of driveways. We can't keep up without injuring ourselves. .
Different plow contractors do better than others. My new neighborhood has a team that is very good and works together. My old neighborhood, the contractor had a junky tuck and plow and never cleared the road well.
Designated routes to determine when and where plows will be. Treatment of roads after snow storms through extra plowing or salt.
Stay ahead of plowing - do not wait until the storm is over to begin cleanup.
I think Worcester does a pretty good job with the storms.
Identify underlying causes of the snow plow driver shortages and leverage relationships to build a robust and reliable coalition of snow removal providers
Make salting sidewalks VERY important, I've almost broken an arm because a neighbor on my street refuses to do so
Effective pretreatment for storms
Send the proper equipped truck to certain roads why send a truck with a plow that does not turn from side to side to plow a culdesac circle they do a crappy job every snowfall small or large storms
I live on a hill… hills need to be treated before, during & after storms
Plowing, salting, sanding must be done early and often.
Better road management would be beneficial to all winter storms in Worcester
The city needs to do a better job of communicating with residents.The 311 alert system should notify residents.There is a disconnect and each district should be notified specifically for their areas.
Change electric lines to underground thus making them less susceptible to storms, provide public transportation geared for winter storms
Adequate pre-treatment is important. Plowing must keep-up with the storm!
Repairing roads to good condition before winter
Think and care how the snow plowing / snow piles affect the disabled, access to sidewalks, etc
Underground utilities
Put power lines and internet cable underground
Faster street clearing after storms.

Pre-treatment of the roads especially with ice.
Treatment of side roads as well as main roads prior to storms. More frequent plowing during storms.
Enforce the cleaning of snow in front of your house have volunteers help the elderly and or disabled
Pretreatment of the roads would be a great start, but it is as, if not more, important to actually remove the snow from roads in a timely fashion.
I pay taxes, fix the roads before winter/fall, dirt streets
Public service announcements. Tell people to stay off the roads.