Planning Autonomous Evacuation for Access and Flood Resilience

By

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Bachelor of Architecture
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ABSTRACT

Resilience planning has been an increasing topic of discussion, with the shifting attitude toward an adaptive approach where landscapes serve a multitude of functions. Cities like Boston are at the forefront in resilience planning with initiatives such as the Climate Ready Boston. The history-rich land morphology of Boston shows a real vulnerability to floods and storm surge events, revealing a 100-year flood's potential to cripple its busiest districts. Technology and mobility, albeit have been progressing as independent entities, do not cross roads with resilience planning and evacuation, and the understanding of landscape morphology and vulnerability plays little to no influence on the idea of districting.

With scarce research on the overlap between technological advancements in mobility with resilience thinking, there is a need to re-examine the integration of technological feats with evacuation in disasters. An analysis of the overlap between mobility, evacuation, and resilience is explored using an ecological understanding of landscape as a key component in concluding boundaries. The notion of a resilience district is hence explored and integrated onto the larger Boston area to derive effective evacuation methodologies using Autonomous Vehicle Clouds (AVCs) and Boss-system independent AVs. The earlier technology is a surgical implementation on a fully autonomous transportation route using a central cloud command center with prompt response-rate as a fleet, whereas the latter AV system integrates into existing interstate roads and highways and can navigate independently.

The thesis proposed an integrated 5-step framework on the Everett-Malden resilience district that provided 10-minute access to evacuation to over 8,000 individuals that are otherwise disconnected in a flood event. The potential application of AV connection systems exposed development opportunities for otherwise-car-occupied land uses bringing significant benefits for the city, public officials, and private developers. On the larger Boston area, the magnifying impacts of the framework can be estimated to benefit over 26,700 households, providing quick means to shelter for over 292,000 individuals. This thesis provides pragmatic analysis of the possible AVCs and AVs evacuation application, and looks at the immediate land uses with high impacts by AV implementation. The goal of this research is to aid in the advancement and integration of technology, evacuation, and resilience planning in order to achieve a better understanding of truly resilient towns and cities.

Thesis Supervisor: Alan Berger
Title: Norman B. and Muriel Leventhal Professor of Advanced Urbanism

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To the rest of my family, thank you for your endless support and for believing in me.

Finally, I dedicate this work for you, grandfather.

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Figure 13. Chronological Record of Natural Events. Copyright 2019 by A. Al-Sammarraie

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1.
Introduction

Over the past few decades there has been increased research on what resilience means with respect to urban planning, and how cities can better prepare for it. The 21st century notion of resilience is leaning toward apprehending landscape as systems, where functions evolve and change in response to a disturbance. Cities, like Boston and other leading metropolitan areas, are at the forefront of pushing the dialogue on resilience planning, especially in a place that underwent significant land metamorphosis and was exposed to frequent floods and drought seasons. Superstorm Sandy was a wakeup call for Boston to rethink climate change's potential impacts of severe storm surges on its crippling infrastructure. The fast pacing advancement in mobility and the lack of integration of technology and resilience thinking calls the need to explore future potential opportunities, such as the utilization of state of the art mobility methods of AVCs and Boss-system independent AVs for flood evacuation.

This thesis will answer several questions. First, what are the collective literatures on resilience planning and technology in mobility, and their overlap with evacuation? Second, what is the appropriate districting methodology to follow in order to successfully integrate autonomous evacuation systems? Third, how can autonomous systems improve on evacuation, and maximize access to vulnerable communities, during flood events? Finally, how would the findings be translated into a case study example of the Everett-Malden district and what are the potential benefits of this framework application? The results of the above research analysis will inform a set of 5 steps for a resilience districting methodology that accounts for an exit strategy before and during severe flood events.

Most of the data this research uses is publicly available and open source. Spatial information such as land use and infrastructure characteristics are attained from the U.S. Census Bureau database and Massachusetts' GIS database. Demographic information such as population and ethnicity are collected from the 2016 Decennial Census, the 2010-2016 American Community Survey. For the mapping, data analysis and framework conclusion the research used tools like ArcGIS, QGIS, Mapbox, Rhinoceros with its computational plugin grasshopper, and for sections in the appendix dealing with data analysis, tools like R and Tableau have been used to arrive to those conclusions.

Chapter two will provide background information on the literature in resilience planning and technology in mobility and evacuation. Chapter three will provide analysis on flood trends in the Boston region and defines a districting framework for evacuation planning. Chapter four will bridge the gap between resilience planning and autonomous mobility to integrate and propose a 5-step districting-framework with a case study of the Everett-Malden area. The conclusion will discuss the implication and opportunities of the 5-step application on the 9 resilience districts for different agencies in the public and private sectors, and the potential benefit of following a resilience-autonomous districting framework.

2.
Literature Review on Resilience and Autonomous Evacuation Systems

Chapter 2 begins by investigating relevant literature on topics of resilience and autonomous driving and the potential for autonomous evacuation systems using Boston, Massachusetts as a case study. This chapter briefly covers literature and background materials regarding resilience and autonomous mobility, and their intersections (or lack thereof) to inform the reader with current discourse on the general themes.

a.What Is Resilience? Costs and Risks of Sea Level Rise

Resilience has been an increasing topic of discussion within urban planning; the impacts of climate change are geography and development-specific. An urbanized coastal city with a long stretch of developed land exposed to the rising sea levels would have to strategize different approaches than a city in an arid region where water is scarce and temperatures extreme. In 2017 alone, the United States (US) had 15 major natural disasters, out of which 11 were water-related catastrophes, costing $1 billion (USD) on average, each, and causing the death of over 320 lives, according to data from the National Oceanic and Atmospheric Administration(Santhanam, 2017). The frequency of flash floods is increasing rapidly, and data from Statista show the gradual increment in lives lost as these events continue to occur.

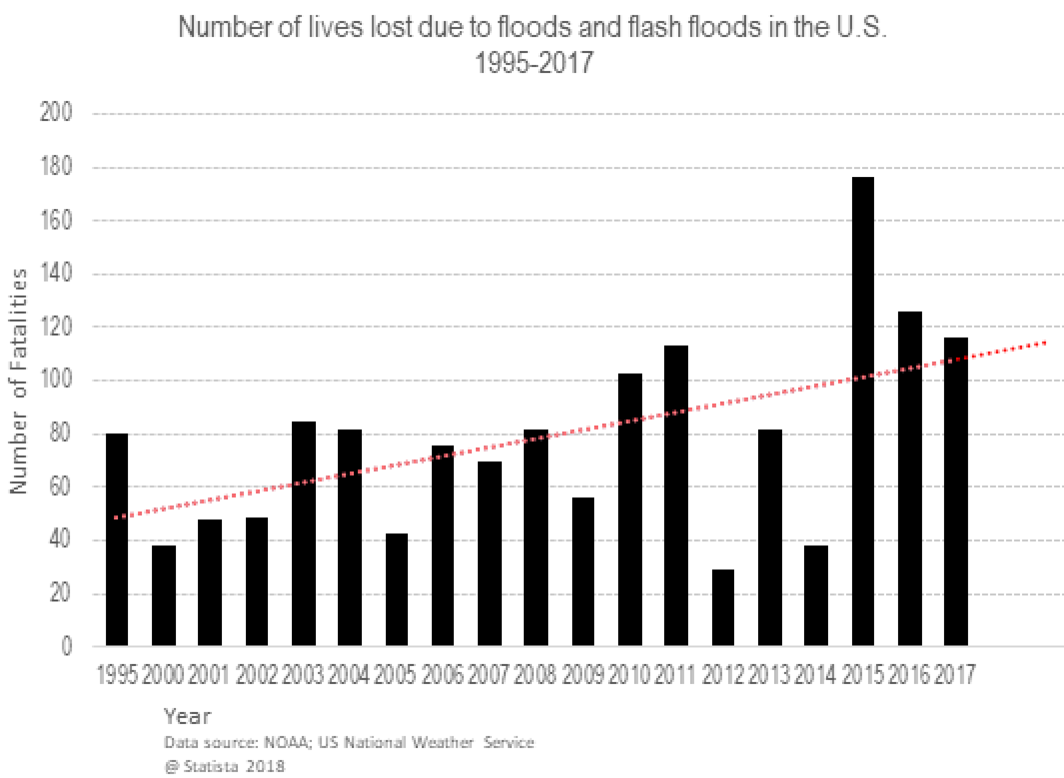
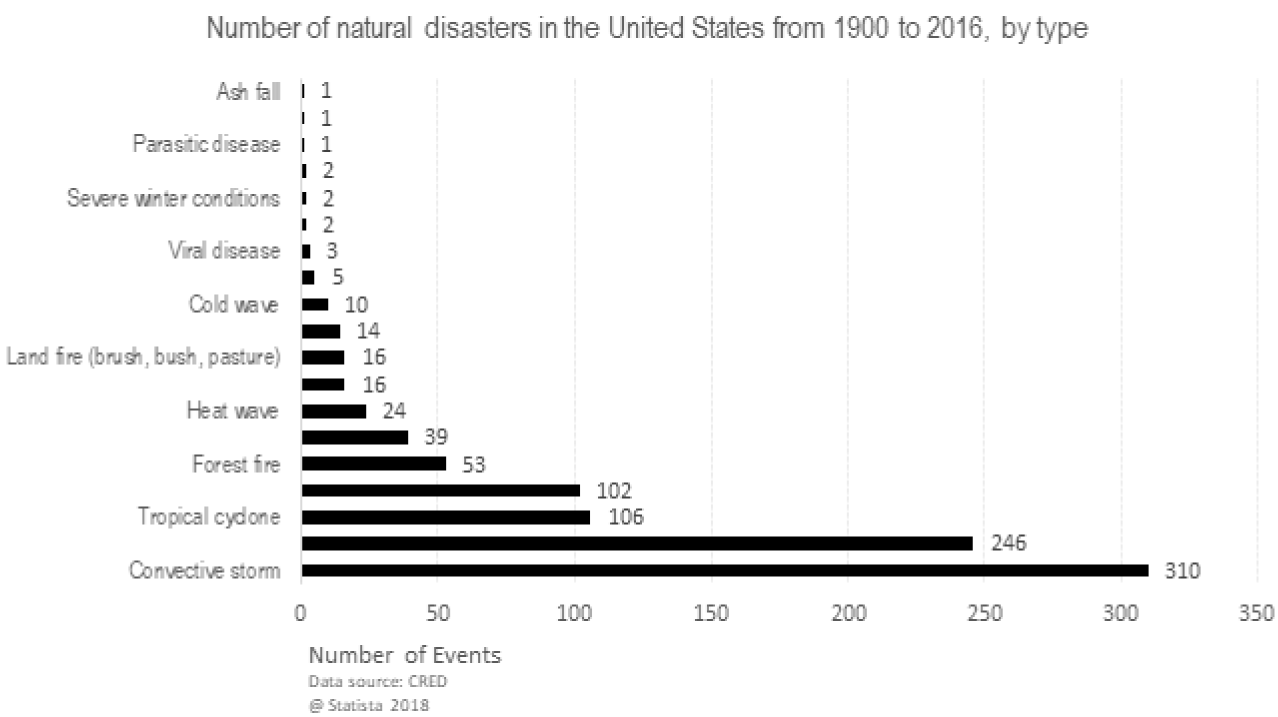


Diagram 1. NOAA, and US National Weather Service. Number of lives lost due to floods and flash floods in the U.S. from 1995 to 2017. https://www.statista.com/statistics/203709/number-of-fat

As the occurrence of droughts, heat waves, storms, and other natural phenomenon increases over time, the fields of urban planning should open the dialogue for what policies, strategies, design guidelines, resource management to prevent loss of life and property and diminish risk. The ultimate goal for professionals working toward achieving resilience is to deal with sudden, as well as incremental, changes to the environment and its impact on urban form and places where people live. It is no secret that resilience planning concept has evolved through time to focus on establishing a “self-organization capacity alongside a change in the value system that can overcome the unequal power relations”.(Eraydin, 2013)



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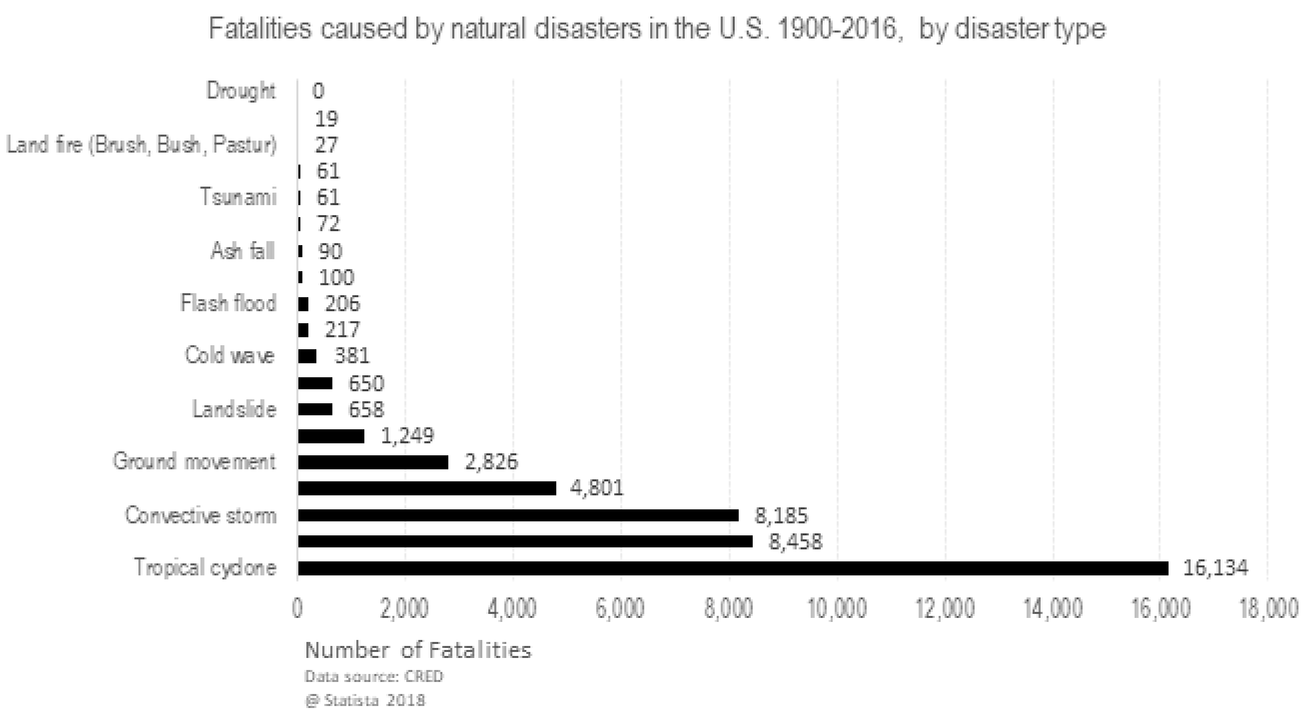
Resilience has been more actively discussed in planning discourse recently, but it is by no means a new concept. It was used early on by physical scientists to describe characteristics of a spring and to explain the stability of different materials, as well as their tendency to absorb shock and retain basic intended functions. Springing from Latin origin “resi-lire”, meaning to return to current state, the word was commonly used to identify certain characteristics of physical elements. It was not until the 1960s, concurrent with the emergence of system thinking, was resilience used with ecological systems.(Davoudi et al., 2012) Multiple definitions in engineering and ecology emerged thereafter. Holling in 1973 understood engineering resilience as the tendency of a certain system to go back to an equilibrium state – be it after a natural disaster such as a flood or earthquake, or a man-made disturbance, and ecological resilience as “the magnitude of the disturbance that can be absorbed before the system changes its structure.”(Davoudi et al., 2012)



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The discourse on resilience in engineering and ecological urbanism sprung the idea of evolutionary resilience. Also known as socio-economic resilience, evolutionary resilience backs the notion that systems change over time with or without external interventions where there is no return to a normative state. Instead, it is viewed as the capacity of intricate and complex sociological and ecological systems to evolve, change, and adapt transforming as a result of external forces.(Davoudi et al., 2012) While this notion of resilience defies scientists' view of the world as a fine-tuned, mechanical, and factually predictable apparatus – one that is chaotic, complex and volatile – it shows existing approaches to environmental systems based on trends as ineffective. The cause and effect are not directly related but rather through a chain of cause-and-effects. In this light it is fair to ask if current planning practices that use past predictions and events to prepare for the future is an impractical approach to resilience planning, and one which should not be a reactive methodology to an ever-changing landscape.

b. Defensive vs. Adaptive Resilient Planning

Early in the 20th-century planning, the understanding of resilience was correlated with an equilibrium – a projected viewpoint of how nature, biodiversity, and ecology are integrated to form a balance.(Ahern, 2011) . Practices of resilient planning steered the dialogue to a “fail-safe” idea of preparedness: a mentality toward planning where resilience is the inability to fail in the face of sudden change. (Ahern, 2011) In the latter part of that century, the ideology shifted to focus on the dynamic relationships of the environment and cities: the unpredictability of nature and the incomplete knowledge of how our planned cities respond to its metabolic cycle, to adapt, re-organize, and recover from change without having to undergo a drastic ‘change of state’. The degree to which the 21st-century world's outlook of resilience depends largely on how cities don't understand it, shifting to a “safe-to-fail” approach where cities re-organize in the face of infrastructural failure to accommodate for the physical and socioeconomic displacement.(Ahern, 2011) Urban planners and designers are newly starting to discover the importance, and necessity, of integrating this resilient adaptive mentality to city design, but there is little built evidence of this theory at the time of writing this thesis.

Despite this evident gap between theory and practice when speaking of resilience, more literature is being published to bridge the gap. This paper interrogates some of these topics, while primarily asking how planning can deploy systems thinking to achieve resilient, adaptive city morphologies. One can understand a resilient system thinking through two primary characteristics: the ability to engross change and disorder, and the persistence of systems while sustaining their essential functions and what they're designed to achieve; as well as surviving, evolving and transforming themselves.(Eraydin, 2013) The earlier conservative view of resilience sought a reversal back to the before-the-shock state that tried to bring in a radical change. In contrast the latter, more radical construct of resilience as a dynamic and evolving system in of itself, a rejection of the status quo. It recognizes the existing conditions are what triggered nature's response in the first place.

Out of these two main resilience-thinking methodologies, it is the latter 'systems' approach that will be considered in this thesis through city-design strategies. Of the many theories that have emerged on resilience-thinking in planning and design in recent years, Johan Colding's 6 guiding principles for resilience thinking are especially useful for the design work in latter sections of this thesis: Clustering different urban patches for biodiversity, strategizing for potential 'emergent' ecological functions to be realized, public-private land supplementation in which publicly and privately managed lands could support each other to function effectively, adopting "conservation targets" using land-use complementation thinking to establish vital ecosystem services in urban areas, replacing usually-inefficient protected zones with land-use complementation designated areas, and utilizing existing ecological land-use complementation structures in the landscape as test sites for "design and adaptive co-management."(Colding, 2007)

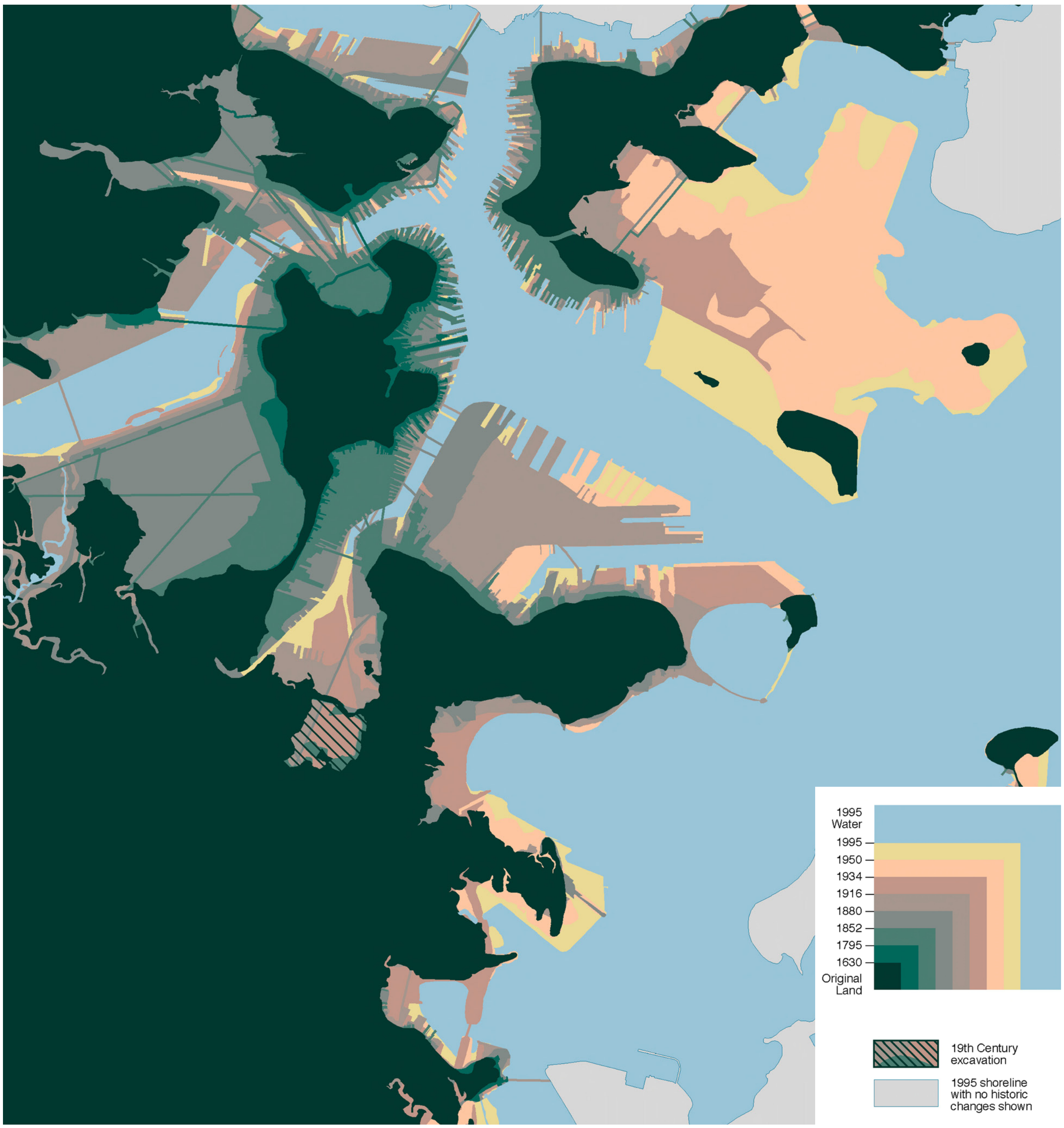


Figure 1 photograph courtesy of the Norman b. Leventhal map center, Boston public library

c. Resilience in Boston

i. Land Morphology and Susceptibility to Flooding

Boston has not always been the dense metropolitan area we know of today. The morphological evolution of the city – formerly known as the Shawmut peninsula, has been dramatic and extensive over the past three hundred years. The transformation of the land since 1630 (see Figure 1) was not solely for the needs of population growth. In fact, much of it was a response to economic and political forces to improve trade, land value, income, promote health, and create better facilities in the public domain. For example, the Mill Pond which was a dam across the northern waterway entry caused accumulation of waste, sewage, and garbage was filled in fearing the “miasmatic theory of disease”, which assumed diseases were spread by foul smells. (Mason, 2017)

Much of this infill land faces issues today of rotted pilings costing an average of $400,000 (USD) per home.(Mason, 2017) There is a strong correlation between the natural land morphology, filled-in land reclamation over time, and the potential flood mapping analysis shown in figure 2. The study shows, flood-prone areas tend to be the ones that were filled, which was primarily material brought in from Beacon Hill. (Mason, 2017)

The city’s unique morphological position and exposure to frequent Nor’easter storms makes it susceptible to floods, especially around the reclaimed land. The Boston Harbor (see figure 3) is the latest example of such risk in the month January, 2018, when a Nor’easter brought the city’s third highest flooding on record combined with a high-tide record of 15.16 feet, disrupting mobility, damaging infrastructure, and killing wildlife.(“Storm brings destructive flooding to Boston,” 2018)

Figure 2 January 2018 Nor’easter Impact

Figure 3 Built Areas Facing Rotted Pilings During Droughts/Floods Higher In The Grey Area

ii. Hurricane Sandy

Perhaps one of the most devastating storms in the Northeast, Super storm Sandy delivered wind gusts of over 80 miles an hour, causing major power-infrastructure damage, flooding of major road ways and regionally connecting arterials, and the loss of over 70 lives on the day of the storm.("Superstorm Sandy," 2016) New England went through major post disaster planning and invested into resiliency thinking for the region. It is estimated that had Sandy hit the Boston region during high-tide 6 hours earlier, the city would have been too overwhelmed to cope and flooding would be so severe that critical infrastructure from the MBTA, to tunnels and sewage networks would have been critically damaged.("Superstorm Sandy," 2016)

Throughout New York, Connecticut, and New Jersey recovery of key infrastructure was slow. It took weeks to provide basic amenities like electricity, and by the end of October (A day after the emergency declaration) there were well above 385,000 people without power.("High winds, rain knock out power to thousands in Mass. - Boston.com," 2012) Although not a direct hit, Sandy impacted Massachusetts. A report from 2012 estimated the damage to the state amounted to a total of $20.8 million, and MA's Middlesex and Suffolk counties were overburdened with over $3 million in damages and future reparations.("Storm Events Database - Search Results | National Centers for Environmental Information," 2019)

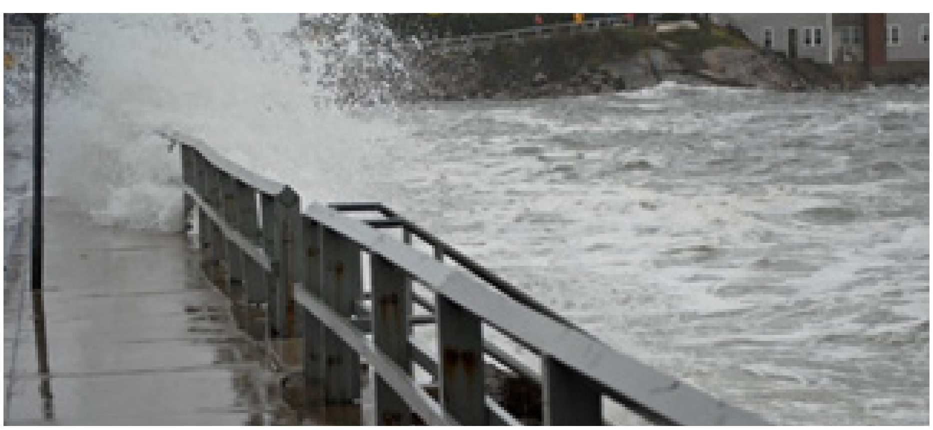


Figure 4Flooding in Marblehead, Massachusetts, caused by Hurricane Sandy on October 29th

A report by US Army Corps of Engineers estimated an average vulnerable population of 115,227 in category 1 and 2, and 236,712 in 2 and 4 hurricanes for Middlesex county. Recommendations in the report included 5 main points of focus: 1. swing bridges locked in “down” position during the warning for evacuation, 2. Coordination with other agencies such as CSX, Pan American, Massachusetts Coastal (MC), AmTrack and MBTA to streamline a seamless transportation schedule, 3. Removal of tolls to expedite travel away, 4. Establish effective cross-agency communication measures, 5. Develop measures for lane reversal along critical highways.(“Superstorm Sandy,” 2016)

Thinking ahead in planning for saving lives and mitigating 100-year flood events, the report by CoreLogic on the potential damage to properties projected a tenfold increase to the 19,169 FEMA estimated number within the Flood Hazard Zone in the Boston Metro Area (191,146, to be precise). The dollar value equates to $48 trillion of reconstruction costs.

iii. Urgency for Resilience Planning and Implementation – Precedents

There is an increasing awareness of the need for resilient measures to be taken for existing as well as future development in and around metro Boston. Numerous reports and studies have been conducted to understand the serious risks Boston face and how to create policy to solve them. Important studies such as Climate Ready Boston (CRB), a climate change preparedness analysis report on several areas within Metro Boston look at physical and social impacts to create vulnerability indices, flood scenarios, and the financial-costs on buildings and infrastructure. Another study by the Federal Emergency Management Agency (FEMA) examines rising sea levels using interactive maps to show the changes of land with 1-foot increments in sea level.

Figure 5 Revere Beach feels the effects of Hurricane Sandy Monday morning. (Jesse Costa/WBUR)

As the issue of storm surges gain increased attention, studies by Surging Seas and Woods Hole Oceanographic Institution (WHOI) have tried to accurately measure the level of floods' impacts on urban form. Leaders in the private sector are also contributing to understand short and long term impacts on of several flood events, as well as private consultancy agencies like Sasaki.("Surging Seas," n.d.)("Sea Change Boston – Sasaki," 2014)

CRB studies and reports are also town-specific, focusing on risk mitigation and flood resilience for certain geographies within Boston. They also think about different areas in urban design, from private developments to public spaces, one of which is the climate resilient design guidelines. Exploring a set of strategies to address flooding and protect public spaces, the report provides sample barrier types and how to overcome them. The goal of this initiative is to create a "design process for evaluating flood barriers to protect Boston's public rights-of-way("Climate Resilient Design Guidelines," 2018). In addition, and building on Climate Ready Boston's initiative, the city choreographed strategies to achieving the goals of its CRB report, ultimately creating a working framework for future developments to follow, with the objective of establishing example guidelines. The 2016 "Action Plan" report by CRB proposes a set of initiatives, broken down into 11 strategies, to strengthen Boston's future adaptability to Sea Level Rise (SLR).(Climate Ready Boston, 2016)

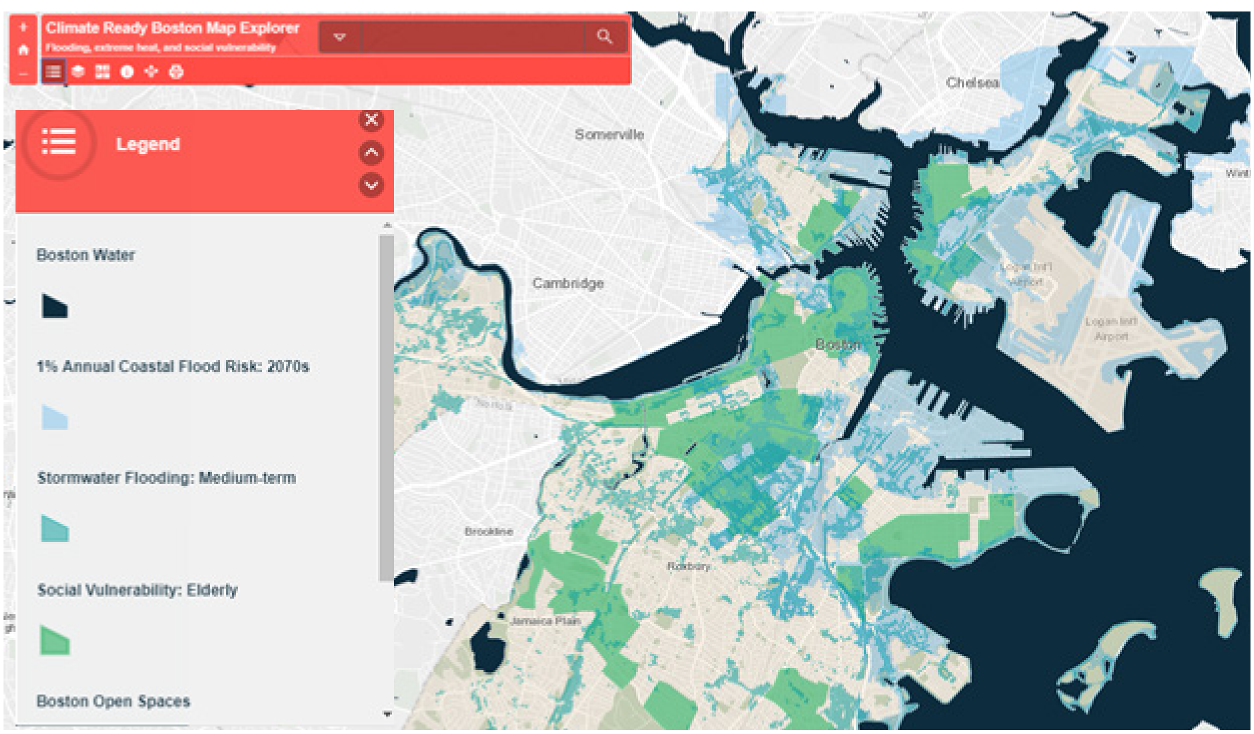


Figure 6 CRB-FEMA Interactive tool for floods and vulnerability assessment. Accessed from https://www.boston.gov/departments/environment/climate-ready-boston-map-explorer

Recent hot summers and increasing flood events led the City of Boston to invest resources on resilience implementation about resilience with plans such as the Resilient Boston Harbor, Sasaki's research on floods impact on the region, and Boston Harbor's analysis of storm surges' impact on urban form in a 50 and 100 year events("Sea Change Boston – Sasaki," 2014)("Resilient Boston Harbor," n.d.)("Climate Change Preparedness - Boston Harbor Now - Boston Harbor Now," n.d.). While all these initiatives analyze impacts and propose planning strategies to mitigate floods' harm on the city, they don't detail what methodologies should be utilized to anticipate land use evolution.

In the urgent need for resilience planning, and to rebuild areas affected by Hurricane Sandy using design-thinking and collaborative means in redevelopment, the Hurricane Sandy Rebuilding Task Force launched Rebuild By Design (RBD) in 2013. With the ultimate goal of collaborative involvement and design-driven problem-solving, the US Housing and Urban Development (HUD) partnered with different organizations in philanthropy, academia, and nonprofit organizations. The competition's objective is to innovate resilience-thinking in planning, and establish a "regionally-scalable but locally-contextual solutions that increase resilience in the region".("Rebuild by Design | HUD.gov / U.S. Department of Housing and Urban Development (HUD)," n.d.) The competition also sought to innovate on understanding regional co-dependence and seeing collaboration strategies in both the regional context, as well as the local level.

The diverse ten teams of scientists, engineers, and designers invested their efforts to understand vulnerabilities within the Sandy-impacted areas, and developed frameworks to build on resilience planning. In the year of 2014, seven teams were selected as the winners of the RBD initiative and awarded $930 million to aid in the implementation and phasing strategies. Two prominent winning teams are Bjarke Ingles Group (BIG) and MIT Norman B. Leventhal Center for Advanced Urbanism (LCAU), where the earlier envisioned design tactics to build a wall of opposition to flood and creating systems of flood mitigation, while the latter proposed an adaptive design framework, planned to adapt and is "safe-to-fail".(Ahern, 2011) While they might seemingly appear similar, the underlying resilience-thinking of the latter is a century ahead of BIG's approach to resilience.

Moving forward, New York City envisioned open spaces to act as retention zones("This NYC Park Is Designed to Be Flooded," 2018). It initiated a climate adaptation program with policy guidelines in anticipation of future events, such as in the case of Vision 2020: New York City Comprehensive Waterfront Plan, comprising of strategies and integrated system thinking for the southern stretch of Manhattan's waterfront. (Aerts & Botzen, 2011) These guidelines build on the initiatives from RBD and push on the resilience planning approaches from both BIG and the LCAU to better prepare the coast, and protect the city inhabitants in the face of future storms.

d. Boston’s Transportation Evolution and Its Relationship (or Lack Thereof) To Resilience

i. Boston’s Evolving Mobility System

In the wake of World War II, the US underwent a major economic boom.(“Transportation,” 2013) Boston had started recovering from the economic stagnation with commencing major investments in federal mobility and evacuation infrastructures. Most notably was the federal highway system i.e. the Central Artery.

Concurrent with the innovative automobile technology at the time, and the demand for less congested roads to speed up commuting, major highways were erected in the early 1950’s of the same era, including the Tobin – Mystic River – Bridge and Storrow Drive. The construction of the Central artery, also known as John F. Fitzgerald Expressway, was a key mobility infrastructure to catalyze movement from the heart of Boston to its neighboring regions creating an interconnected system of ‘nodes’. It was not long until the city saw Route 128, Route 3, Callahan Tunnel, remainder of I-9, Mass Pike extension, all weaved together as one network. (“Transportation,” 2013) The John F. Fitzgerald expressway was a technological feat at the time, trips that would otherwise consume 25 minutes now take a whopping 2, and as the demand for vehicular mobility

Figure 7 Construction of central artery 1954

increased, issues of traffic jams and accidents started to accumulate. With evident failure and increasing public concerns, Governor Michael Dukakis initiated an effort to decimate and replace the Central Artery with the first underground-underwater mobility network. Decades later and an accruing federal and state debt in billions of dollars, the "Big Dig's" submerged section opened for public.(Boston Sunday Globe Magazine, 1954)

The state of mobility has not improved with time. In fact, commuting to the downtown Boston from areas beyond the I-495 can take up to 4 hours during peak times. The more lanes or roads are built, the higher utilization rate becomes, causing further backlog.(O'Connor, 2017) Moreover, a recent report by INRIX, an organization which publishes annual congestion ratings, found Boston to have the worst mobility situation in the United States, where drivers waste an average of 164 hours per year, ahead of Los Angeles (LA).

ii. Where Mobility and Resilience Meet: Evacuation Planning

Boston's Resilience Strategy, released in July of 2017, outlines the importance of having robust and resilient infrastructural systems to meet the city's and people's needs, and summarizes 3 steps towards

Figure 8 I-93 South at rush hour

a needed resilience planning, the first two address the out-of-date built and technological systems to accommodate for fast response, aiming to develop a “redundant and reliable public transportation network to provide equitable accessibility for all Bostonians.” And prepare “for the impacts of climate change and other threats while accelerating sustainable infrastructure, environment, and communities.”(“Boston Resilience Strategy,” 2019)

So how is evacuation planned in a city like Boston, for example? Ready.gov, a governmental service for emergency and evacuation preparation, has set out a plan in evacuation to prepare evacuees in emergency response.

The current evacuation planning is set into three stages: a before, during, and after areas of preparation. The before stage involves research of where to go, planning for communication, ensuring adequate supplies and emergency kits are available. During an emergency, individuals should download and open a FEMA app, snapshot shown above, to receive real-time alerts and locate disaster recovery centers. After a disaster, evacuees are advised to re-connect with their family members and communities.

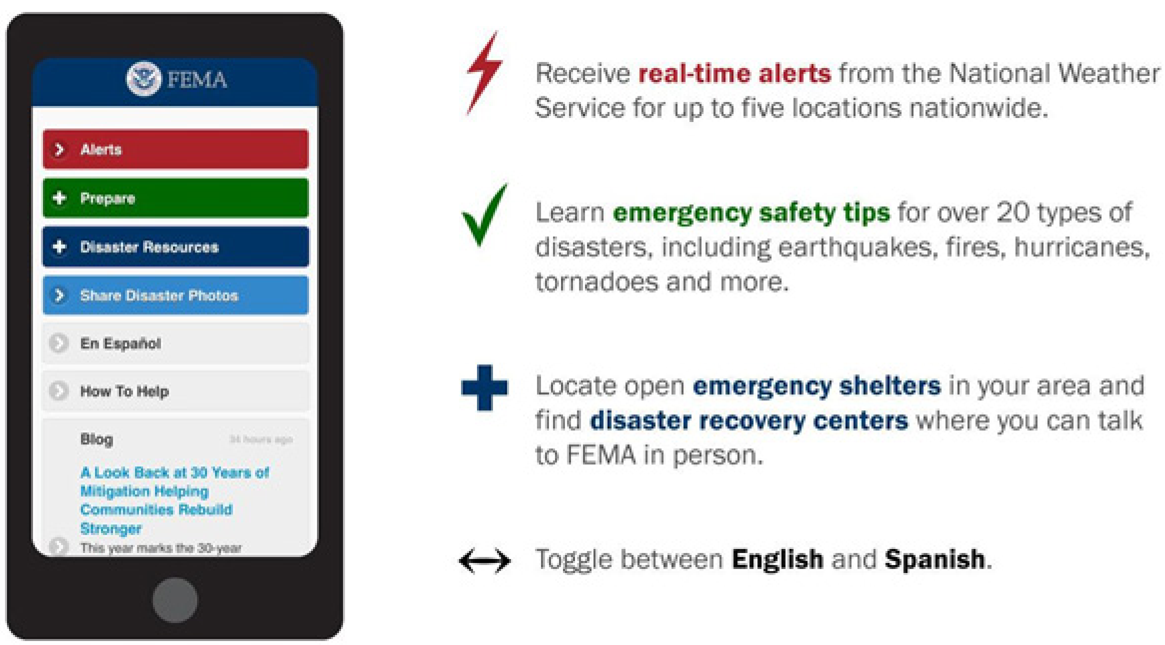


Figure 9 FEMA App for evacuation planning

There are no clear systems on how to evacuate, or a tool for example showing the fastest and best routes to take during a disaster so residents can respond quickly. Ultimately, the current practices leave a big part of the evacuation to be dependent on the evacuees' knowledge of local context and, quite frankly, luck.

e. Technology in Mobility and Infrastructure

i. Autonomous Vehicles Are Coming

For the past 100 years, the personal car has dominated the integration of mobility solutions, development protocols and the resultant urban form from city streets to suburban territories. Today we are witnessing a rapid advancement in car technology, and the trend towards fully automated mobility systems is becoming a reality. Research on the challenges and opportunities for this technology and the preparation for smart infrastructure is more than ever before.(Campbell, Egerstedt, How, & Murray, 2010)

Semi-to-fully autonomous vehicles (AV) are expected to be introduced into the market over the next couple of decades, and policy makers are already starting to think about the technologies' implications on city form. Some predictions include independence for affluent-non drivers in the next 5 to 10 years, leading to potential increased accessibility, and greater chance for productivity at an earlier age. However, most impacts on urban form are expected to take shape when middle and low-income class have access to this technology. Other benefits such as safety, efficiency and energy conservation, health and pollution-reduction, are only expected to be real when AVs are a financially accessible commodity. Some studies expect this to happen sometime in the next twenty years, but see a struggle for cities to catch up with policy and regulation in addressing obstacles such as human error, damage to AV property, and restructuring systems of vehicle ownership and licensing.(Litman, 2018) AVs implementation is faces several challenges, with some speculating increased efficiency and maximized accessibility, and others see a doubling of the very problems vehicles insert into cities: increased vehicular density, sprawled urban form, and gentrifying pricing.(Berger, 2018)

ii. Socio-Economic Potential

Numerous studies of AVs benefits on parking and road area-reduction are penetrating the mobility research field, suggesting large swaths of land having pressures removed for vehicular requirements. On a high-level, technology, in general, is starting to directly impact cities' form and function as it scales, such as the case of shared economy with the players like Uber, Lyft, and Airbnb. But perhaps its impact would not be seen as rapidly as it would from AV Systems' implementation into metropolitan regions as this would impact cities' most underutilized land: car-oriented infrastructure.

The AV technology has promising socio-economic benefits, such as improved response and crash savings, efficiency in distance and time travel, parking benefits, and fuel efficiency. According to Energy Information Agency's report, it is estimated by 2050 AVs can enhance fuel efficiency up 44% with potential advancement in speed and industrial manufacturing production by up to 25%(Study of the Potential Energy Consumption Impacts of Connected and Automated Vehicles, 2017). In addition, the benefits to the average owner are expected to reach up to four thousand dollars per year(Fagnant & Kockelman, 2014). According to an analysis by a group of researchers on the benefits this technology has on central business districts urban form, the obsoleteness of parking spaces and their supply and demand, as well as the reduced necessity for street widths within cities expect 90% of parking to be eliminated at low market penetration rates of 2%.(Zhang, Guhathakurta, Fang, & Zhang, 2015) Not only their benefits to parking efficiency, but risk-averse Autonomous Driving (AD) systems have the potential to transform travel behavior in the urban sphere creating pedestrian-oriented movement patterns.(Millard-Ball, 2018)

While these metrics have already been identified, there is little research on the best uses for the reverted landscapes, and much less focusing on resilience planning and evacuation. This sets a great opportunity to think about resilience and evacuation's benefits for city planning, their benefits need to be seized as we start to get more room for development, and less areas for road infrastructures. The cost-benefit of Autonomous Driving systems free expansive parking lots and impervious surfaces, and paint a radically new way of envisioning the city, where evacuation lines can be designed in this planning renaissance phase.

iii. Technology and Mobility for Evacuation and Rescue

Technology and mobility are starting to draw more attention for disaster response and planning. There are two topics the paper discusses with regards to the subjects of technology, mobility, and evacuation: An independent Boss AV system, and Autonomous Vehicular Clouds (AVCs).

1. The first is an independent autonomous apparatus called Boss (The DARPA Urban Challenge winning research) which is a compilation of AV, on-board sensors that use GPS, radars, lasers, radios and cameras, and a local database of information. This instrument can function in disconnected areas, tracks surrounding vehicles and detects static obstacles, ultimately adjusting for an optimum route against the road model. It has a 3-component planning system integrating mission, behavioral, and motion planning to evacuate urban environments.

The mission planning component analyses best and safest street route to take to achieve the mission goal. The behavioral component determines which (and when) to change lanes/streets and executes error recovery re-routes. The motion planning component decides on the best course-of-action to evade hindrances as Boss ensures achieving the primary goal of reaching evacuation target.(Gelenbe & Wu, 2012)

2. The second is a networked, interconnected compilation of cyber-physical-human systems that are becoming a crucial component of all large scale physical infrastructures and moving people/goods. Otherwise known as Autonomous Vehicular Clouds (AVCs) that are comprised of Cyber-technical systems (CPS) using wireless technologies and responding intelligently and quickly to emergencies, micro-sensing and micro-electro-mechanical systems (MEMS), and distributed decision-making within the network. While this method acts as a fleet rather than a singular, independent entity as in the case of Boss, it allows for immediate local understanding of events and larger mapping and sharing of information during an evacuation scenario. (Gelenbe & Wu, 2012)(Eltoweissy, Olariu, & Younis, 2010)

The AVCs function as a platform absorbing information from the surroundings (and other cars within the network), ultimately feeding it to the cloud-infrastructure to assist in safe navigation, pollution and traffic mitigation. There are existing efforts to realize AVCs in planning, pioneered by companies like Google with the Google car. The system is a distributed transport network with a high degree of independence in evacuation procedures, and have interconnected storage, intelligence, and learning capabilities.(Gerla, Lee, Pau, & Lee, 2014)

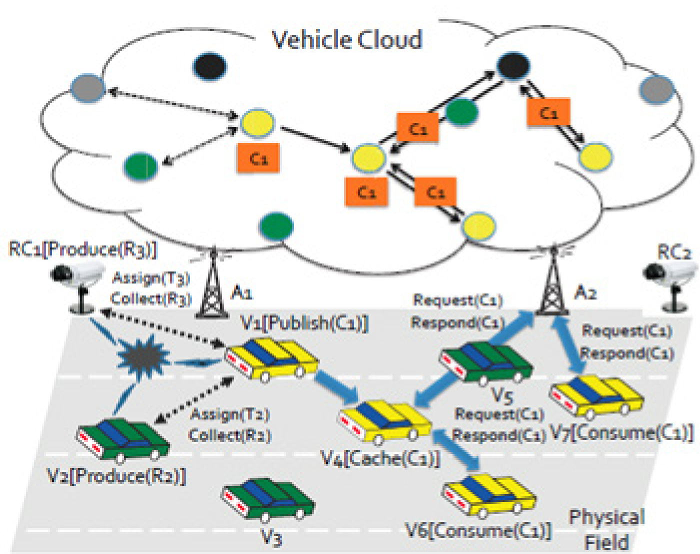


Figure 10 Gerla et al's demonstration of networked AV systems

The problem with the mentioned technological feats in evacuation is they have not been advanced and applied beyond their competition scale. There are currently no planning agencies who accept the potential in this technology with respect to evacuation planning. The Boss AV system provides great prospect for regional connectivity, and has the great advantage of accessing remote areas that might lack infrastructure such as wireless connection towers. It also requires less physical intervention and can function in remote areas, far from the urban core such as around suburban territories. AVCs on the other hand work as a network of carriers feeding into each other and back to the central towers, calculating best re-routing decisions and gathering more information on the local scenario, their quick awareness and adjustment to navigation could aid challenging aspects in disaster response and access to shelters, where moving thousands of people to safety makes time a valuable asset.

f. How Some Large Metropolitan Planning Organizations Are Preparing (or not) for Autonomous Vehicles (AVs) in relation to evacuation

A recent report by KPMG on the progression toward autonomous systems has shown that countries such as the Netherlands and Singapore have the highest scores in readiness to AVs, ranked systematically through policy and legislation, technology and innovation, infrastructure, and people's acceptance. Although hindered by its sheer size and largely disparate environment, the US is in the third order ranked 1st in technological innovation with key industry partnerships.(Threlfall, 2018) It is no surprise to see places such as New York City, Boston, and San Jose working hard to push for AVs, as they are hubs of technology industry and have progressive agendas in city planning. In 2016, Boston was leading with a 191-acre waterfront industrial district that is set to have autonomous driving as a primary mobility apparatus. Backed by key Massachusetts Institute of Technology self-driving start-up nuTonomy, who partnered with Lyft – a ridesharing platform –followed by other initiatives attempting to incorporate existing infrastructure of public transportation with autonomous systems.("Top 5 American Cities for Autonomous Vehicle Development | DMV.ORG," 2017)

Regionally, metropolitan planning organizations (MPOs) are venturing into autonomous vehicles with early adoption scenarios. Atlanta, San Francisco, and Seattle are key players of adoption prediction on travel behavior and regional connectivity. Others like San Diego and Pittsburgh are leading the region on connected and autonomous transportation methods.

Future planning should address the most agreeable and pressing component in urban environments of sustaining and protecting human lives. While it is likely that MPOs are open to discuss AVs in their vision plans, they are neglecting the crucial need for city planning to concretely incorporate AV mobility systems. The usual outcome for the attempts would include AVs thinking in a tertiary fashion, coupled with many other variables to create less-concrete projections of their use and application.(Guerra, 2016) More importantly, reflecting on the impacts of disasters such as Hurricane Sandy and AVs potential to save lives has not really been discussed as vigorously. For example, in time of this research there was no literary work on the potential benefit AVs could have brought to a past flood event. All of these points are reassuring cities general perception of AVs to be superficial.

g. AVs and Planning for Resilience

It is important to think about autonomous systems in lieu with saving lives in disasters. Research has shown Connected AVs have a higher response rate to sudden changes, and reduce traffic flow and shockwave buildup.(Talebpour & Mahmassani, 2016) In a disaster situation where time is of the essence, making the most effective decisions in the least amount of time is key to ensure the maximum number of vulnerable communities taken to safety in the least number of trips. A live update on local events, high computation capabilities, and internal communication can ensure the best and most optimum route toward disaster zones.

Within the urban planning field, there is increased research exploring economic and environmental costs on cities like the efficiency in time-cost and travel speed, and alleviation of traffic congestion. In contrast, little research is taken on how automation can benefit cities in times of distress. With even less literature in harnessing AVs capacity to mitigate climate change and save human lives in natural catastrophes. Initiatives like the Smart Emergency Response System (SERS) conducted in 2013-2014 at SmartAmerica challenge with teams including Massachusetts Institute of Technology, MathWorks, National Instruments and others sought to establish an autonomous cyber-physical system for this purpose. While it is not topography-specific, the system attempts to utilize existing infrastructure and integrate a set of technological tools achieving optimum routes and escape methods around obstacles, using 6 main hardware elements: WiFi drones, Biobots (dogs with sensors), KUKA robotic arms, Haptic devices for remote operations, ATLAS humanoids, and a fleet of AVs and unmanned autonomous vehicles (UAVs).(Mosterman, Escobar Sanabria, Bilgin, Zhang, & Zander, 2014) Others have thought about these cyber-physical-human systems in large scales to contemplate evacuation methods, ultimately assessing the best and optimum evacuation routes with sensor networks, communication systems, and computers to enhance the human outcome of emergency scenarios.(Gelenbe & Wu, 2012)

Conventional planning techniques seldom mention the capacity of planning to address disasters through technology. A research has already shown that all interviewees who are related to the field of planning through governance or profession to see the profession through a generic lens. When thinking about future planning – in response to planners' neglect post-the-steam engine leaving the stage for engineers – professionals still follow the status quo of planning by limiting planning thought to traffic safety, capacity, land use, and travel behavior. There was a strong emphasis on the uncertainty of future planning – that the practice is unsure where and what to think about.(Guerra, 2016)

i. Access in Disaster Response – Lessons Learned from Harvey

To get a better understanding of the response time frame in flood-related disasters, this chapter examines how Houston dealt with disaster over the 6-day timeline of Hurricane Harvey. Houston and Boston exhibit different characteristics and have different demographic makeup, however the means of providing egress to people during the evacuation process has been documented adequately and the lessons drawn have overarching relevance to other cities implementing disaster preparation measures.

When a region gets hit by a storm and/or flooding, two critical steps are key to ensure a minimum life-loss cost: access and coordination. People will need to have access to information, communication networks, and connecting infrastructure that can take large numbers of people to safety. Ample time for preparation before event anticipation and the first 72 hours after a disaster are crucial to mitigate as much damage, and save as many lives in the affected area. The United Nations Office for Coordination of Humanitarian Affairs (OCHA), which is the UN's emergency coordination organization, outlines 5 key steps in dealing with disasters relating to storms and flooding and are summarized below.(OCHA, 2017)

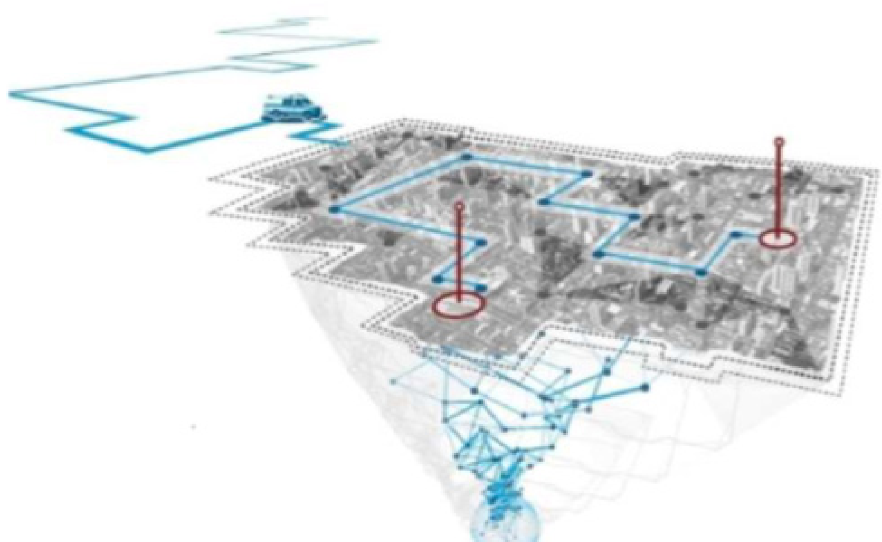


Figure 11 Mosterman et al. Illustrative presentation of the optimization process on a geographic map. The command centers (in red) assess available resources and incoming requests to generate the best course of action for a rescue mission

1. Preparation
2. Skilled Staff Deployment
3. Understanding local context
4. Access response capacity
5. Funding mobilization and operation planning

All of the 5 steps share a common theme of dealing with accessibility in one form or another. Whether it is to gathering information in preparation for a disaster, such as understanding trajectory of a storm and its potential power, understanding geospatial characteristics for staff deployment in most effective strategies, or information on local context and connection to evacuation routes, accessibility to these different elements are the backbone of an optimized evacuation process.

There are human and material costs from delayed action after a disaster. Hurricane Harvey was the priciest and most shattering category 4 hurricane to hit Texas since 1961, with estimated damage between $150-200 billion. The hurricane had an impactful landing, after which it demoted to a tropical storm for the next 5 days causing catastrophic inundations(“Preparation, Response and Lessons Learned from Hurricane

Figure 12 Rescue boats fill Tidwell Road as they help flood victims evacuate as floodwaters from Tropical Storm Harvey rise Monday, Aug. 28, in Houston. AP Photo/David J. Phillip`

Harvey," 2018). We can look at the timeline to get a better idea on response times and how they fluctuate, especially in their early stages (See appendix A). We realize high frequency as the storm forms; Harvey's severity from category 3 elevated to category 4, and its eye of the storm making landfall in just 8 hours. The next few days see a gradual degradation in severity as the storm exits through the southern coast. So the early stages in a storm are the most critical and damaging. In fact, the same study that outlined this timeline explained the Harvey's most important issues to be four main elements which are listed below.("Preparation, Response and Lessons Learned from Hurricane Harvey," 2018)

1. Lack of access to patients, hospitals, and transport methods (for people and ambulances)
2. Quick reaction in moving people and goods in hour-by-hour basis
3. Malfunctioning critical infrastructure
4. Inadequate redundancy to absorb people

h. Conceptualizing and Designing a New Autonomous Evacuation System

This thesis explores the potential of autonomous mobility to mitigate flood's impact on life loss during disaster events. Instead of assessing AVs or flood impacts separately, it will look at the potential overlap where AVs can provide an obvious utility by transferring people and goods during disaster response times. Specifically, the paper will look at current projections of flood events in the Boston region, configure adapted autonomous "resilience districts" and compare them against existing evacuation routes to modify for resilient connectors – this can have huge impact on reducing lives lost during flash floods or storm surges, which have been increasing in the recent years.

To set precedent for the districts, this thesis will study the impact of one of the Everett-Malden area looking at the effect of autonomous evacuation on surrounding urban form, and set guidelines for flood resilience design around the AV routes using the following principles:

1. Analyze 100-year flood-vulnerable areas and secure critical infrastructure
2. Setting a flood-prone zone, or 'Tier 1' by creating a thick hard/soft system of defense and fully autonomous evacuation line utilized by AVCs
3. Locate and densify safe area, this will be called Tier 3, and designate AV lanes on existing 'evacuation' classified roads for Boss AV-like technology
4. Identify medium-risk zone, or Tier 2, and use to incentivize transfer to Tier 3
5. Replace car dependent land-uses that are reverted due to AV technology with ecological elements for flood mitigation, and future miscellaneous land-uses.

Using these principles and looking at a specific district within the area of study, it will analyze micro-scale components and assess land-use implications of using autonomous evacuation systems, ultimately gaining a better understanding of how might conventional planning prepare proactively for autonomous mobility and zoning.

3.
Floods, and Resilience Districts in Boston

a. Intro to Flood Events in Boston – General Climatology

Flooding in the Boston Metro region is generally a result of heavy rainfalls and snowmelts, nor'easters, and tropical storms that occur at seasonal transition periods. Severe events such as the floods of 1936, 1968, 1987 are triggered by heavy rain and snowmelt, alternatively, those in 1927, 1938, and 1955 are a byproduct of the heavy winds, storms and intense hurricanes preceding them. A record of all these events is displayed along a timeline below demonstrating the frequency of flood/drought events in Massachusetts, where the color denotes the type of natural event and the size of the shape correlates the probability of it to happen (bigger circle relates to flood events that are expected to happen less frequently).("USGS WSP-2375, Massachusetts," n.d.)

Massachusetts Record of Floods and Droughts

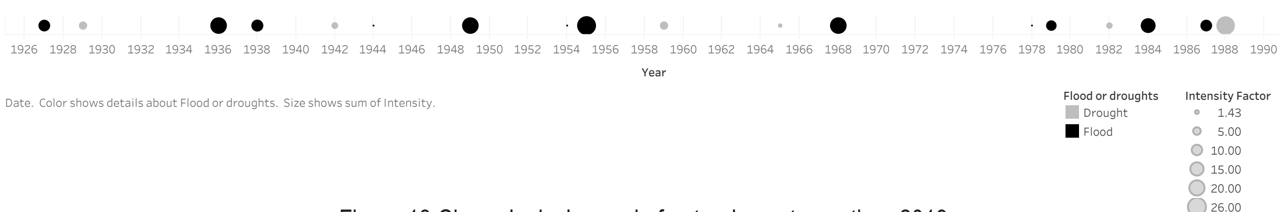


Figure 13 Chronological record of natural events - author, 2019

Floods are the primary natural events causing losses to life and infrastructure in the region. They are boundary-agnostic and function primarily in a way to stabilize Earth's metabolic cycle through heatwaves, droughts and floods. The frequent intense flood events historically show an average of 6 years between each two, with that gap narrowing (see Figure 13). Superstorm Sandy in the late 2012 was a wakeup call for the region to start consider critically methods of disaster mitigation. Multiple initiatives are being done since to prepare for climate change, with the latest being Climate Ready Boston's Charlestown report, putting Boston high on the map and one of the leaders in the topic of resilience.

There are several studies on how sea level rise (SLR) would affect the city of Boston. It is agreed among most researchers that an average of 19 inches (1.5 ft) increase to be a realistic estimate impacting the city by 2050, with some studies by William & Mary's Virginia Institute of Marine Science (VIMS) suggesting a more severe impact on the east and gulf coasts.("Boston Sea Level Projected To Rise 1.5 Feet By 2050," 2018)

b. Current Planning Districts/Townships

The current geo-political boundaries for the different townships in Massachusetts aim to manage and govern smaller subdivisions within the state, and are defined as administrative boundaries managed by local governments. These boundaries, otherwise known as districts, are a product of the established mechanisms by the state of Massachusetts and are broken down into governance areas for:

1. General State Law
2. Special Act of the Legislature and
3. Municipal Home Rule Authority, Bylaws, and Regulations. Taken from the district planning document of the state of Massachusetts on Mass.gov

The Boston Planning and Development Agency (BPDA) established a zoning law for the City of Boston to build on Massachusetts districts guidelines. Driven by factors such as shape, density, development types, and neighborhood character to create the boundaries for planning different neighborhoods.("Zoning | Boston Planning & Development Agency," 2018) With 26 neighborhoods set as planning districts within the

Figure 14 Existing township boundaries

City of Boston, the districting mechanisms here focus on health, wellbeing, generating economic benefit such as taxation, and seeking sustainable planning approaches of waste recycling and maintaining clean water.

c. Defining a Resilience District:

The chapter defines a resilience district as a set of lines that reinforce natural topography, act as a boundary to share resources, and are influenced by existing socioeconomic and infrastructural elements, such as where population densities occur, and where major transits or hospitals can be located. The resilience districts are designed to mitigate impacts from a natural phenomenon that affect the dense cores, and demote developments in flood-prone areas through a tiering system. Alan Berger explains his research on Rebuild By Design, (44:02) in “Sink or Swim”, that resilience districts are an incremental approach to climate preparation, versus the application of large, singular walls or civil engineered infrastructures in a region that suffers from “megaproject fatigue.”(Berger, 2015)

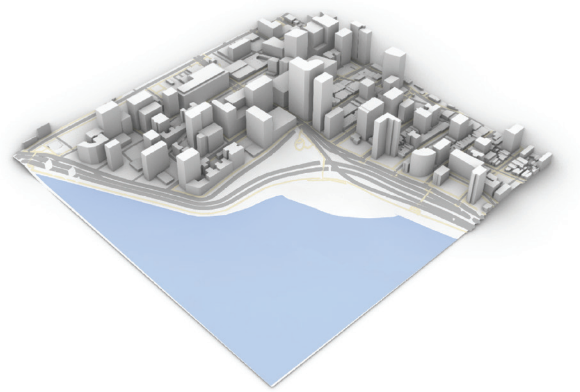
This research builds on the 4 steps of a resilience district explained by Alan Berger in “Sink or Swim” to integrate the process of density transfer and flood mitigation farther, the steps described in his lecture are outlined below (Berger, 2015):

1. Identify and protect critical infrastructure within the area such as energy supply centers and food storage
2. Build a thick line of defense using a combination of infrastructure and soft systems
3. Up-zone and transfer density from the most vulneravle area
4. Downzone vulnerable areas around the edge through legislation and policy such as through insurance premiums

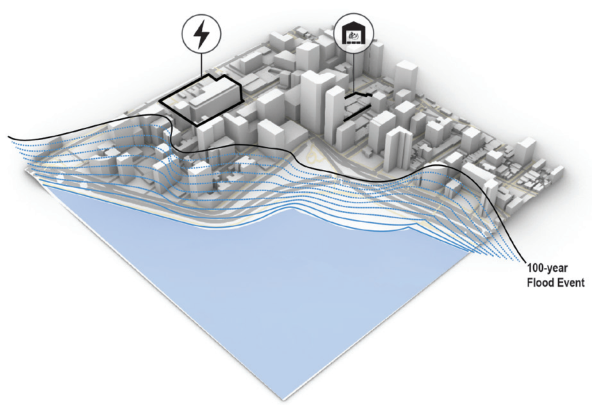
Building on these 4 points, the chapter below imagines an integrative process of analysis and implementation, ultimately understanding districts to have sublayers of vulnerability within, and with the use of policy and urban design the process of density transfer can be realized in the future. As a result of this thinking, the research proposes the following iteration in the set up of resilience districts to have the following steps:

1. Analyze 100 and 500-year flood-vulnerable areas that may impact critical infrastructure and take steps to secure these areas
2. Setting a flood-prone zone, or ‘Tier 1’ by creating a thick hard/soft system of defense through the integration of landscape strategies and infrastructural developments
3. Locate and densify safe area, this will be called Tier 3
4. Identify medium-risk zone, or Tier 2, and use to incentivize population to move to Tier 3 through regulation, such as setting attractive living costs, insurance premiums, and policy measures.

The following example attempts to conceptually illustrate these 4 steps:



1 ANALYZE AND PROTECT
IDENTIFY FLOOD-VULNERABLE AREAS AND SECURE CRITICAL INFRASTRUCTURE



1 **ANALYZE AND PROTECT**
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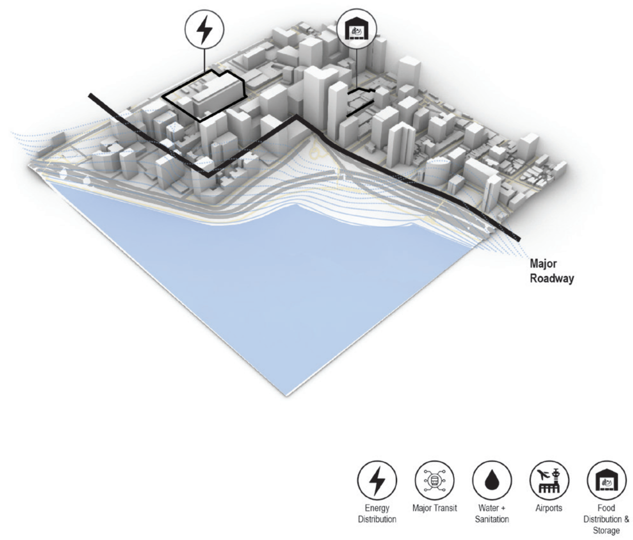
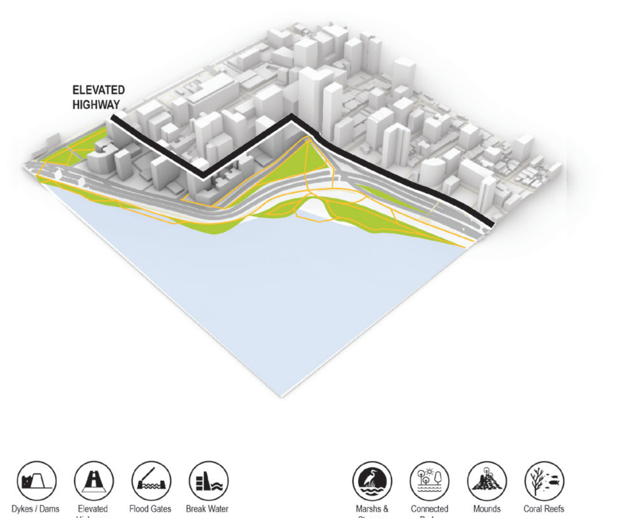


2 **SET TIER 1**
CREATE THICK HARD/SOFT SYSTEM OF DEFENSE



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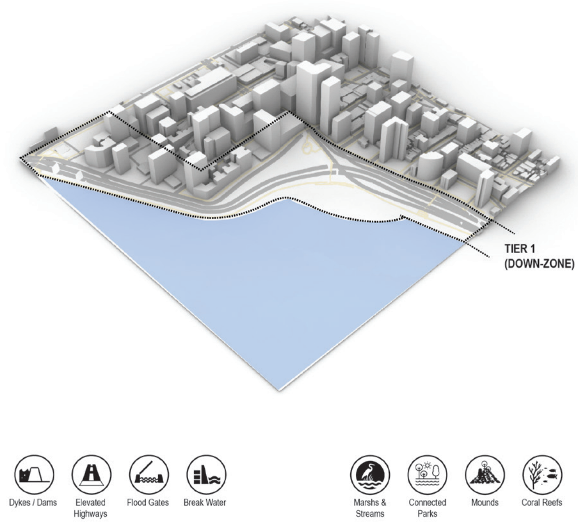
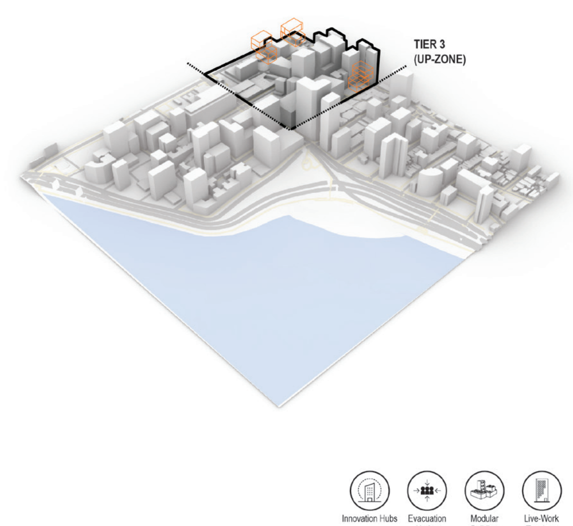
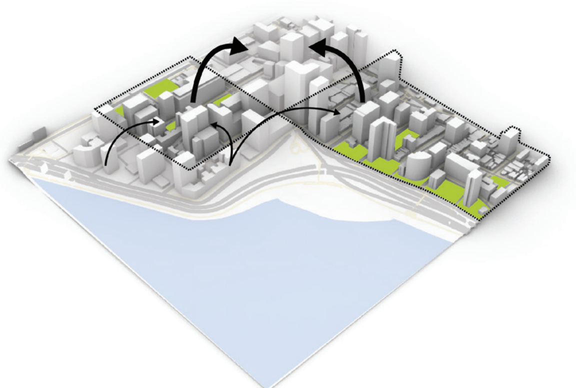


3 **SET TIER 3**
LOCATE AND TRANSFER DENSITY TO SAFE AREAS



4 **SET TIER 2**
IDENTIFY MEDIUM-RISK TIER AND INCENTIVIZE TRANSFER TO TIER 3



Flood analysis of the Boston Metropolitan region shows major areas of Boston to be well under one foot of water, with some being flooded with over 10 ft from floods in a 100-year surge event ("Woods Hole Oceanographic Institution," 2019). In order to understand evacuation as a function of floods and storm surges, district boundaries should incorporate all the elements that help manage townships and progress their economy. Most importantly, district boundaries must be responding to natural phenomenon, where topography makes it unviable to develop, for example. Floods and storms are the key determinants in setting a tiered districting approach, comprising of a downzoned area, a transitionary area, and an up-zoned area.

Downzoned areas, or tier 1s, are ones that are most prone to 100-year flood events, and are incentivized to be down-zoned, with objectives of establishing landscape elements and hard infrastructure to connect and protect areas within. Any existing critical infrastructure within this district must be protected in the short term and transferred to a safe location in longevity.

Transitionary areas, or tier 2s, are the areas between the highly vulnerable coastal floodplain and the dry inlands, with the goal of promoting density transfer in tier 1, and ultimately pushing its inhabitants to move to tier 3. It is set to facilitate movement of resources and people to the safer up-zoned tiers 3.

Up-zoned areas, or tier 3s, are areas facing minimal risk from 100 and 500-year flood events, and act as an attraction area for flood-vulnerable communities to move to through policy and regulation.

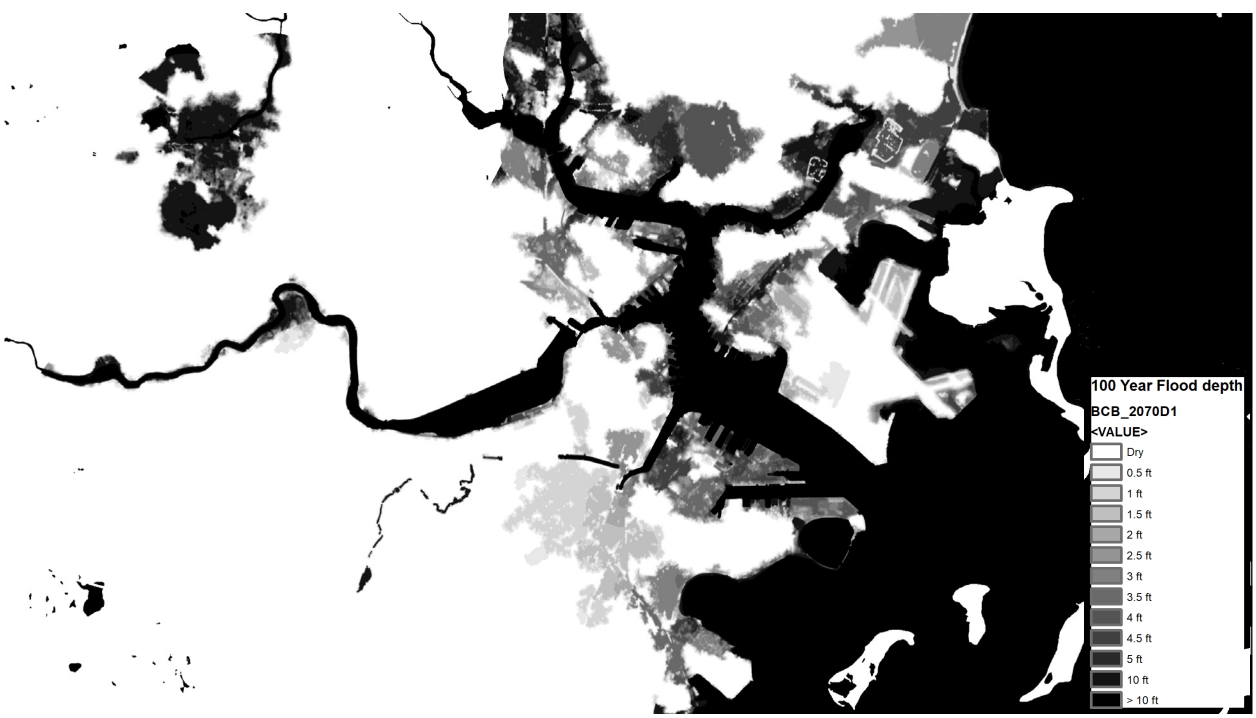


Figure 15 Regional 100-Year Flood Analysis

d. Boston Resilience Districts

Applying the definition of resilience districts to Boston yields the map of 9 select districts around the Boston area (see Figure 16). The lines denote the boundaries of each district, and the colors explain the tier structure from the previous section. Dark gray indicates areas of high flood-risk and is bound by major roadway systems, light gray is the transitional medium flood-risk zone that promotes transfer through up-zoning whether through policy and land use designation, or through a credit/tax system. To relate the Boston Resilience districts with the flood analysis, one can observe the vulnerability to flooding as one of the key mechanisms in establishing the logic of boundaries between zones.

The mechanism of devising the districts rely on ecological, as well as socioeconomic characteristics to find opportunities of sharing resources. For example, Somerville and Cambridge being dominated by educational institutions and occupied by a similar demographic of young populations, have floodplains bleeding through their territories, and their common use shared public infrastructure are envisioned as a singular district that has differently regulated tiers – based on flood severity and the need for resilience planning. To demonstrate further why this districting is suitable in thinking about autonomous evacuation, this chapter selects one of the designated districts highlighted in Figure 17, and show the breakdown of the 3 tier designations within this boundary.

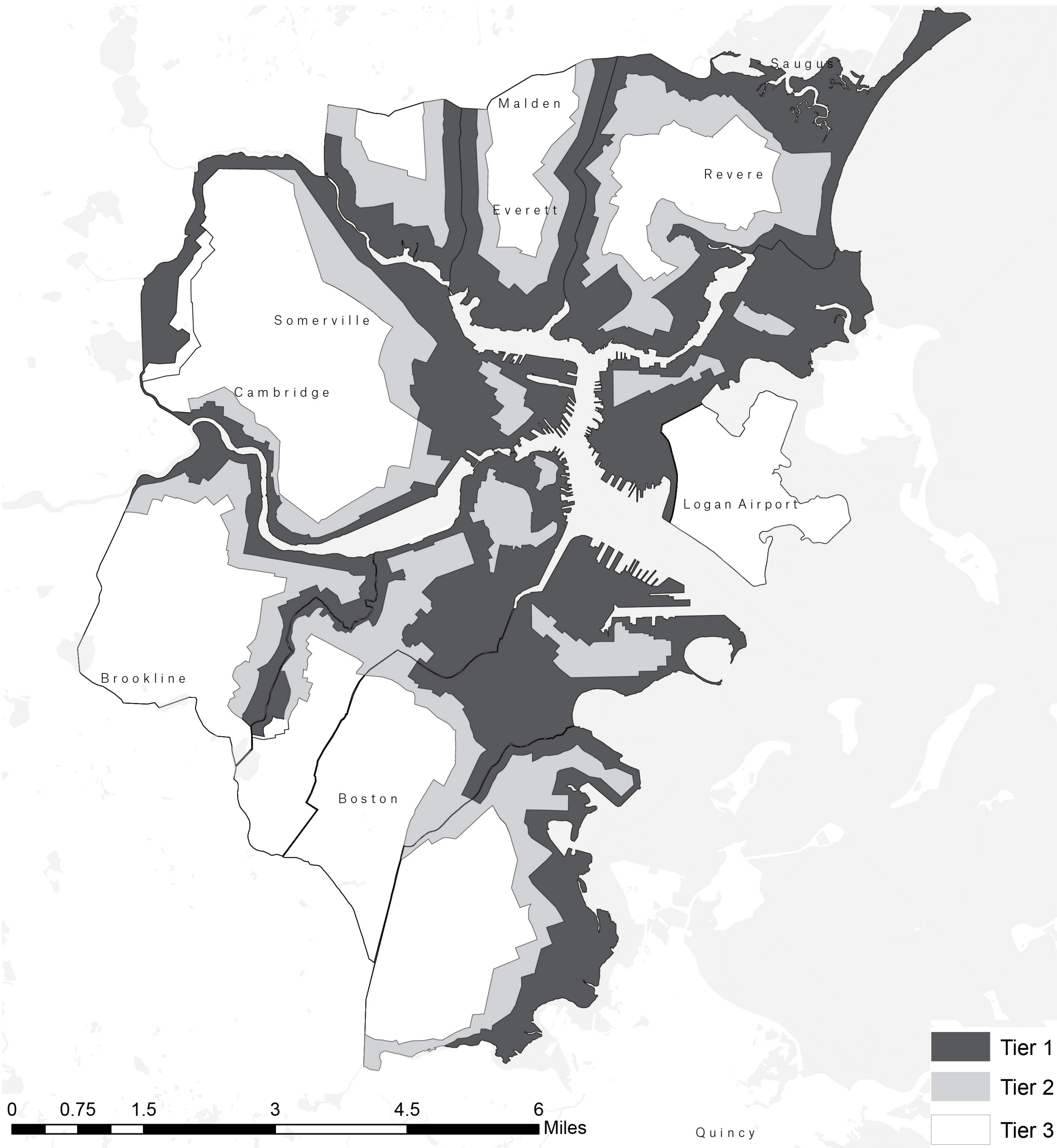


Figure 16 Tiers within the Boston Resilience Districts

e. Everett-Malden: Case Study District

The Everett-Malden district, shown in Figure 17, is used in the following flood-risk analysis and later in thinking about autonomous evacuation. Specifically, an analysis is carried exploring the district and each tier to observe different information, such as the 100-year flood event affecting it, economic characteristics, social qualities, and infrastructural components to reveal areas of risk, density, and potential development. The selected district i.e. Everett-Malden is understudied as most of the research focus is around the, otherwise popular, Boston area, Cambridge, and Seaport Square, making it of real value as a leader for the following research. With only one major evacuation route connecting the Everett-Malden area to the CBD being the 99, efficiency, autonomy, and optimization in times of crises are arguably key to save inhabitants' lives.

Indeed, as the 100-year flood analysis diagram shows, much of the south and the west of the district is highly susceptible to being 10 ft under water (Figure 17). These are the areas at the gateways of these towns and into the neighboring metropolitan area. The exceedance probability map showing how likely flood would exceed the 1 percent depths disclose concerning impact on the residential district just off the shore. On the West and the homes adjacent to Eastern Ave toward the Eastern portion of the district are facing flood exceedance likelihood of 20% and 100%, respectively.

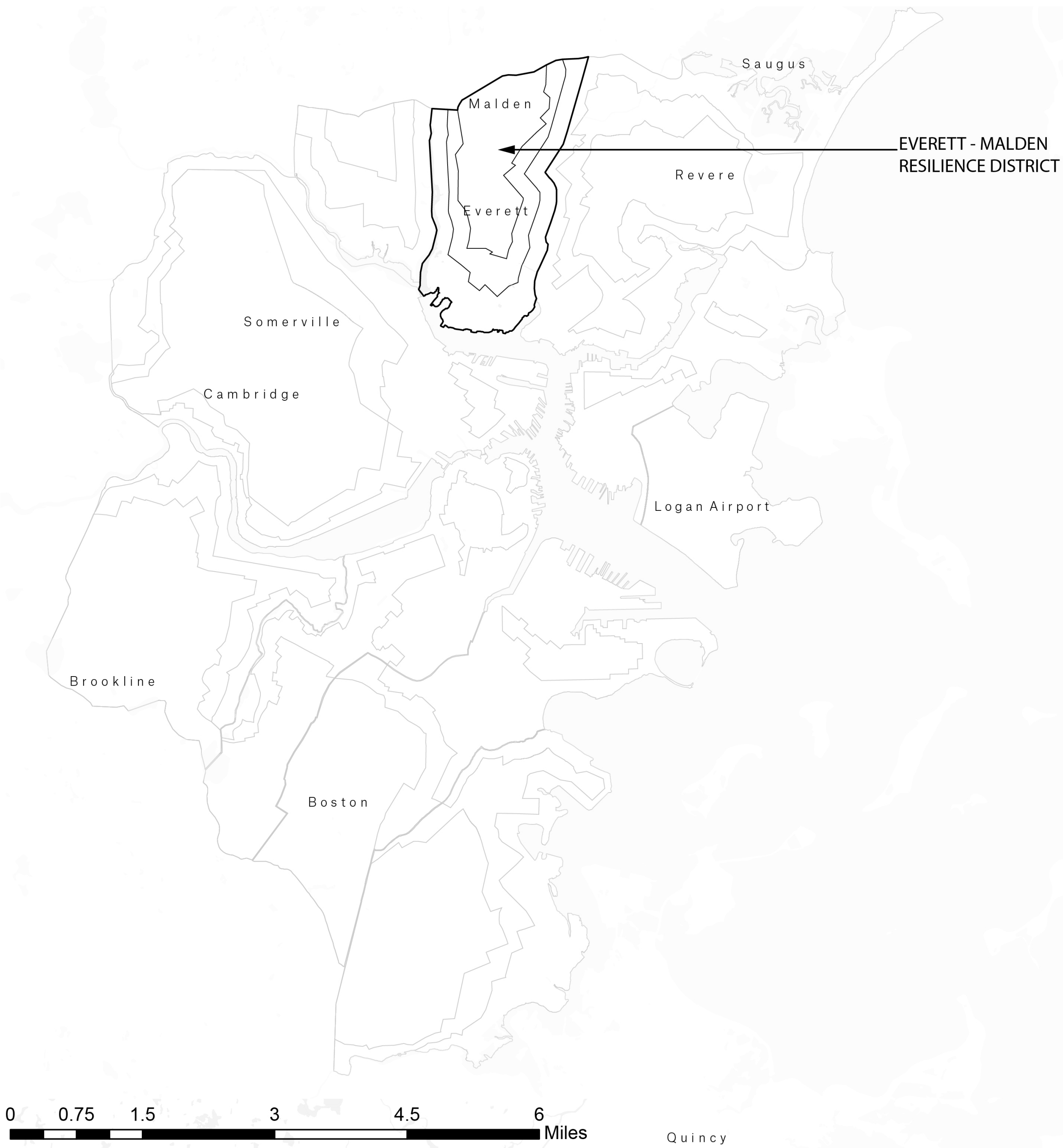


Figure 17 Identifying The Everett-Malden Resilience District

f. 100-Year Flood Analysis

The flood analysis map is given in a 100-year time frame. Some studies use 2070 as the scenario timeframe as a standard measure, others refer to it as the 1% flood scenario.

For the given period, the paper explains the potential impacts for each level of seawater/storm surge flood, taking into account three measures in the backend of the analysis:

1. Based on topographic nature and other characteristics, what is the likelihood of a particular location to experience a flood in a given year and,
2. At what depth is a given location likely to be flooded in a 100-year flood situation
3. Takes into account the impacts of storm surge and the ability of water to drain quickly inland (i.e. the bathtub effect)

Storm surge is the product of water forcefully moved inland by strong winds stirring "cyclonically around the storm", where the wind's influence on surge being forced towards the shore is greatest.("Storm Surge: Coastal Systems Group," 2019)

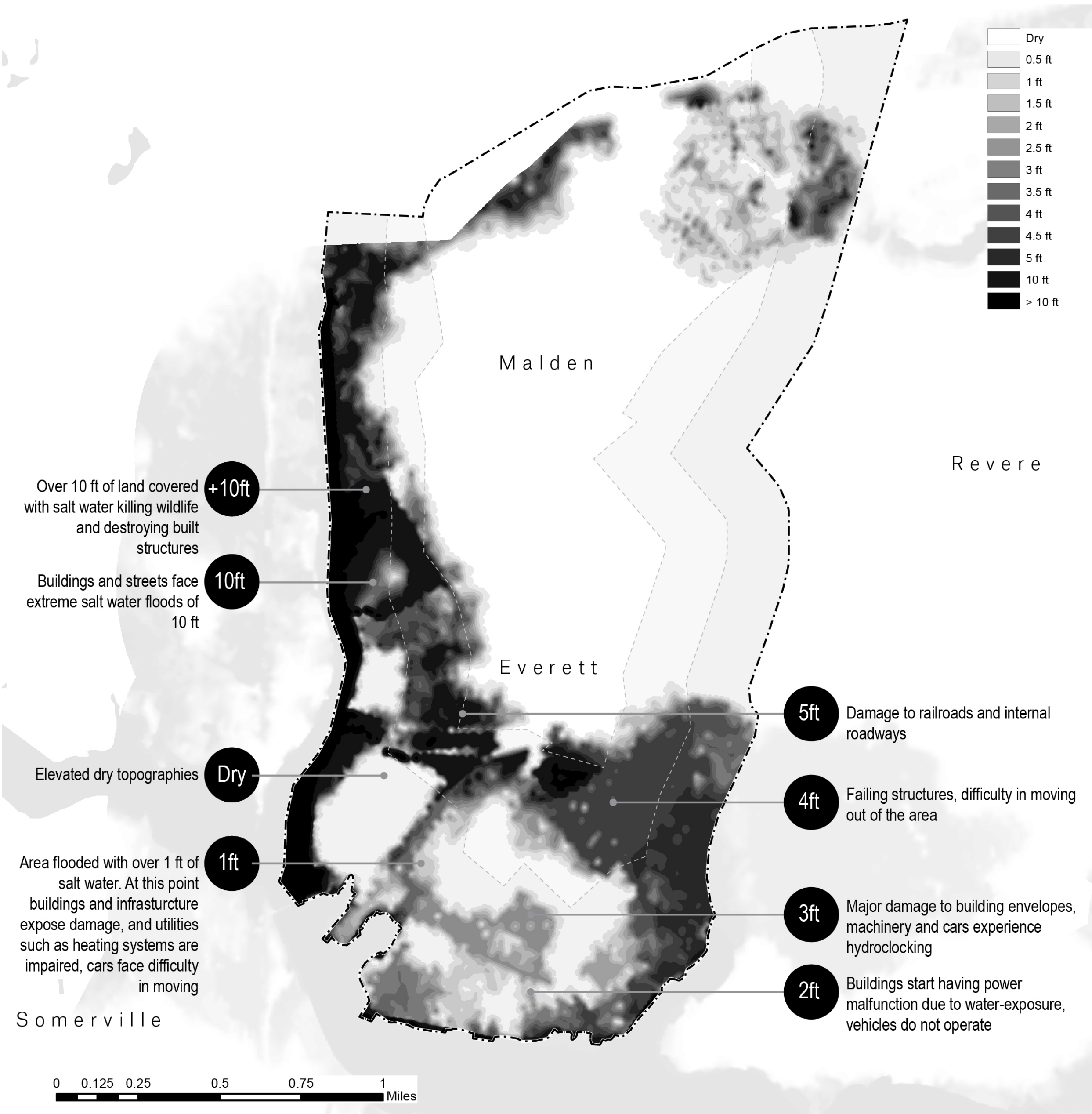


Figure 18 100-Year Flood Analysis

i. Flood Exceedance Probability Analysis

There is a high confidence (100%) of flood exceedance in a storm surge on the eastern and most critical portion of the district. This is the place where major food distribution centers and rail lines operate on a regional level, transporting goods and facilities to the downtown area southward, as well as to the wider region in the state.

The only entry point from the south is expected to flood beyond 3 feet with 30% confidence levels as per the analysis. In such a situation, serious damage can cause deficiency in the most crucial (and only) road to the towns of Somerville, Cambridge, and Boston to the wider region to the north through this district.

Other key utilities such as regional railroads, local retailers, food suppliers, and a high school the north of the district face a probability of exceeding their estimated flood levels.

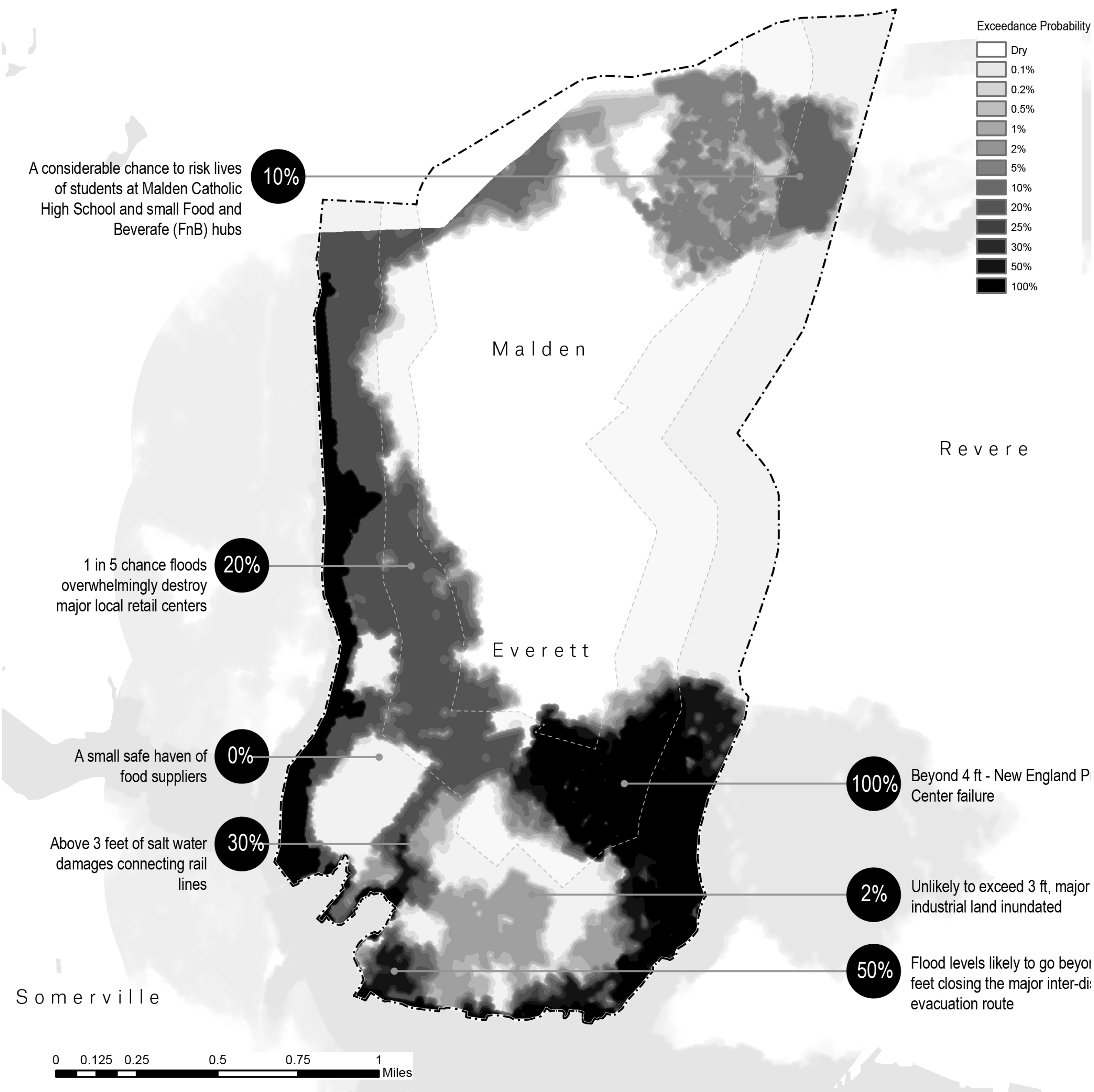
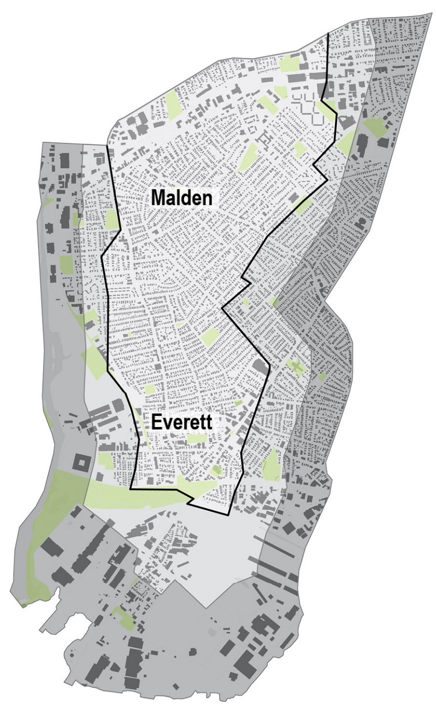


Figure 19 100-Year Flood Exceedance Probability Analysis

g. District Breakdown

Known for its safety as a family's choice to live makes the resilience district of Everett-Malden of peculiar importance as a residential area. We learned from the flood analysis (Figure 17) much of the Eastern and Western parts of this district are prone to inundation, with most vulnerability lying around the main ports of entry/exit at the southern part of the Everett-Malden district. In addition to flood risk, the demographic breakdown of this district reveals some new relationships within its inner territories and the peripheries. First, the highly vulnerable tier 1 is the densest in this district – mainly white – with relatively high income compared to the rest. Second, the land value depreciates toward the inner, safer portion of the district, setting a great opportunity for planning and development interventions in for transferring residents from the downzoned tier.

The up-zoned tier is susceptible to receiving density having ~11,000 persons/sqmi compared to tier 1's 14,000 persons/sqmi. It is also culturally diverse with ~6000 people per square mile being of ethnically different backgrounds, has lower land costs to purchase or develop, and with only 0.3 sqmi area in a floodplain.



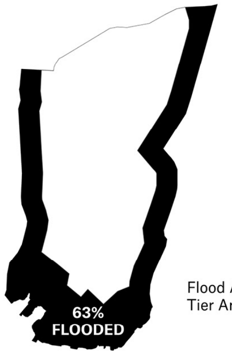
	TIER 1 / DOWNZONE	TIER 2 / TRANSITION ZONE	TIER3 / UP-ZONE

TIER 1 / DOWNZONE

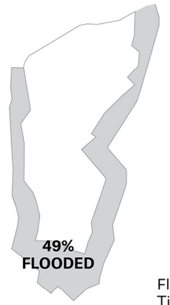
TIER 2 / TRANSITION ZONE

TIER3 / UP-ZONE

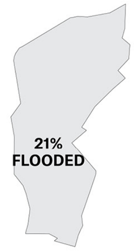
FLOOD RISK



Flood Area: 0.95 sqmi
Tier Area: 1.53 sqmi

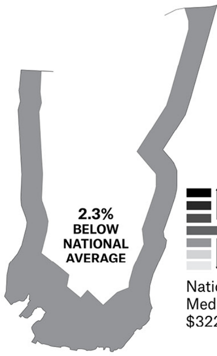


Flood Area: 0.46 sqmi
Tier Area: 0.93 sqmi



Flood Area: 0.30 sqmi
Tier Area: 1.41 sqmi

MEDIAN LAND VALUE

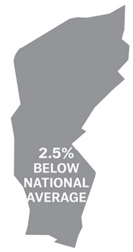


National Average

National Average: $330,000
Median Home Value:
$322,500

National Average

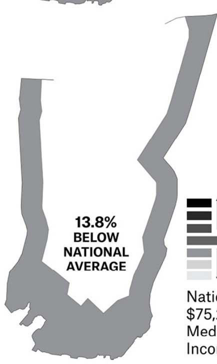
National Average: $330,000
Median Home Value:
$332,400



National Average

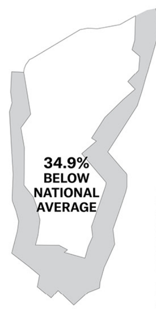
National Average:
$330,000
Median Home Value:
$321,770

MEDIAN HOUSEHOLD INCOME



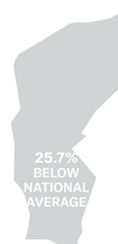
National Average

National Average:
$75,297
Median Household
Income: $64,861



National Average

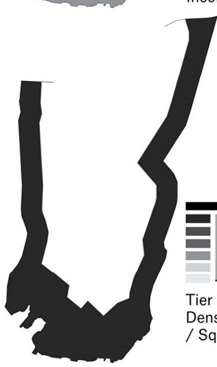
National Average:
$75,297
Median Household
Income: $49,012



National Average

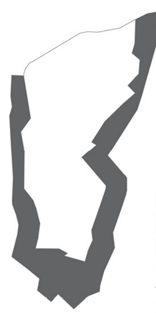
National Average:
$75,297
Median Household
Income: $55,967

POPULATION DENSITY



16,000 People / sqmi
4,000 People / sqmi

Tier 1 Mean Population
Density: 13,668 People
/ Sqmi



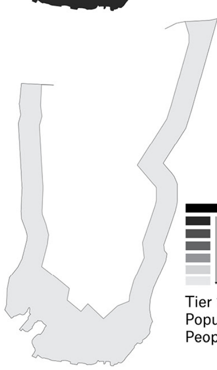
16,000 People / sqmi
4,000 People / sqmi

Tier 2 Mean Population
Density: 10,321 People /
Sqmi

16,000 People / sqmi
4,000 People / sqmi

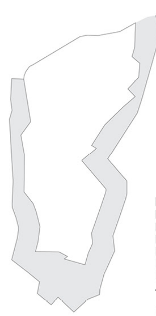
Tier 3 Mean Population
Density: 10,952 People /
Sqmi

NON-WHITE POPULATION DENSITY



16,000 People / sqmi
4,000 People / sqmi

Tier 1 Mean Non-White
Population Density: 4,402
People / Sqmi



16,000 People / sqmi
4,000 People / sqmi

Tier 2 Mean Non-White
Population Density: 4,698
People / Sqmi

16,000 People / sqmi
4,000 People / sqmi

Tier 3 Mean Non-White
Population Density: 6,03
People / Sqmi

4.
Autonomous Vehicles, Infrastructure, and Evacuation

a. From Harvey to Boston Metro - Existing Conditions

i. Existing Regional Evacuation Network

How would Boston Metro cope with a storm event as severe as Harvey? What evacuation methods would actually work and what would be completely flooded should the city face such a devastating landfall? Figure 22 shows the existing road evacuation network (road classes 1,2,3, and 4 as defined by MassDOT(“Massachusetts Document Repository,” 2019)) acting as the backbone for moving people and goods to shelters, critical infrastructure, and dry areas and away from the coast. The way these connections have been identified, as explained on the MassDOT website, is through their potential to link to neighboring regions, capacity to absorb density, and are classified as ‘highway systems’ in the classification list. Adequate connection systems are key to guaranteeing people can move to shelters during storms, fast, so the idea of redundancy – or providing as many connections to the ‘safe zone’ - is a significant strategy to overcome unpredictable failure.

In a 100-year flood event, we see critical areas of the infrastructure to be flooded. Figure 23 which is flood map illustrates the existing system under flood stress with only 1+ foot floods outlined – these are the flood levels that can cause moving automobiles to malfunction due to damage and floating(“In Flash Flooding, Your Vehicle Can Be Biggest Danger,” 2015). In such a scenario, deploying teams for rescue, such as ambulance vehicles to disaster areas or emergency resources transport, is stalled by complications of flood exposing these major connectors’ weakness. The vulnerability of infrastructure can be felt by those affected through the lack of resource access, shortage of shelter (as in the case of Harvey), medical supplies, and food for protecting those affected by storm surges.

Figure 22 Boston Metro's Existing Evacuation Network

ii. 100-year floods of 1ft+ that affect existing evacuation network

In Boston's downtown region alone, 45 linear miles of critical infrastructure become fully submerged in a case of 100-year flood, leaving a large part of Boston disconnected from neighboring towns, isolating it from Dorchester to the south and Cambridge-Everett-Chelsea to the North/Northwest. Figure 23 demonstrates the inundation covering these critical-regional arterials that would otherwise allow for access to aid, shelter, and surrounding medical care to the densest parts of Boston which happen to occur closely to the flooded portions of the city. The resultant fragmented network can have severe implications to future events, especially in thinking solely about moving people from disaster areas with very little access to evacuation mechanisms.

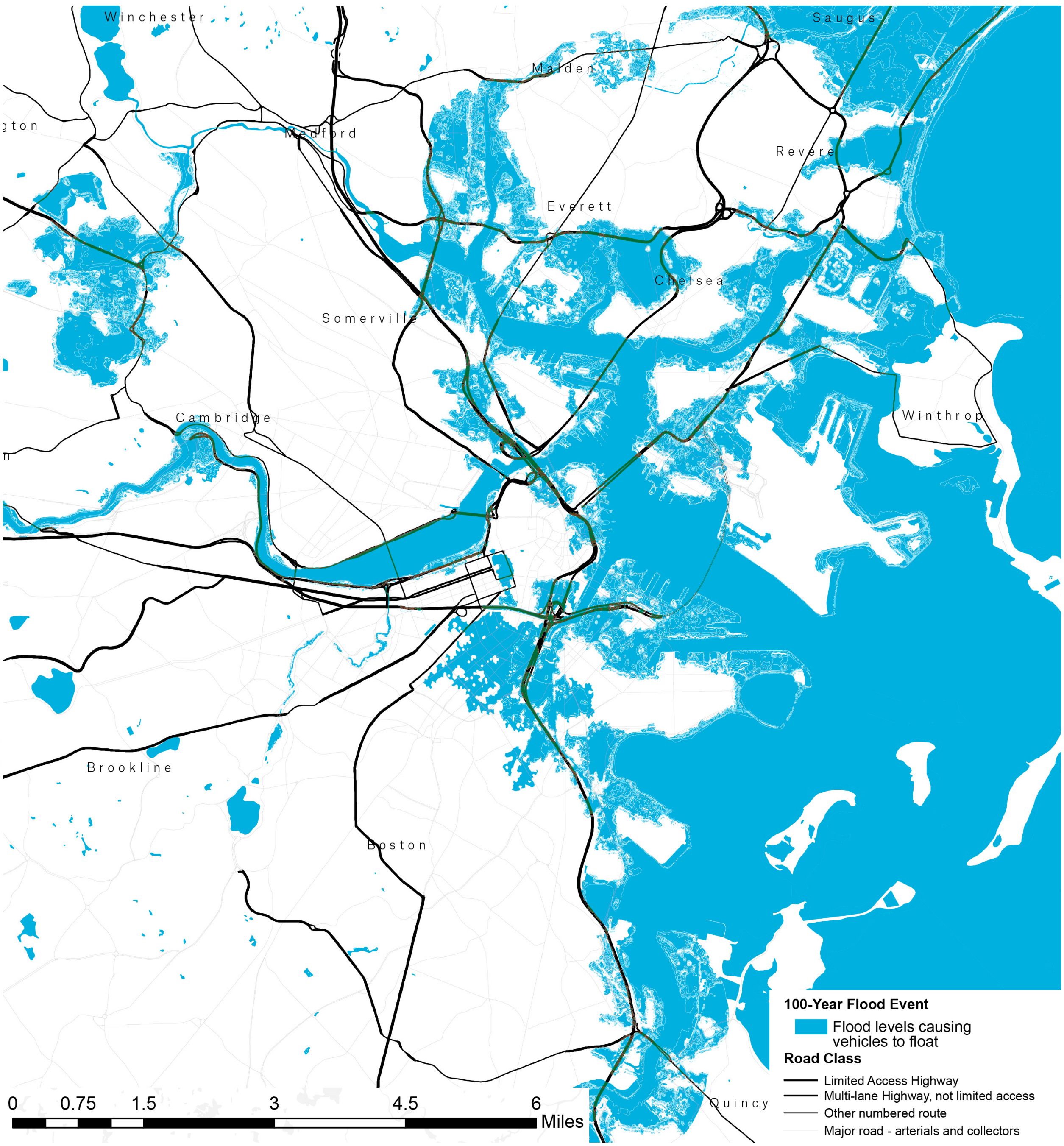


Figure 23 Spatial Flood Analysis of levels above 1 ft

iii. Effective Existing Evacuation Network After A 100-Year Flood Event

After filtering out the inoperable road systems, it is clear the most disconnected areas happen around North and South Dorchester, going North to downtown Boston, Seaport Square, Chelsea and beyond. Coincidentally these are areas with relatively high densities that struggle with finding egress to the surrounding territories.

In the Everett-Malden district alone, there are more than 11,600 individuals living in the most vulnerable areas of the district. In the next section, the research zooms in to this district to look closer at its spatial and demographic make-up, and their relationship to the main connecting regional routes. For reference, the maps in appendix B show both the total population count and density within tier one in all the identified 10 resilience districts (see appendix B).

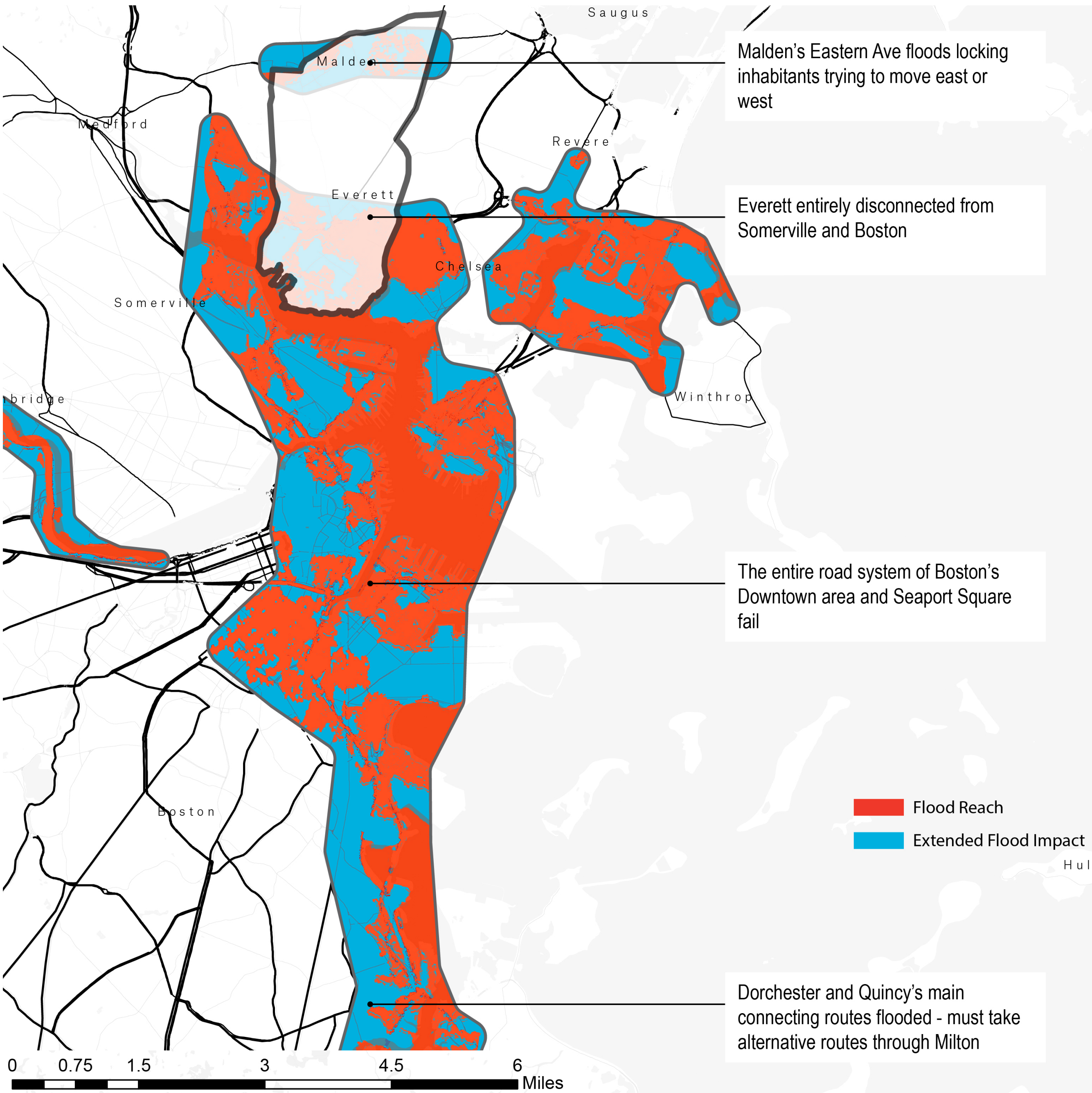


Figure 24 Regional Impact of Flood on Existing Evacuation Roads

b. Everett-Malden Resilience District

Pedestrian access to AV evacuation checkpoints are key in flood prone extents to ensure safe population egress. Set at walking distances, these nodes act as the collection hubs for moving people across the region. The map above shows existing conditions in the district of study, overlaid by the district tiers, with the main evacuation regional connections with darkest lines as evacuation routes. In addition, they also serve as the only connections to the neighboring towns that are otherwise segregated by natural topography and water bodies.

Adding the layer of floodplain helped identify some of the most vulnerable developments within the district – building footprints within Tier 1 – and superimposed the flood analysis to recognize weak zones for evacuation. From this process of layering, the analysis exposes the current building footprints within the 100-year floodplain where vehicular access is crippled to connect to major evacuation routes. Next, the project applies a cost-distance analysis for 5, 10, and 15 minutes of walking and was able to find weak areas of access to evacuation routes that otherwise connect flooded urban developments with surrounding major highways.

Figure 25 The Everett-Malden Resilience District Key Characteristics

c. Urban Densities Impacted by 100-Year Flood Event

The cost-distance analysis takes into account topography and existing roadways (or pathways, for the case of walking) and calculates the fastest and shortest path of travel. For reference and to better understand travel outreach, a 5, 10 and 15 minutes' simulations were run, and the results were visualized in the concentric lines in Figure 26.

The results exposed 6 areas mainly on the south and west of the district having low accessibility rate. The walking results reveal weak linkages to the 2 main evacuation roads: one to the north, and the other to the south of the district. Using the urban cores as a frame of reference, demographic data was extracted from the census portal to see severity on urban densities.

The data reveals a considerable number of people to be affected by lack of access. Specifically, 8,240 people within these zones cannot get to a means of evacuation within 10 minutes in a flood event*. Delving deeper into the data, the study found 86.9% (or 7,165) of this affected population to be classified as non-white. The diagram in Figure 27 shows the population breakdown and location of this density, with a higher number of people to gravitate toward the most vulnerable southern portion adjacent to route 99.

**The analysis-methodology estimates a proportional population based on the coverage of the subject area over the total census area and multiplies by the total population number.*

Figure 26 Cost Distance Analysis around Urban Densities in the Everett-Malden Resilience District

i. Tier 1 Densities Without A 10-Minute Access to Evacuation

What are the potentials of setting a dedicated-route for autonomous vehicles during emergency declaration to evacuate residents? And what design guidelines could cities consider ensuring resilient connecting arterials, which act as the framework for moving people from danger as well as mitigating flood damage? Thinking in line with the distinct tiers helps address most vulnerable areas to floods.

To contemplate the quick transport of 8,240 people to evacuation areas, this analysis concludes nodes for collection where the data revealed a much needed up-to-date transport methods to provide access for the thousands of inhabitants.

To find the best evacuation node locations, an average distance between 2000 and 3000 feet is set as a parameter between each point along the floodplain, this is the average distance it takes to walk for 10 minutes. The locations are decided based on the analysis shown on the map above, where over 15% of building inhabitants lack timely access to major connecting infrastructure.

The current state-of-the-art technology in evacuation can find an appropriate application in the district through two frameworks that the paper will discuss in the coming section: one that functions as a system of Autonomous Vehicle Clouds (AVCs) which make up the prompt response apparatus locally within tier 1, and the other is a fleet of independent Boss AVs connecting the major routes to the larger framework.

As for the AV route designation, the system platform is a reconfiguration of the existing underutilized road infrastructure for autonomous mobility. Ultimately, the roads connect to every development's periphery and onto the major highways. The major highways for independent AVs with an allocation of specific lanes for autonomous mobility become active during a flood event. Using the road as an urban design element with implementation guidelines to mitigate floods from the south makes it a crucial component to preserve the up zoned-tiers to the North, and promote densification in the dry areas. Ultimately, each resilience district would have a 'secondary' autonomous AVCs collection route transporting into a 'primary' independent AVs regional tying with the existing highway infrastructure.

Figure 27 People without a 10-Minute Access to Evacuation Infrastructure

ii. Advanced Evacuation Framework: Proposed Technological Implementation from Literature

Building on the current advanced tech in evacuation, the research proposes a framework utilizing AVCs locally and Boss independent AVs on a broader scale. The local, quickly-responsive AVCs system serve as an ideal evacuation apparatus due to the AVs collective feedback-loop capability of acting as a large scanner of the flooded region. A central communication and command center could be located in a dry, flood-free, zone somewhere in tier 2, 3, or even within tier 1 if there is a patch of underutilized invulnerable land.

The fully AV route (colored in blue) ultimately spills into the existing highway framework and terminates at transfer hubs. The transfer hubs take individuals into Boss AVs that use their independent database, radars, cams, and sensors to navigate through the road system following the 2 designated AV lanes in the 7 lane-average highway system.

The replicability of this system can be applied to all the 9 districts with minimal infrastructure costs, the AVCs fully autonomous routes can be allocated instead of existing underutilized neighborhood roads, and repurposed for AVC internal evacuation. Additionally, the overall connecting highway system can integrate the independent Boss AVs by making minor adjustments to existing roads, such as color coding lanes for AV sensors to detect, and designating specific lanes for Boss AV systems through state and federal policy and legislation.

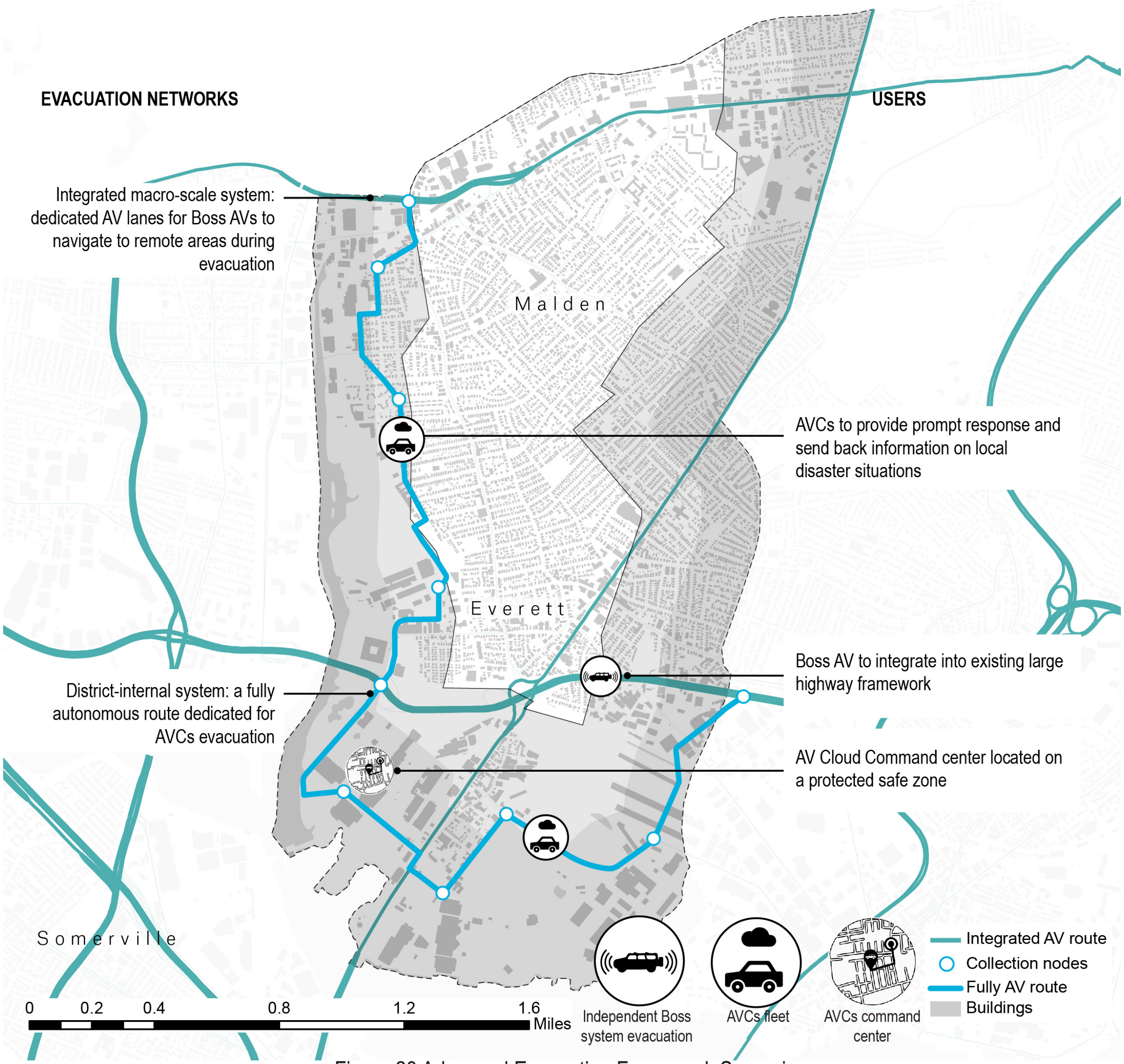


Figure 28 Advanced Evacuation Framework Scenario

d. An Integrated Resilience District Model with an Autonomous Evacuation System

In the process of envisioning an autonomous mobility system, it became apparent that there is a great opportunity of reinterpreting the resilience districting in a more integrated and robust way. A districting methodology where autonomous evacuation networks act as fundamental elements in flood mitigation and tier designation; one where the hard/soft thick line of defense incorporates hard elements of autonomous elevated routes, if necessary. The paper proposes an integrated resilience districting methodology that is not too dissimilar to the one explained earlier, but necessary to maximize accessibility:

1. Analyze 100-year flood-vulnerable areas and secure critical infrastructure
2. Setting a flood-prone zone, or 'Tier 1' by creating a thick hard/soft system of defense and fully autonomous evacuation line utilized by AVCs
3. Locate and densify safe area, this will be called Tier 3, and designate AV lanes on existing 'evacuation' classified roads for Boss AV-like technology
4. Identify medium-risk zone, or Tier 2, and use to incentivize transfer to Tier 3
5. Replace car dependent land-uses that are reverted due to AV technology with ecological elements for flood mitigation, and future miscellaneous land-uses.

In the case of the Everett-Malden district, we know the most impacted and vulnerable area to the south/southeast to contain primary infrastructure, such as freight and commuter rail lines, a power plant in the flood zone, energy storage facilities, and New England's main produce distribution center. As an additional means of protection, not only would tier one have 'soft' systems to absorb and slow down, but the evacuation connection provides an opportunity to create a hardened, elevated, and reinforced evacuation spine, protecting much of tier 2 and 3 from experiencing a 100-year flood event based on the analysis shown in the earlier section.

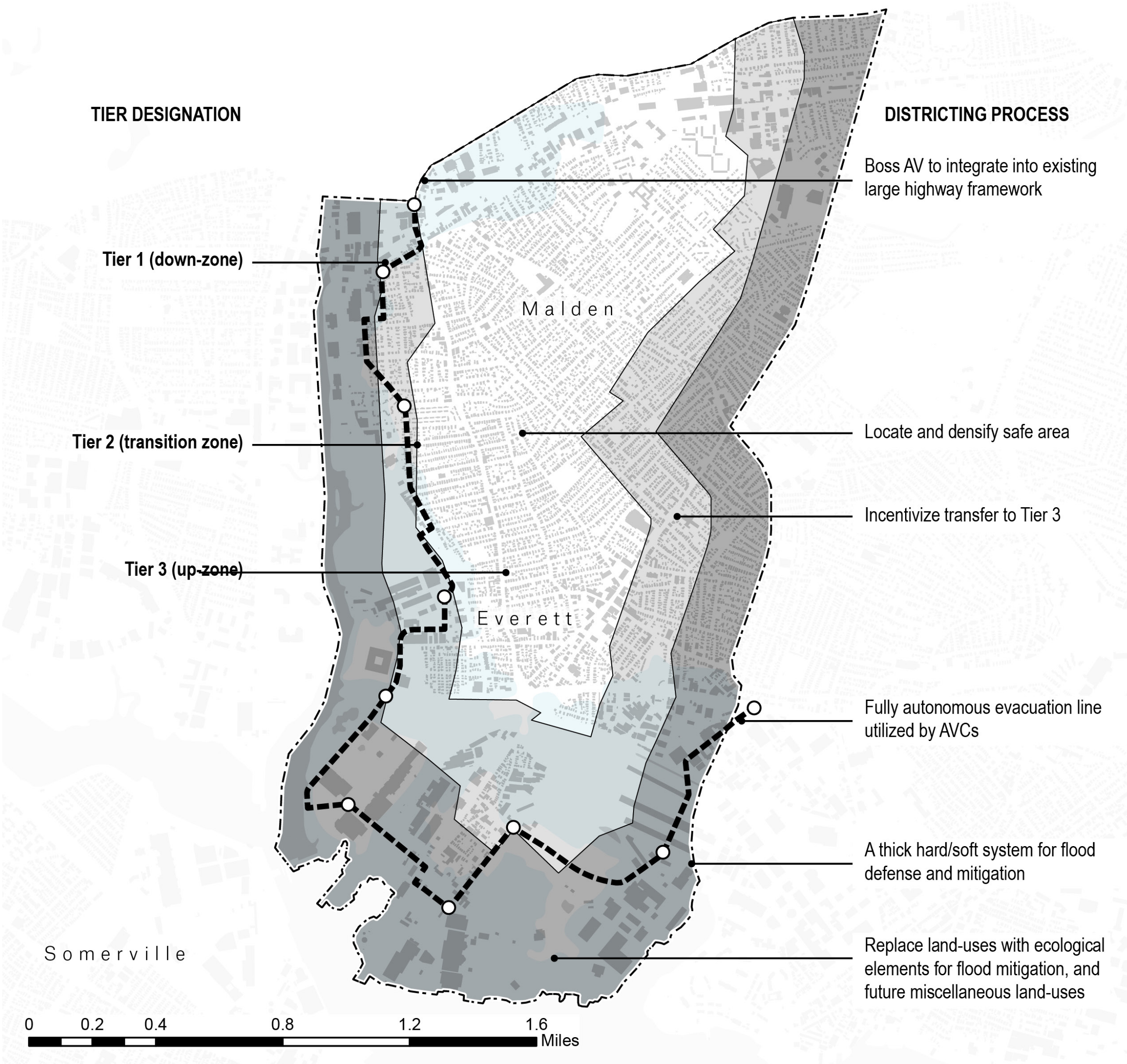


Figure 29 AV-Integrated Resilience District Approach

e. How to Identify Land-Use Opportunities?

Once the autonomous route is implemented, what are some expectations in terms of land use variances to be observed in the short term? In his book "Autonomous Driving and Urban Land Use", Dirk Heinrichs describes the potential impact of autonomous transportation systems to Land use and, ultimately, urban form. He demonstrates a systemic analysis of available literature on the city of the future, with the specific emphasis on urban development, land use, and transport. Based on the level of significance of automated driving scenarios: from availability and integration of intelligent communications infrastructure to the willingness of adoption in general for mobility by the urban population, the book explains three scenarios for adoption and the implications to urban land use.

The "Hypermobile City" scenario, most relevant to our case here, uses networked mass taxi systems, with high-transit volume freeways along commuter routes reserved for guided lanes, has dense, up-zoned centers in the urban area under the cooperation of state-private sector efforts in developing mobility technologies(Heinrichs, 2016).

The scenarios in the overview table are extracted from "Autonomous Driving and Land Use" and the Hypermobile City has been highlighted (Heinrichs, 2016).

Scenario	Form of AV	Urban Land Use	Driving Factor
Regenerative City	• Flexible, multimodal and networked public transport system as the backbone of urban mobility • semi-autonomous cars (autopilot) on freeways	• Formation of intermodal mobility hubs • Reduction in land consumption for urban parking spaces due to new parking systems	• Technological development (in the energy system) • Conscious and responsible use of resources • Legislation and acceptance promotion by the state
Hypermobile City	• **Highly networked (autonomous) mass taxi systems** • **Autonomous cars on freeways with high transit volumes or along commuter routes, on reserved "guided lanes"**	• **City centers of high density** • **Growth of low-density suburbs**	• **Increasing acceptance of information and communications technology due to its lifestyle and commercial benefits** • **Cooperation of state and private sector in developing the necessary ICT technologies**
Endless City	• Predominantly car-dominated • Low level of networking with public transport (high proportion of informal "paratransit" provision) • No notable developments in automated driving	• Suburban growth • General decline of settlement densities	• Limited state power to steer development • Technological development restricted to efficiency gains in discrete areas

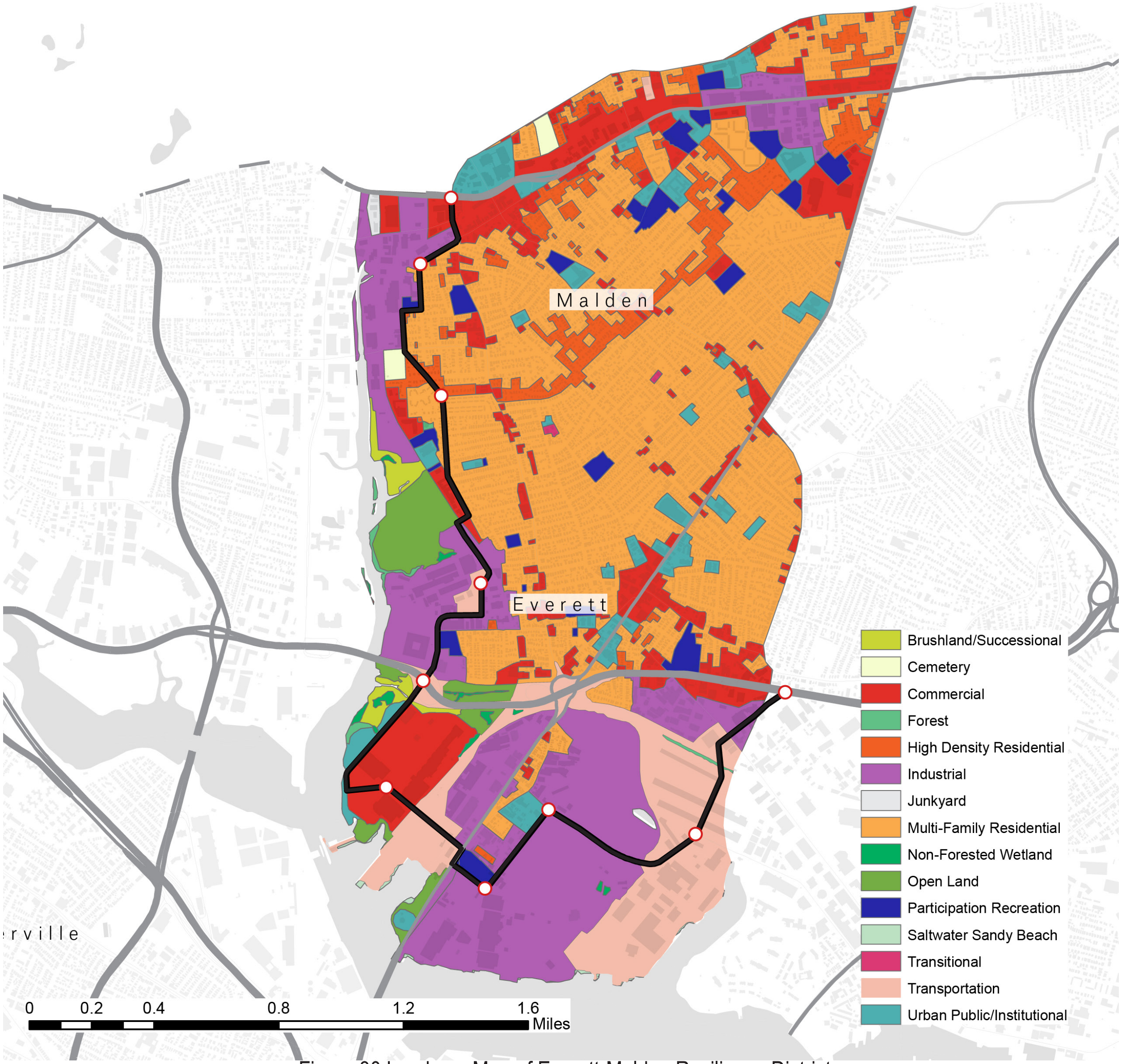


Figure 30 Land use Map of Everett-Malden Resilience District

i. AV Impacted Land-Use Breakdown

In this section, the research classifies current land uses from high to no impact. High impact are uses that rely heavily on the automobile such as parking designated areas, transportation, and industrial uses. Low and no impact uses are ones that are least likely to be affected by the AV route introduction into the landscape, for instance areas such as cemeteries and high density residential areas would see little to no influence on their form by AV technology. Most of the area along the route is dedicated for industrial and transportation uses which are heavily impacted by automation. One can notice a heavy influence of the route on 'freeing up' land for other, rather urgent, applications such as flood mitigation. Figure 30 and Figure 31 reveal opportunities for addressing flood-vulnerabilities along the AV route.

In terms of classification methodology, car-dependent land uses have been classified in accordance with the 'parking ratios' consultants assign for every use in the region, the higher the ratio, the more land coverage is expected to be allocated for vehicles. The summarized classifications are in the following table

IMPACTED LAND USE CLASSIFICATION

High Impact	• Industrial • Transportation • Transitional
Moderate Impact	• Commercial • Urban Public/Institutional • High Density Residential
Low Impact	• Multi-Family Residential • Residential
Negligible Impact	• Cemetery, • Forest, • Junkyard, • Non-Forested Wetland, • Open Land, • Participation Recreation, • Saltwater Recreation, • Brushland/Successional

Figure 31 AV-Influenced Land use based on the Impacted Land use Classification Table

f. Identifying Flood Vulnerabilities

As a large expanse of critical infrastructure (i.e. evacuation routes) malfunction for the event they're designed to alleviate, what steps are taken in conjunction to incorporating technological advances to mobility, to ensure they are resilient in the face of floods and storms must be taken seriously. The existing evacuation shows vulnerabilities beyond the Boston boundary, malfunctioning for a large number of people living in around the coasts. The same applies to our district, Figure 33 shows all primary evacuation corridors to be affected causing a district-wide lockdown, crippling both east-west movements as well as crippling north-south connections in the district.

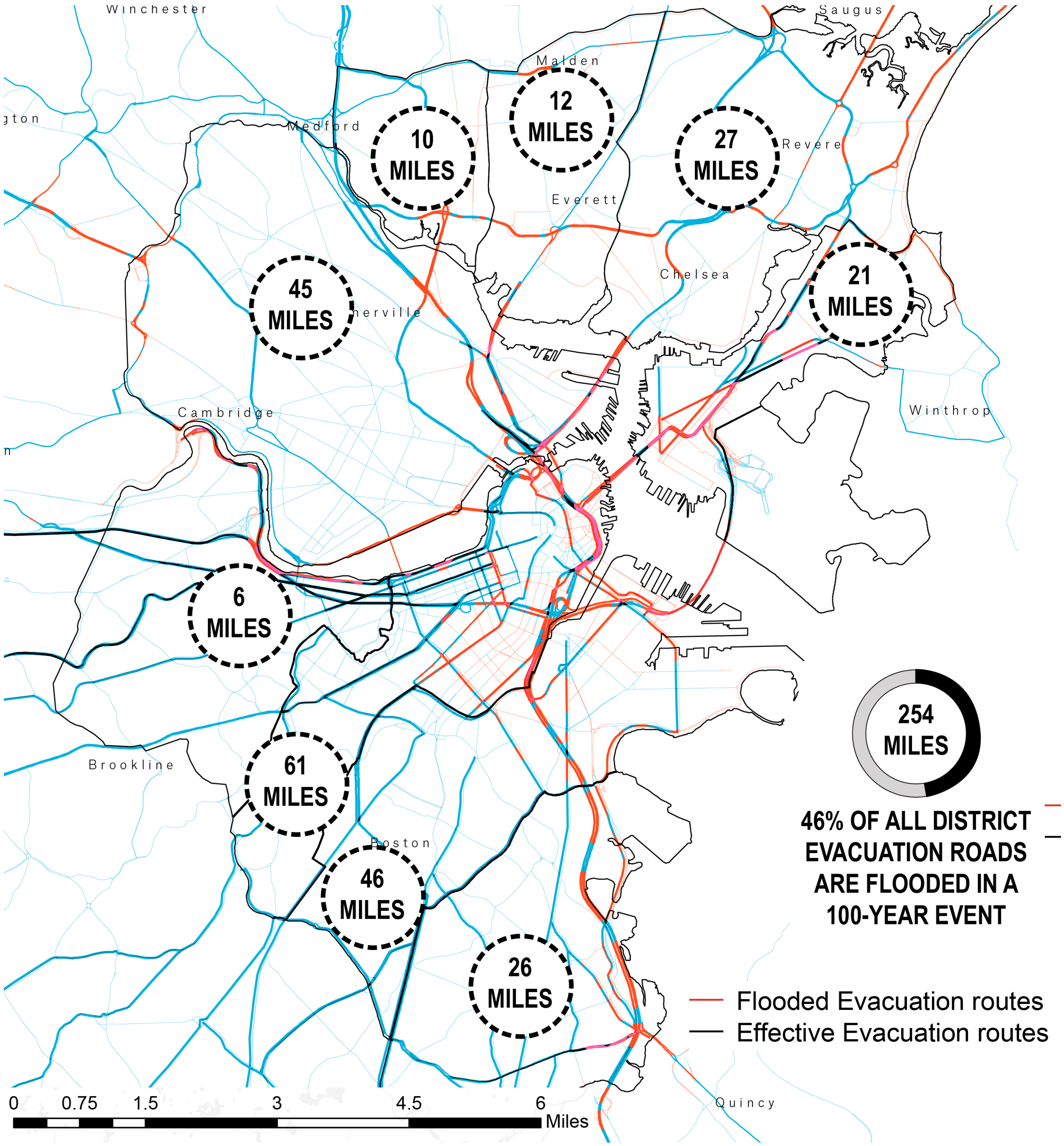


Figure 32 By-district Analysis of Flooded and Effective Evacuation Routes

i. Everett-Malden Flood Vulnerability

Hardening the edge through methods which the proposal describes in the next section would remove much of the floods that cause dysfunctional evacuation. For example, having the autonomous route as an elevated spine through the tier 1 reduces inundation on the upper tiers, and protects major routes from going out of service by a) elevating the street, using techniques such as sea walls around the southern district to protect the produce and energy distribution centers, as well as landscape urbanism methods in order to organize subsequent urban form on the nature of landscape using berms, reefs, native plants along the edges that absorb large amounts of water, and their repercussions as a large scale system on the district.

The next step involves down-zoning vulnerable areas from flood-prone territory into safe, dry, inland mainly in 'tier 3'. Ahern's adaptive system thinking of having a resilient landscape planned to morph as environmental processes take place can find an application in this district, where downzoned landscape within the tier would be allowed to evolve to their local elements, allowing the return of native marshes and floodable basins(Ahern, 2011). The framework plan explains a possible application of the mentioned steps in section h. Applying the 5-step framework to the Malden-Everett district., showing opportunities of immediate and long term developments, and incorporating the AV evacuation as part of the thick line of defense.

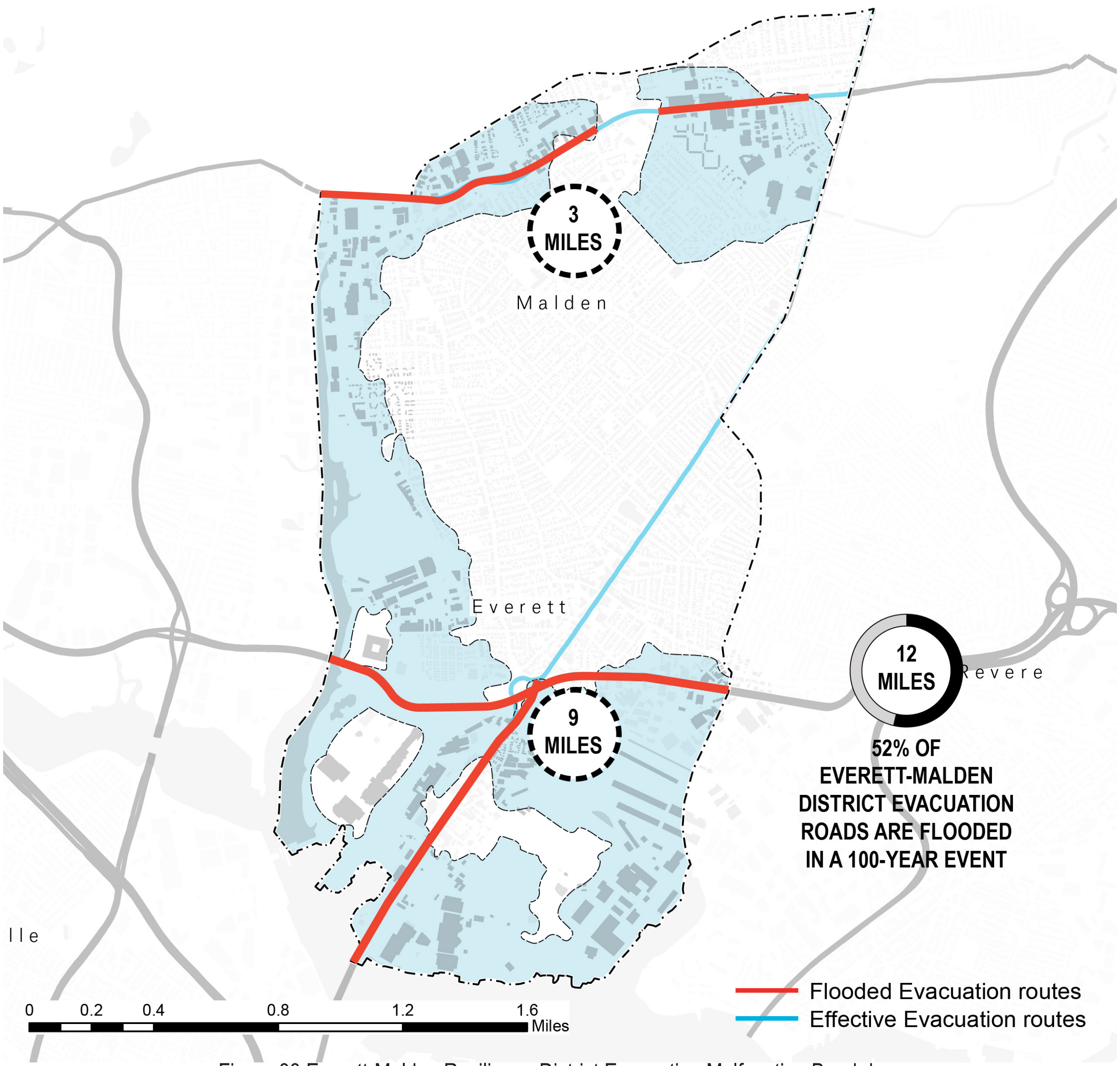


Figure 33 Everett-Malden Resilience District Evacuation Malfunction Breakdown

g. Applying The 5-Step Framework to The Everett-Malden District

The 5th step of "Replacing car-dependent land-uses with ecological elements, and future miscellaneous land-uses" looks at the externalities of applying AVs as systems of evacuation. In the proposed district – and based on the Land-use impact table the research showed earlier – one can see the most impacted land by AVs to happen along the proposed autonomous route, allowing for thinking about resilient 'design' strategies for future work, and how to take advantage of the freed, otherwise impervious surfaces for flood mitigation and thinking of a new form of landscape urbanism.

Within the land, noticeable area coverage of land-uses classified as being impacted by the AV evacuation route, these plots have been highlighted on the framework plan above showing where areas of possible intervention and resilience opportunities most likely to occur – most of the land is reverted to other purposes once vehicular requirements are not as necessary as zoning regulations scale up to technological advancement in mobility.

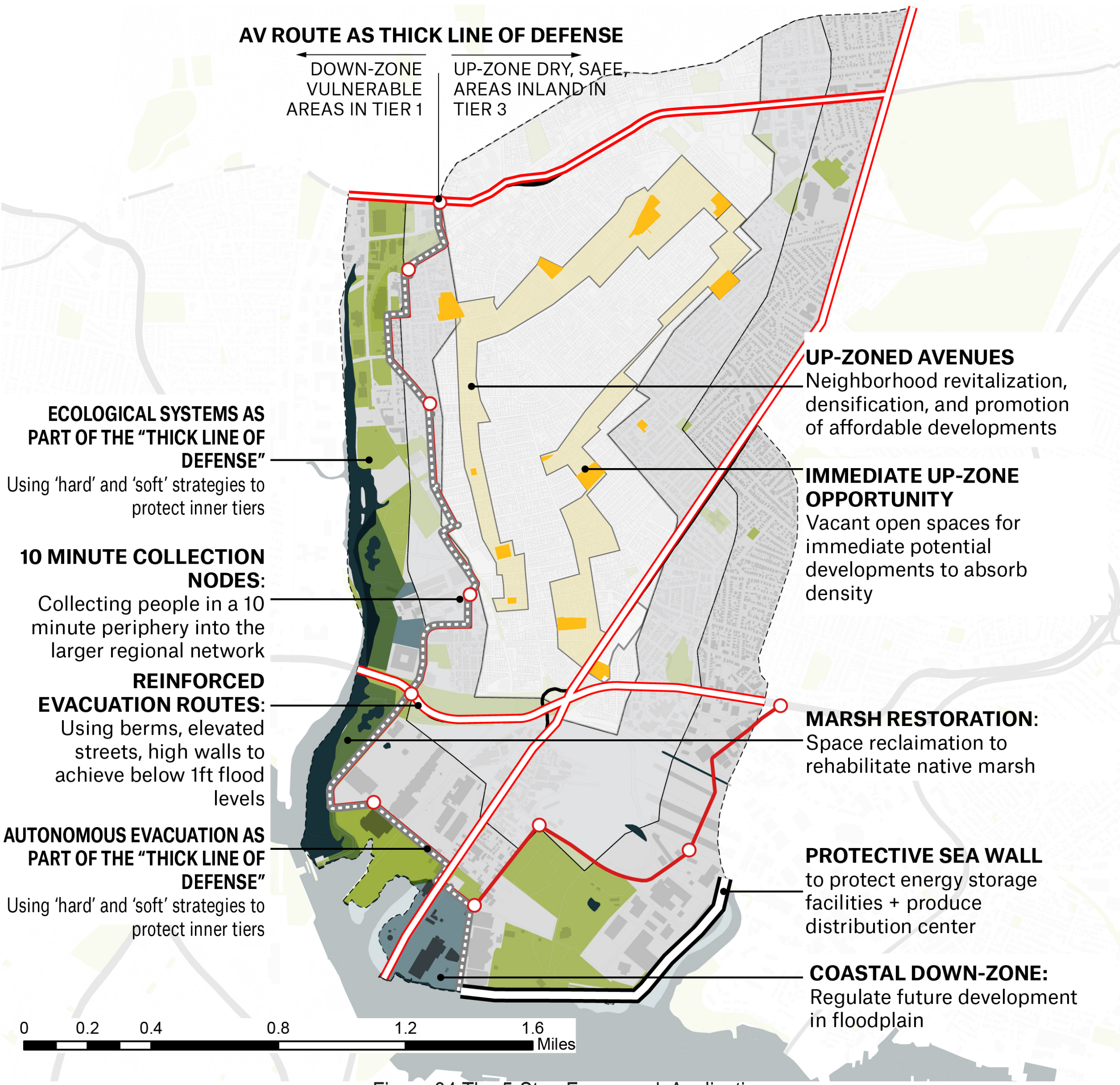


Figure 34 The 5-Step Framework Application

i. Externalities On Urban Form: Land Uses of “Moderate” To “High Impact” To The Proposed AV Network

Figure 35 highlights the surrounding uses categorized to show “Moderate” and/or “High Impact” in the Everett-Malden district and along the AVC route. Areas of dense commercial activity, mixed use and high residential areas, as well as industrial land uses are to experience unprecedented revival of land looking for their future developers. The heavy transportation and industrial use in the south contain large impervious surfaces allocated for vehicular parking, transport of goods and people, and heavy machinery.

In the next chapter, and to conclude this thesis, the research looks at the large scale opportunities of applying autonomous evacuation systems to all resilient districts. The study will apply the discussed metrics in the Everett-Malden resilience district of integrating fully-autonomous collection and evacuation routes, and semi-autonomous major evacuation infrastructure to see its impact on urgent accessibility for major events, and look at the externalities of this system on land uses and urban form, quantifying the conclusions in dollar values for the readers to understand the overall importance.

Figure 35 Externalities on Urban Form

5.
Conclusion

As resilience evolves in the planning field along with technological advancements in mobility – especially autonomous systems - there is a much needed exploration on the role AV systems can bring to evacuation during flooding events. The fields of resilience planning and technological advancement in mobility and the need to integrate these two areas with a meaningful research were explored in chapter 2. Chapter 3 investigated the trends of flood events within the Boston area, and analyzed the resilience districting process which includes floods and topography as one of the districting drivers. And chapter 4 conducted spatial analytics to understand impacted evacuation infrastructure, and proposed an integrated 5-step resilience districting methodology using the Everett-Malden district as a case study.

A key lesson from this research is understanding districting as a by-product of socioeconomic characteristics, but also influenced by natural phenomenon such as vulnerability to floods and floodplains, integrated with state-of-the-art transportation technologies for truly resilient towns and cities. Looking beyond the Everett-Malden resilience district, flood vulnerability in the Boston area is a pressing problem impacting 26,700 households, putting the lives of over 292,000 individuals at risk from lack of access to working evacuation means.

Another important conclusion is seeing conventional evacuation-planning as inadequate in a large flood event. While the research showcases Everett-Malden as an example case-study for the lack of effective evacuation, it is a more widespread problem in the larger Boston metro. 254 linear miles within the resilience districts are completely crippled in a storm event, leaving 46% of the larger system disconnected from key dense areas close to the coast. There is little to no research, planning, or legislation done by cities to improve safety and evacuation methods. Cities ought to start considering AVCs and AV systems for evacuation planning

There are promising opportunities of AVs application. Just by evacuation application of AVCs and Boss AV systems, city and state agencies, as well as real estate developers can see great opportunity for future land uses and development. An estimated 58,000,000 sq ft of land is expected to be highly impacted by this implementation within the 9 resilience districts, multiplied by the average land price in the state today brings a $14.5 billion of development potential for high return on investment projects. City planners and public officials get the opportunity to envision their future city plans in a new light where the plaguing car-oriented lands can be turned into active recreation spots or new city markers.

Finally, Boston's progressive resilience planning and urban design initiatives are an important vehicle for transforming our understanding planning for evacuation and resilience. The results of these initiatives can cause a ripple effect influencing other progressive cities concerned about disaster planning and resilience. It needs to be a leader, as in the words of James Cascio, "to strive for an environment, and a civilization, able to handle unexpected changes without threatening to collapse. Such a world would be more than simply sustainable; it would be regenerative and diverse, relying on the capacity not only to absorb shocks like the popped housing bubble or rising sea levels, but to evolve with them. In a word, it would be resilient."(CASCIO, 2009)

6.
Moving Forward

Completing this research opened the door for future exploration in several areas, namely within land use impacts and urban form, and thinking of a transitionary strategy for other transportation means. The research's analysis of AV evacuation riggers thinking about the larger impact on other transportation means. For example, how other privately owned AVs, such as the Teslas, are integrated into the evacuation system and what underlying inequities are associated with them. Currently, there is a limited research capacity on the impact of autonomous driving on land use evolution in cities.

Given the nature of planning development in the country historically, an intriguing area of exploration would consider intermediary, and immediate, solutions integrating policy, public transportation means, and state legislation. For example, how would public buses and school buses operate in an evacuation scenario, and revisit the guidelines for public transport vehicles with including elements such as amphibious AV ability (the capacity to navigate through flooded regions and drylands). The impacts beyond the implementation of AVs solely for evacuation is a promising area to further research.

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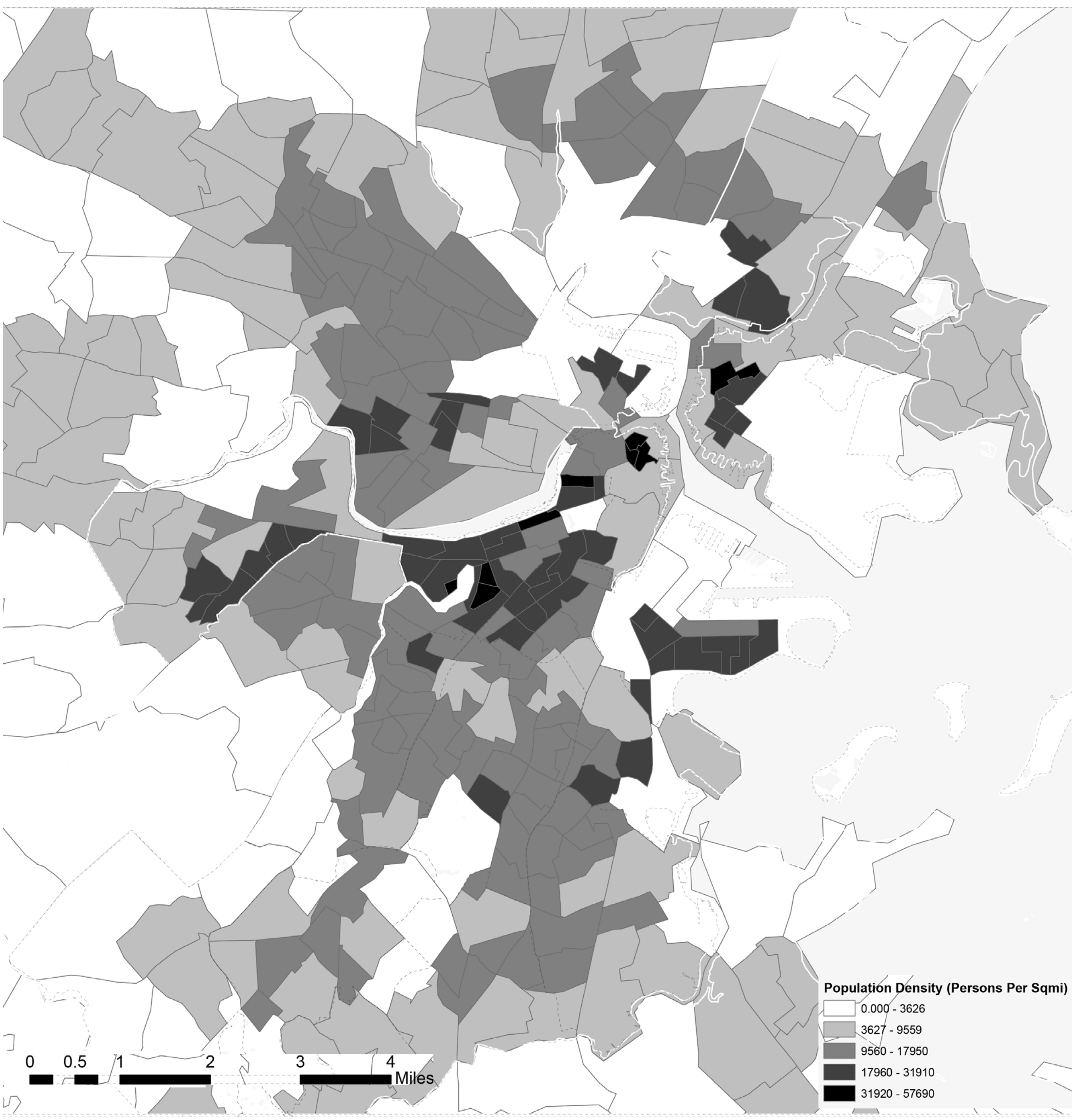
8.
Appendix A

Chronological events of Hurricane Harvey("Preparation, Response and Lessons Learned from Hurricane Harvey," 2018)

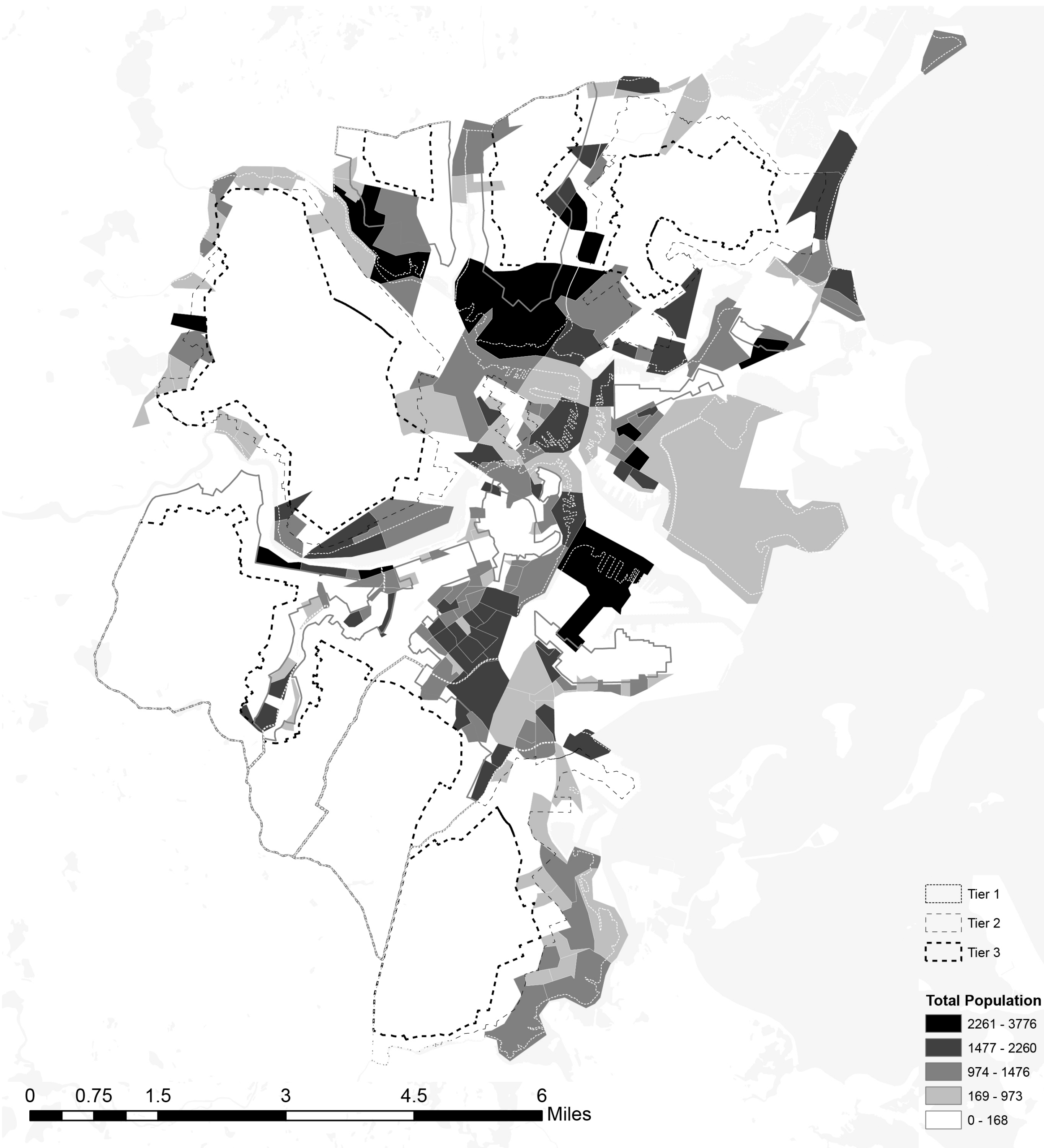
	Storm Chronology	MCHD EMS Operational Timeline	HFD Operational Timeline
Friday, August 25	• By 2 p.m., Harvey is upgraded to a Category 3 hurricane, with sustained maximum winds of 120 mph (195 kph) • By 6 p.m., Harvey is upgraded to Category 4, with maximum sustained winds of 130 mph (215 kph) • At 10 p.m., Harvey makes landfall as a Category 4 hurricane when the eye of the storm comes ashore near Rockport, Texas	• Perishable food delivered to stations • Emergency operations began at 7:00 p.m. • Staffing ramped up for EMS, public health and facilities • Medical directors Dickson and Patrick arrive at Medical Command (MedCom) and begin prep work	• Daily briefings begin at the Houston Emergency Operations Center with a 24/7 presence by HFD command-level personnel • Three community shelters are identified for potential evacuees • HFD assists with the evacuation of East Houston Regional Hospital ahead of the storm
Saturday, August 26	• By 2 a.m., Harvey is downgraded to a Category 3, with maximum sustained winds of 115 mph (185 kph). • Two hours later, it's downgraded further to a Category 2, but remains stalled over Southeast Texas. • Over the next several days, Harvey will change direction several times, bounce back out into the Gulf of Mexico, and make landfall again, continuing to dump rain on the entire region.	• County emergency operations center (EOC) fully activated • Four ambulances and a strike team leader are deployed with EMTF-6 • Shelters begin opening overnight as floodwaters began to rise • Medical reserve corps volunteers contacted to help staff official shelters • Epidemiology starts shelter surveillance contacts	• Units in stations in flood-prone areas are relocated, and rescue and evacuation boats are staged near areas known to have flooded in previous storms • Braes Bayou crests in southwest Houston, beginning catastrophic neighborhood flooding overnight • HFD and police high-water rescue vehicles and boats are staged throughout the city, as well as dump trucks and other improvised high-water vehicles from other departments
Sunday, August 27	• Harvey begins moving slowly southeast toward Houston area • Flooding emergencies occur throughout southeastern Texas coast	• Station 42 isolated by rising floodwaters • Shelters begin requesting more medical volunteers, equipment, and supplies to support medically fragile residents • MedCom activated to assist with consults and transport decisions, initating EMS treat and release along with EMS refusal to transport protocols	• George R. Brown (GRB) Convention Center opens as evacuee shelter with capacity around 4,500 people • Multiple HFD and HPD stations and vehicles damaged or lost to rising flood waters • HFD call volume up by more than 450%, with over 4000 water rescue calls • Rescue efforts begin in earnest, as there is catastrophic flooding throughout the city • Houston Airport System shuts down airports for all commercial flights, open only for relief flights
Monday, August 28	• Harvey finally moves east of Montgomery County, and heavy rain ends • Rivers and waterways continue to flood areas of Montgomery County	• Inaccessibility to patients become an issue, MedCom queues calls to check back with these patients until rescue • Medical directors initiate an active CPR/cardiac arrest situation from MedCom radio due to lack of access • Administration building loses power and begins running on generator power • Oxygen at regional stations is stocked • Posting is suspended and ambulances are moved back to their home stations as quickly as possible after calls	• GRB shelter nearly hits its 4,500-person capacity, with evacuees still arriving • HFD personnel take a leading role in coordinating medical care and transports at GRB • Disaster Medical Assistance Teams enroute to GRB to provide shelter medical support • Army Corps of Engineers begins controlled releases from Addicks and Barker Reservoir dams, increasing flooding downstream • Multiple hospitals, including some of the city's highest-volume EDs, go on internal disaster status, mostly due to access issues from high water • Rescue operations ongoing, with over 20 helicopters, innumerable boats, and other local, regional, state and federal assets
Tuesday, August 29	• Harvey is downgraded to a Category 1 storm, with maximum sustained winds of 90 mph (150 kph) • Harvey causes catastrophic flooding for Southeast Texas region	• National Guard helicopters arrive at Station 30 to assist with evacuations • Materials management delivers water, blankets, oxygen and other supplies to stations • All queued patients from MedCom are accessed/transported • Multiple patient transport situation are diverted with medical director field evaluation.	• GRB shelter approaches 10,000 people (more than double its initial stated capacity) • HFD continues to respond to rescue calls around the city with the help of police, the U.S. Coast Guard, the Department of Public Safety, the Texas Guard and volunteers. • Federal DMAT teams take over medical care inside the GRB shelter, but HFD medical direction and EMS supervisors maintain overall medical control and transport decision-making
Wednesday, August 30	• Harvey makes its third landfall, just west of Cameron, Louisiana • Harvey continues through southwestern and central Louisiana • Harvey weakens to tropical depression	• Community Paramedicine staff are deployed to assist at shelters and bring supplies to affected people • Oxygen distribution and dialysis access is one of the biggest challenges • Nursing home from Orange County arrives at Lone Star Airport via helicopters; EMS staff assist on site until EMTF arrives to transport them to Lufkin-area facilities • MedCom discontinued at 7:00 p.m.	• HFD call volumes begin approaching normal levels • Ongoing rescue operations continue • Federal teams manage GRB medical care with HFD medical direction and transportation officers

8. Appendix B

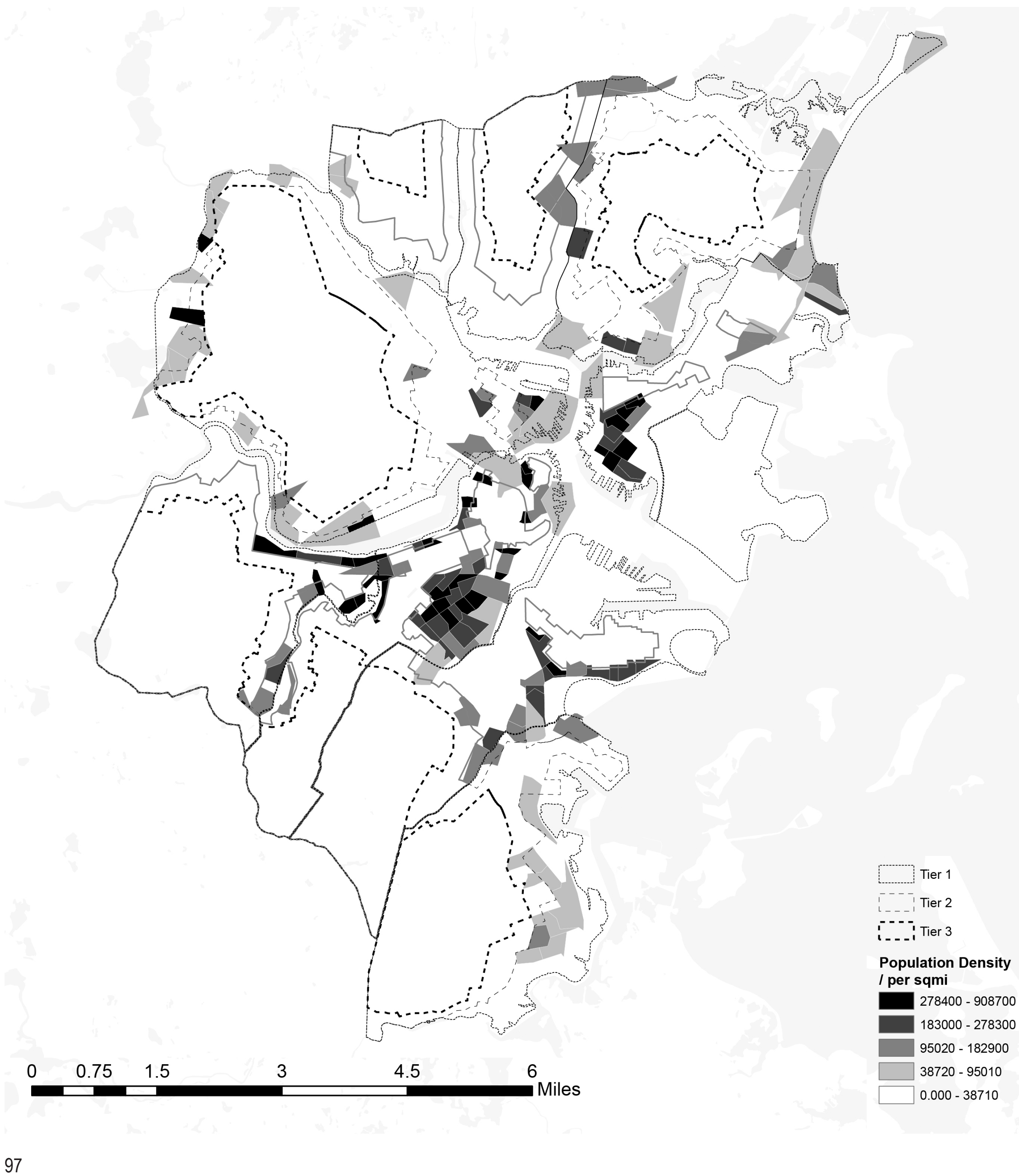
Population Density in the Boston Greater Area


Population Density (Persons Per Sqmi)
0.000 - 3626
3627 - 9559
9560 - 17950
17960 - 31910
31920 - 57690
0 0.5 1 2 3 4
Miles

Total population within Tier 1 of all 10 resilient districts:


Tier 1
Tier 2
Tier 3
Total Population
2261 - 3776
1477 - 2260
974 - 1476
169 - 973
0 - 168
0
0.75
1.5
3
4.5
6
Miles

Population Density within Tier 1 of all 10 resilient districts:



Tier 1
Tier 2
Tier 3
Population Density / per sqmi
278400 - 908700
183000 - 278300
95020 - 182900
38720 - 95010
0.000 - 38710
0 0.75 1.5 3 4.5 6
Miles

Planning Autonomous Evacuation for Access and Flood Resilience