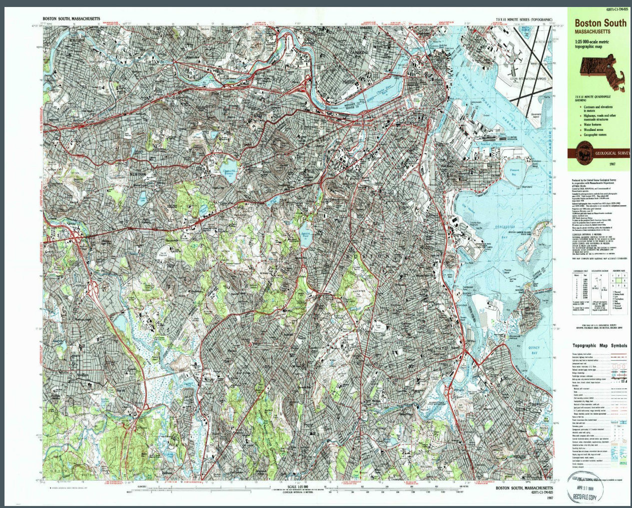
The Water Remembers

Historical Wetlands & Stormwater Flooding in the MAPC Region



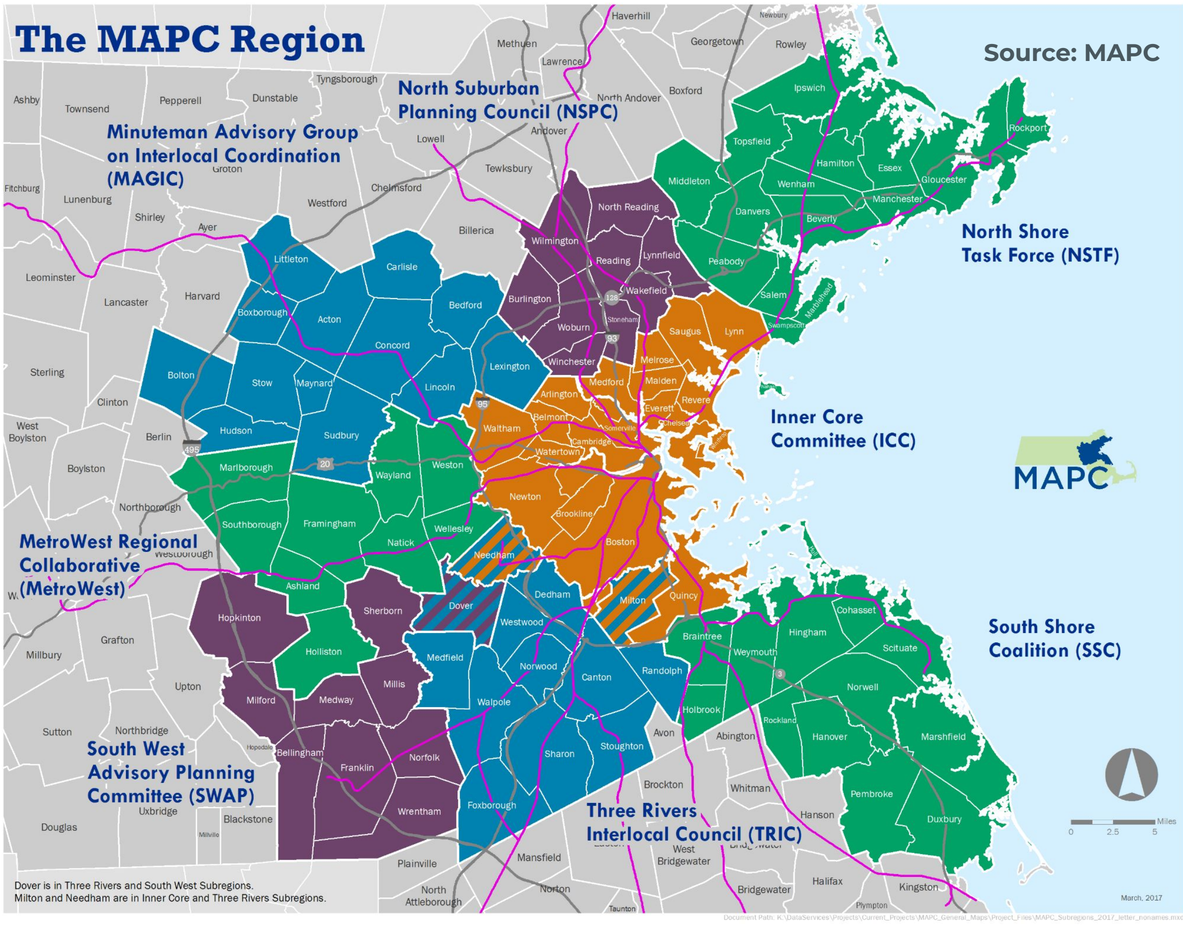
Cheng | Homeyer | Mire | Nolan | Storr

Tufts University Department of Urban & Environmental Policy & Planning

2023 Field Projects

Meet The Partners

The **Metropolitan Area Planning Council** (MAPC) is a Regional Planning Agency for metropolitan Boston, serving 101 cities and towns, 3.3 million residents, and 2 million jobs. MAPC is governed by representatives from each city and town in the region, as well as gubernatorial appointees and designees from major public agencies. MAPC's work covers a diverse range of topics, including transportation, land use, economic development, housing, environment, public health, clean energy, arts and culture, and procurement.



The **Norman B. Leventhal Map & Education Center**, created in 2004, is a nonprofit organization operating out of a public-private partnership with the Boston Public Library. Its mission is to use its collection of 200,000 maps and 5,000 atlases for the enjoyment and education of all through exhibitions, educational programs, and a website that includes more than 10,000 digitized maps.

Meet The Team

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Tufts UNIVERSITY | GRADUATE SCHOOL OF ARTS AND SCIENCES Urban and Environmental Policy and Planning

MAPC

Norman B. Leventhal Map & Education Center at the Boston Public Library

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Glossary of Key Terms

- **Best Management Practices (BMPs)** - Structural, vegetative, or managerial practices used to treat, prevent, or reduce water pollution.
- **Clean Water Act (CWA)** - Establishes the framework for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters.
- **Conservation Commission** - Official Massachusetts municipal agencies that are responsible for protecting the land, water, and biological resources of their communities through the enforcement of the Massachusetts Wetlands Protection Act.
- **Coordinate reference system (CRS)** - A coordinate-based local, regional, or global system used to locate geographical entities.
- **Federal Emergency Management Agency (FEMA)** - The agency responsible for helping people before, during, and after disasters; administers the National Flood Insurance Program.
- **FEMA Flood Zone** - Flood hazard areas defined as the area that will be inundated by a flood event having that has a 1% chance of occuring in any given year.
- **Geographic information systems (GIS)**- A computer system that stores, analyzes, interprets, and displays geographically referenced information.
- **Georeference** - GIS method used to align aspatial rasters or images with geographic coordinate reference systems.
- **Grid-ditching** - Shallow, narrow, hand-dug ditches designed to remove standing water from marshes to prevent the breeding of mosquitoes.
- **Historical geographic information systems (HGIS)** - The practice of doing geospatial analysis with historical data.
- **Inland Wetlands** - defined by the Massachusetts Department of Environmental Protection (Mass DEP) as "areas where water is at or just below the surface of the ground"
- **Low-impact Development (LID)** - Land planning and engineering approach to manage stormwater runoff through green infrastructure. LID emphasizes conservation, use of natural on-site features to protect water quality, and managing stormwater as close to the source as possible.

Glossary of Key Terms

- **MAPC** - The Metropolitan Area Planning Council is a Regional Planning Agency for metropolitan Boston and a key partner for this research project.
- **Microinsurance** - An insurance strategy that targets low-income populations to offer protection from specific hazards. It allows for sporadic payments to protect a wide variety of risks.
- **National Flood Insurance Program (NFIP)** - Program created by FEMA to provide flood insurance to property owners, renters and businesses within municipalities that participate in the program.
- **Parametric Insurance** - A non-traditional insurance product that offers pre-determined payouts based on a trigger event, such as a natural disaster.
- **Stormwater Flooding** - Also known as “inland flooding”, “urban flooding”, or “pluvial flooding”. Occurs when rainfall causes the occurrence of shallow to moderate standing water in low-lying areas far from rivers, waterways, and the coast. Stormwater flooding is distinguished by water flowing into subsurface spaces, such as basements, garages, subway stations, and underpasses.
- **Transformation** - Used to warp and fit rasters to a coordinate system.
- **Time horizon approach** - An approach to HGIS that combines features of map years to provide one extent representative of the entire range of time. It is based on the assumption that spatial features appearing in a later date were also present at all earlier time periods.
- **Vectorize** - The process of distilling points, lines, and polygons from a scanned image. Vectorization produces a vector data set from a raster.
- **Waters of the United States (“WOTUS”)** - A threshold term in the Clean Water Act, establishing the geographic scope of federal jurisdiction over waterways.
- **Wetland** - Land that is covered by water seasonally or permanently. Wetlands are a distinct, functioning ecosystem distinguishable from other types of land or water bodies based on dominant vegetation. Wetlands are typically transitionary zones and have key physical, chemical, and biological characteristics for flood mitigation.
- **Wetland Mitigation Banking Program** - A program that allows a stakeholder to alter wetlands at a site of interest, in exchange for the restoration, creation, or enhancement of wetlands at alternative locations to compensate for the unavoidable impacts of development.

Executive Summary

Project Background & Research Question

In March 2010, an unprecedented eighteen inches of rain fell in the Boston metropolitan area within seventeen days. This amount of rain—in addition to snowmelt from winter storms—caused flooding that affected thousands of homes and the closure of roads and public transportation. A state of emergency was declared, and the Federal Emergency Management Agency (FEMA) later provided tens of millions of dollars in disaster assistance. The majority of flood claims did not fall within FEMA flood zones. The resulting dataset of disaster assistance claims can be used to understand where stormwater flooding occurred, and that the majority of claims did not fall within FEMA flood zones.

This project explores the relationship between historical alterations of wetlands, sociodemographic data, and flood claims from the March 2010 storms. This research was guided by the following question:

Is there a relationship between the alteration of historic wetlands and stormwater flooding claims, and are these effects disproportionately experienced by specific socio-demographic populations?

Study Area

This research examines five towns within Metropolitan Area Planning Council (MAPC) region: Boston, Randolph, Stoughton, Wilmington, and Woburn.

These towns were selected because of their high density of flood claims from the March 2010 storm, different development patterns over time, and availability of historical maps.

Methods

This research was divided into three phases: literature review, a historical map search and proof of concept, and spatial analysis.

The background context phase consisted of a literature review of peer-reviewed journal articles and books.

The second phase consisted of obtaining historical maps with delineated wetlands and developing a standard operating procedure for the geospatial analysis.

The final phase was a geospatial and statistical analysis. The relationship between stormwater flooding claims from the March 2010 storm and the alteration of historic wetlands was examined by looking at the correlation between FEMA flood claim data, locations of historical and present-day wetlands, and sociodemographic data..

Literature Review

The literature review for this project provided valuable information, informing the data collection of this study. Research focused on the history of wetlands alteration and defining the relevant time periods. While motivation and reasoning for wetland alterations in the United States have changed over time, most major alterations took place before the passage of the federal Clean Water Act (CWA) and the Massachusetts Wetlands Protection Act of 1972.

The primary limitation that arose during the literature review and historical map search was the changing definition of wetlands over time. Differing definitions resulted in large disparities in the extent of wetlands' representation on historical maps. Additionally, maps with pertinent information were difficult to find before 1880, limiting the temporal scope of the study and, ultimately, the known areas of historical wetlands.

The literature review also examined the limitations of FEMA flood maps, highlighting the geographic, methodological, political, and financial limitations behind their creation. Finally, the use of a time-horizon methodology for geospatial analysis was identified as the optimal procedure for carrying out this research.

Analysis

Historical maps, ranging between 1893 and 1987 were analyzed and combined to establish the "true" extent of historical wetlands. The historical extent was then compared with the most recent Massachusetts Department of Environmental Protection (Mass DEP) Wetlands map from 2005 to find the area of wetlands lost. The research then analyzed the correlation between areas of historical wetlands and FEMA flood claim data through spatial and statistical analyses. Finally, an exploration of median household income and percent minority composition by census block group was conducted to examine the relationship between areas of wetland loss, incidence of flooding, and the demographics affected communities.

Results

The statistical analysis conducted reveal between 40% and 72% wetlands loss among the areas of focus across the time period of study. While the analysis of the study area suggests some relationship between wetland loss and flood claims from the 2010 March storms, further research must be done to address the significance of this potential relationship. This project establishes important procedures for studying the extent of historic wetlands, quantitatively assesses wetlands loss in the selected municipalities, and provides insight into historical patterns of wetland alteration as well as the creation a handbook for municipalities to follow in their own studies.

Key Takeaways

01 Proportionally, buildings within historical wetlands had **55% more flood claims**

02 Minimum **40% decrease** in historical wetlands

03 Wetlands loss through **shrinking**

04 **Standardized methodology** for future research

Recommendations & Future Studies

Wetlands alterations are just one factor that may contribute to increased stormwater flooding. As such, the policy recommendations for the MAPC region are diverse. The recommendations include improving information accessibility, such as stormwater flooding information in planning, retrofitting buildings and utilities, funding stormwater management, promoting innovative insurance strategies, restoring natural habitats, and municipalities carrying out their own analysis of the potential impacts of wetland alterations.

Future research in this area should include broader geographic and temporal scopes to further explore the relationship between the alteration of wetlands and stormwater flooding patterns.

Introduction

March 2010 Storm

March of 2010 was the rainiest month ever recorded at the Blue Hills Observatory in Milton, Massachusetts.

Eighteen inches of rainfall were recorded between March 13th and March 31st—almost 40% of Boston's typical annual rainfall (Herbst et al., 2023).

This rainfall, combined with snow melt from earlier winter storms, caused widespread **stormwater flooding** throughout the Boston metropolitan area, affecting thousands of homes, closing roadways, shutting down public transportation, and releasing raw sewage into waterways.

Governor Deval Patrick declared a State of Emergency and called in the National Guard to assist in the storm's aftermath. More than 27,000 flood claims were submitted, resulting in approximately $60 million in disaster assistance being awarded (Herbst et al., 2023).

Figure 2: Flooding in Braintree, MA, March 2010
(Source: March 2010 Flooding at Hancock/Washington Street, n.d.)

Figure 1: Woburn, MA, March 2010
(Source: MAPC)

Within the Metropolitan Area Planning Council (MAPC) region, 984 residents received an estimated $10 million in flood insurance reimbursements (Herbst et al., 2023).

Climate Change Impacts

This extreme precipitation causing widespread inundation in communities across Massachusetts echoes the impacts of climate change induced intensified weather patterns occurring throughout the country (Oakford et al., 2022). The March 2010 storms were particularly devastating because of the significant amount of precipitation that fell as rain, rather than the usual snow, on the still frozen and saturated winter ground (Herbst et al., 2023).

Stormwater Flooding

Stormwater flooding, sometimes referred to as "inland flooding", "urban flooding", or "pluvial flooding", occurs when rainfall results in shallow to moderate standing water in low-lying areas far from rivers, waterways, and the coast (Oakford et al., 2022).

Stormwater flooding is also distinguished by water flowing into subsurface spaces, such as basements, garages, subway stations, and underpasses (Herbst et al., 2023).

Importance of Wetlands

Many factors can cause or exacerbate stormwater flooding, including the alteration of natural flood mitigation features, such as filling wetland areas.

Inland wetlands are defined by the Massachusetts Department of Environmental Protection (Mass DEP) as "areas where water is at or just below the surface of the ground" (Massachusetts Department of Environmental Protection, n.d.).

Wetlands are crucial to flood mitigation because they act like sponges, temporarily storing flood waters and slowly releasing the water back into the surrounding area at a manageable rate (Suuberg, n.d.). Wetlands' function of delaying inundation prevents flood waters from rising rapidly, which can threaten lives and property (Massachusetts Department of Environmental Protection, n.d.). In contrast, impervious surfaces, such as paved roads, cannot absorb water, causing increased runoff and subsequent damage.

In Massachusetts, the legacy of past decisions to fill wetlands may be associated with current stormwater flooding patterns.

Figure 3: Massachusetts Wetlands
(Source: MassDEP, n.d.)

FEMA Flood Maps

While resources, such as the **Federal Emergency Management Agency's (FEMA)** flood maps, attempt to inform stakeholders about potential flood risks, they often fall short. Notably, current FEMA flood maps are limited in their ability to address stormwater flooding.

Many areas experiencing stormwater flooding are outside of the 100-year floodplain data, and FEMA maps fail to adequately warn Americans about their flood risk.

Inland property owners do not have access to predictive flooding models, leaving them in the dark about their vulnerability to stormwater flooding (Herbst et al., 2023). These limitations are acutely felt in the MAPC region; following the March 2010 storms, 94% of federal disaster flood claims filed were from properties outside of the FEMA flood hazard zones (Herbst et al., 2023)..

Project Overview & Goals

The partnership between Tufts University Department of Urban and Environmental Policy and Planning, MAPC, and the Norman B. Leventhal Map and Education Center evaluates the relationship between historical wetland alterations and modern-day stormwater flooding in the MAPC region.

Moreover, this research seeks to illuminate how this relationship can inform climate resilient urban and environmental policy and planning. A 2021 MAPC analysis found a strong visual correlation between historical wetlands and residential disaster claims from the March 2010 storm events within the town of Newton (Figure 4). Given that most Massachusetts towns are located near inland wetlands, the relationship between stormwater flooding and historical wetlands may offer another piece to the puzzle for flood mitigation measures. The goal of this project is to contribute to MAPC's growing body of research on the many factors contributing to stormwater flood risks that affect homeowners and municipalities.

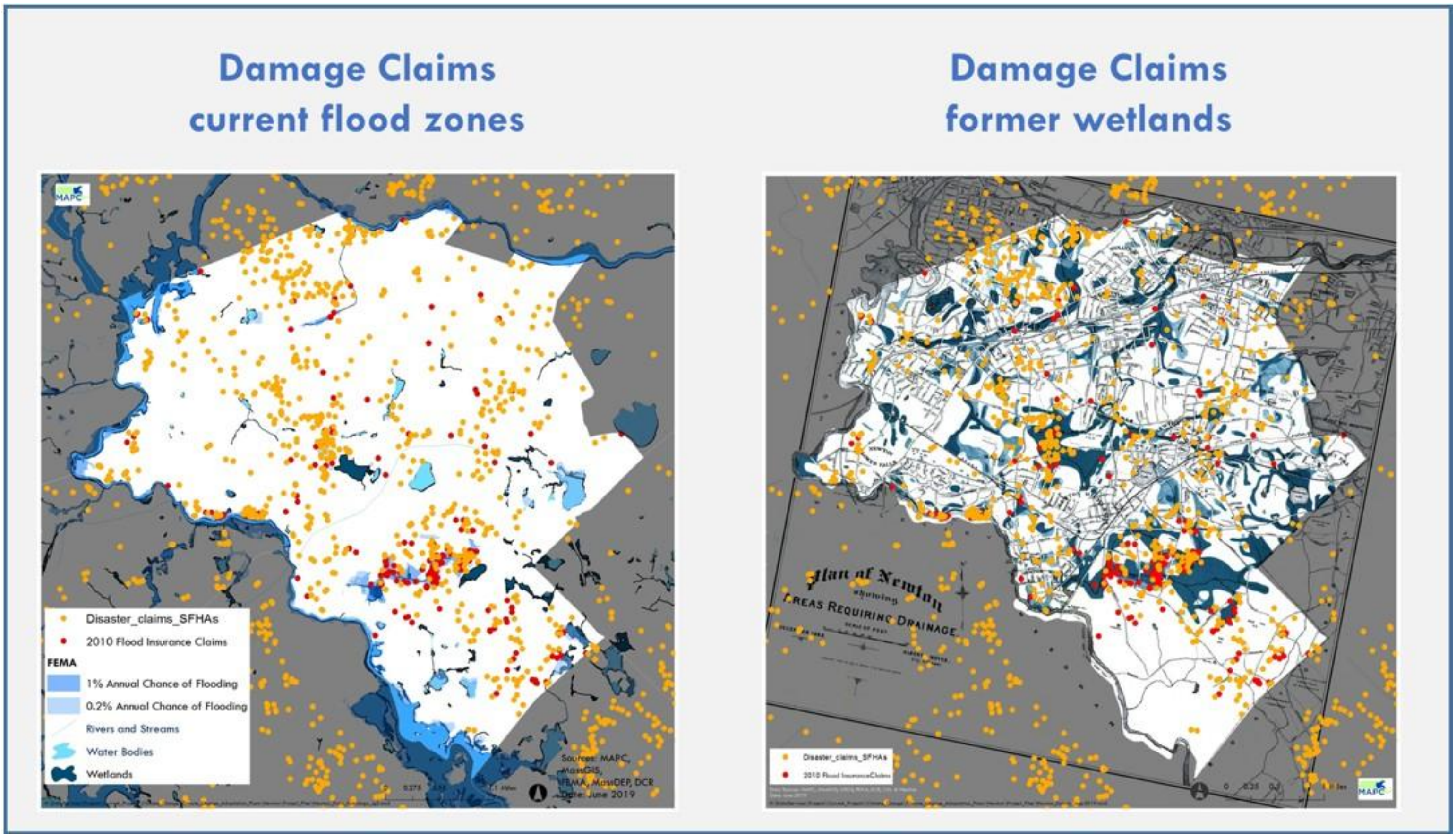
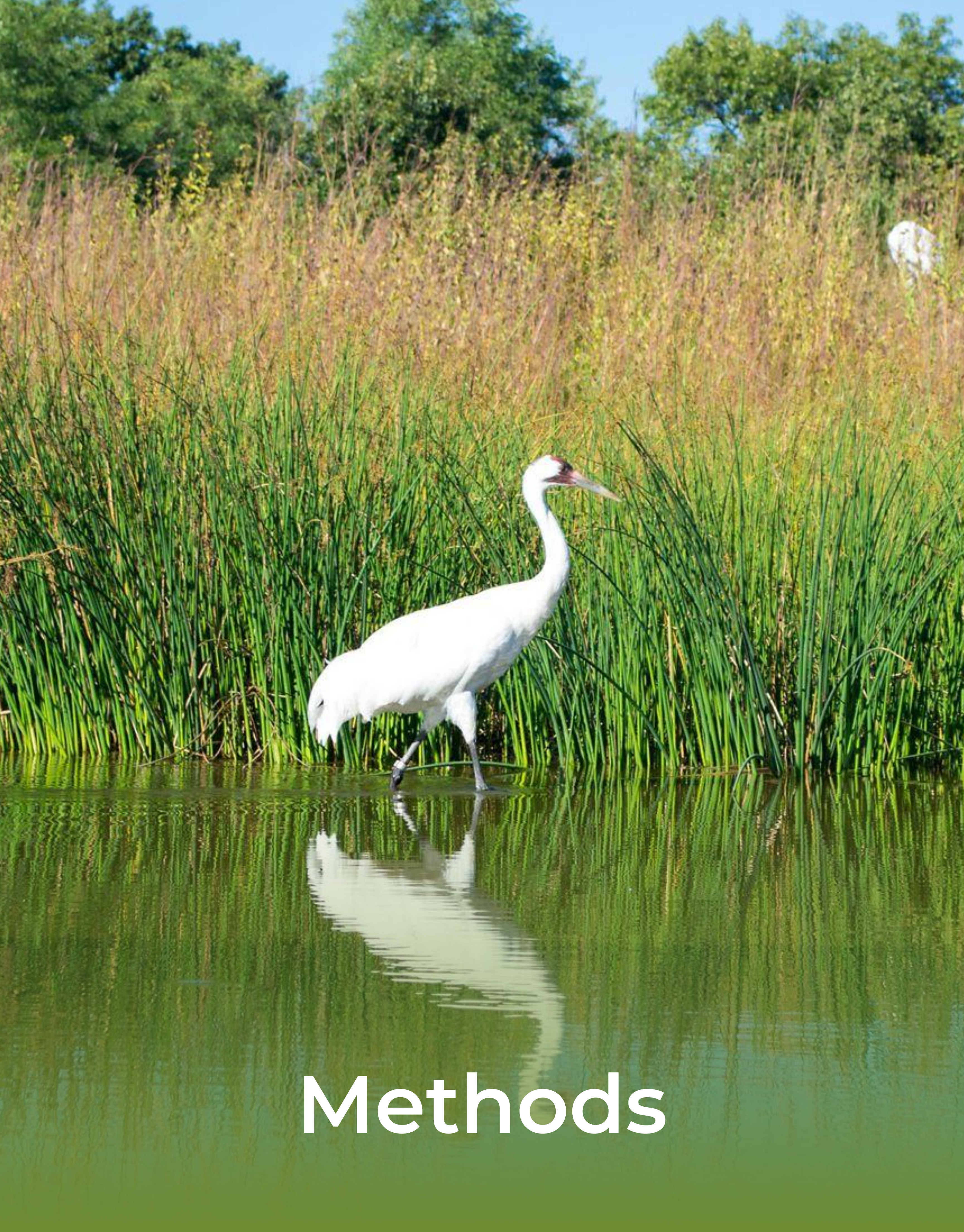


Figure 4: Preliminary MAPC Analysis, Newton, MA. (Source: MAPC Project Proposal)



Methods

Methodology

01

Literature Review

02

Historic Map Search & Proof of Concept

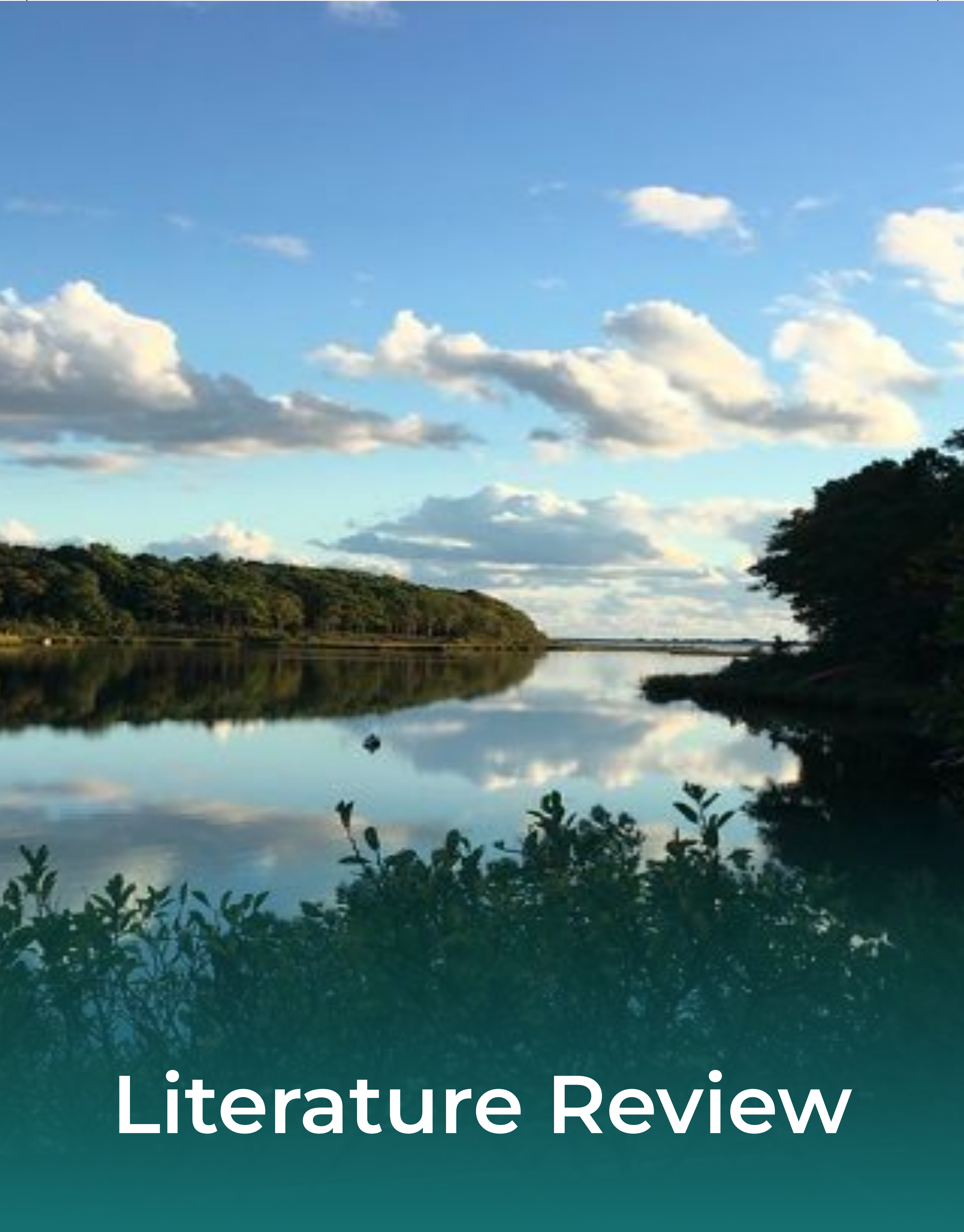
03

Geospatial Analysis

01 The first method used to analyze the relationship between historical wetlands and modern stormwater flooding was a comprehensive literature review. This literature search reviewed the cultural, political, and societal changes over time regarding wetlands, existing stormwater flooding policies, and the methodology and subsequent limitations of current FEMA flood maps.

02 The second method was a meta-analysis of scientific papers that employ **historical geographic information systems (HGIS)** methods to study changes in water resources over time. Eleven papers were reviewed and analyzed to understand: 1) commonly used methodologies 2) the limitations that exist in HGIS, specifically HGIS studies of wetlands, and 3) the limitations and conclusions of these studies to inform our HGIS analysis of wetland alteration in the MAPC region.

03 The third method was a geospatial analysis of historical wetland alteration in Boston (specifically Mattapan), Woburn, Wilmington, Stoughton, and Randolph, through georeferencing historical maps and vectorizing wetland areas. The municipalities were chosen because they had many flood claims from the 2010 storms, exhibit varying sociodemographic characteristics, are in different MAPC subregions, and had sufficient historical maps available for use. Historical wetlands created through vectorization were analyzed with FEMA flood claim data from the 2010 storms to determine a relationship. Ultimately, a GIS database, organized by municipality, was created to store georeferenced historical maps, **vectorized** historical and present wetlands, and the findings of the geospatial analysis.



Literature Review

Timeline of Human Modification of Wetlands

PRE-COLONIAL ERA

This timeline illustrates defining periods of human modification to wetlands, with the start of each new period marked by a notable change in the motivation for, type of, or extent of wetland alteration.

While wetland alteration in the Greater Boston area largely follows national trends, special attention is paid to this smaller geography to provide greater specificity to the MAPC region.

NATIONAL

Minimal human alteration of wetlands by Native peoples, who stewarded the fertile lands for sustenance and resources

REGIONAL

- Much of the MAPC region was home to the **Massachusett tribe of the Algonquin Native Americans** since 2400 BC
- Wetlands support **year-round horticultural settlements**
- **Disease** brought by early European explorers decimated the tribe's population

See Appendix I for more information about the alteration of wetlands by humans over time.

COLONIAL ERA

In the colonial era, wetlands were valued insofar as they could be altered to support various aspects of colonial life: providing **food, game, building material, and animal feed**

Figure 5: Commercially Valuable Salt Hay (*Spartina patens*)
[(Source: Francis, Mary Evans, 1876-1941, No restrictions, via Wikimedia Commons)]

NATIONAL

REGIONAL

City of Boston founded in 1630

Figure 6: "Map of the environs of Boston"
(Source: Norman B. Leventhal Map Center at the BPL, via Flickr licensed under CC BY 2.0)

LATE 1800s & EARLY 1900s

Figure 7: Modern Mosquito Ditching Efforts in Plymouth, MA (Source: Glinski, 2022)

- ➔ Agriculture shifts westward
- ➔ Wetlands increasingly seen as **vectors of disease carried by mosquitoes**
- ➔ Federal legislation & technological innovation supports **widespread ditching efforts**

NATIONAL

REGIONAL

- ➔ Large scale **urban & industrial growth projects** in Boston
- ➔ Wetland degradation & alteration
- ➔ Over 2,000 hectares of salt marsh & mudflat filled to support **landmaking** in Boston between 1830 & 1930

Figure 8: "The Filling-in of Back Bay, 1858
(Source: New England Life Insurance Company, Boston - DSC08177.JPG" by Daderot, via Wikimedia Commons CC0 1.0)

THE GREAT DEPRESSION

NATIONAL

- ➔ Wetland modification proliferates to **boost the national economy** & **limit disease**
- ➔ New Deal programs systematically drained wetlands using a **grid ditch system**

Figure 9: Worker Standing Next to Ditch in MA Marsh (Source: Glinski, 2022)

REGIONAL

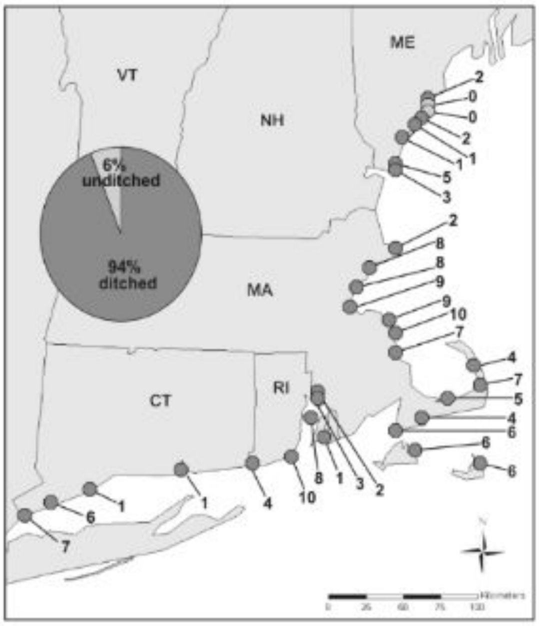


Figure 10: Ditching Frequency in New England (Source: Silliman et al., 2009)

- ➔ A **grid ditch system,** still evident in MA salt marshes today, **dug by hand from 1928-1934 by New Deal programs**
- ➔ By 1938, 94-95% of tidal marshes along MA coast ditched

POST WORLD WAR II

Figure 11: Rosie the Riveter
(Source: National Women's History Museum)

Notable loss of wetlands nationally due to **increased transportation & housing needs** after WWII

NATIONAL

REGIONAL

- **WWII soldiers return to Boston**, causing housing shortages
- Depression-era **ditch system degrading**
- **Construction of 1-95** necessitates filling of tidal wetlands

Figure 12: Interstate 95 in Massachusetts
(Source: Doug Keer via Flickr, licensed under CC BY-SA 2.0)

ENVIRONMENTAL MOVEMENT

NATIONAL

In the 1970s, much of the **first legislation preventing additional degradation & promoting restoration of wetlands** was passed

The 1972 **Clean Water Act's Section 404** protects waters of the United States from dredging and filling except by permit from the Army Corps of Engineers; extended to wetlands in 1977

REGIONAL

- ➔ In 1965, **MA passed the Hatch Act, the nation's first inland wetlands protection** which stressed the value of wetlands for water supply & flood control and required permits for wetland alteration
- ➔ In 1972, the **Massachusetts Wetlands Protection Act (MAWPA)** created a general framework for MA wetlands protection which extends beyond CWA's Section 404

Figure 13: "Corps restores wetlands at Steamboat Slough"
[(Source: Flickr by PortlandCorps, licensed under CC BY 2.0.)]

Present Day

National Level

Wetlands are protected by the **Clean Water Act (CWA)** in sections 402 and 404. Section 402 requires a federal permit for activities that may discharge into **waters of the United States (WOTUS)**.

Section 404 of the CWA is another permit-based program that prevents the deposition of fill or dredged materials into WOTUS (EPA, 2023). Despite federal protection, wetlands continue to be lawfully altered as a result of the **Wetland Mitigation Banking Program (WMBP)**. Through WMBP, if a stakeholder wishes to alter wetlands at a site of interest, WMBP allows for the restoration, creation, or enhancement of wetlands at alternative locations to compensate for development impacts. WMBP is most commonly used by developers and the agricultural sector.

Waters of the United States (WOTUS) are defined as any navigable water; which is any waterway that is tidal and/or that has been, currently is, or may be used in the future for commercial transport (EPA, 2020).

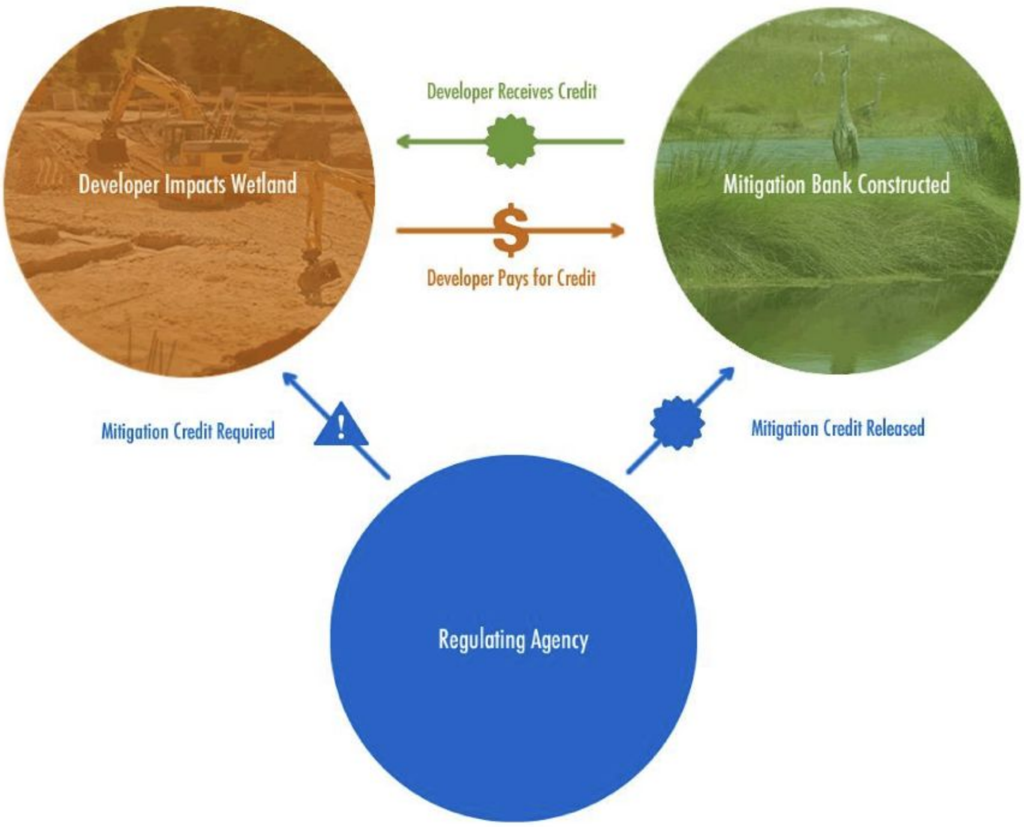


Figure 14: Wetlands Mitigation Banking Diagram (Source: Patrick W. Hook & Spenser T. Shadle, 2013)

State Level

Wetlands are protected by the **Massachusetts' Wetland Protection Act (WPA)**.

The WPA requires a careful review of proposed projects that intend to alter wetlands, or cause disturbances to other bodies of water such as 100-year floodplains, riverfront areas, waterways, salt ponds, fish runs, and the ocean (Protecting Wetlands in Massachusetts | Mass.Gov, n.d.).

In 1996, the Massachusetts Department of Environmental Protection (MassDEP) created stormwater management standards for municipalities to abide by in the **Massachusetts Stormwater Handbook** ("Handbook"). Last updated in 2008, the Handbook guides wetland and water quality regulations in the Commonwealth. The stormwater management standards, or **Best Management Practices (BMPs)**, aim to prevent stormwater discharges from polluting surface waters and encourage groundwater recharge.

Besides BMPs, the Handbook promotes **low-impact development (LID) techniques** and the removal of illicit discharges to stormwater management systems. Because natural hydrologic conditions were typically ignored in past development, the Handbook uses LID techniques to minimize discharge rates and increase recharge rates. Additional considerations of the Handbook includes environmentally sensitive site design and erosion and pollution control measures during construction.

Figure 15: Connecticut Wetland (Source: League of Women's Voters, Ridgefield, CT, n.d.)

Local Level

Conservation Commissions enforce the WPA in Massachusetts communities. These commissions ensure that proposed activities will not alter resource areas, public interests , or benefits provided by wetlands. Beyond Conservation Commissions, many communities have exceeded WPA guidelines, implementing stringent bylaws, such as limiting construction within a certain distance of wetlands.

Mattapan, Wilmington, Woburn, Stoughton, and Randolph have all implemented local wetland bylaws that exceed WPA guidelines.

The Handbook provides local bylaws for municipalities to consider implementing through LID and other stormwater flooding controls. Municipalities can create additional stringent bylaws to further protect water quality and educate the public about stormwater management. Examples include pet waste management, labeling of stormwater drains, and the proper operation and maintenance of septic systems. The Department of Public Works in each town is responsible for enacting and maintaining stormwater infrastructure.

Wetlands

A wetland is an area where the land is covered by water either seasonally or permanently.

Wetlands are a distinct, functioning ecosystem distinguishable from other types of land or bodies of water based on the vegetation found. Wetlands are typically transitionary zones and have key physical, chemical, and biological characteristics based on water depth, soil moisture, salinity, and fluctuations in water levels. Because there are so many different types of wetlands based on different sets of characteristics, the diversity of wetland ecotypes makes it difficult to have an extensive definition that is inclusive of all wetland systems while excluding aquatic ecosystems from the definition (Rader et al., 2001).

Examples of different types of wetlands include estuarine wetlands, salt marshes, brackish water wetlands, mangroves, freshwater wetlands, and swamp forests (Finlayson, 1991). Freshwater marshes account for over 90% of wetlands in the United States (Finlayson, 1991).

Benefits of Wetlands

Since the 1970s, the many benefits of wetlands have become more widely recognized.

Important functions of wetlands include flood prevention and protection, water quality improvement, and providing habitat for biologically productive ecosystems.

Wetlands' function as flood control and prevention is especially important, as climate change weather events have increased the intensity and occurrence of stormwater flooding. Wetlands can mitigate these effects by storing and slowly releasing rainfall and runoff and significantly reducing flood peaks (Finlayson, 1991). Moreover, wetlands also provide a pivotal role in carbon sequestration (Keddy, 2000).

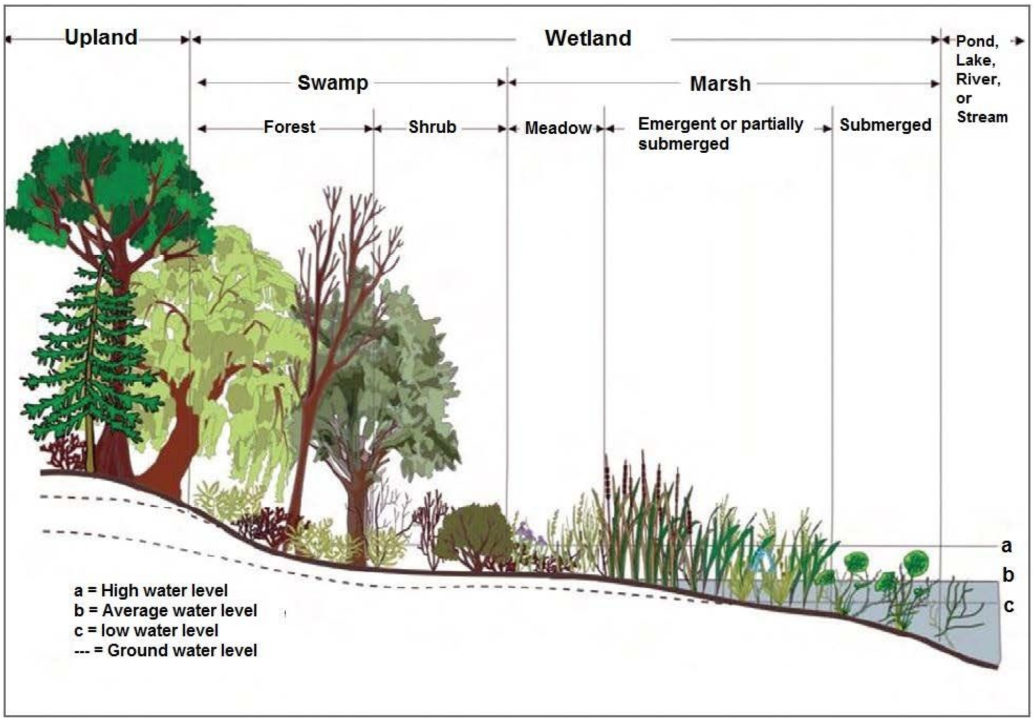


Figure 16: Diagram Modified from Environment Canada (2002)

Wetlands are extremely beneficial during major weather events, which have been increasing in frequency and intensity with the effects of climate change.

Studies show that residential properties within 150 meters of tidal wetlands experience less flood damage than properties located next to more impervious surfaces (Atoba et al., 2021).

US coastal wetlands are estimated to provide $23.2 billion per year in stormwater protection (Cohn et al., 2022). Wetlands that control the flow of water by retaining surface water form a significant portion of a drainage basin in a floodplain (Motts & O'Brien, 1981). Similarly positioned, coastal wetlands can counteract the forces of erosion and sea level rise during weather events (Finlayson, 1991).

Moreover, from these sponge-like qualities, wetlands' capability to store and slowly release water back into the watershed allows for toxic substances and pollutants to be filtered and cleansed (Bromberg & Bertness, 2005). Based on their many benefits, it is critical to protect and maintain wetland ecosystem integrity to mitigate climate-induced weather patterns and sea level rise.

Loss of Wetlands

Often written off as "nature's ugly mistakes" and areas of disease, wetlands have been altered and lost throughout human history, and more than half of the wetlands in the US have been destroyed due to agriculture, pollution, recreation, and expansion of urban and suburban areas (McGlothlin & Spray, 2004).

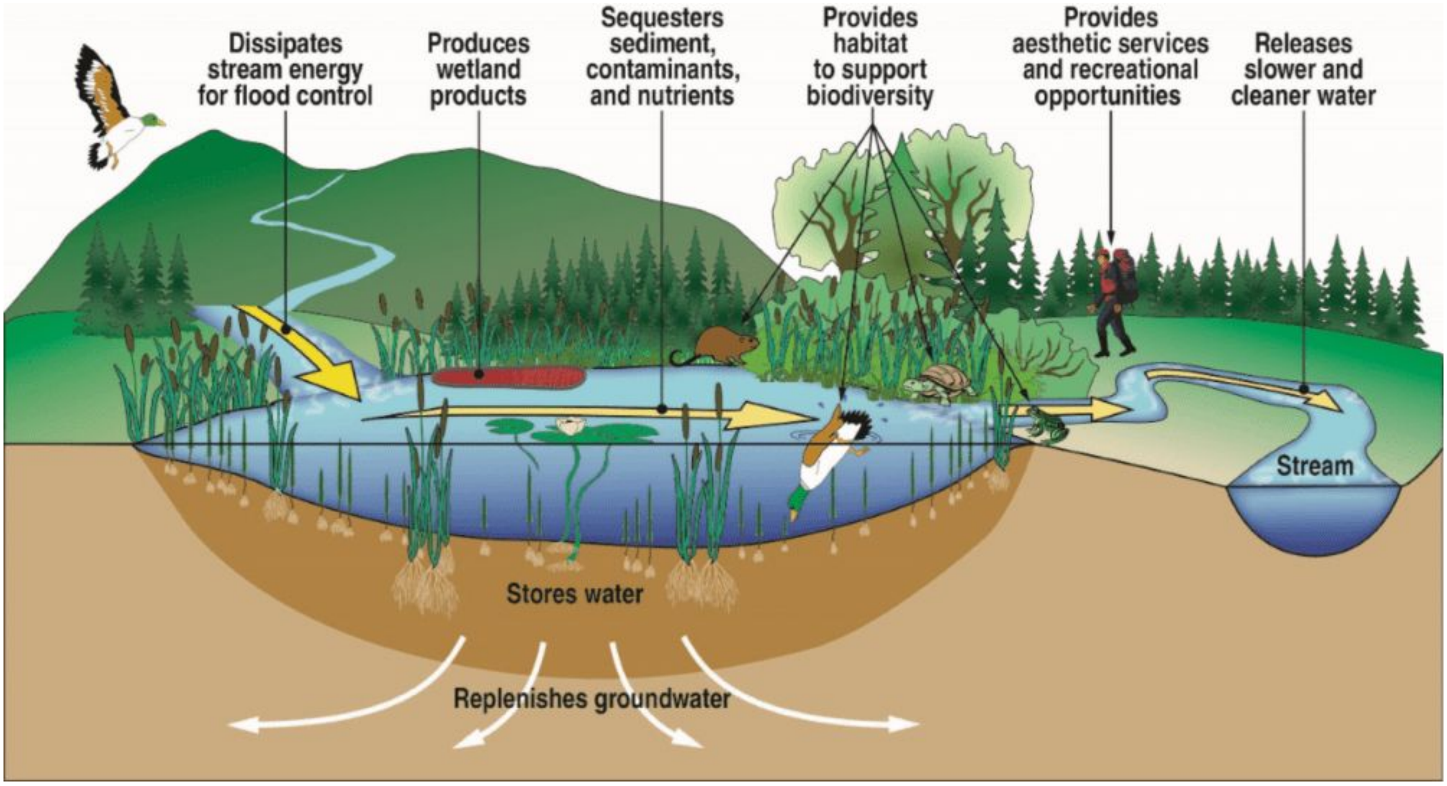


Figure 17: Diagram from Booth and Shock (2016) Environmental Perspectives Vol. 3

Wetland alteration in the New England area has followed national trends as increased population densities and suburban sprawl along the Atlantic seaboard caused the filling of wetlands for residential, industrial, and commercial use.

According to Bromberg and Bertness, wetland loss can be correlated with national economic and cultural trends. For example, coastal habitats and freshwater wetlands in the densely populated New England region have long experienced particularly detrimental anthropogenic effects (Bromberg & Bertness, 2005). Increased population densities throughout time and suburban sprawl contributed to the substantial conversion of wetlands into impervious surfaces.

Coastal cities located from New York, New York to Boston, Massachusetts, have formed a nearly contiguous border of developed land and loss of wetlands (Bromberg & Bertness, 2005).

The loss of wetlands has been characterized by negative effects such as nutrient runoff, phragmite invasion, overfishing, and sea level rise that continue to threaten remaining salt marshes (Bromberg & Bertness, 2005). The "hardened" urban shoreline has drastically altered its ecological integrity, much to the detriment of biodiversity and natural hydrological functioning, illustrating the need to preserve and restore these highly important ecosystems.

Wetlands Definition Controversy

Due to the varying characteristics of wetlands and the lack of precise boundaries, there is no one definition of wetlands.

Besides the physical and biological differences between swamps and marshes, both of which are classified as a wetland, the definition of wetlands has been tried and challenged at the Supreme Court when the Clean Water Act expanded the definition of a wetland to be included as a WOTUS. The most widely accepted definition of "wetlands" is from the US Fish and Wildlife Service (USFWS).

According to USFWS, a wetland must contain the following characteristics:

1) saturated sediments or soils covered by shallow water for at least part of the growing season, and

2) hydrophytes, a plant that grows in or on water, as the dominant plant at least periodically (Rader et al., 2001).

While wetlands were historically considered major impediments to societal improvements, the rise of the environmental movement and the general increase in knowledge and scientific advancements demonstrated how ecologically and economically important wetlands are. In 1977, the Clean Water Act expanded the definition of WOTUS to include wetlands. However, the protection of wetlands as waters of the U.S. has been challenged in courts under multiple presidential administrations (Kusler & Kentula, 1990).

As of March 2023, a revised definition of WOTUS took effect that indicates wetlands are considered jurisdictional waters of the U.S. under the Clean Water Act and are in the regulatory jurisdiction of the U.S. Army Corps of Engineers.

Massachusetts Wetlands

In Massachusetts, wetlands are found throughout the state, from the Atlantic Coast to the Berkshires (Massachusetts Department of Environmental Protection, n.d.) As of 2005, there are 590,457 acres of wetlands in Massachusetts, comprising 14% of total land cover in the state (Rhodes et al., 2019).

Wetlands are most abundantly distributed in lowland areas where the topographic relief is dominated by depressions and where the greatest amount of groundwater storage and discharge occurs (Motts & O'Brien, 1981).

Fresh, salt, and brackish wetlands exist in the Boston metropolitan area. Freshwater wetlands comprise 82% of acreage of all wetland resources in Massachusetts (Rhodes et al., 2019).

Since the colonial period, almost one third of Massachusetts' wetlands have been destroyed (Massachusetts Department of Environmental Protection, n.d.). Although there is a long history of wetland loss in New England, Massachusetts has recently experienced a total increase in wetland prevalence of 4,925 acres between 1990 and 2017 (Rhodes et al., 2019). This increase is largely due to beavers changing the hydrological features of areas (Rhodes et al., 2019). The observed increase in wetland cover may also be due to the implementation of strict state wetland protection policies and restoration recognizing the ecological importance of wetlands.

Despite the observed increase of wetlands, their health and function are still threatened.

Due to climate change, Massachusetts wetlands are expected to be significantly altered. Increased temperatures, the prevalence of invasive species, and increased precipitation pose threats to wetland health (Commonwealth of Massachusetts, 2022).

However, the greatest projected loss of wetlands is due to rising sea levels; 77% of coastal wetlands are expected to experience frequent flooding by 2070 (Commonwealth of Massachusetts, 2022).

According to the state's 2022 Climate Assessment, the increase in environmental pressures facing wetlands has been designated as a "most urgent impact," with the magnitude of occurrence and the adaptation gap within Massachusetts both being "extreme" (Commonwealth of Massachusetts, 2022). Although climate impacts on coastal wetlands have been well-documented, there has been less research regarding the projected effects of climate change on inland wetlands in MA.

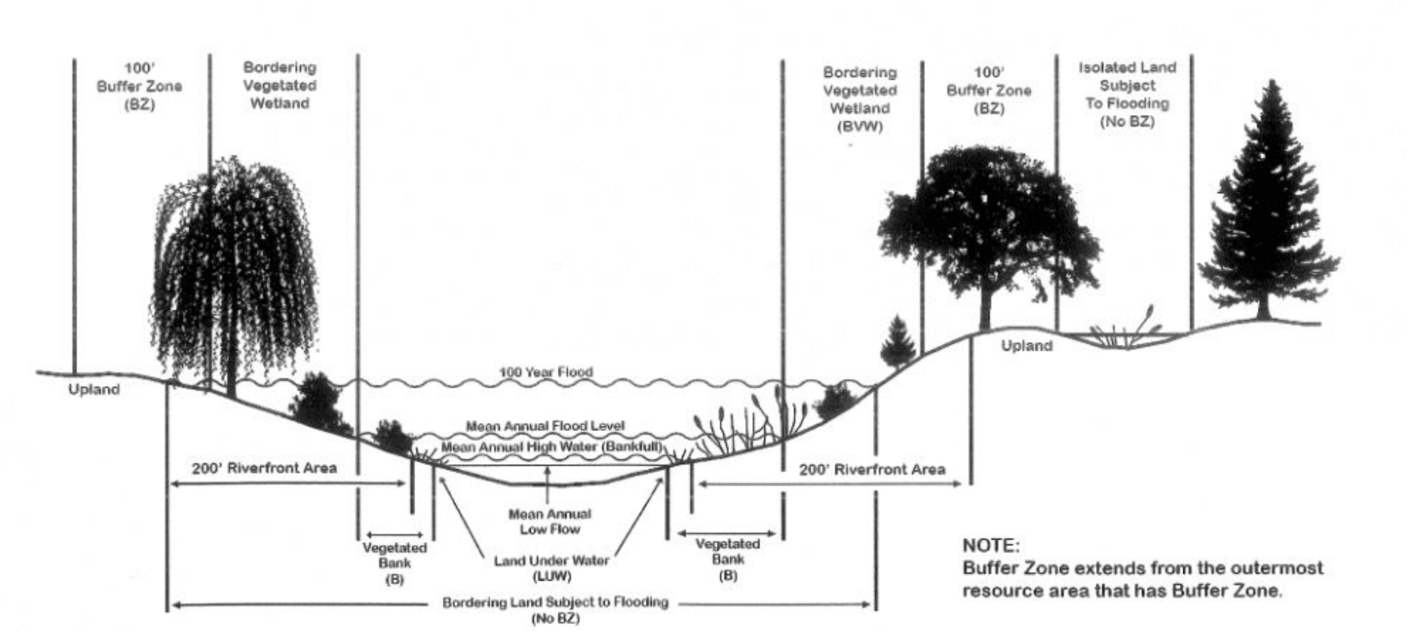


Figure 18: Inland Wetland Resource Areas and associated Buffer Zones. Modified from Massachusetts Department of Environmental Protection (personal communication) and MA WPA regulations

FEMA Flood Maps

The National Flood Insurance Protection Act (NFIPA) was enacted in 1968 (American Institutes for Research, 2005). Designed to provide monetary compensation to individuals that lost value due to flooding, the NFIPA required knowledge of areas of high flood risk vulnerability (Maidment, 2012). Thus, national floodplain maps (officially known as "flood insurance rate maps") were created. Initially, flood maps were delineated by straight lines that followed recognizable land features to help insurance agents easily understand them. However, all maps created after 1973 were mandated to be curvilinear for improved accuracy and realism (American Institutes for Research, 2005).

In 1979, the Federal Emergency Management Agency (FEMA) was created and became the agency responsible for maintaining and creating flood hazard boundaries, which it remains to this day (American Institutes for Research, 2005).

Flood maps are divided into several categories denoting the specific flood risk to each area. **FEMA flood zones** are at the greatest risk of flooding, located within the 100-year floodplain, and are at risk of increased flooding from storm induced waves (Understand the Differences between FEMA Flood Zones, n.d.). Properties with federally-backed mortgages located within these areas are required to purchase flood insurance. Alternatively, areas can be categorized as moderate or low risk zones. Moderate risk zones are areas within the 500-year floodplain, whilst areas outside of the 500-year floodplain are categorized as low risk zones (Understand the Differences between FEMA Flood Zones, n.d.). Neither moderate nor low risk zones require buildings within the area to purchase flood insurance.

FEMA Flood Map Limitations

Despite being hailed as "the gold standard for understanding flood risk in the United States" (Eby, 2019), the national flood maps have long been the subject of scrutiny. In several instances over the last three decades, FEMA flood maps have proven to be inaccurate or out of date (American Institutes for Research, 2005). Currently, it is estimated that 75% of all flood maps are out of date (Understand the Differences between FEMA Flood Zones, n.d.).

Longstanding limitations of flood maps are the result of four primary constraints: geographic, methodological, political, & financial.

Geographic Limitations

FEMA flood maps are not geographically comprehensive.

- ➔ Flood maps are created only for participating communities that voluntarily adopt & enforce floodplain management (American Institutes for Research, 2005; Pralle, 2019). Thus, if a community does not enact a floodplain management policy, it does not receive flood maps, creating gaps in national flood risk data.
- ➔ The NFIP does not operate on federal lands. One million of the United States' four million miles of rivers and streams and 60,000 miles of coastline are not mapped (Maidment, 2012).
- ➔ FEMA flood maps focus overwhelmingly on coastal flooding at the expense of covering riverine and stormwater flooding (Wing et al., 2018). Due to these geographic limitations, designated flood hazard zones are not reliable indicators of flood risk.

Methodological Limitations

FEMA relies on out-of-date data and methods to make flood risk projections.

- ➔ Flood maps are created based on historical flow data from river gauges. While useful for understanding past flood events, this data does not consider future changing environmental conditions and is thus inaccurate for projecting future flooding (Pralle, 2019; Understand the Differences between FEMA Flood Zones, n.d.). As climate change continues to become a more pressing issue, this deficiency will further exacerbate inaccuracies in existing flood maps.
- ➔ The areas of flood risk are rigidly delineated. While useful for mapping purposes, real-life flood events rarely occur along such strict boundaries. There may be blurred lines between moderate and low risk flood areas, for example, that are not represented in the flood maps, ultimately leading to inappropriate flood risk designations.

Political Limitations

The making of flood maps is a deeply political process (Pralle, 2019). Flood map creation is an iterative process, which compromises scientific validity.

- ➔ Maps are "a collaboration between [the] community and FEMA. Every community that participates in the **National Flood Insurance Program** has a floodplain administrator who works with FEMA during the mapping process" (Flood Maps, 2021). After the floodplain administrator consults on the flood maps, additional challenges are permitted.
- ➔ Challenges to flood maps occur frequently due to the financial burden of residing within a designated flood zone. If located outside of a flood zone, the property owner is not compelled to buy flood insurance, thus incentivizing the underestimation of flood risks. This often disadvantages historically marginalized communities, such as Black, Indigenous & People of Color and low-income communities.
- ➔ If private citizens, businesses, or developers intend to challenge a map, they must hire an engineering firm or land surveyor to conduct studies providing evidence to substantiate changing the maps (Pralle, 2019). This process can cost hundreds or thousands of dollars, creating a financial barrier for small or poor communities.
- ➔ When individuals challenge the flood maps, they are usually successful: map challenges have an 89% success rate (Pralle, 2019). Thus, individuals with the disposable income & political power to challenge maps are often able to shift map boundaries as they desire.

Financial Limitations

The greatest internal limitation that FEMA faces is their financial constraint. The creation of a national flood map is an expensive task. This is the main reason an overwhelming number are out-of-date is because it is nearly impossible for FEMA to update flood maps in a timely & accurate manner (Understand the Differences between FEMA Flood Zones, n.d.).

- ➔ A 2013 study estimated a cost of $4.5 to $7.5 billion to finish creating all maps, & between $100 million to $300 million annually to maintain maps (Pralle, 2019). That same year, FEMA requested a total budget of $789 million (Department of Homeland Security, 2013).
- ➔ The creation & maintenance of the national flood map system can be 6-10x the cost of FEMA's budget.

Historical GIS Meta-Analysis

To inform the study of historical wetlands in the MAPC region, a meta-analysis was conducted to assess methods and techniques for using historical maps in **geographical information systems (GIS)** analysis of water resources, such as wetlands, salt marshes, and coral reefs. The findings were used to create a standard operating procedure (SOP) for historical wetlands analysis using available resources to fulfill project goals. This section provides a broad overview, while a more detailed version can be found in Appendix III.

Analysis Methods

Ten scientific papers and one meta-analysis were analyzed. The study areas span the globe and range in time spans of 100 years to 240 years. They assess changes in wetlands, salt marshes, benthic habitats, land use, and habitat change through the comparison of historical maps to modern maps.

The most common analysis method employed was georeferencing—a GIS method used to align aspatial rasters or images with geographic **coordinate reference systems (CRS)**. This is accomplished by using ground control points (GCPs) to link matching points on the raster and the established CRS. Because the rasters may be distorted or projected differently than the coordinate system, **transformations** are used to warp and fit the raster to the coordinate system.

Figure 19 shows an example of georeferencing a historical map with the web-based application Allmaps Editor. The historical map on the left is aligned with a digital map using an existing CRS on the right using control points, shown as red numbered points.

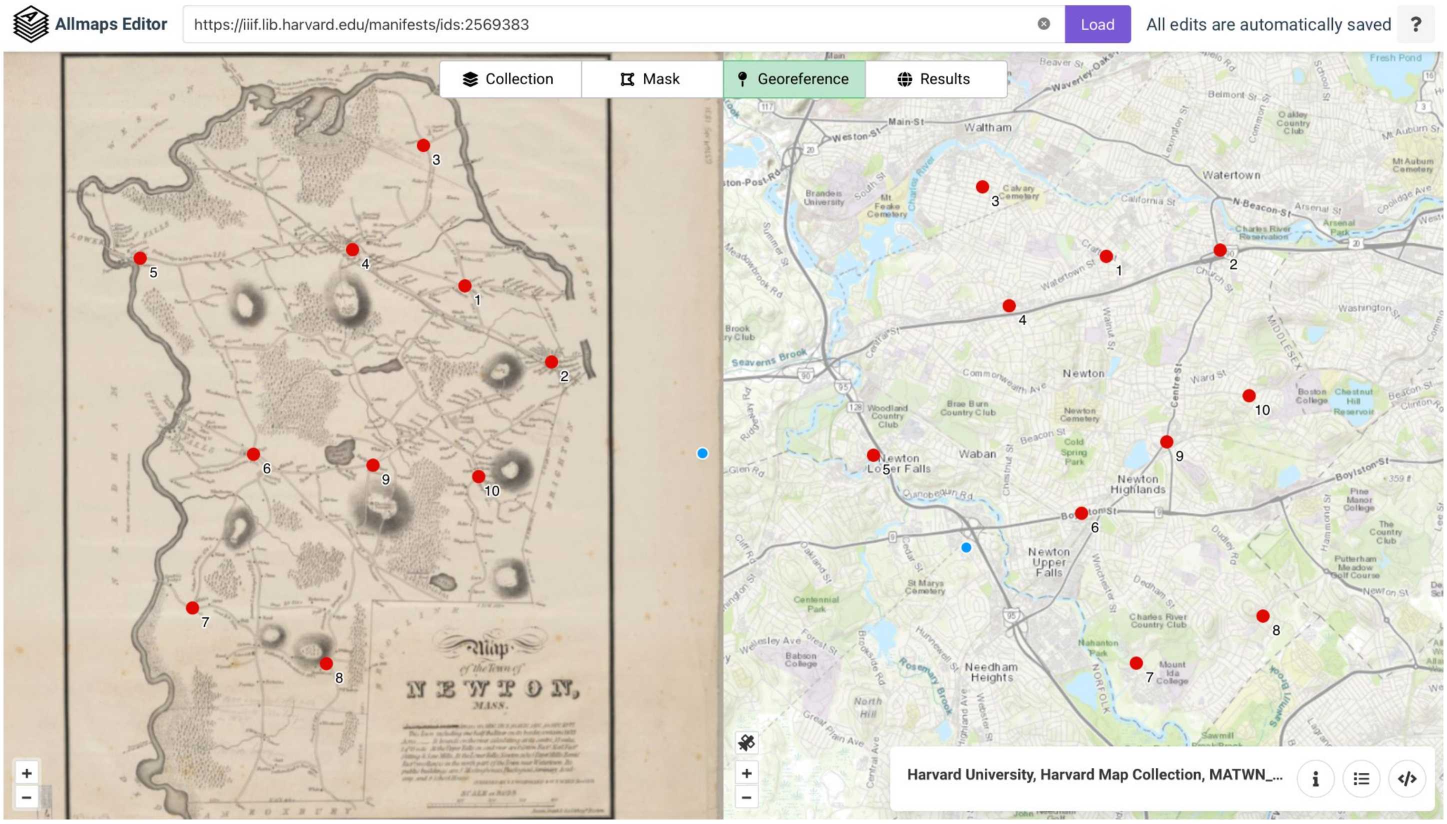


Figure 19: Example of Georeferencing a Historical Map Using Web-based Application [(Source: Allmaps Editor)]

Georeferencing is a GIS method used to align aspatial rasters with geographic coordinate reference systems (CRS). Rasters can include aerial photographs or digitized historical maps.

Feature Analysis

Once the georeferencing process is complete, raster images are tied to coordinate systems and can be analyzed with modern GIS methods. Most studies converted the historical features into vectors to compare their historical extents to their current extents.

Two studies on changes of wetlands over time vectorized historical wetlands from several time periods, then combined each time period's extent with those of all successive time periods to create a representative "true" historical wetlands extent. This practice of combining wetland extents is based on the assumption that all wetlands existing in a time period also existed in the past but were not included in maps because of the broader definitions. Using the historical extents as represented on the original maps would skew analyses.

Considerations and Insights

HGIS methods have strong potential to inform future climate resiliency scenarios when employed to assess long-term trends in water resource changes. Methods need to be chosen carefully, however, because of the limitations of HGIS methods and historical understandings of water resources. A meta-analysis by Schaffer and Levin (2015) detailed the following common issues and subsequent guidelines in HGIS, which this historical wetlands study will draw from:

Registration accuracy is dependent on the GCPs chosen and the historical maps' relations to modern maps. Georeferencing should be done with coordinate grid lines or points, or recognizable features, such as mountain peaks, road intersections, and prominent buildings.

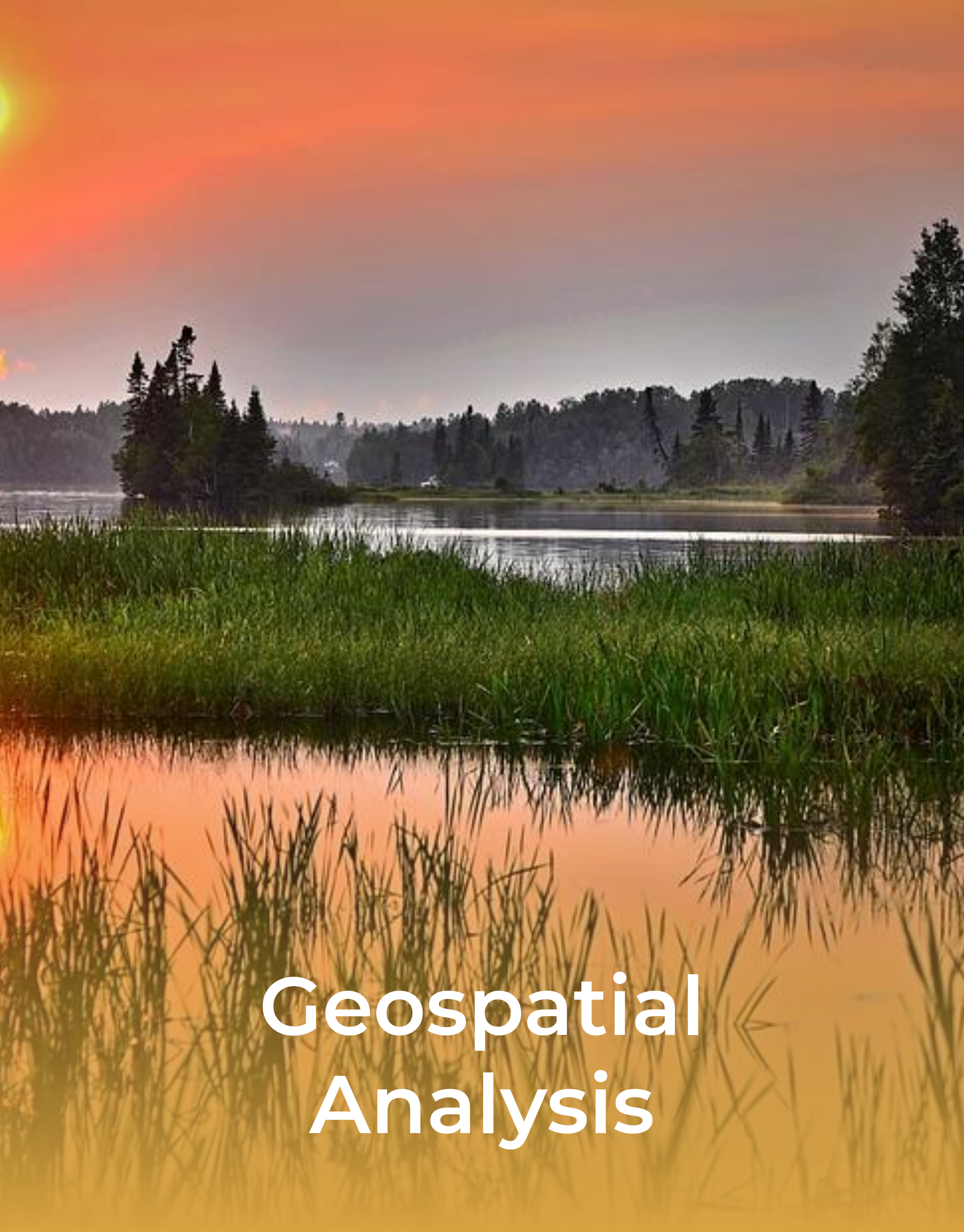
Map generalization depends on the scale of the historical map, the on-screen scale of the digitized map, and the scale of the screen, which can all impact the size, shape, and accuracy of the features when vectorizing. Analysts should make note of these different scales and use caution when interpreting the analysis.

Positional Accuracy differs between feature types, particularly through time. Historical extents of rivers, for example, are the least accurate when compared to modern day, as river banks are constantly eroding and growing.

Attribute Accuracy is dependent on the surveyor, map maker, and feature type of interest of the historical map. The intents of the surveyor and map maker and artistic ability of the map maker heavily influence the resulting map. Further, features often do not have clear borders or symbols or are defined inconsistently across maps and time periods.

Completeness of Information depends on the scale of the map and map maker's expertise and intent. Other contemporary historical sources may be needed to contextualize the maps of interest.

When applying HGIS techniques to wetlands, it is important to note that wetlands are generally underrepresented on historical maps, and the **time horizon approach** may be appropriate to construct a representative historical extent. All types of wetlands can be combined to alleviate concerns about differing definitions and symbology for types of wetlands. Consideration should be taken for the survey year and season, and research should be conducted on historical weather patterns— particularly precipitation—to inform interpretation of historical wetlands extents. Lastly, on-screen scales should be kept consistent when vectorizing features.



Geospatial Analysis

Overview

Geospatial analysis for this project consisted of three parts:

- ➢ creation and analysis of **historical wetlands datasets**,
- ➢ analysis of the relationship between **historical wetlands and flood claims from the March 2010 storm**, and
- ➢ analysis of the relationship between **historical wetlands and sociodemographic characteristics**.

The following subsections describe the data and methods employed with the goal of easy replication for other municipalities within the MAPC region. Additional information may be found in Appendix III, Appendix IV, and Appendix V. Results follow for this study's MAPC region focus municipalities.

Historical Wetlands

Data

The maps used in this analysis were primarily sourced from the U.S. Geological Survey (USGS) online databases. The present-day wetlands shapefile was downloaded from MassGIS; the most up-to-date version was created in 2005.

Maps were chosen for their completeness and the presence of consistent wetlands symbology. Maps with survey years within the following time periods were selected for each study area:

- 1880s-1900s
- 1940s
- 1970s-1980s

Where 1880s-1900s maps were not available, the next earliest map was used. Randolph and Stoughton, and Wilmington and Woburn were georeferenced and vectorized together because the full extent of the municipalities were split between multiple maps. For Boston, both 1893 and 1903 were chosen because the 1903 map displayed many more wetlands—in both count and size—than the 1893 map, despite being surveyed only thirteen years later. Table 1 details the maps used for each focus municipality.

Table 1: Historical Maps Used in Geospatial Analysis (Source: Tufts Team)

Municipality	Year		Map Source	Map Scale	Notes
	Map	Survey			
Boston	1893	1886	USGS	1:62,500	Both 1903 and 1893 were chosen because of stark differences in wetlands depicted between them.
	1903	1898-1900	USGS	1:62,500	
	1946	1943	USGS	1:31,680	
	1987	1978	USGS	1:25,000	
Randolph & Stoughton	1917	1884-1886	USGS	1:62,500	The full extent of Stoughton was split between multiple maps, some of which also included Randolph. Maps from the same time period were georeferenced and vectorized together for wetlands of both Randolph and Stoughton.
	1920	1915	US Army Corps	1:62,500	
	1941	1936	USGS	1:31,680	
	1941	1936	USGS	1:31,680	
	1971	1969	USGS	1:24,000	
	1975	1974	USGS	1:24,000	
Wilmington	1917	1886	USGS	1:62,500	
	1944	1942	USGS	1:31,680	
	1987	1978	USGS	1:25,000	
Woburn	1903	1903	USGS	1:62,500	
	1946	1943	USGS	1:31,680	
	1972	1971	USGS	1:24,000	
ALL	2005	1990-2000	MassDEP		

Historical GIS Methodology

The historical GIS (HGIS) methodology detailed in this section was developed based on the findings of the historical GIS meta-analysis and guidance from Esri. The following steps were employed for all five focus municipalities using the NAD 1983 Massachusetts State Plane coordinate system from 2011. For more detailed technical instructions, see Appendix IV.

01

Step 1

Historical Map Georeferencing

Purpose: Align images of historical maps to a geographic CRS using around twenty GCPs.

02

Step 2

Clip Georeferenced Maps to the Maximum Overlapping Extent

Purpose: Keep only the maximum intersecting extent of all historical maps used for each study area to ensure accuracy and comparability between layers.

03

Step 3

Vectorize Historical Wetlands

Purpose: Identify and delineate historical wetlands as vectorized polygons for each georeferenced historical map at an on-screen scale of 1:7000.

Figure 20. shows two examples of the historical map's original wetland and the resulting vectorized polygon, displaying the team's procedure for vectorizing.

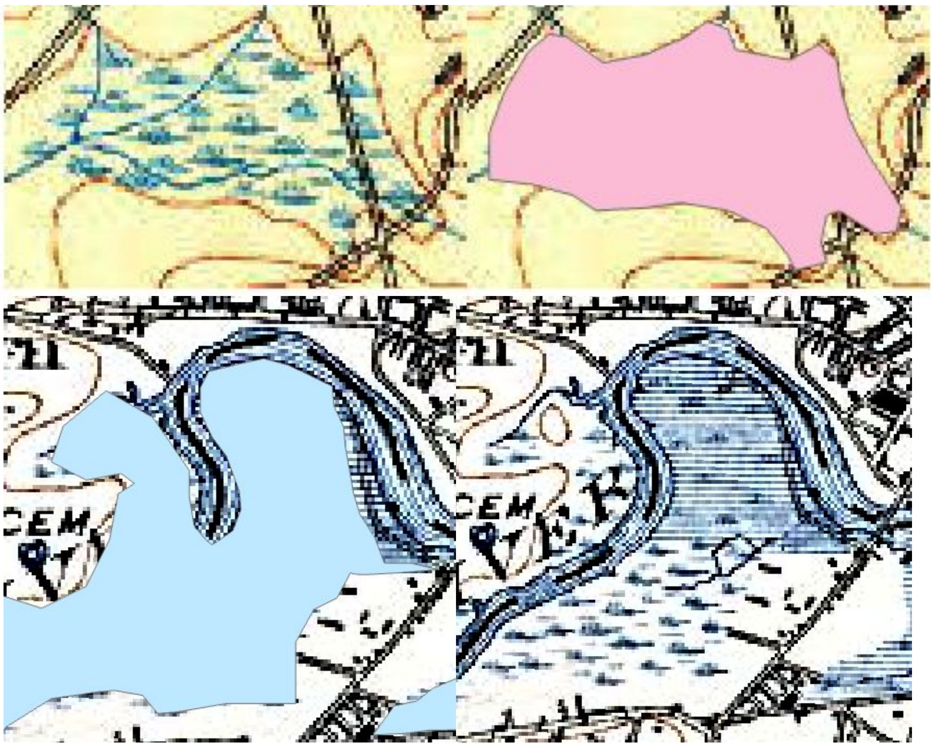


Figure 20: Examples of the wetlands vectorized on the historical maps (Source: Tufts Team)

04

Step 4

Create Present Wetlands Extent Layer

Purpose: Filter existing shapefile of present-day wetlands to the study area extent; excluding water bodies and irrelevant features.

05

Step 5

Create Historical Wetlands Extent Layer

Purpose: Create a representative historical extent of wetlands for each time period using a time horizon approach.

The wetlands analyzed for Boston and the order of their combinations are shown in Figure 21 below.

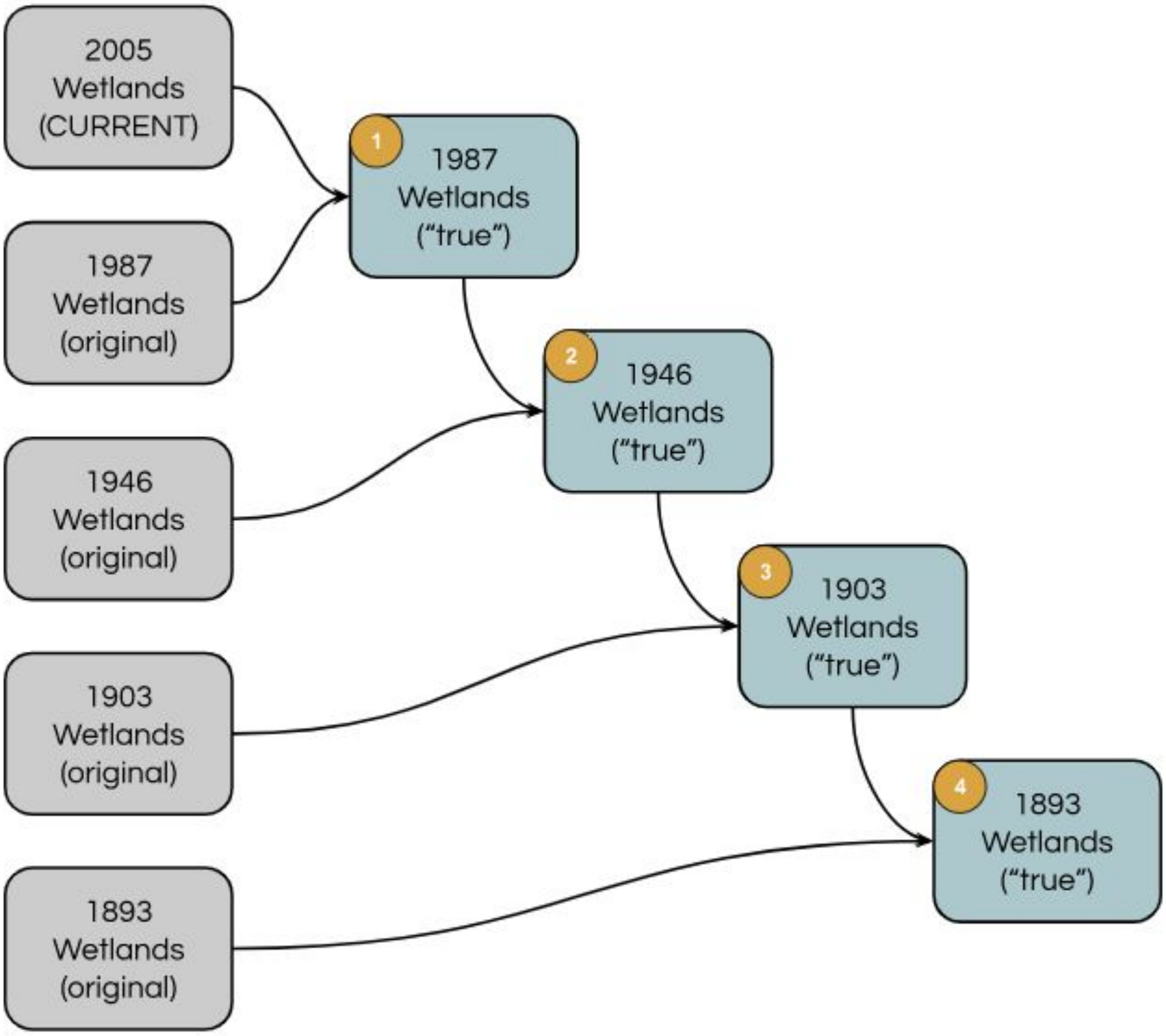


Figure 21: Conceptual diagram of time horizon combination of historical maps (Source: Tufts Team)

06

Step 6

Determine Area Lost Between Historical and Present Wetlands Extents

Purpose: Visualize and calculate wetland loss between historical and present wetlands.

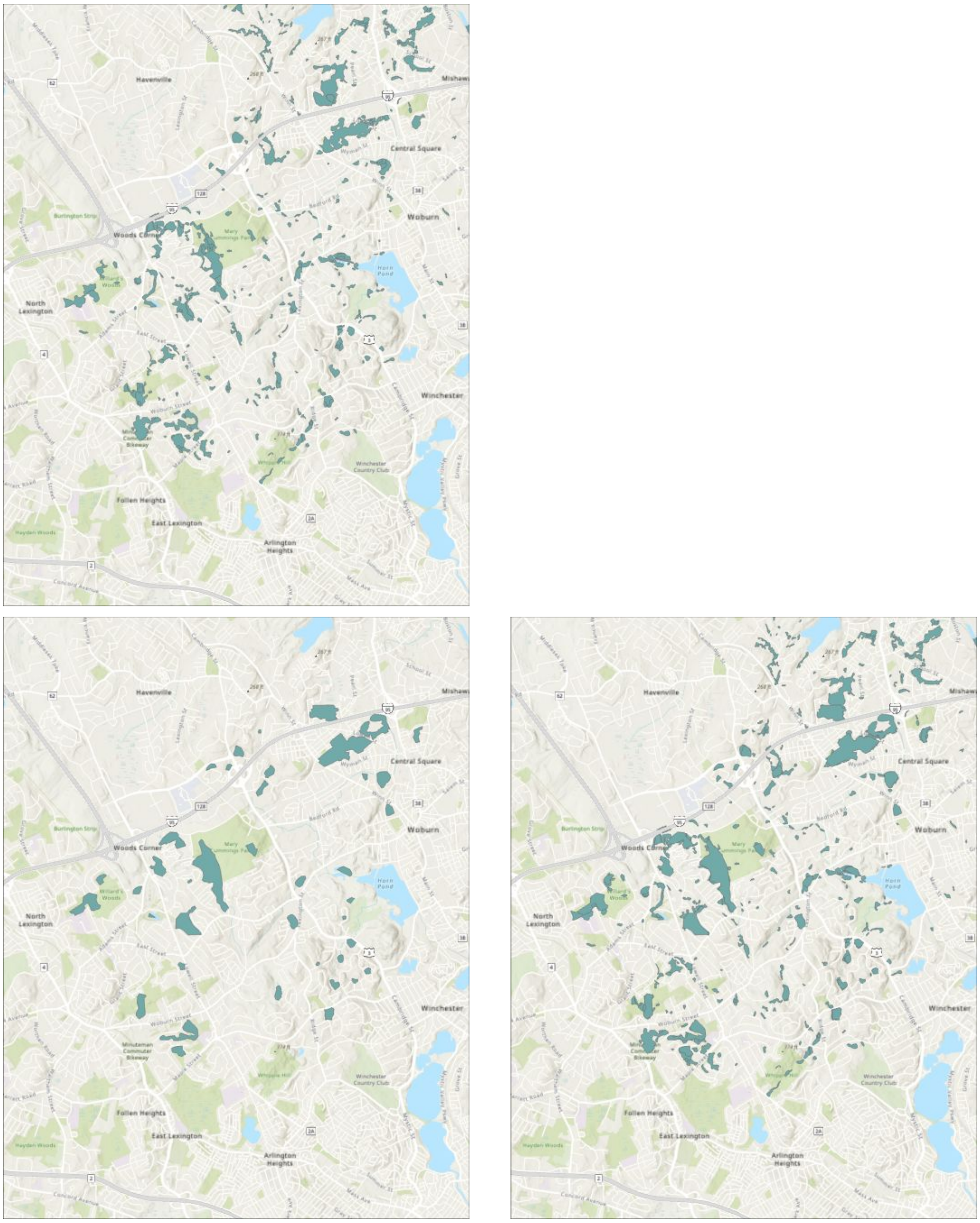
Below Figure 22 depicts the original wetlands layers derived from each historical map and the results of the "true" representative layer merges in Steps 3 and 4, respectively. The example images in this figure depict an area in the west of Woburn, near Woods Corner.

Original Historical Map Wetlands

"True" Wetlands

2005

1971



1946

1903

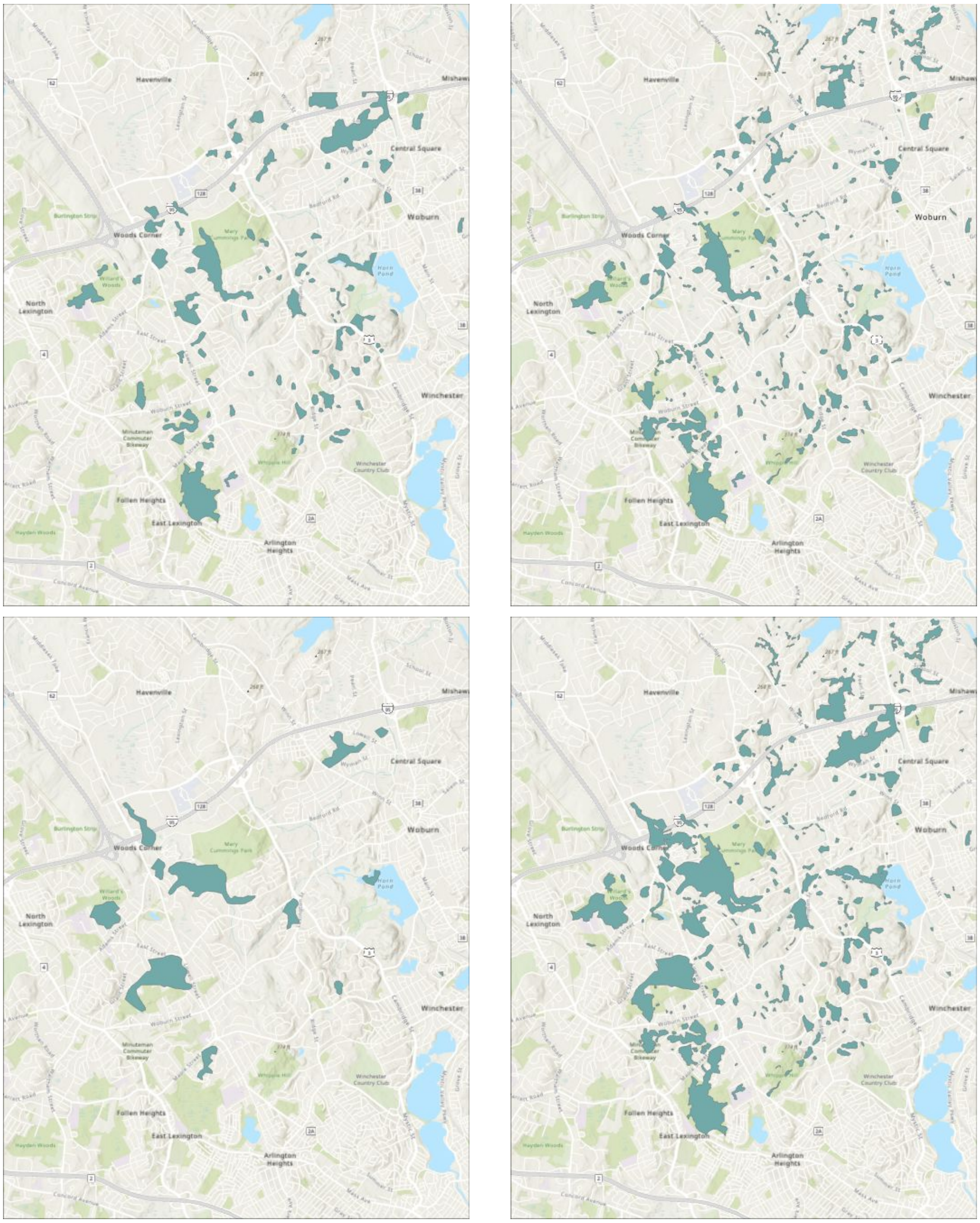


Figure 22: Original and "true" wetlands extents in historical maps (Source: Tufts Team)

Finally, the map of the representative historical extent of 1893 is mapped with the current wetlands extent of 2005 in the Figure 23 below.

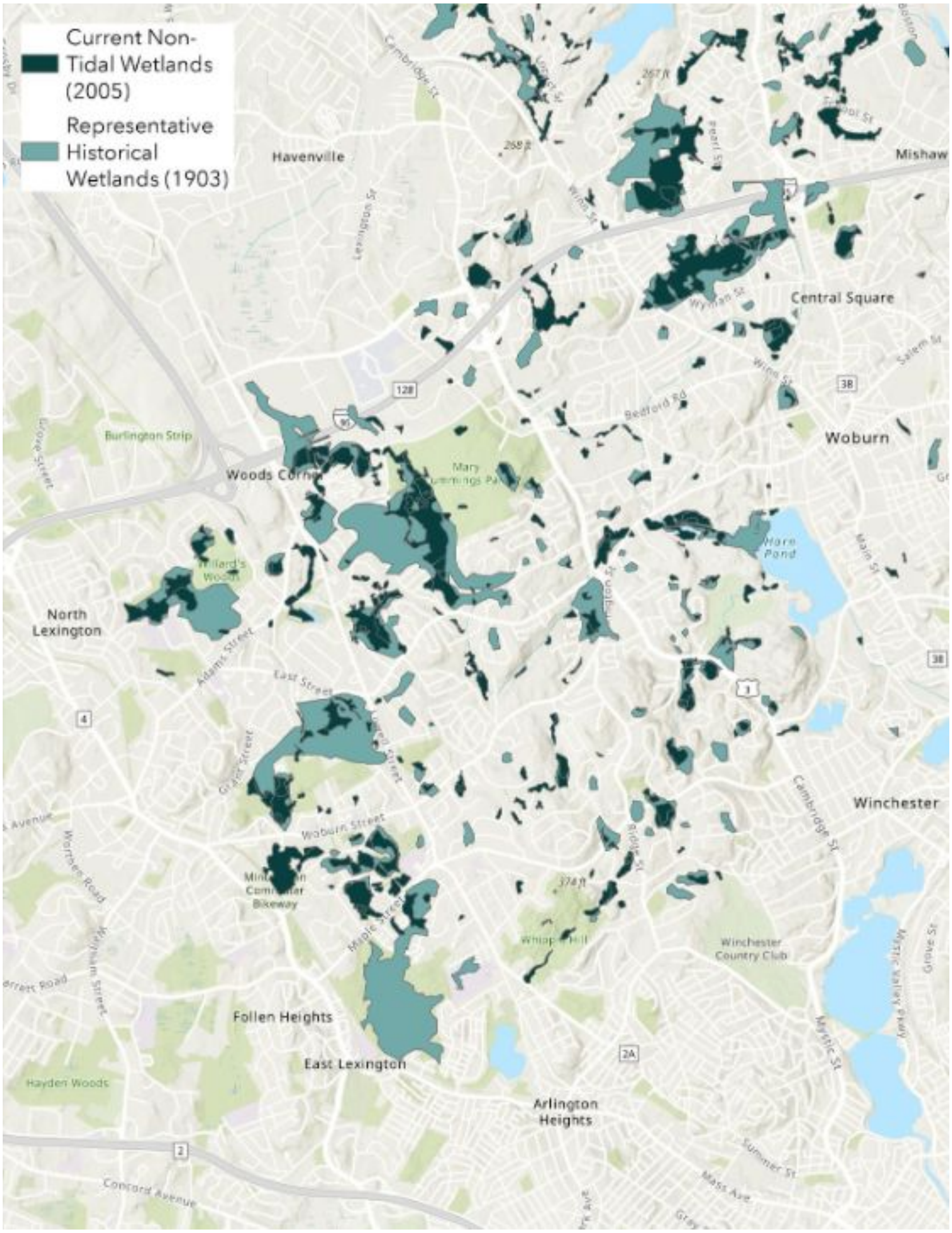


Figure 23: Representative 1903 Wetlands and Non-Tidal 2005 Wetlands (Source: Tufts Team)

Flood Claims

The next step in this study's geospatial analysis was assessing the relationship between historical wetlands and modern stormwater flooding. Flood insurance and disaster assistance claims data from the March 2010 storms for 100 municipalities in the MAPC region were obtained by MAPC from FEMA, the Massachusetts Emergency Management Agency (MEMA), and the **National Flood Insurance Program** (NFIP) via the Massachusetts Department of Conservation and Recreation (MDCR). While there were 19,395 approved claims across these three sources, this dataset does not encapsulate all instances of flooding and flood damage in the MAPC region during the March 2010 storms.

The vast majority of the claims were not covered under flood insurance and were instead disaster claims, indicating that current flood zone designations are insufficient to plan for modern stormwater flooding. To investigate potential flooding risk factors, MAPC joined attributes for residential claims with parcel attributes from the Massachusetts Land Parcel Database (MLPD) to assess their relationships and any predictive factors, comparing them with parcels without claims. This project takes MAPC's studies further by relating March 2010 flood claims with historical wetlands in the five focus municipalities of Boston, Randolph, Stoughton, Wilmington, and Woburn.

This analysis addresses the following questions in this narrowed study area:

- **What is the correlation between distance to historical wetlands and flood claim status?**
- **What is the correlation between other variables of interest and flood claim status?**
- **Are there geographical or municipal differences in these relationships?**
- **If no apparent relationships exist, what is missing from the analysis?**

Data

Because claims data includes sensitive and personal identifiable information, MAPC is not permitted by federal regulations to share the data outside of their organization and maintains strict policies for internal use, including storing the data on a secure server with limited access.

MAPC therefore created a dataset with scrambled or perturbed flood claim locations and relevant attributes with which the Tufts Team developed an analysis workflow using the programming language Python. This workflow was then sent back to MAPC to run on the original complete dataset and return anonymized outputs to the Tufts Team that investigate the relationships between variables of interest described in Table 2.

Table 2: Flood Claims Analysis Variables of Interest (Source: Tufts Team)

Variable	Description
Claim status	Whether a parcel did or did not have a claim
Type of claim	Flood insurance or disaster assistance claim
Distance to historical wetland	Calculated between parcel and nearest historical wetland
Distance to present-day wetland	Calculated between parcel and nearest present-day wetland
Distance to water body	Calculated between parcel and nearest water body (e.g. river, lake, ocean)
Distance to 1% flood zone	Calculated between parcel and nearest 1% flood zone (i.e. 100-year flood year)
Distance to 0.2% flood zone	Calculated between parcel and nearest 0.2% flood zone (i.e. 500-year flood year)
Year built	Year the residential building was built

Methods

01

Statistical Analysis

The first step in flood claim data analysis was exploratory statistical analyses on variables of interest for all locations (i.e. the five focus municipalities and the entire study area) by investigating statistical summaries and figures, such as histograms and boxplots.

02

Crosstab Assessment

The Team then shifted to a municipality-level approach to compare metrics across the study area and narrowed the variables to three: distance to historical wetlands, distance to present-day wetlands, and year built. Because MAPC has conducted analyses on the broader dataset across the MAPC region, these variables were chosen to add to existing work rather than duplicate it and to compare with the timeline of wetlands alterations. Each variable was recategorized, and crosstab contingency tables were created to show the relationship between each category and claim status. The contingency table for distance to historical wetlands, for example, details the percentages of buildings with claims and buildings overall that are within, less than 100 feet, and greater than 100 feet from historical wetlands.

03

Construct Relative Claim Index

Finally, the Tufts Team constructed a new metric named the Relative Claim Index (RCI) to more easily compare these categorical distributions detailed in the crosstabs across locations.

Equation 1:

$$RCI_{location,\ category} = \frac{\%\ buildings\ with\ claims}{\%\ all\ buildings} - 1$$

The RCI (Equation 1) was calculated for each location and category by first dividing the percent of buildings with claims by the percent of buildings overall, then subtracting one. The resulting RCI distills crosstab results into a single number and is an indicator of whether there were relatively more or fewer buildings with claims, compared to buildings on average for each location and category. A positive RCI represents proportionally more buildings with claims, while a negative RCI represents proportionally fewer buildings with claims. An RCI value of zero shows that either no buildings are present in the location and category or that there are equal proportions of buildings with claims and buildings across the location.

Sociodemographic Analysis

Data

To investigate relationships between areas with historical wetlands and sociodemographic characteristics of current residents, the Team conducted a qualitative sociodemographic analysis on the study area's five municipalities.

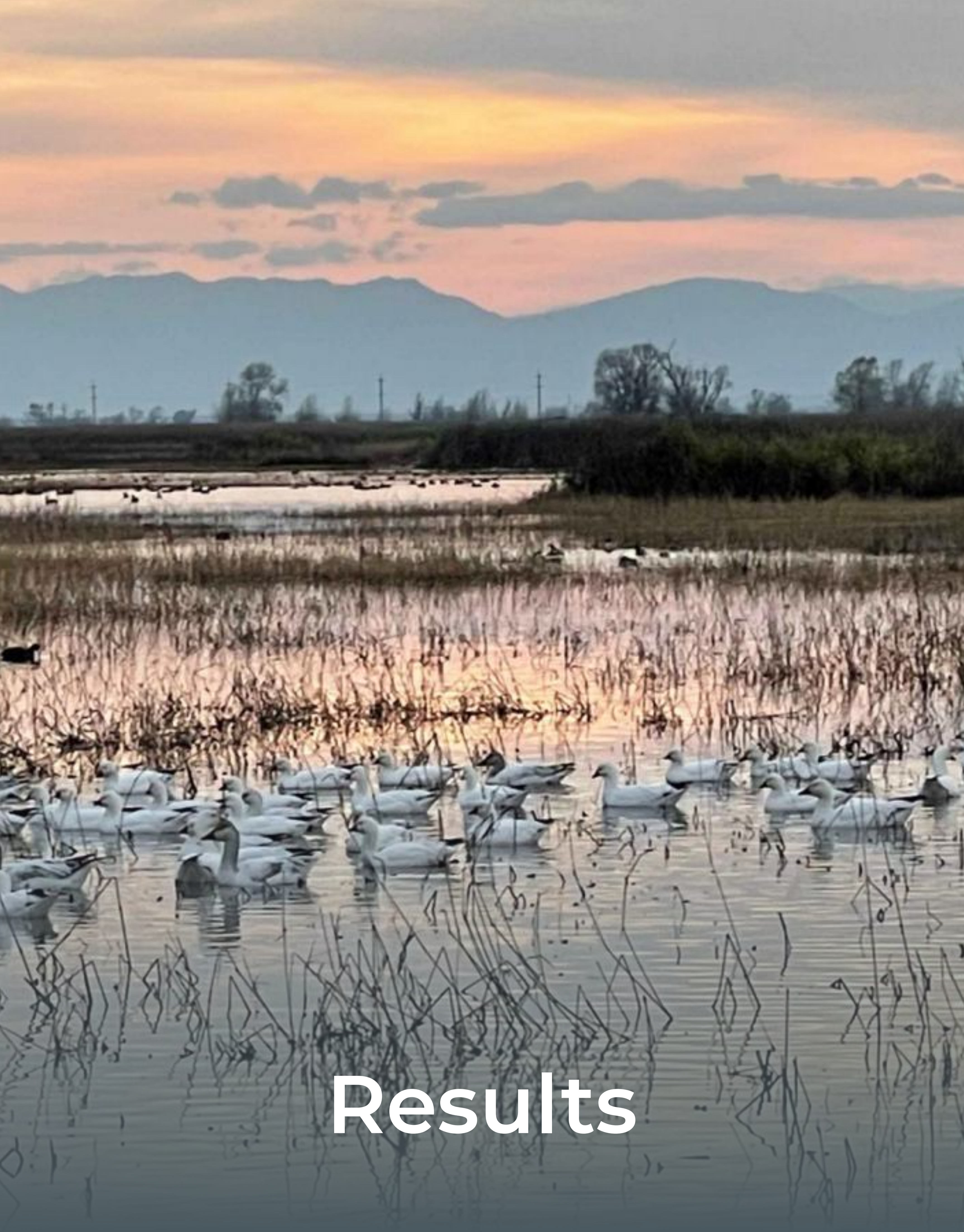
Data for two variables—minority population and median household income—were acquired from Social Explorer at the census block group (CBG) level from the U.S. Census Bureau's American Community Survey 5-year estimates for 2010-2014 (Social Explorer, n.d.).

Data Cleaning

The aspatial data was merged with MassGIS's CBG shapefile for Massachusetts and filtered for the study area municipalities. With the sociodemographic data at the census block group, the Team then created a variable for wetland loss at the same scale. To do this, the Team created a feature class of areas within each municipality where there was a historical wetland but no present day wetland. Next, the square area of these lost wetlands was calculated for each census block group and represented as a percentage of the census block group's total area.

Data Visualization

Finally, the Team created maps showing the bivariate distribution for each municipality to compare minority population and median household income to the percentage of wetlands lost for each CBG. This data visualization technique allowed the Team to assess areas within each municipality where, for example, median household income is low and wetland loss is high and vice versa to inform equity implications of MAPC's on-going work with modern stormwater flooding.



Results

Boston

Historical Wetland Alteration

Present Day and Historical Wetlands in Boston

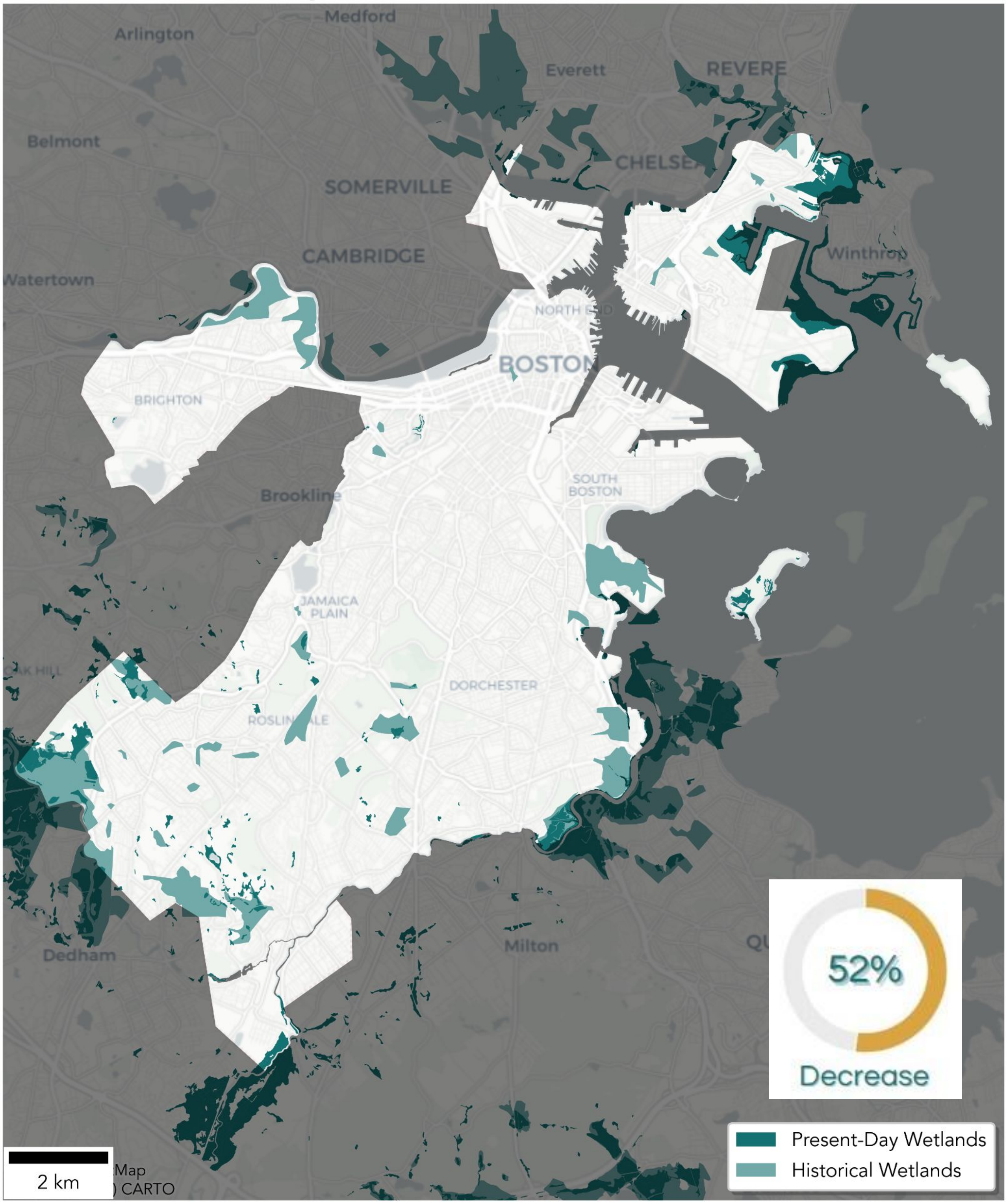


Figure 24: Present Day and Historical Wetlands in Boston (Source: Tufts Team)

Flood Claims and Wetlands

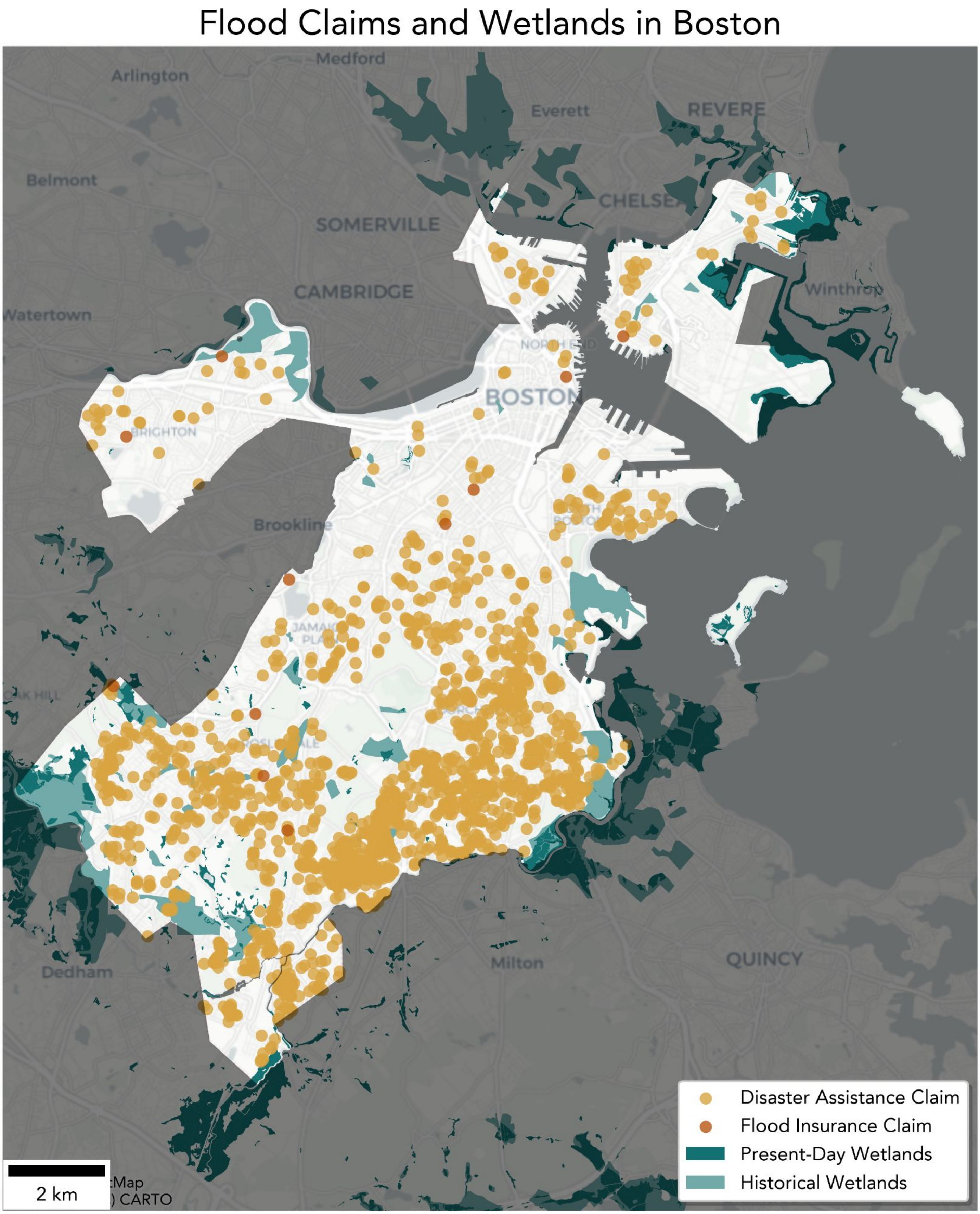


Figure 25: Flood Claims and Wetlands in Boston (Source: MAPC & Tufts Teams)

Sociodemographic Variables & Wetland Loss

Wetland Loss & Median Household Income in Boston

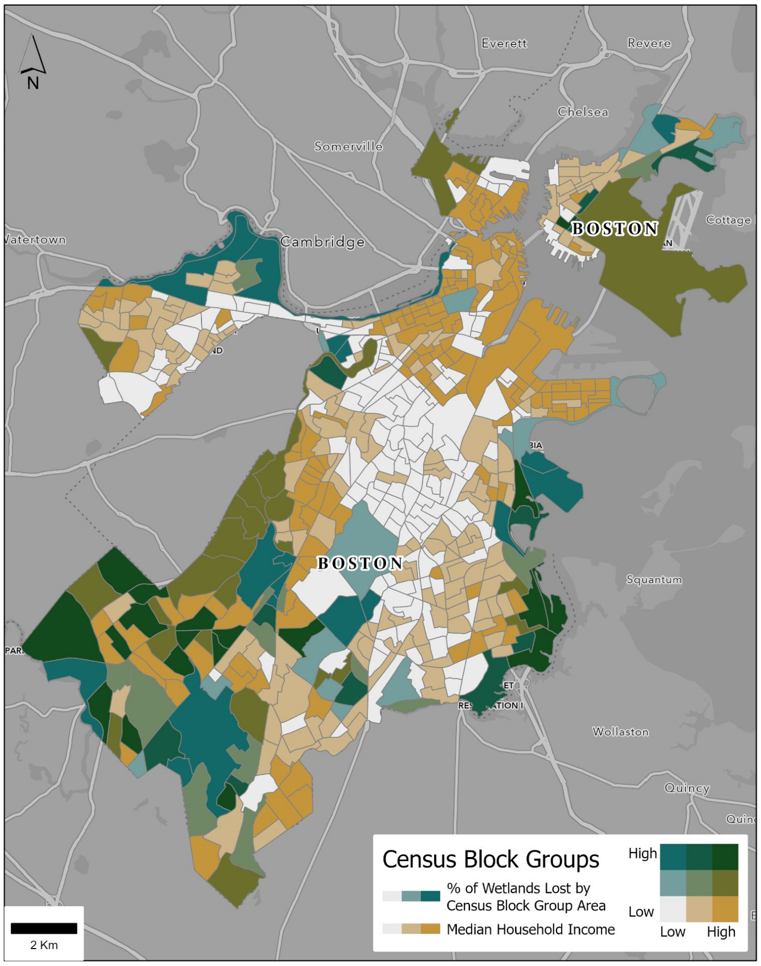


Figure 26: Bivariate distribution of wetland loss & median household income in Boston by census block group (Source: Tufts Team)

Census block groups (CBGs) with a high percentage of wetland loss and low median household income are more scattered, including areas within Dorchester, Roslindale, West Roxbury, Hyde Park, and Allston/Brighton. These CBGs are primarily near bodies of water, such as the Boston Harbor and the Charles River.

Wetland Loss & Minority Population in Boston

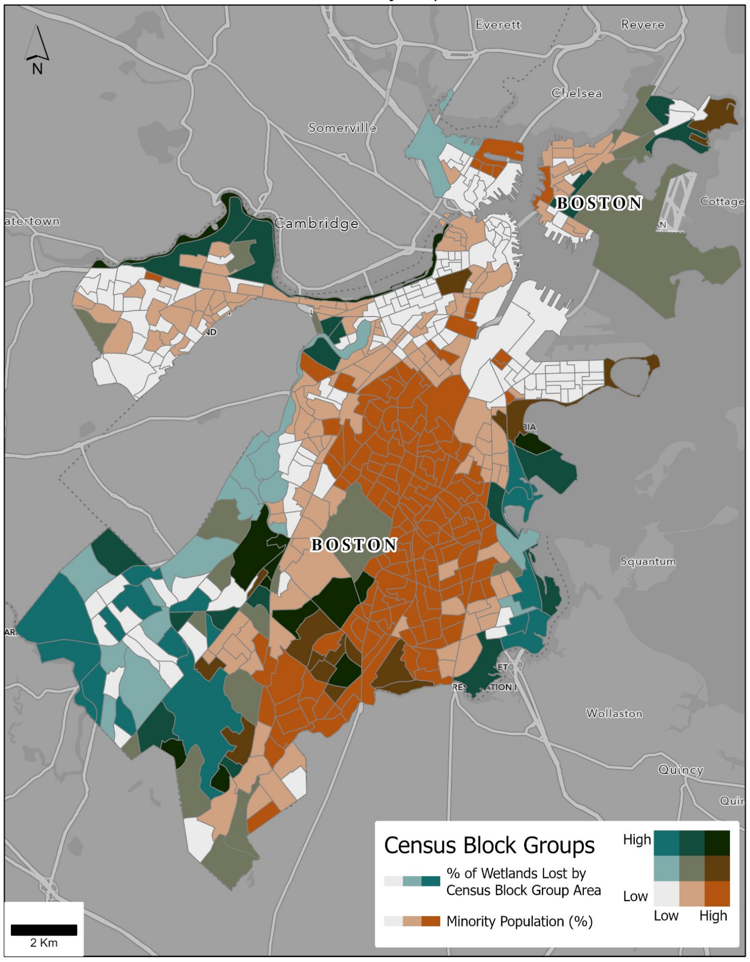


Figure 27: Bivariate distribution of wetland loss & minority population in Boston by census block group (Source: Tufts Team)

CBGs with a high percentage of wetland loss and high minority populations are primarily within the Roslindale, Mattapan, and Jamaica Plain neighborhoods. These are historically Black and underserved areas in Boston. CBGs with low wetlands loss and minority populations are evident in Back Bay, North End, Seaport, and near Brookline, which are known to be wealthier and whiter areas. These are also, however, former wetland or tidal areas that were filled in earlier in history, but are not reflected on maps used in this study.

Analysis of Claim Status and Parcel Attributes

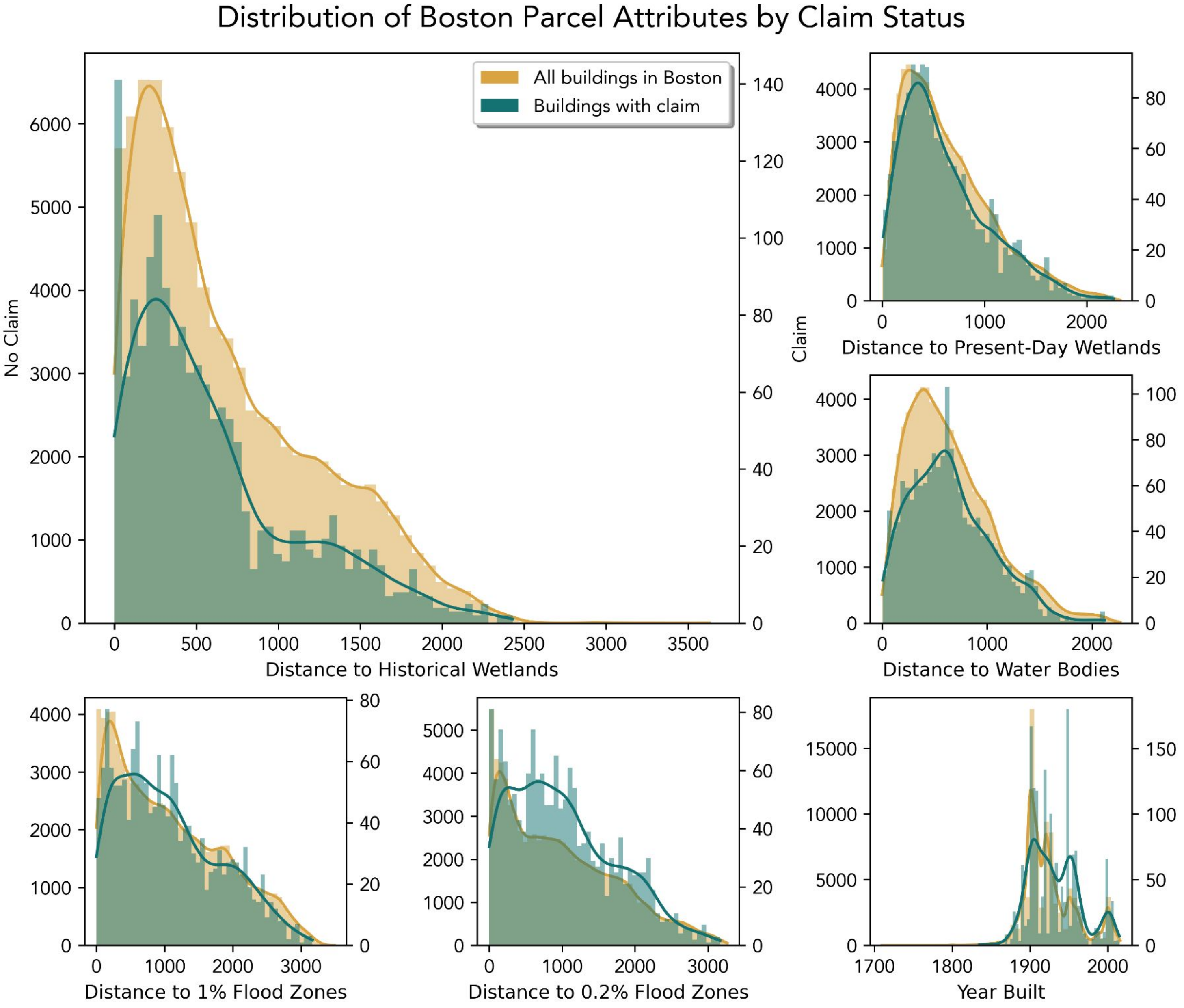


Figure 28: Distribution of Boston buildings' parcel attributes by claim status (distances are in meters) (Source: MAPC & Tufts Team)

Figure 28 shows the distribution of parcel attributes of interest in Boston by claim status, where histograms in gold represent all buildings in Boston and those in teal represent buildings with claims in Boston.

All distance attributes are right-skewed: there are proportionally more buildings close to historical wetlands, present-day wetlands, and floodplains than far from them. Buildings in Boston, regardless of claim status, are as far as 2,500m from present-day wetlands and water bodies and as far as 3,500m from flood zones, though 2010 floods occurred at those far ranges.

The clearest difference in claims status is in year built: while the distribution of year built for all buildings skews older—primarily before 1940—the distribution of buildings with claims is flatter, with a clear peak in the mid-20th century.

Appendix V shows histograms for the remaining locations. Overall statistical trends are discussed in the section "Comparing Across Study Area".

Randolph

Historical Wetland Alteration

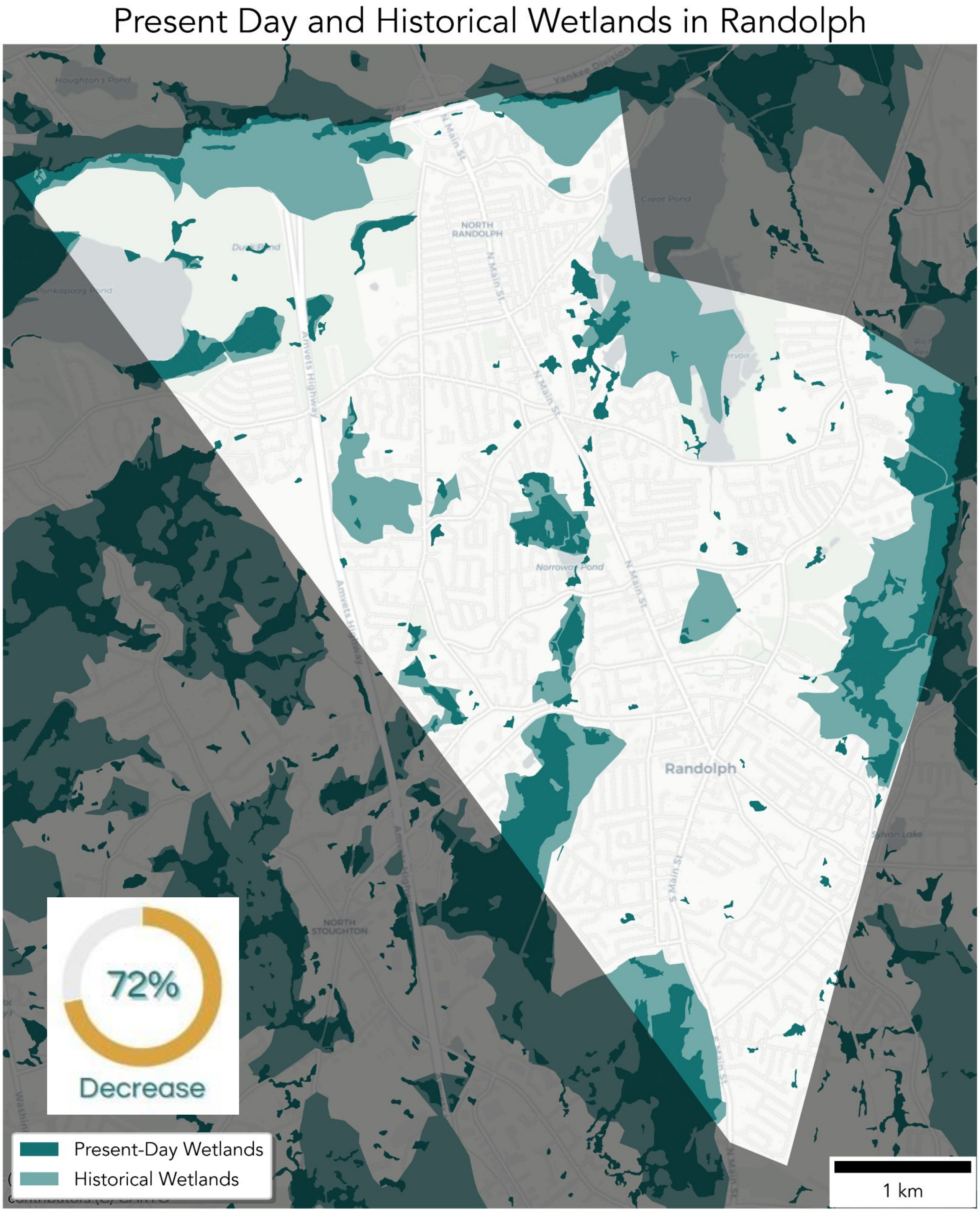


Figure 29: Present Day and Historical Wetlands in Randolph (Source: Tufts Team)

Flood Claims and Wetlands

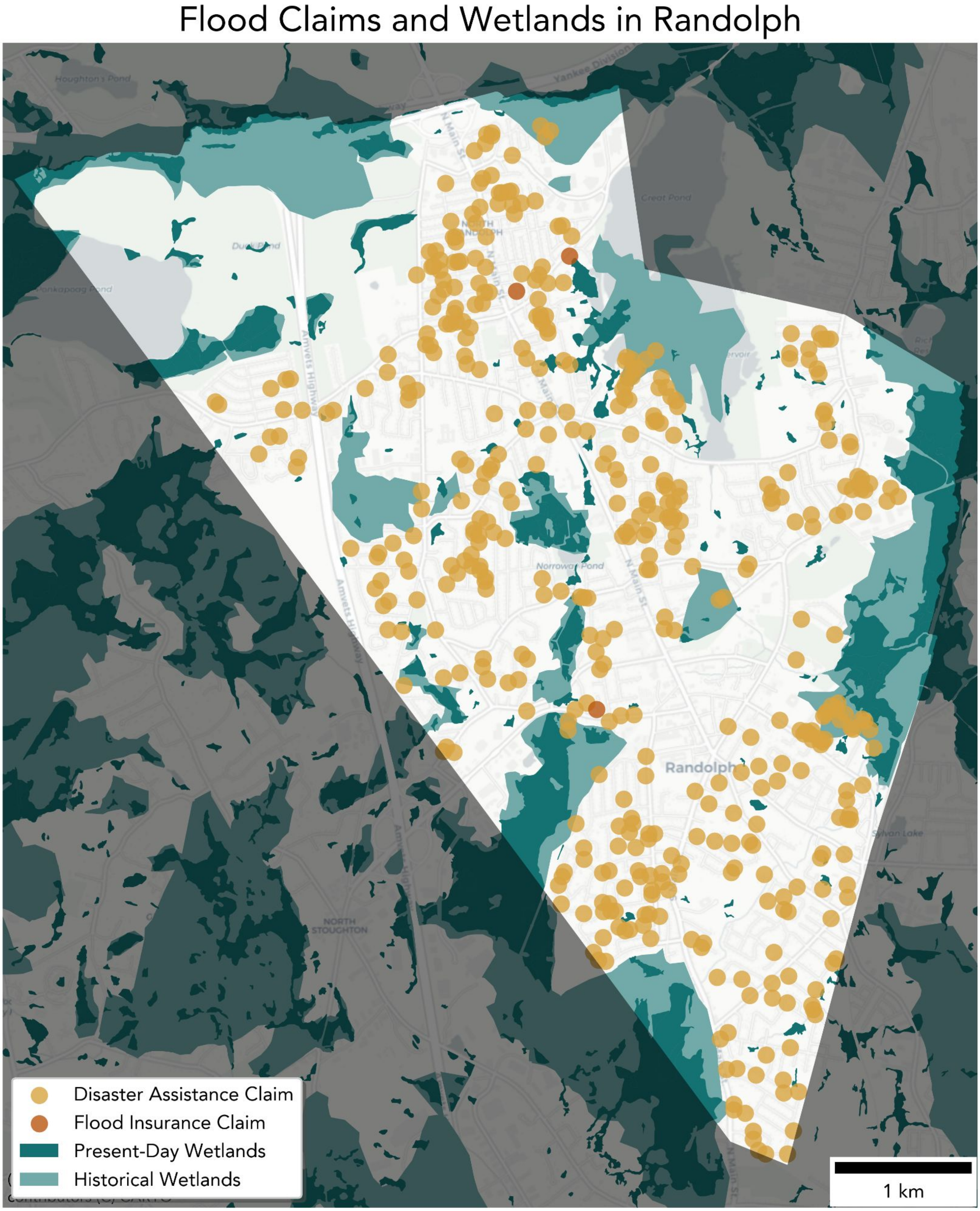


Figure 30: Flood Claims and Wetlands in Randolph (Source: MAPC & Tufts Teams)

Sociodemographic Variables & Wetland Loss

Wetland Loss & Median Household Income in Randolph

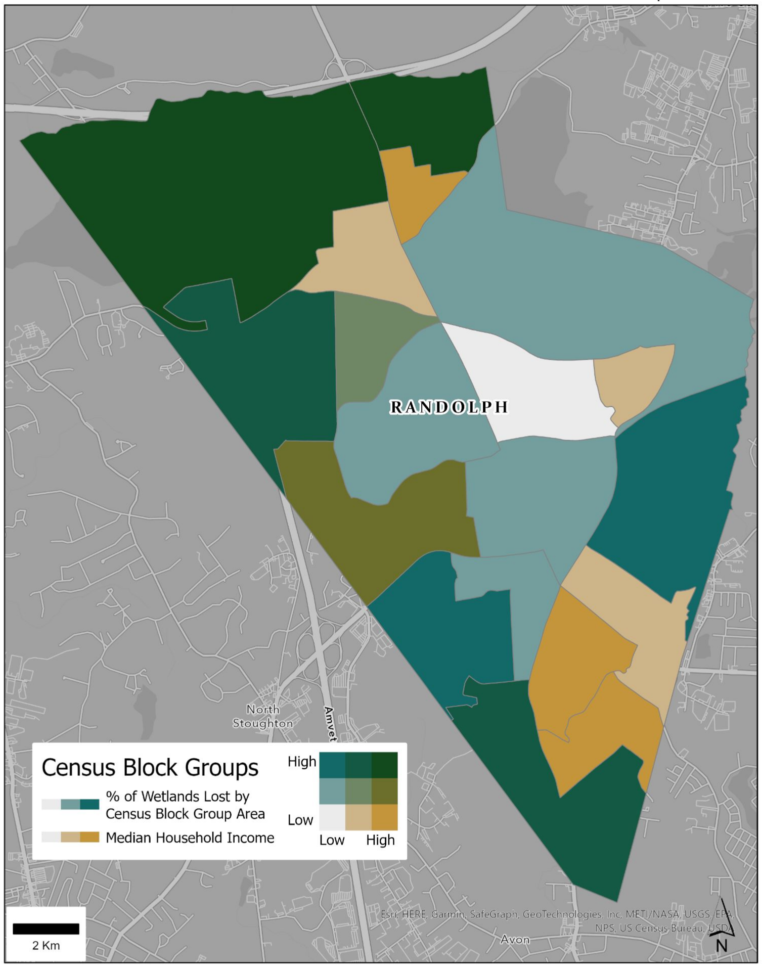


Figure 31: Bivariate distribution of wetland loss & median household income in Randolph by census block group (Source: Tufts Team)

Within Randolph, CBGs on the western portion of the town have the highest percentages of wetland loss, highest minority population, and lowest income. These border Stoughton's CBGs with similar characteristics, shown in the next section.

Wetland Loss & Minority Population in Randolph

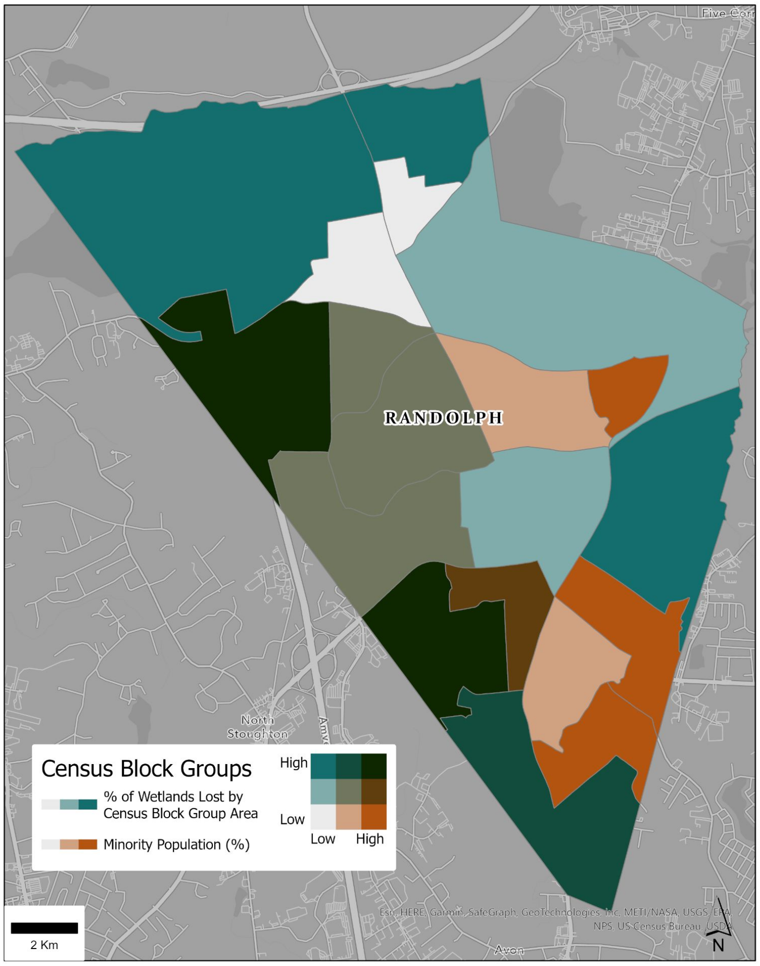


Figure 32: Bivariate distribution of wetland loss & minority population in Randolph by census block group (Source: Tufts Team)

Stoughton

Historical Wetland Alteration

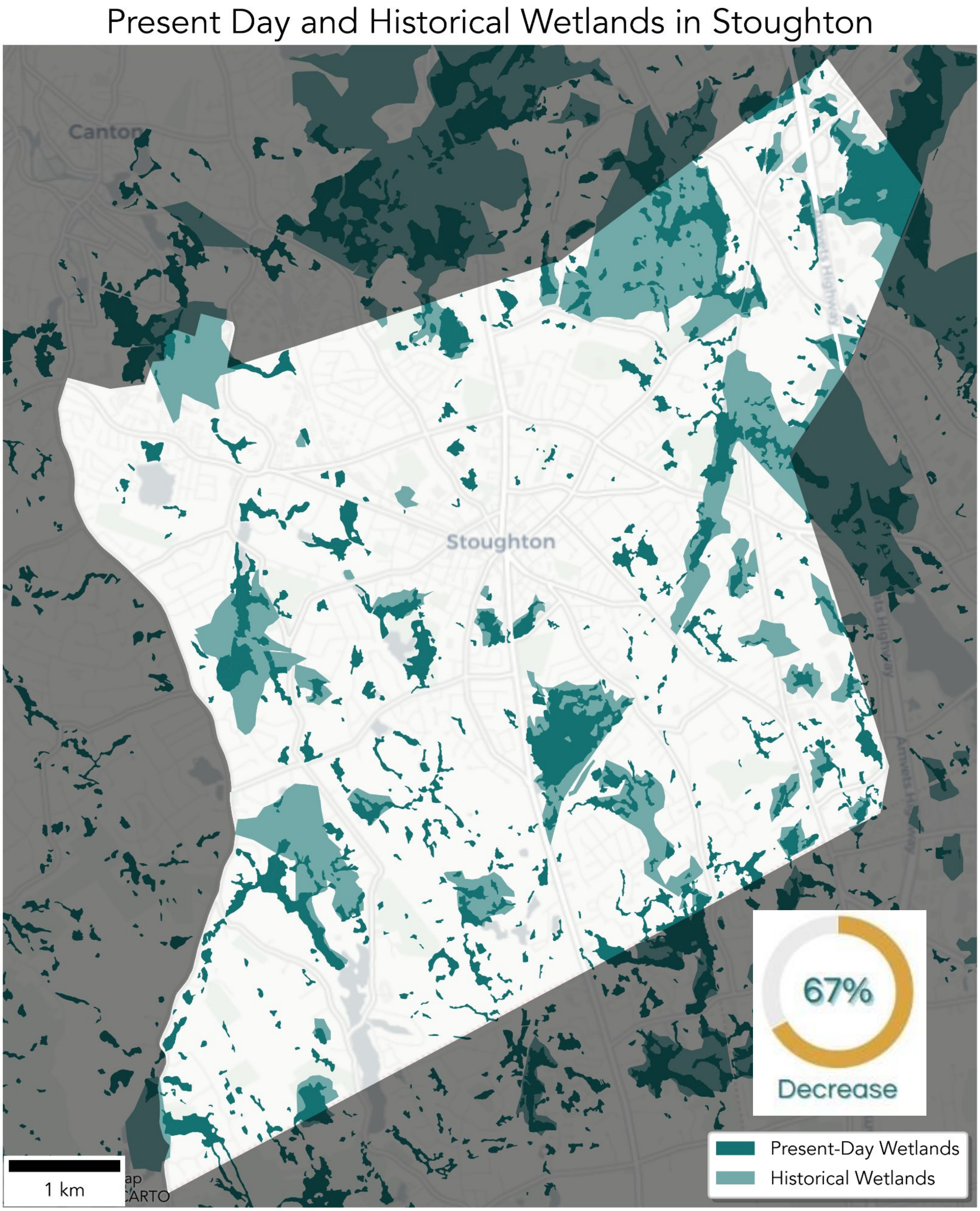


Figure 33: Present Day and Historical Wetlands in Stoughton (Source: Tufts Team)

Flood Claims and Wetlands

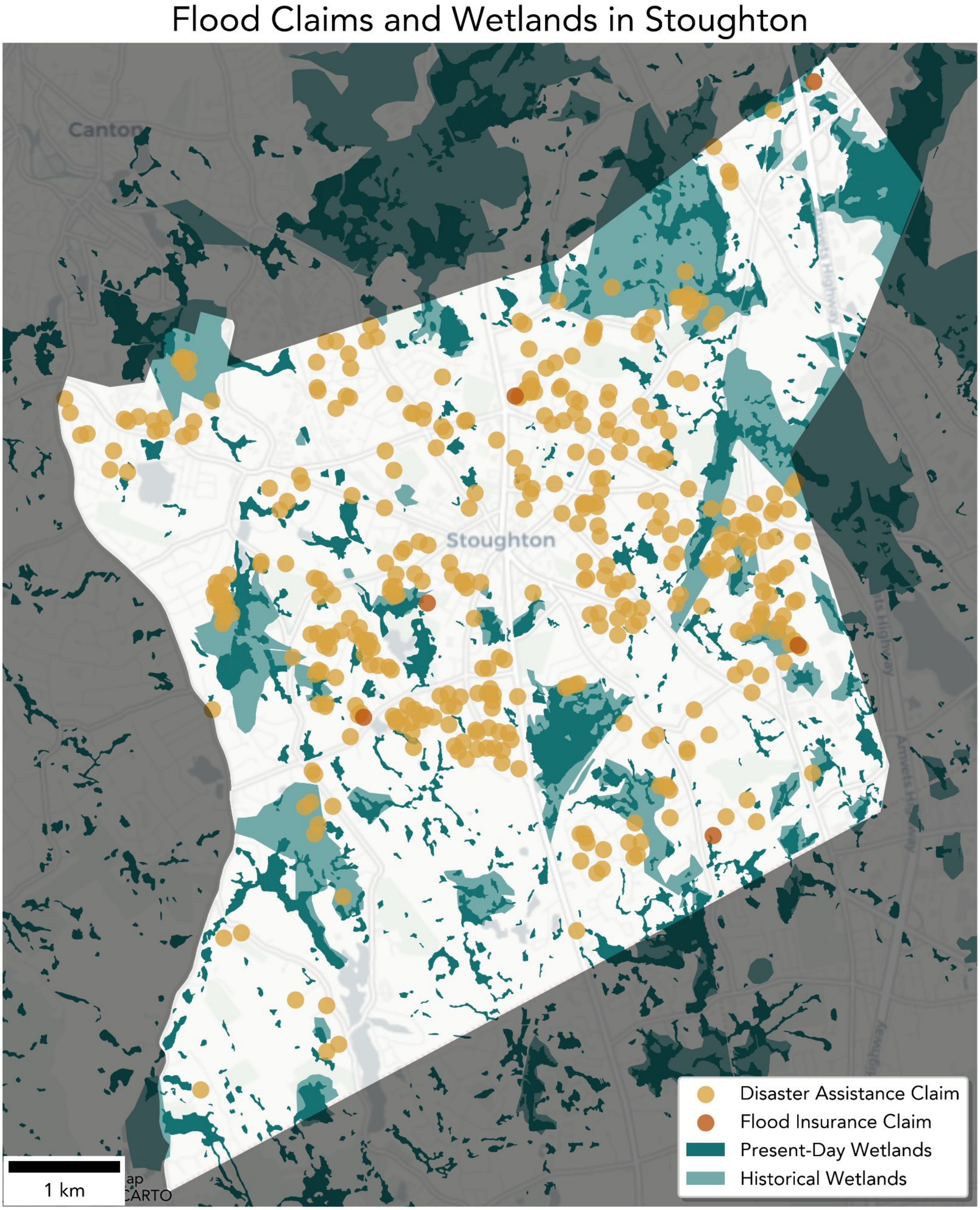


Figure 34: Flood Claims and Wetlands in Stoughton (Source: MAPC & Tufts Teams)

Sociodemographic Variables & Wetland Loss

Wetland Loss & Median Household Income in Stoughton

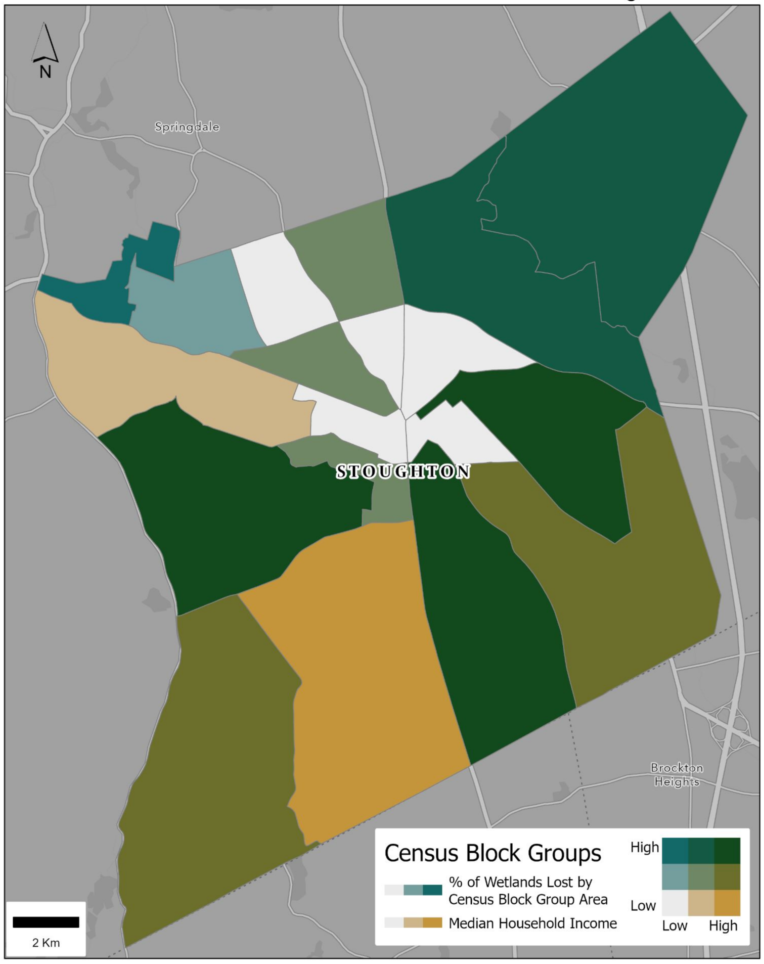


Figure 35: Bivariate distribution of wetland loss & median household income in Stoughton by census block group (Source: Tufts Team)

Within Stoughton, the two census block groups in the northeast region of the town have the highest rates of wetland loss, highest minority population, and lowest income. These areas are primarily industrial or commercial and have relatively few residents.

Wetland Loss & Minority Population in Stoughton

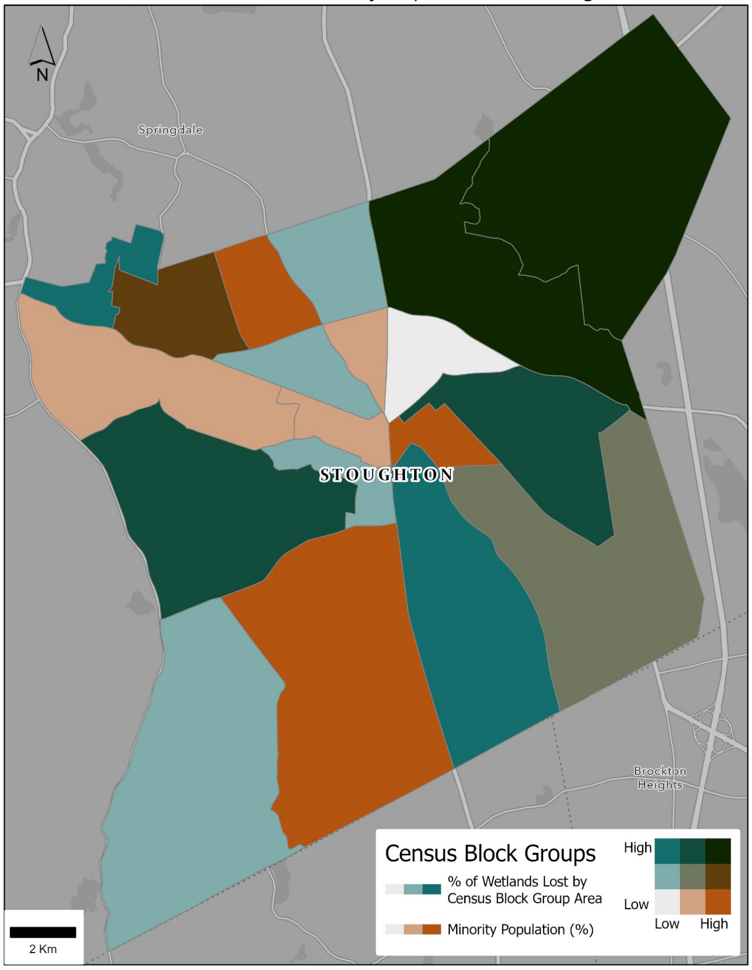


Figure 36: Bivariate distribution of wetland loss & minority population in Stoughton by census block group (Source: Tufts Team)

Wilmington

Historical Wetland Alteration

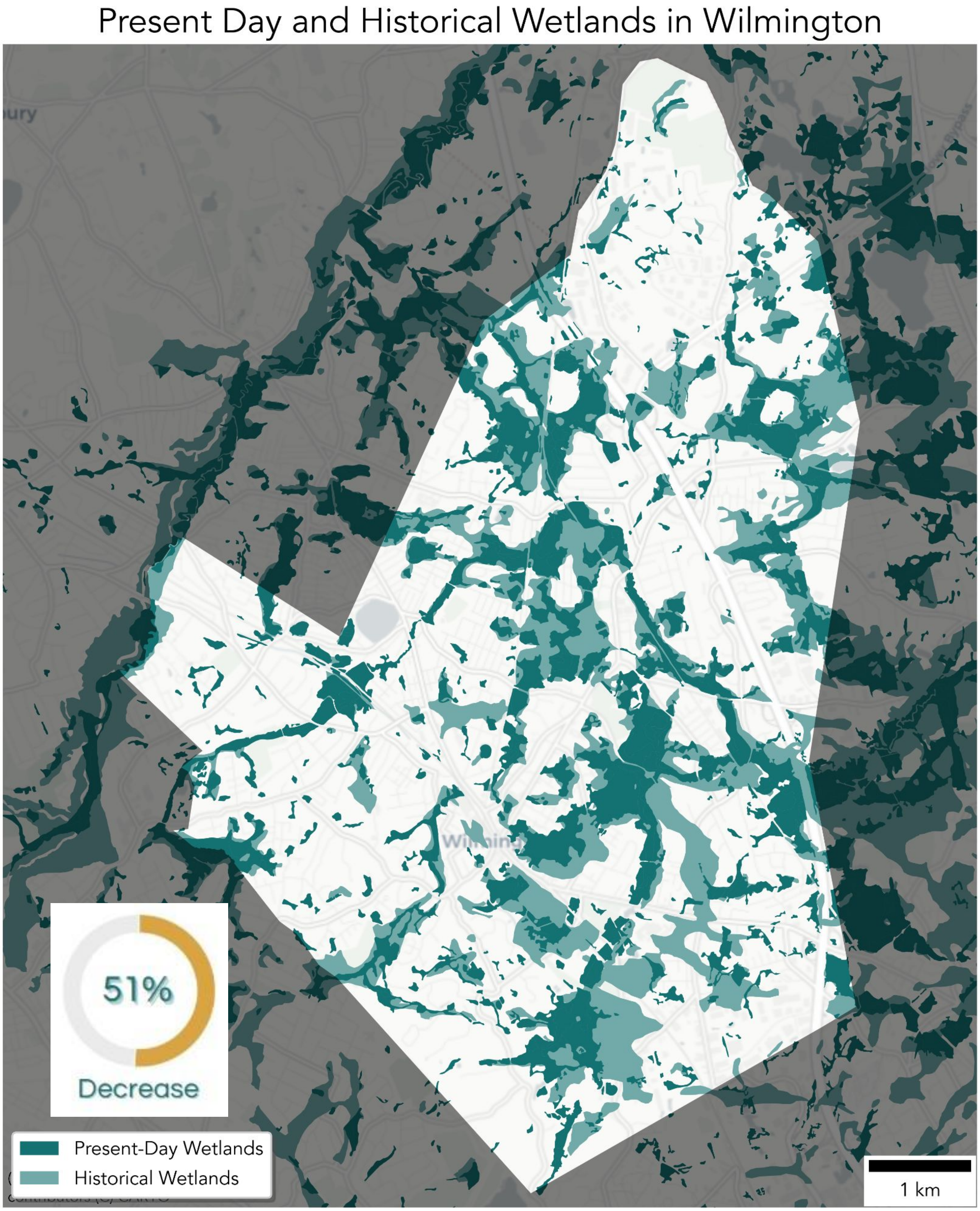


Figure 37: Present Day and Historical Wetlands in Wilmington (Source: Tufts Team)

Flood Claims and Wetlands

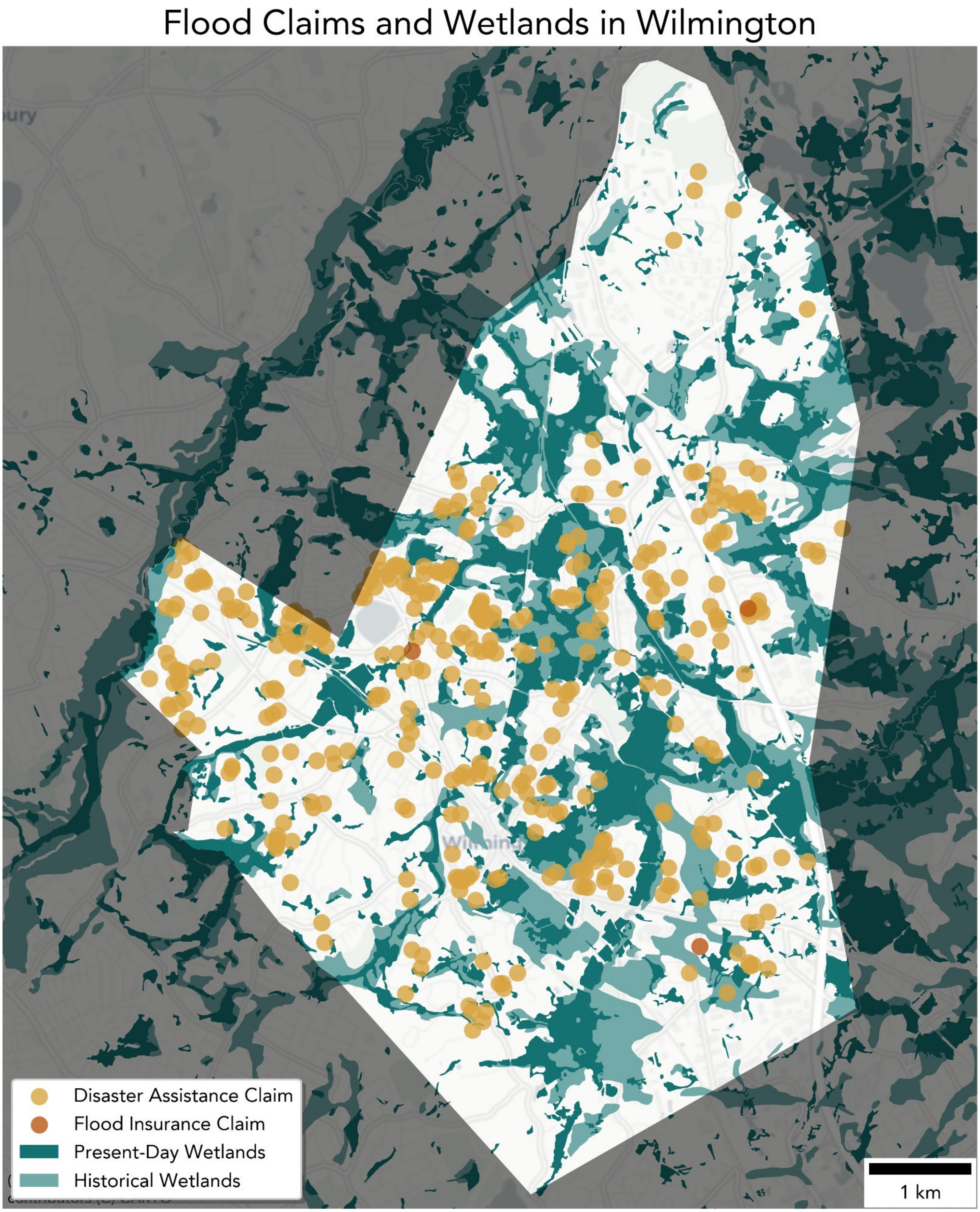


Figure 38: Flood Claims and Wetlands in Wilmington (Source: MAPC & Tufts Teams)

Sociodemographic Variables & Wetland Loss

Wetland Loss & Median Household Income in Wilmington

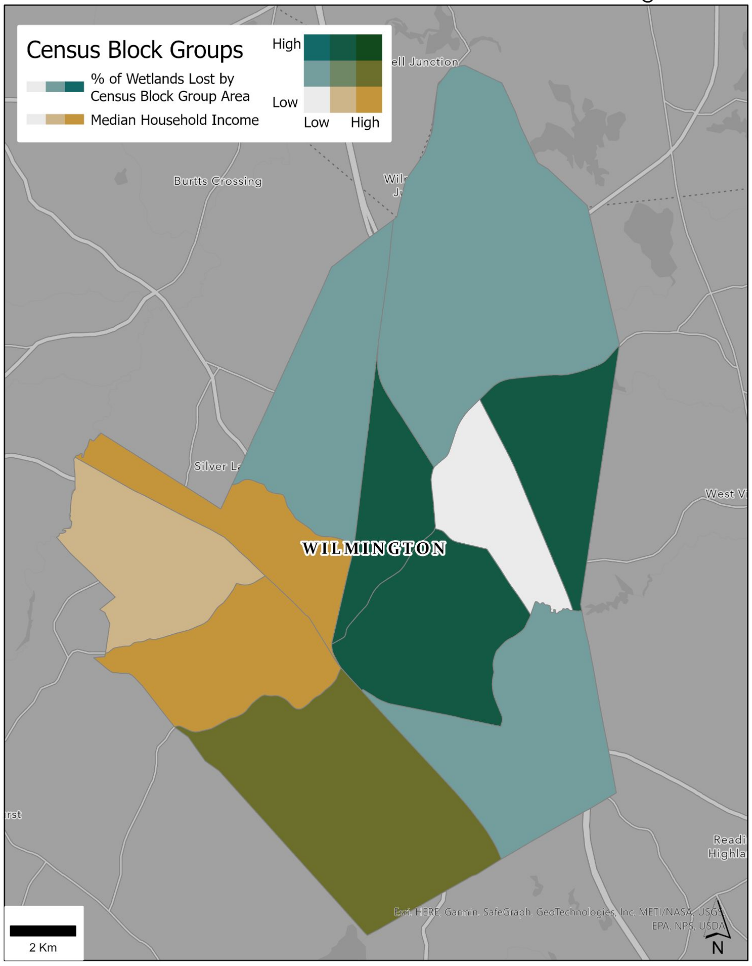


Figure 39: Bivariate distribution of wetland loss & median household income in Wilmington by census block group (Source: Tufts Team)

Within Wilmington, CBGs in the town's geographic center have the highest percentages of wetland loss, highest minority population, and lowest median income. They are starkly different from the three adjacent CBGs to the west, which exhibit the opposite characteristics.

Wetland Loss & Minority Population in Wilmington

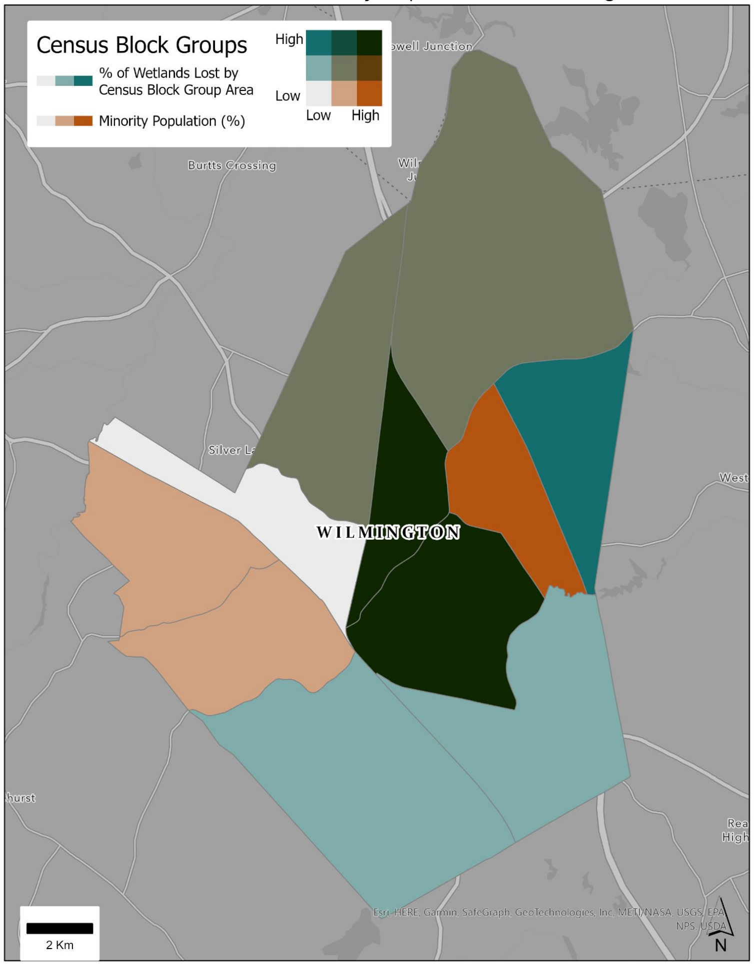


Figure 40: Bivariate distribution of wetland loss & minority population in Wilmington by census block group (Source: Tufts Team)

Woburn

Historical Wetland Alteration

Present Day and Historical Wetlands in Woburn

Figure 41: Present Day and Historical Wetlands in Woburn (Source: Tufts Team)

Flood Claims and Wetlands

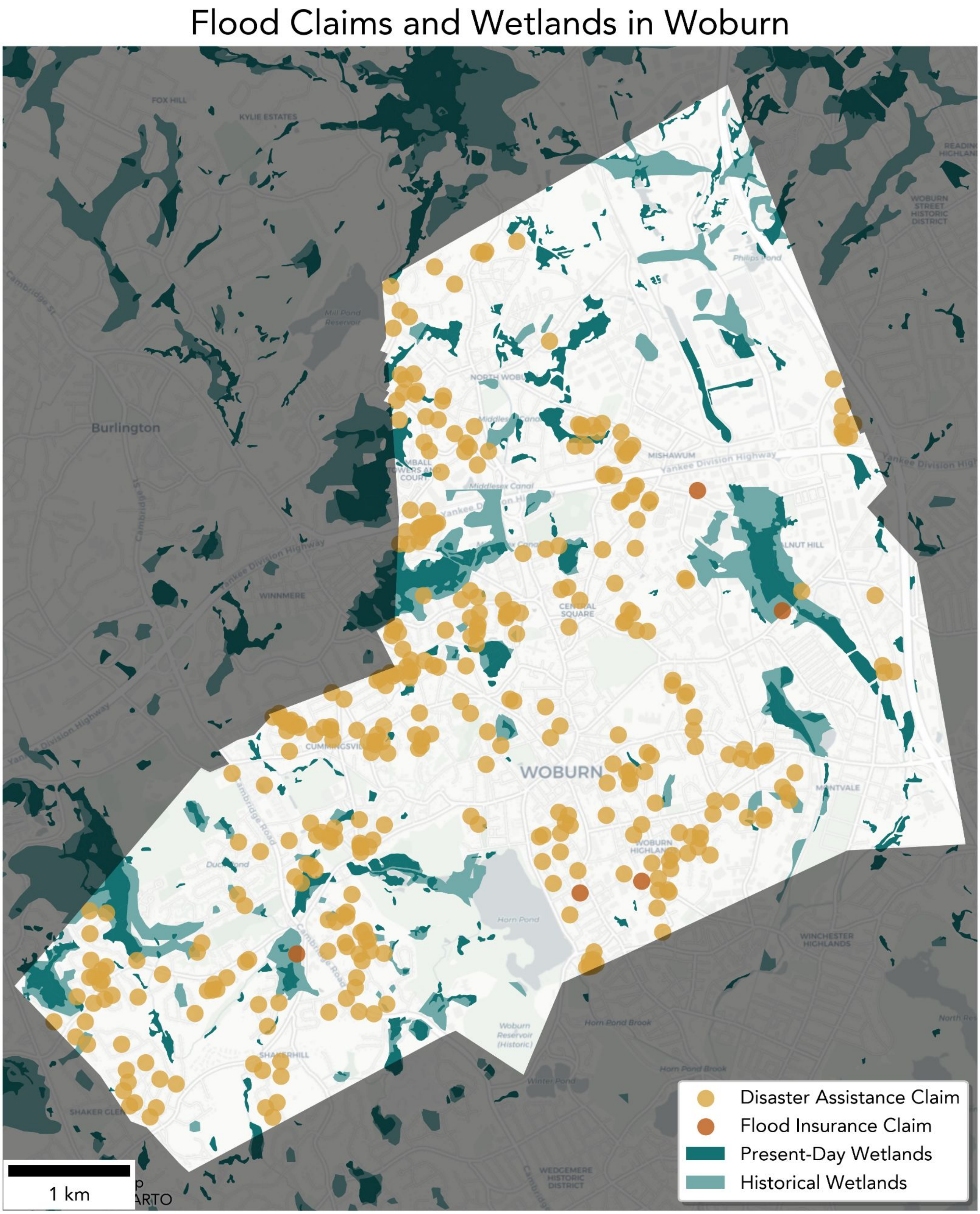


Figure 42: Flood Claims and Wetlands in Woburn (Source: MAPC & Tufts Teams)

Sociodemographic Variables & Wetland Loss

Wetland Loss & Median Household Income in Woburn

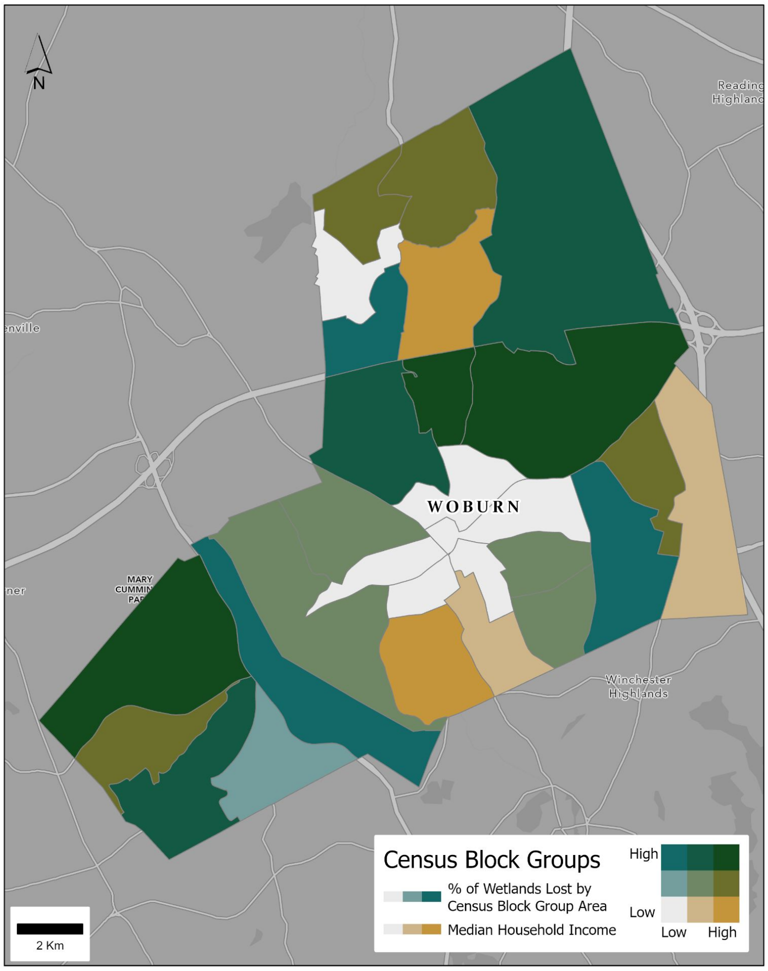


Figure 43: Bivariate distribution of wetland loss & median household income in Woburn by census block group (Source: Tufts Team)

Within Woburn, the census block groups with the highest rates of wetland loss, highest minority population, and lowest income overlap and are more scattered than within the other municipalities in the study area. CBGs with high wetland loss either house or border water bodies, such as the Horn Pond Recreational Area and various brooks.

Wetland Loss & Minority Population in Woburn

Figure 44: Bivariate distribution of wetland loss & minority population in Woburn by census block group (Source: Tufts Team)

Comparing Across Study Area

Statistical Analysis

While wetland loss from the 1880s to present day is evident and consistent across the entire study area, relationships between flood claims and variables of interest are less clear. Analyzing histograms of the six variables did not result in meaningful comparisons or trends across the study area or for all variables of interest. The Team therefore shifted the analysis to a municipal-level approach to compare across the study area and narrowed the variables to three parcel attributes:

- **distance to historical wetlands**
- **distance to present-day wetlands**
- **year built**

Because MAPC has conducted analyses on the broader dataset across the MAPC region, these variables were chosen to add to existing work rather than duplicate it as well as to compare findings to the timeline of wetlands alterations presented in the Literature Review.

Figure 45 breaks down attributes by municipality and claim status, highlighting differences within the study area for buildings with claims and without claims. Buildings within Boston are overall farther from wetlands—both historical and present-day—than the other four municipalities. Because the historical maps used began in the 1880s, however, it is likely that the distance to historical wetlands metric used does not encapsulate the true relationship between buildings and unaltered historical wetlands.

Boston buildings are also, on average, older than other municipalities' buildings. This is consistent with literature review findings that both settlement and wetland alteration in the MAPC region began in Boston.

Differences in attribute distributions by claim status are difficult to identify in these boxplots, especially because Boston buildings skew the y-axis in the two distance attributes. A crosstab assessment was utilized to compare categorical differences rather than numerical differences.

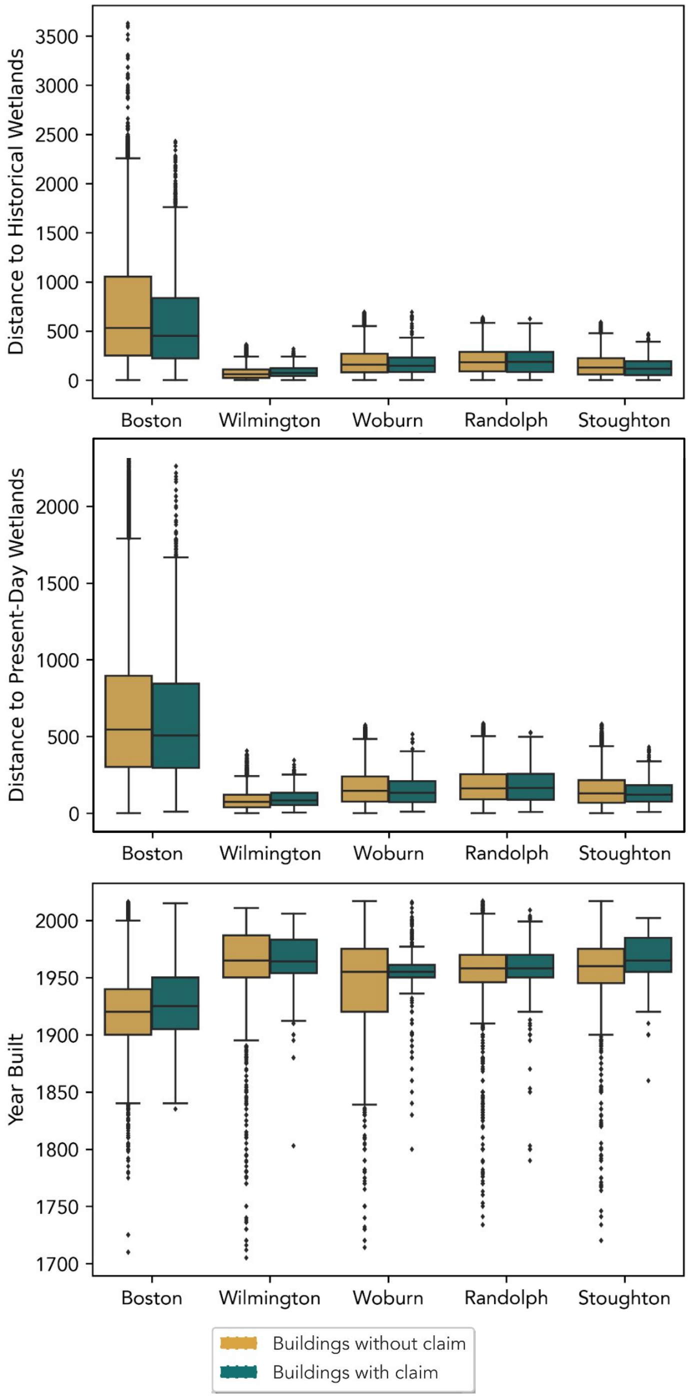


Figure 45: Boxplot Distribution of Parcel Attributes by Municipality and Claim Status (Source: MAPC & Tufts Teams)

Crosstab Assessment

Crosstab contingency tables were constructed for each location and variable to show the relationship between each variable category and claim status. Results for the entire study area are referred to as “MAPC” in figures. The crosstab bar plot in Figure 46 shows in gold the proportion of all buildings in a location that are within, less than 100 feet from, and greater than 100 feet from historical wetlands, and in teal are proportions of buildings with claims in the same three categories.

The majority of all buildings are farther than 100 feet from historical wetlands, as are the majority of all claims. The proportion of buildings with claims exceeds the proportion of all buildings less than 100 feet from or within historical wetlands in the MAPC study area, though the relationship does not hold across all municipalities.

Similar bar plots were also created for distance to present-day wetlands and year built and are in Appendix V. To make them more easily understandable, the relative proportions were distilled to a new metric:---the Relative Claim Index.

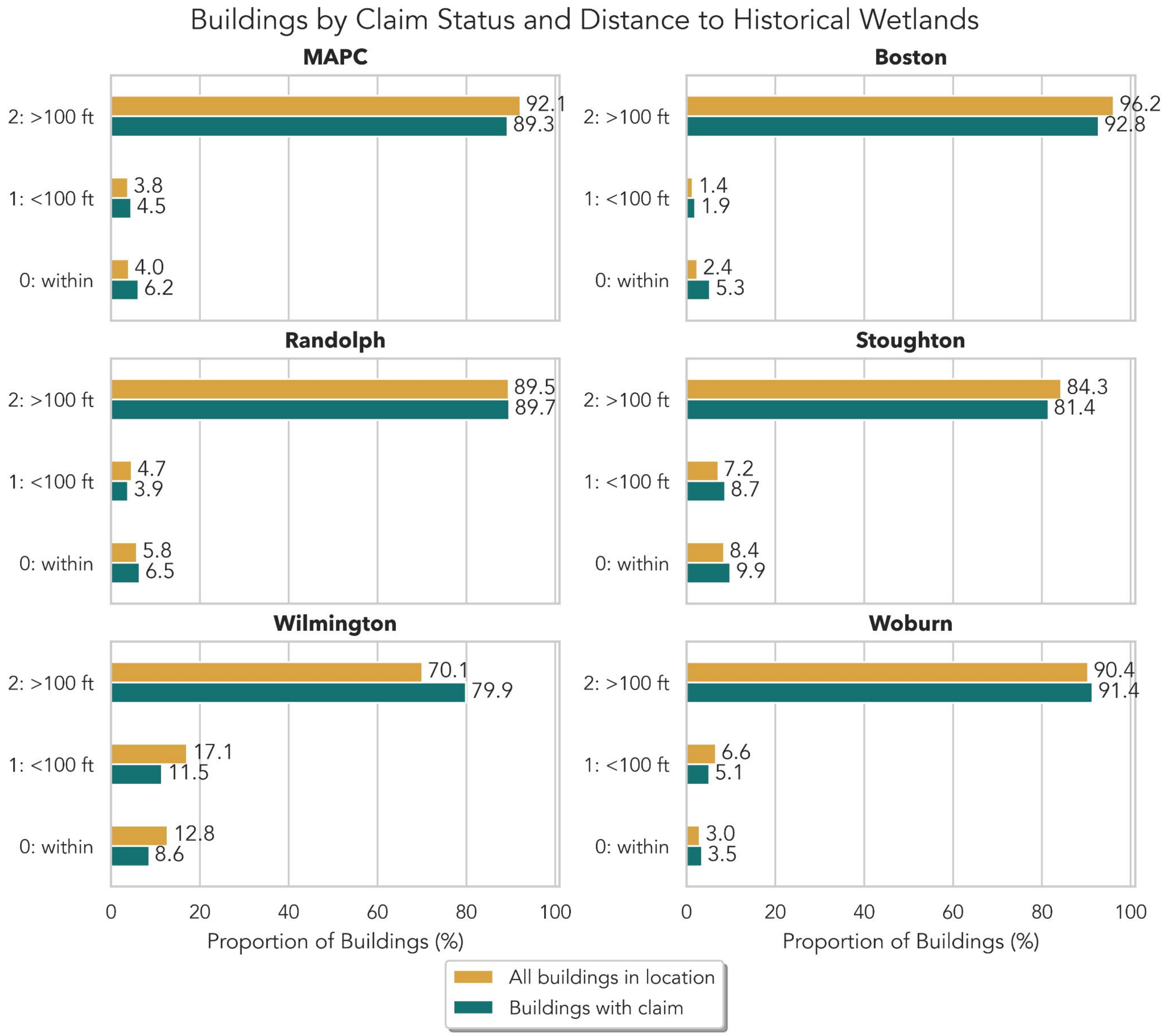


Figure 46: Crosstab Bar Plot of Buildings by Claim Status and Distance to Historical Wetlands

(Source: MAPC & Tufts Teams)

Relative Claim Index

The Tufts Team created the Relative Claim Index as an indicator of whether there were relatively more or fewer buildings with claims, compared to buildings on average for each location and category. A positive RCI represents proportionally more buildings with claims, while a negative RCI represents proportionally fewer. An RCI value of zero shows that either no buildings are present in the location and category or that there are equal proportions of buildings with claims and buildings across the location.

(+) RCI = proportionally **more buildings with claims**

0 RCI = **equal proportion** of buildings

(-) RCI = proportionally **fewer buildings with claims**

Historical Wetlands

Figure 47 depicts the RCIs for municipalities by distance to historical wetlands. In the entire study area, 4.0% of all buildings were within historical wetlands while 6.2% of buildings with claims were within historical wetlands. The resulting RCI of 0.55 indicates that, in the study area, there are proportionally 0.55 times (or 55%) more buildings with claims that are within historical wetlands than buildings on average in historical wetlands.

RCI w/in historical wetlands in MAPC:

$$\frac{\text{6.2\% of buildings w/ claims}}{\text{4.0\% of all buildings}} - 1 = 0.55$$

The study area and four out of the five municipalities have positive RCI values for buildings within historical wetlands. This suggests that there is a positive correlation between a building being within a historical wetland and having a flood claim.

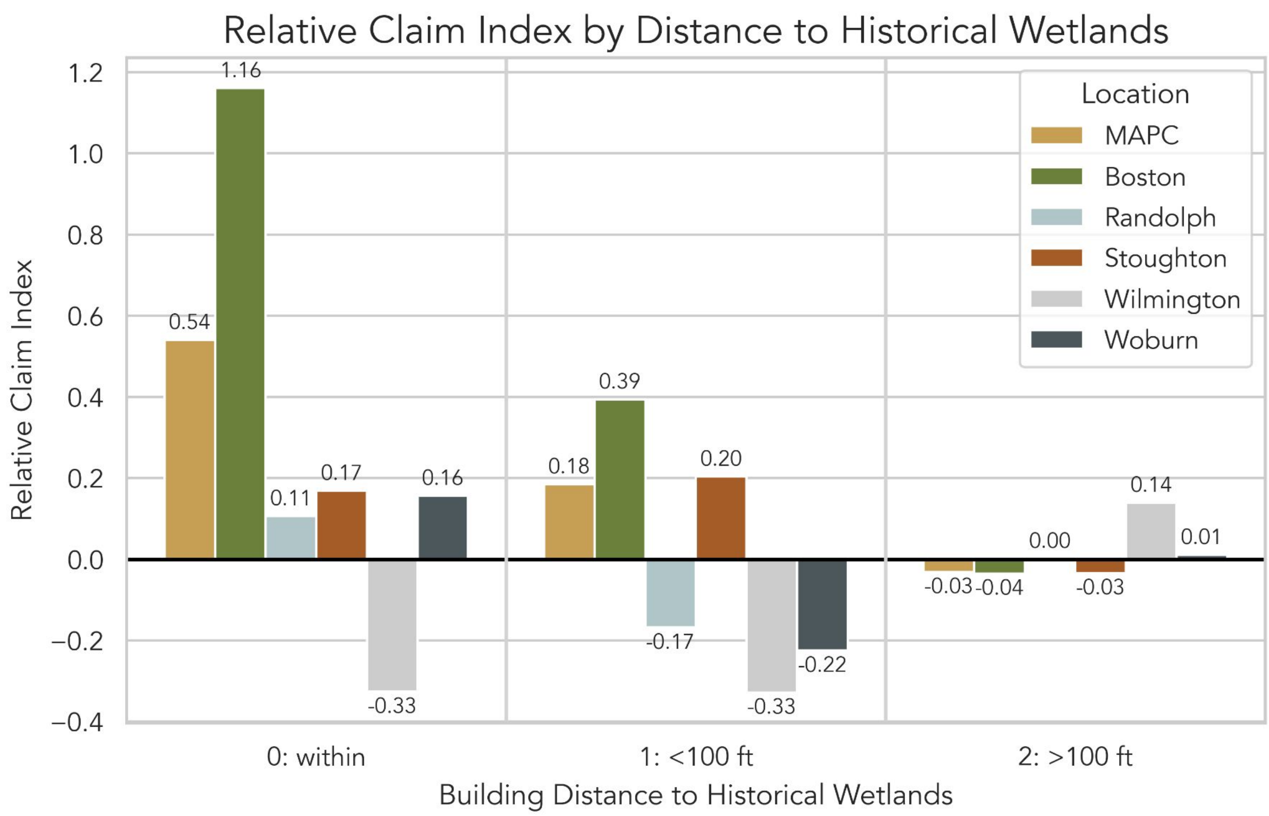


Figure 47: RCI for Municipalities by Distance to Historical Wetlands Source: MAPC & Tufts Teams)

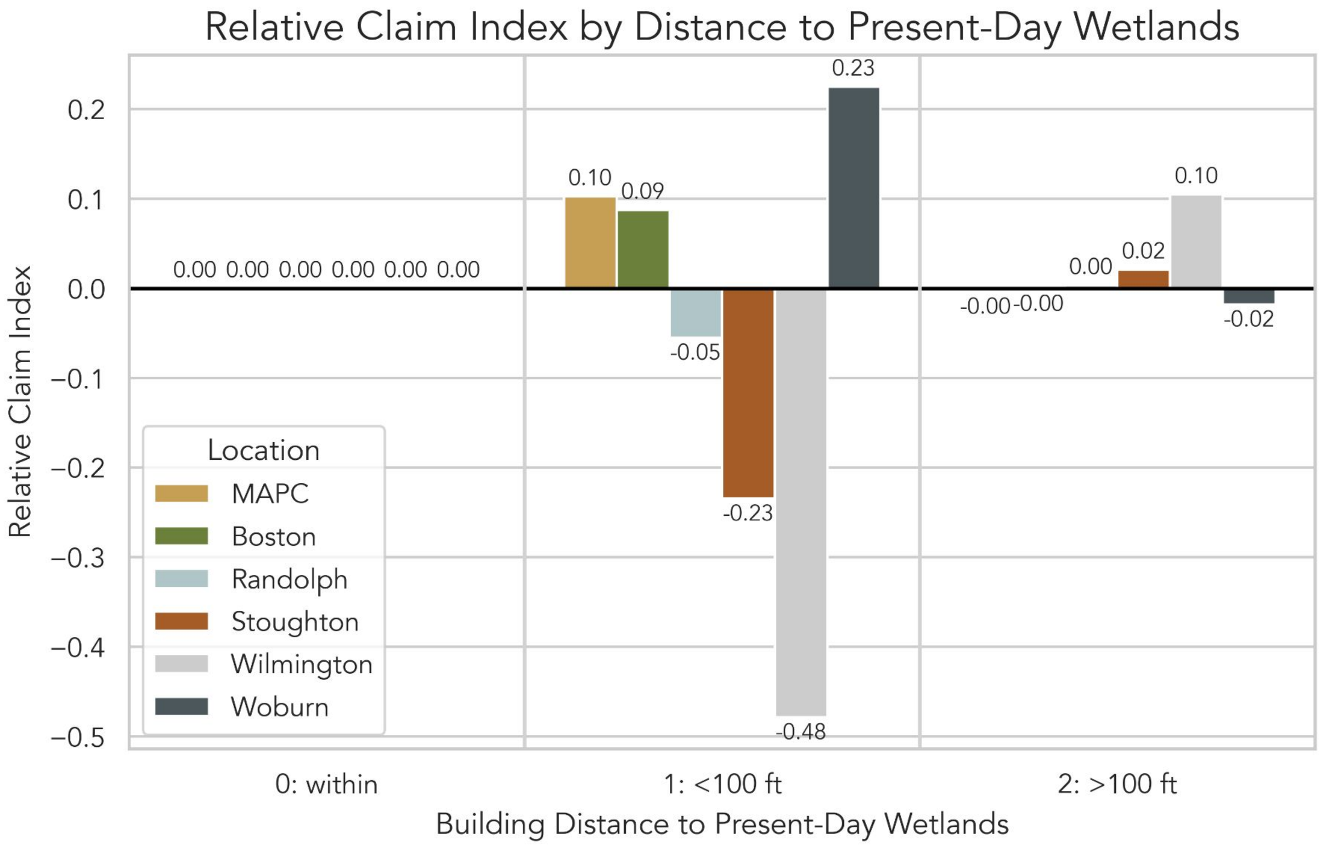


Figure 48: RCI for Municipalities by Distance to Present-Day Wetlands (Source: MAPC & Tufts Teams)

RCIs are slightly positive for buildings less than 100 feet from historical wetlands for MAPC, Boston, and Stoughton while they are negative for Randolph, Wilmington, and Woburn. For buildings greater than 100 feet from historical wetlands, RCIs are all negative or negligible except for Wilmington. Wilmington appears to be somewhat of an outlier in distance to historical wetlands, possibly because such a large and widespread proportion of its municipal area has historical wetlands.

Although Randolph and Stoughton & Wilmington and Woburn border each other, RCI values for historical wetlands differ within each pair both in magnitude and in sign. This distinction points to the importance of localized context in studies and policies pertaining to stormwater flooding and historical wetlands.

Present-Day Wetlands

Figure 48 shows the RCI for municipalities by distance to present-day wetlands. There are no buildings within present-day wetlands in the entire study area, resulting in RCIs of zero.

RCIs for the other two distance categories are highly variable and overall lower than RCIs for historical wetlands. While RCIs for historical wetlands range from -0.33 to 1.16, RCIs for present-day wetlands range from -0.48 to 0.23. There are also many more RCIs close to or at zero across all distance categories.

This distinction signals that, within the study area, proximity to present-day wetlands may have less impact on flood claim status than proximity to historical wetlands. Knowledge of present-day wetlands locations and extents, therefore, may not be as helpful or meaningful as knowledge of historical wetlands locations and extents.

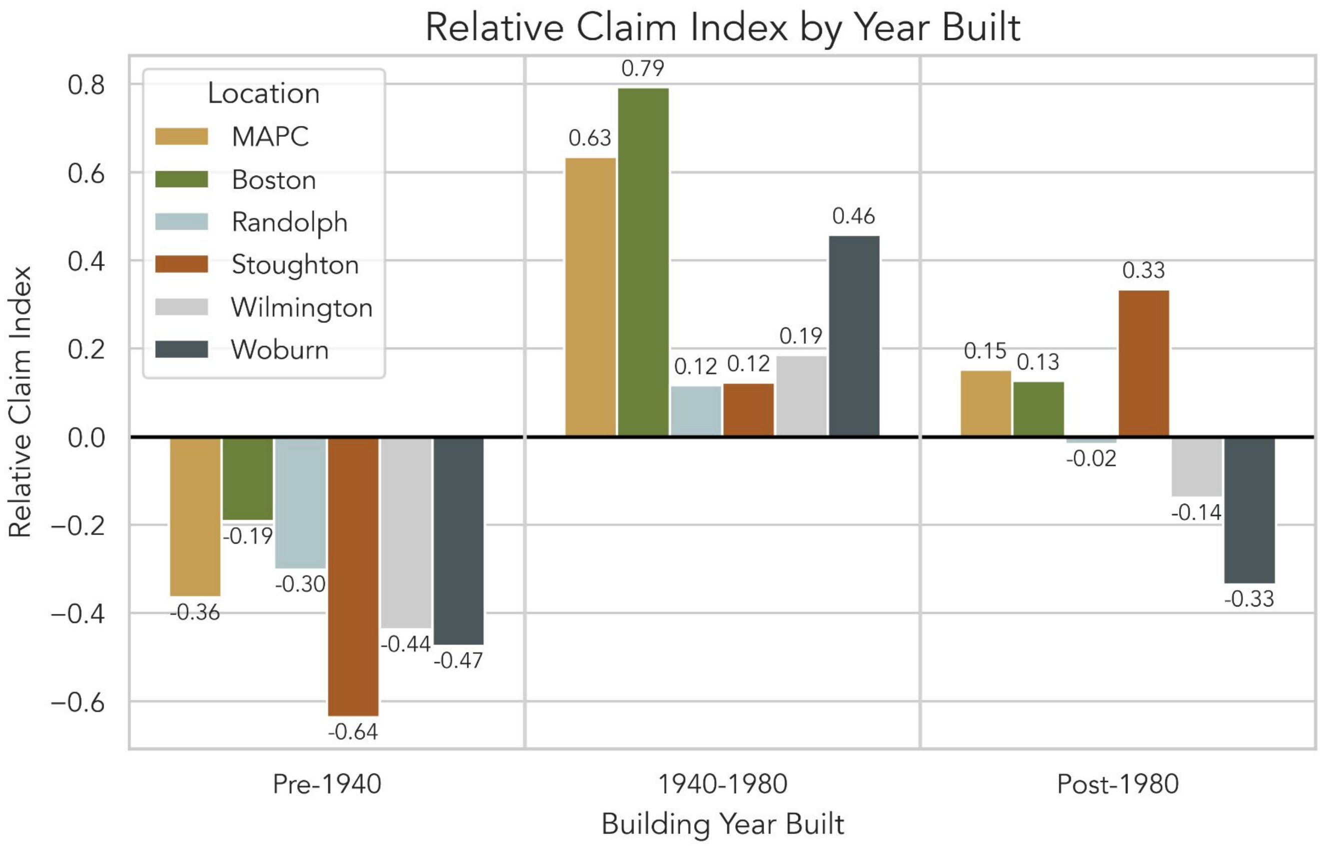
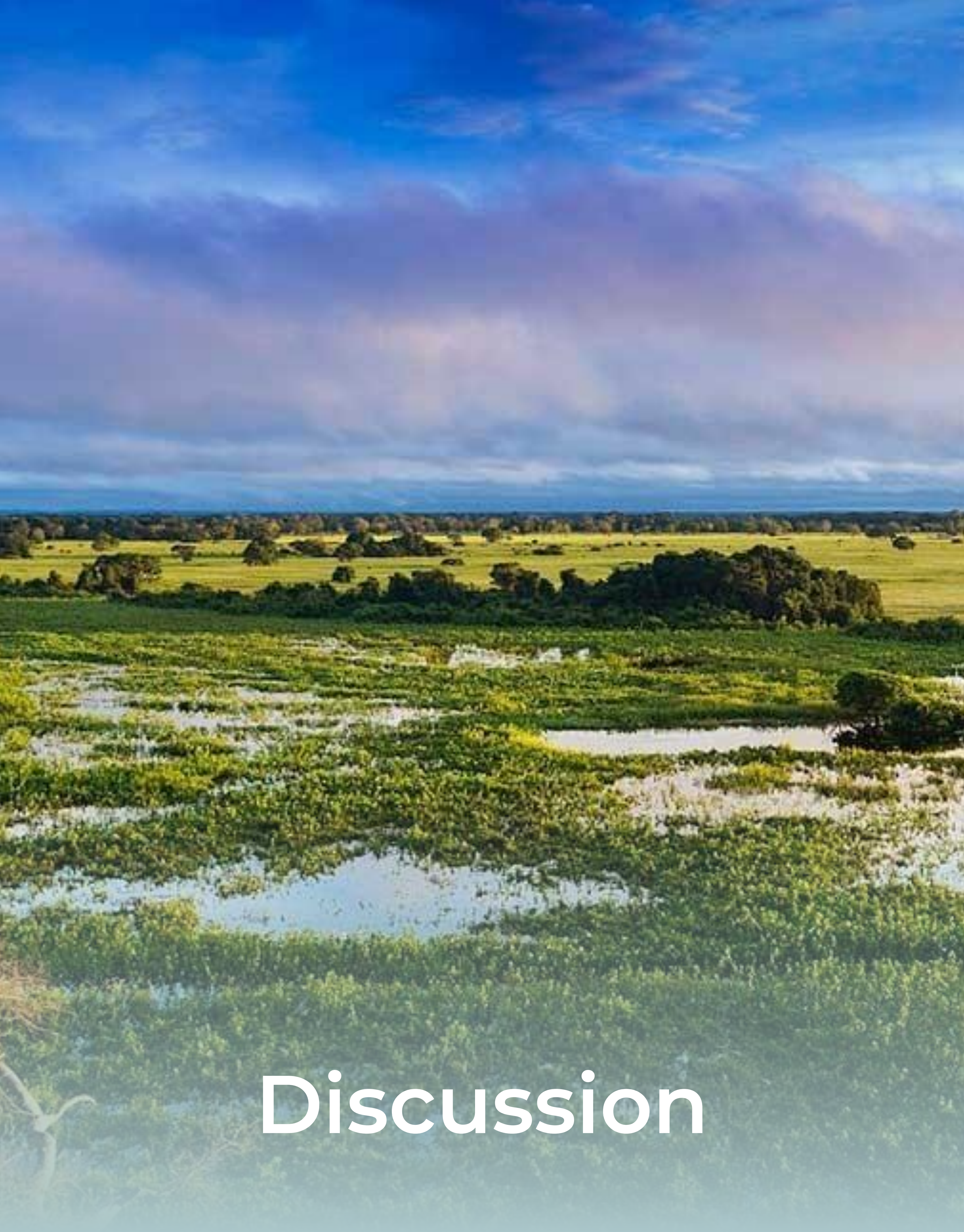


Figure 49: RCI for Municipalities by Year Built (Source: MAPC & Tufts Teams)

Year Built

Finally, Figure 49 shows RCIs for each location by the buildings' year built. The trend here is apparent: in buildings built before 1940, there are proportionally fewer claims across all municipalities and the MAPC study area, while buildings built between 1940 and 1980 have proportionally more claims. This coincides with the period after WWII that saw massive projects to build transportation infrastructure and housing—frequently by degrading wetlands—and before wetlands protections regulations were widely accepted or acted-upon.

While the exact reason and history behind the relationship between flood claims and a building's year built is beyond the scope of this study, this finding is likely relevant to municipalities and MAPC in assessing stormwater flooding and climate change vulnerability.



Discussion

Discussion

This research provides valuable insights into the patterns of historical wetland alterations within the MAPC municipalities of Boston, Randolph, Stoughton, Wilmington, and Woburn.

- **A major trend across the study area is the minimum 40% loss of wetlands over time.**

This drastic reduction of wetlands has important implications for stormwater flood mitigation based on the literature review findings of the ecological benefits of wetlands—acting as sponges to store excess precipitation during extreme storm events.

- **There is a higher relative claim index of flood claims closer to historical wetlands in comparison to present-day wetlands.**

The flood claims analysis revealed that, while the vast majority of claims are far from historical wetlands, there are proportionally 55% more buildings with claims in historical wetlands than buildings overall across the study area, indicating a positive correlation between a building being within a historical wetland and having a flood claim. A higher RCI indicates that areas that have lost wetlands over time made more flood claims after the March 2010 storm, and are perhaps suffering from proportionally more flooding, than the study area overall. This finding underscores the importance of wetlands in stormwater flood mitigation.

- **Across all locations, the proportion of buildings with claims that were built between 1940 and 1980 exceeded the proportion of buildings overall built in the same time period.**

This shows a clear relationship between flood claims and a building's year built, and more research should be done on a local level to explore location-specific relationships.

- **While there has been a dramatic loss of wetlands in the five municipalities, this loss can be seen as shrinking of historical wetlands into their present-day extent, and all present day wetlands are within historical extents.**

This lack of movement and apparent shrinkage can potentially be explained by development and alteration of wetland areas around pre-existing wetland habitat. Further research should be pursued into wetland shrinking, because the results found from this study suggest that knowledge of present-day wetlands is not as meaningful as understanding the extent of historic wetlands.

- **Regardless of trends across the study area, knowledge is still power for individual homeowners, municipalities, and planning agencies trying to better manage stormwater flood risk.**

For example, in Stoughton and Randolph, there are notable areas, specifically in northeastern Stoughton and southeastern Randolph, where clustering of claims occurs within historical wetlands. For residents of those areas, knowing they reside within a historical wetland, and consequently may be more at risk of stormwater flooding, is crucial information for understanding and managing the many factors contributing to stormwater flooding.

Finally, the sociodemographic analysis shows census block groups associated with major wetlands loss, high minority populations, and low median incomes across the study area. This trend often coincides in town centers and commercial areas and near water bodies. While the results shown in bivariate distribution maps are varied, this type of analysis can be employed by municipalities and planning agencies like MAPC to better understand areas with high levels of wetland loss—and perhaps more risk of stormwater flooding—that are historically underserved and may need greater assistance after extreme flood events like the March 2010 storm.

Limitations

Broad Limitations

While the statistical analysis of the five municipalities presented here does not show a statistically significant relationship, this finding may not be generalizable to the entire MAPC region nor be reflective of the actual relationship between modern day stormwater flooding and historical wetlands. This analysis was limited by several factors which may have influenced results.

Geographic

Geographically, this study was limited in scope due to time and resource constraints. The MAPC region comprises 101 towns and municipalities, all with differing political, cultural, and environmental backgrounds.

Although the five selected study areas did not demonstrate statistically significant relationships between historical wetlands and current flooding patterns, these results may not be representative of the entire MAPC region. Further study analyzing different municipalities within MAPC should be conducted to confirm the results of this research.

Scope of Available Flood Data

This research was also limited by the scope of available flood data used for analysis. Analysis relied only on flood data from the March 2010 storm. Because this data arose from such a devastating weather event, it provides a useful lens into potential flood patterns in many towns. However, flood claim data from one storm may not be indicative of true stormwater flooding patterns. For example, this storm may have produced unknown and unusual flood patterns due to its severity as a climate-induced intensified precipitation event.

Furthermore, the data only reveals approved flood claims, omitting areas that received flooding but were not eligible to apply for or were not successful in their applications for flood relief funding. Additionally, the flood claim data collected for the March 2010 storm does not account for the severity of flooding, nor capture the actual damage that resulted. Thus, the March 2010 storm may not be an accurate representation of consistent stormwater flooding patterns within the MAPC region.

Historical Map Availability

Temporally, this study was limited by the availability of historical maps, especially from before the 20th century. Maps of historical wetlands extents are only accurate from the late 1800s or early 1900s, depending on the municipality. For this reason, wetlands that were lost prior to the late 1800s are not included in the analysis. This temporal limitation is especially important in areas like Boston, where significant wetland alteration occurred prior to the 1900s.

Technical Limitations

The primary limitation of the developed HGIS methodology is the time horizon combination approach to wetlands analysis. As previously discussed, this approach makes many assumptions about the existing historical data's relationship to true historical conditions and does not account for the possibility that wetlands increased over time. Though this assumption that wetlands could only decrease over time due to human activity may not hold true in all places, it allows for a consistent reconstruction of representative wetland extents over time accounting for evolving scientific understandings of wetlands, surveying processes, and cartographic techniques and standards. Indeed, the sudden appearance and disappearance of the Wollaston wetlands in a 50 year time period may point to the validity of this method and underlying assumption.

Challenges of this methodology stem from both the process and the analysts carrying out this analysis.. Inconsistencies with final wetlands vectors indicate some issues with the georeferencing process, such as an insufficient number of GCPs or unequal distribution of GCPs. There may also be slight differences in georeferencing and vectorizing choices between multiple analysts, such as the number and locations of GCPs and how close to wetlands symbology polygons were drawn.

Finally, while the 2005 wetlands shapefile shows wetlands extents going around river edges and the vectorization step of this methodology specifies the same, rivers change over time and are among the least reliable features in HGIS. The time horizon combination method will tend to result in fuzzier edges, causing rivers and streams to potentially be lost, resulting in an overrepresented historical extent of wetlands.

Figure 50: Wetlands Habitat ([Source: iStock]())

Policy Recommendations

Many targeted approaches can be used to provide municipalities and homeowners with the best tools to combat stormwater flooding. Accessibility and education are two primary ways homeowners can learn about the threats of stormwater flooding and the associated risks. With increased exposure and knowledge about stormwater flooding, homeowners can take advantage of local, state, and federal programs that can help mitigate and manage stormwater flooding impacts.

Table 3. Policy Recommendations (Source: Tufts Team)

Recommendation	Description	Similar Policy	Key Partners
Restore wetlands in strategic locations to reduce the impacts of stormwater flooding	Prioritize wetland restoration in areas that have the greatest potential benefit to people, plants, and wildlife.	The city of Toronto has implemented a planning tool called Integrated Restoration Prioritization. Through using desktop and field assessments, places were located that would benefit from the restoration of wetlands. These projects typically remove tile drains and re-grade the land to re-establish natural water drainage and/or capture overland flows before the water enters an area that frequently floods (Toronto and Region Conservation Authority, n.d.). The EPA also has recommendations for what kind of wetlands, such as constructed and stormwater wetlands, to integrate into developments as a best management practice for controlling stormwater flooding as part of their National Pollutant Discharge Elimination System program (EPA, 2021).	• Regional Planning Agencies • State agencies • Municipalities
Use GIS methodology to explore local wetland alterations and stormwater flooding pattern	The GIS methodology of this report provides a replicable SOP that municipalities can use to explore if a connection exists between historic wetland alteration and stormwater flooding patterns.	N/A	• Municipalities • Regional Planning Agencies • State agencies

Recommendation	Description	Similar Policy	Key Partners
Strengthen development and building recommendations	Local stormwater regulations, floodplain overlay districts, and low-impact development requirements are examples of regulations that can be strengthened. Municipalities should adopt rainfall standards that incorporate future rainfall estimates for the life of a project in addition to incorporating low-impact development requirements across the zoning code and regulations. As communities identify flood-prone areas, they should additionally expand their Floodplain Overlay Districts to regulate new development and redevelopment that do not conflict with the building code. There can also be further action taken by Massachusetts to help existing buildings (Herbst et al. 2023)	FEMA's Community Rating System Program along with the NFIP program provides funding for community improvement projects. FEMA also outlines suggested planning considerations in 44 CFR 60.22 (FEMA, 2022a).	• Local governments • State agencies • Utility companies • Municipalities • Regional Planning Commissions
Promote innovative insurance strategies to address the needs of low-income households	Massachusetts' State Insurance Commissioner should look into how parametric or microinsurance could be used to address the needs of low-income households when a disaster strikes. These insurance strategies are designed so that when a disaster happens, there is an immediate payout that depends on the severity of the disaster. Both programs work by having low coverage and low premiums and can achieve payouts due to a lack of administrative costs when processing claims (Herbst et al. 2023).	California's insurance program, Jumpstart, allows for a low monthly price for disaster insurance and releases a payout based on the USGS seismic data, and only requires a yes/no answer to a text message to have funds released (Jumpstart, n.d.). The Puerto Rican government has adopted Rule Number 103 which establishes a regulatory scheme for insurance products that are directed at providing financial protection for the low-income population (Rule 103: Requirements for Submitting and Processing Parametric Catastrophic Microinsurance in Personal Lines, 2020).	• State Insurance Commissioner • State government regulatory bodies
Improve understanding of the causes and impacts of stormwater flooding	Municipalities and Regional Planning Agencies should further explore local stormwater flooding patterns. Examples of further research topics are groundwater dynamics, interviews with affected residents, and other natural and built environmental factors (Herbst et al. 2023).	A 2016 study centered around flooding in West Virginia looked into the intersection of water and societal relations and how to improve them for water justice purposes. This process involved an interdisciplinary group of scientists including two human geographers and two hydrologists (Caretta et al., 2021). This approach can be used in the MAPC region as it has been impacted by major flooding, has been subject to wetland alterations, and is facing environmental justice issues.	• Community groups • Regional Planning Agencies • Councils of Governments • State agencies

Recommendation	Description	Similar Policy	Key Partners
Finance property retrofits and repairs, prioritizing low-income households	Due to the unpredictable nature of stormwater flooding, mitigation and retrofitting should be handled on the parcel and building levels. In 2021, the Safeguarding Tomorrow through Ongoing Risk Mitigation (STORM) Act was passed by Congress. STORM provides funding for states to create hazard mitigation revolving loan programs. Massachusetts should take advantage of such funding to focus on utility elevations and basement flooding protections. MassSaves should work in tandem with energy savings and stormwater flooding protections (Herbst et al. 2023).	Florida's My Safe Florida Home Program is available to homes in areas prone to damage from wind debris and provides free hurricane inspections to single-family homeowners. The incentive to participate is that residents can apply for two dollars of state grant money for every dollar spent on eligible home improvements and no state sales tax on purchases of impact-resistant home fixtures from July 1, 2022, through June 30, 2024 (Florida Department of Financial Services, n.d.). A version of this program should be implemented in Massachusetts for single and multi-family homes that have repeatedly experienced flooding.	• Senators • Congressional Representatives • Municipalities • Regional Planning Commissions • Councils of Governments • State agencies
Fund stormwater management	An impediment to improving local stormwater management is the availability of funds. New funding streams are needed to support this work in the long run. One way to raise funds for these improvement projects is the adoption of stormwater utilities that charge property owners a stormwater fee to support improvements (Herbst et al. 2023).	Multiple municipalities in MAPC communities have already adopted stormwater utilities (Herbst et al. 2023). Outside of utility costs, additional potential funding sources include public agency grant funding, philanthropic grant funding, the Clean Water State Revolving Fund, and developer fees (National Municipal Stormwater Alliance, n.d.).	• State governments • Local governments • Utility companies • Public agencies • Philanthropic organizations
Incorporate flood data into planning projects	Municipalities, Regional Planning Commissions, and state Emergency Management Agencies should analyze and incorporate flood data into stormwater management, hazard mitigation planning, capital investments, and other planning efforts. The assistance should be prioritized for communities that are classified as environmental justice communities (Herbst et al. 2023)	MAPC currently includes 2010 data in hazard mitigation plans (Herbst et al. 2023). FEMA's Community Rating System (CRS) establishes stormwater flooding goals, and if met, CRS can provide discounts of up to 45% on flood insurance premiums for properties within these communities (FEMA, 2021).	• State agencies • Regional agencies • Local governments

Recommendation	Description	Similar Policy	Key Partners
Enable further access to federal flood claim data	FEMA should re-evaluate how information from flood claims can be aggregated and proactively shared with municipalities, Regional Planning Commissions, Councils of Governments, and state agencies. Priority should be to overburdened and under-resourced communities. Congress should revise the Privacy Act and the National Flood Insurance Program (NFIP) to make claims data available for hazard mitigation planning (Herbst et al. 2023).	Not applicable to this recommendation as federal policy heavily limits access to FEMA data due to individual privacy concerns that are protected under the Privacy Act of 1974.	• Senators • Congressional Representatives • Municipalities • Regional Planning Commissions • Councils of Governments • State agencies
Track and utilize local flood risk data	Encourage communities to routinely record and map flooding service calls to first responders and public works departments. Then use the data to create maps to share on municipal websites and in outreach materials to highlight flood risks in places outside of Special Flood Hazard Areas (Herbst et al. 2023).	The city of Woburn has developed website materials and brochures that cover the definitions of stormwater flooding and basement flooding and residential strategies to reduce flooding and flood damage, and information for residents to connect with the City's stormwater management program (Herbst et al. 2023).	• First responders • Public work departments • General public • City governments
Require flood history disclosure	Massachusetts should adopt legislation that requires property sellers to disclose previous flood history as it is currently one of fifteen states that have no statutory or regulatory requirements for a seller to disclose a property's past flood damages to a potential buyer. Tenants should also be informed of flood risk and previous flood damage to their units (Herbst et al. 2023).	In the state of Louisiana, a seller of a residential property must provide buyers with a Property Disclosure Document that discloses flood damage and flood insurance information (FEMA, 2022b). New York has recently passed legislation that requires landlords to tell potential renters a home's flood risk, its flooding history, whether a house is within a FEMA-designated floodplain, and whether a home has experienced flood damage (Scata, 2022).	• State government • State agencies • Massachusetts Association of REALTORS • State legislators

Conclusion

Wetlands provide a crucial ecological service to surrounding communities. Drastic reduction of historic wetland areas throughout Boston, Stoughton, Randolph, Wilmington, and Woburn shows not only loss of entire wetland areas, but that many remaining wetlands have shrunken from their original extent over time. However, despite this reduction of wetland extent from the late 1800s to present day, remaining wetlands still function properly as flood prevention and protection. Wetlands' ability to store and then slowly release rainfall and runoff and reduce flood peaks is potentially demonstrated in the results of the geospatial analysis, where more FEMA flood claims occur further away from wetland areas.. As the impacts of intensified weather events from climate change become more apparent, stormwater flooding is a major issue within the MAPC region that FEMA flood maps do not capture.

Buildings located within historical wetlands were proportionally 55% more likely to have submitted a successful flood claim from the March 2010 storm than all buildings across the study area. While this figure is not statistically significant among the five municipalities chosen for this study, it does reveal a potential relationship between historical wetlands and flooding vulnerability.

The impacts of the March 2010 storm were widely felt throughout the MAPC region, with many claims from outside of FEMA flood zones. Further, the results support the literature that wetlands provide critical benefits to surrounding areas and that FEMA flood maps are severely limited in their ability to predict stormwater flooding patterns. Despite the lack of conclusive results on the relationship between historical wetlands and flood claims from the March 2010 storm, knowledge of the extensive amount of wetland loss within the study area is important for municipalities and MAPC so that planning initiatives can consider the benefits of wetlands and the limitations of FEMA flood maps. Moreover, additional major storms both before and after March 2010 should be studied to find further significance in stormwater flooding patterns.

Municipalities should continue their efforts to protect and preserve existing wetlands. Municipalities can work with their local Conservation Commissions to enforce the WPA and their associated stringent bylaws. Green infrastructure, such as rain gardens or constructed wetlands, should be considered and implemented on a wider basis to mitigate stormwater flooding effects.

To better prepare for climate-induced weather events, education is necessary at the local and regional level so homeowners are aware of the stormwater flood risks in their area, the ecosystem services wetlands provide, the limitations of FEMA flood maps, and their potential vulnerability to extreme weather events..

Having this information and data widely accessible will only increase interest, innovation, and mitigation of stormwater flooding in the MAPC region.

Key Takeaways

01 Proportionally, buildings within historical wetlands had **55% more flood claims**

02 Minimum **40% decrease** in historical wetlands

03 Wetlands loss through **shrinking**

04 **Standardized methodology** for future research

**See Appendix IV "GIS How-to Handbook"*

Figure 51: Waquoit Bay in Falmouth, MA (Source: Citizens for the Protection of Waquoit Bay)

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Appendices

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Appendix I:
Timeline of Human Modification to Wetlands

Pre-Colonial

This time period is defined by minimal human alteration of wetlands by Native peoples, who stewarded the fertile lands for sustenance and resources.

Regional Level

Much of the MAPC region was home to the Massachusett tribe of the Algonquin Native Americans since 2400 BC, who relied on wetlands to support year-round horticultural settlements before disease brought by early European explorers decimated the tribe's population (Bowen et al., 2019; Rozsa, 1995).

Colonial

In the colonial era, wetlands were valued insofar as they could be altered to support various aspects of colonial life: providing food, game, building material, and animal feed (Bromberg & Bertness, 2005; Finlayson, 1991; McGlothlin & Spray, 2004).

Regional Level

The city of Boston was founded in 1630, and similar wetland alteration occurred in Massachusetts as the rest of the US (Rozsa, 1995

Late 1800s and Early 1900s

Wetland modification from the late 1800s to the early 1900s, including the Civil War Era, was defined by the agricultural and infrastructural needs of a growing American population.

National Level

Federal legislation set the stage for widespread wetland alteration as agriculture shifted westwards and wetlands fell out of favor in the eyes of most Americans. Moreover, wetlands were increasingly seen as vectors for diseases carried by mosquitoes, and technological improvements encouraged widespread ditching efforts (Bromberg & Bertness, 2005; Rozsa, 1995).

Regional Level

Several large scale urban and industrial growth projects in Boston contributed to wetland degradation and alteration. These projects aimed to deal with pollution from a growing population, address public health concerns, promote trade and industry, create new public parks, and provide transportation. To support "landmaking" to address these needs, over 2,000 hectares of salt marsh and mudflat in the Boston area were filled in for various industrial and urban growth projects between 1830 to 1930 (Bromberg & Bertness, 2005).

Great Depression

During the Great Depression era, widespread human modification of wetlands continued throughout the United States with a marked change in motivation—boosting the national economy.

National Level

New Deal programs were leveraged to drain wetlands systematically using a **grid ditch system**. Mosquito management via ditching of wetlands was carried out on a large scale during the 1930s by the Civilian Conservation Corps (CCC) and the Works Program Administration (WPA), primarily aiming to boost the national economy during the Great Depression and secondarily to limit disease within residential and urban areas (Glinski, 2022; Rozsa, 1995; Silliman et al., 2009).

Regional Level

The grid ditch system, still evident in Massachusetts salt marshes today, was dug by hand between 1928 and 1934 by the CCC and WPA (Massachusetts Open Marsh Water Management Workgroup, 2010). By 1938, 94-95% of the tidal marshes along the New England coast had been ditched (Bromberg & Bertness, 2005; Glinski, 2022).

Post-World War II

Increased transportation and housing needs after WWII caused notable direct losses of wetlands (Rozsa, 1995).

Regional Level

There were housing shortages in Boston as soldiers returned from WWII and the Depression-era ditch system became degraded, especially on the North Shore. In the mid 1900s, the construction of I-95 resulted in the filling of tidal wetlands to create an elevated base for highway construction (Rozsa, 1995)

Environmental Movement

The environmental movement of the 1970s in the United States created much of the first legislation preventing additional degradation and promoting restoration of wetlands as individuals and the government recognized the extensive destruction of this ecologically valuable landscape.

National Level

Passed in 1972, the Clean Water Act's Section 404, protects waters of the United States from dredging and filling except by permit from the Army Corps of Engineers (Bromberg & Bertness, 2005; Rader et al., 2001). This protection was extended to wetlands in 1977 (Kusler & Kentula, 1990). Despite these efforts, wetlands continued to disappear nationwide at an average annual net loss of 290,000 acres annually until the mid-1980s (Bohlen, 1993).

Regional Level

The state of Massachusetts has one of the strictest wetland regulation programs in the nation (Motts & O'Brien, 1981). In 1965, the state of Massachusetts passed the nation's first inland wetlands protection under the "Hatch Act," which stressed the value of wetlands for water supply and food control and required permits for wetland alteration by developers (Motts & O'Brien, 1981; Rozsa, 1995). In 1972, the Massachusetts Wetlands Protection Act (MAWPA) created a general framework for wetlands protection in the state and extended protection beyond that required by CWA's Section 404 (Meyer & Konisky, 2007).

Appendix II:
Literature Review Search Terms

Sources found for the literature review on wetlands and FEMA flood maps were found from searches on Tufts University's Tisch Library search engine JumboSearch, JSTOR, and Google Scholar.

Key search terms included “Massachusetts OR Boston,” “Wetlands OR Swamp OR tidal flats OR salt marsh OR freshwater marsh OR tidal marsh OR catchment OR drainage.” Other search terms were “historic” and “wetland alteration.”

Sources in the GIS meta-analysis were found from searches on Tufts University’s Tisch Library search engine JumboSearch and Google Scholar.

Key search terms included “historic*”, “(gis OR map*)”, “(wetland OR swamp OR marsh OR drainage OR catchment OR "tidal flat")”. Searches were also conducted for sources citing or cited by a previously reviewed paper.

Papers were selected if the study employed the HGIS method of georeferencing and was concerned with water resources or coastal features. Eleven papers were reviewed in detail: ten conducted HGIS analysis while one was a meta-analysis of challenges and approaches in HGIS landscape research (Schaffer & Levin, 2015).

Appendix III: Historical GIS Meta-Analysis

Introduction

The purpose of this meta-analysis is to assess methods and techniques for using historical maps in geographical information systems (GIS) analysis to inform a study of historical wetlands in the MAPC region. While there are many different applications of historical GIS (HGIS), this review looks specifically at the application of HGIS on different water resources, such as wetlands, salt marshes, and coral reefs. Findings from this review were used to create a standard operating procedure (SOP) for historical wetlands analysis, taking into account project goals and resources available.

Methodology

Sources in this review were found from searches on Tufts University's Tisch Library search engine JumboSearch and Google Scholar. Key search terms included "historic*", "(gis OR map*)", "(wetland OR swamp OR marsh OR drainage OR catchment OR "tidal flat")". Searches were also conducted for sources citing or cited by a previously reviewed paper.

Papers were selected if the study employed the HGIS method of georeferencing and was concerned with water resources or coastal features. Eleven papers were reviewed in detail: ten conducted HGIS analysis while one was a meta-analysis of challenges and approaches in HGIS landscape research (Schaffer & Levin, 2015).

Study Scope

Table 3A summarizes the ten HGIS papers' study areas and scopes. The study areas range in geography and include regions in North America, Europe, Australia, and the Pacific Islands. They assess changes in wetlands, salt marshes, benthic habitats, land use, and habitat change. All compare historical maps to modern maps in spans as large as 1773-2017 (around 240 years) to as narrow as 1858-1956 (around 100 years).

Four of the ten studies compare multiple maps across a time series to examine changes throughout time. Two of those four papers, which studied changes in wetlands, combined a time period's vectorized wetlands extent with those of all time periods after to create a representative "true" historical wetlands extent for that time period. Definitions of wetlands have changed over time—earlier definitions are broader and include fewer wetlands than modern definitions. The practice of combining wetlands extents is based on the assumption that all wetlands existing in a time period also existed in the past but were not included in maps because of the broader definitions. This method is discussed in greater detail in the Analysis Methods and Limitations sections later in this meta-analysis.

Table 3A: Paper Study Areas and Scopes (Source: Tufts Team)

Paper	Study area	Topic of interest	Timeframe	Time series
(Birch et al., 2015)	Sydney estuary, Australia	Catchment land use and metal loading	1788-2010	Yes: 1788, 1850, 1892, 1936, 1943, 1978, 2010
(Bromberg & Bertness, 2005)*	New England, USA	Salt marsh loss	Late 1700s/ early 1800s to 2005	No
(Costa et al., 2020)	British Columbia, Canada	Changes in kelp forests	1858-1956	No
(Gimmi et al., 2011)*	Canton Zurich, Switzerland	Wetland cover change	1850-2000	Yes: 1850, 1900, 1950, 2000 Combined all historical to create extent
(Lawson et al., 2021)	Fiji; two cities (one developed, one not)	Land use and habitat change (coral reef, mangrove, hardened shorelines)	1840-2021	No
(Levin et al., 2009)*	Coastal Israel	Wetlands: swamps and natural rain pools	1799-2006	Yes: 1799,1880, 1895, 1919, 1930, 1936, 1944, 1964, 1986, 2000s Combined all historical to create extent
(McClenachan et al., 2017)	Florida Keys, USA	Changes in coral reefs	1773-2017	No
(Timár et al., 2008)	Banat region, Romania and Serbia	Historical wetland /marshland and lake following centennial flood event 2005	1769-2005	No
(Zlinszky & Timár, 2013)	Lake Balaton, Hungary	Wetland system; socio-hydrology	1770s-2000	Yes: 1770s, 1780s, 1830s, 1870s
(Zlinszky, 2010)	Lake Balaton, Hungary	Historical wetlands, level of lake	1776-2010	No

*reviewed in Schaffer and Levin, 2015 meta-analysis

Data Used

Data Sources

Historical Maps

All ten HGIS analysis papers reviewed used multiple sets of historical maps. These include national surveys (Bromberg & Bertness, 2005; Gimmi et al., 2011; Levin et al., 2009), military maps (Timár et al., 2008; Zlinszky, 2010; Zlinszky & Timár, 2013), topographic maps (Birch et al., 2015; Gimmi et al., 2011; Levin et al., 2009; Zlinszky & Timár, 2013), and navigational charts (Costa et al., 2020; Lawson et al., 2021; McClenachan et al., 2017). Map sources included university libraries, historical societies, government agencies, journals, books, atlases, and internet sources. Maps created after the mid-1800s tended to have projections and geodetic datum specified while earlier maps did not.
Some studies used maps originating in a source from a different geographical region. Costa et al. and McClenachan et al.'s studies focused on benthic features in British Columbia, Canada and the Florida Keys, USA, respectively, and used historical maps created by the British Admiralty when Canada and the United States were colonies of England (Costa et al., 2020; McClenachan et al., 2017).

Satellite Images or Aerial Photos

Five of the ten papers used satellite imagery or aerial photographs (Birch et al., 2015; Costa et al., 2020; Levin et al., 2009; McClenachan et al., 2017; Timár et al., 2008). Images were used for four reasons: to determine current conditions (Levin et al., 2009; McClenachan et al., 2017), to delineate the extent of recent floods (Timár et al., 2008), to augment maps in a specific time period (Birch et al., 2015), and to validate results of georeferenced maps (Costa et al., 2020).

Reasons for Selection

Eight of the ten papers stated reasons for selecting maps (Bromberg & Bertness, 2005; Costa et al., 2020; Gimmi et al., 2011; Lawson et al., 2021; McClenachan et al., 2017; Timár et al., 2008; Zlinszky, 2010; Zlinszky & Timár, 2013), while two did not (Birch et al., 2015; Levin et al., 2009). The most common reason for the selection of maps in a paper was accuracy and detail: the maps were either created by trusted sources, such as country surveys or militaries, or had been successfully used previously. Some maps were chosen specifically for the level of detail of benthic features, such as coral reefs and kelp forests, that also included accompanying notes and methodology (Bromberg & Bertness, 2005; Costa et al., 2020; McClenachan et al., 2017). Bromberg and Bertness specified that "maps were included only if they were constructed by trigonometric survey, depicted land use types within distinct borders, and had accurately represented geographic formations" (Bromberg & Bertness, 2005). Overall, studies began with maps starting from at least the second half of the 18th century because surveying and mapping methods had advanced in accuracy.

Analysis Methods

Georeferencing

Georeferencing is a GIS method used to align aspatial rasters or images (which can include aerial photographs, satellite imagery, and digitized paper maps.) This is accomplished by using ground control points (GCPs) to link matching points on the raster and the coordinate system. Because the rasters may be distorted or projected differently than the coordinate system, transformations are used to warp and fit the raster to the coordinate system. The accuracy of the transformation is reflected in the Root Mean Square Error (RMSE,) where lower RMSE values indicate higher accuracy.

Nine HGIS papers employed georeferencing for historical maps. When specified, the number of GCPs ranged from minimums of four to thirteen points. Types of GCPs used include coordinate grids, historical buildings, fortresses, stable coastal rock features, and deep coastal channels. First order polynomial, third order polynomial, spline, and projective transformations were employed. Studies who used different transformations on different maps did so to minimize the RMSE.

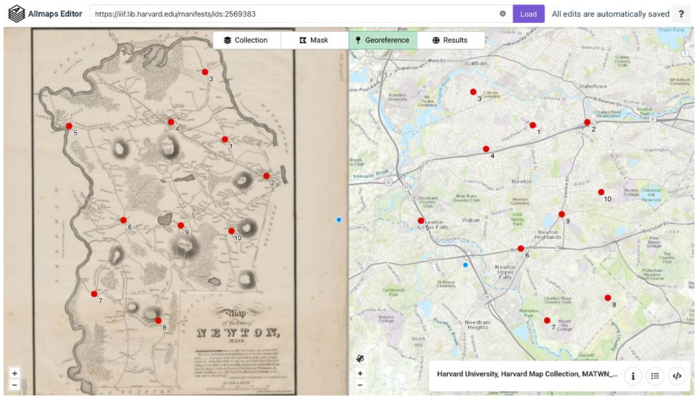

Figure 3A: Example of georeferencing a historical map with Allmaps Editor

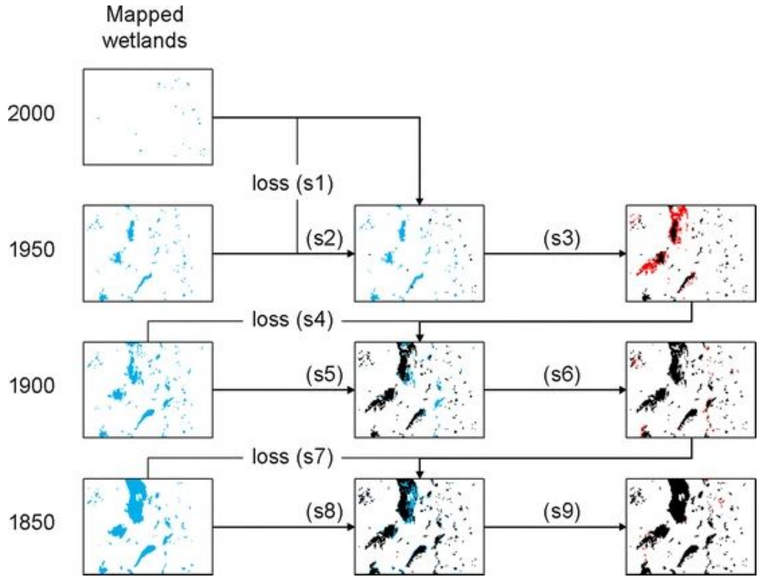

Figure 3B: "Conceptual diagram illustrating reconstruction of comparable time series of wetland cover. Wetlands as represented on the maps are indicated in blue, wetlands adopted from previous reconstruction steps are shown in black, and wetlands gained from suitability models are shown in red," (Gimmi et al., 2011).

Feature Analysis

Once the georeferencing process is complete, raster images are tied to coordinate systems and can be analyzed with modern GIS methods. The purposes of the reviewed papers were by and large to compare historical extents of features to current extents. This was accomplished through overlay, vectorization, and rasterization, with vectorization of features being the most common.

As previously mentioned, two studies on changes of wetlands over time vectorized historical wetlands, then combined a time period's vectorized wetlands extent with those of all successive time periods to create a representative "true" historical wetlands extent. The practice of combining wetland extents is based on the assumption that all wetlands existing in a time period also existed in the past but were not included in maps because of the broader definitions.

These issues are further supported by conclusions drawn from, and limitations described in, the ten HGIS studies. The studies state that at least four GCPs should be used per map—more if using a higher order transformation—and the first order polynomial transformation is most common and appropriate for maps at local scales, but multiple transformations can be tested to minimize the RMSE. When possible, further research should be done on the methods used and context surrounding historical maps; some features shown on maps can be older than the map or copied from other maps and not part of novel surveys. The mid-1700s is an ideal starting point for HGIS studies. However, the mid-1800s are more useful starting points because surveying and cartography methods and technology were sufficiently advanced and became standardized around that time period. Unfortunately, maps from this time may not completely capture true historical extents as many ecological changes have already occurred.

Geographic Methods

Map Acquisition

Gimmi et al. and Bromberg and Bertness used maps that were already available as scanned and georeferenced layers (Bromberg & Bertness, 2005; Gimmi et al., 2011). Levin et al. and Costa et al. scanned some of the maps used (Costa et al., 2020; Levin et al., 2009), while Birch et al. and Bromberg and Bertness took photographs of some of the maps (Birch et al., 2015; Bromberg & Bertness, 2005). These and the remaining papers also used maps that were already digitized.

Georeferencing

Georeferencing is a GIS method used to align aspatial rasters or images to a geographic coordinate system. Rasters can include aerial photographs, satellite imagery, and digitized paper maps. Georeferencing is accomplished by using GCPs to link matching points on the raster and the coordinate system. Because the rasters may be distorted or projected differently than the coordinate system, transformations are used to warp and fit the raster to the coordinate system. The accuracy of the transformation is reflected in the Root Mean Square Error (RMSE), where lower RMSE values indicate higher accuracy.

Timar et al.'s digitized 1800s military maps included projections or geodetic datum and did not require georeferencing (Timár et al., 2008). The remaining nine studies whose historical maps did not all include projections or geodetic datum employed georeferencing (Birch et al., 2015; Bromberg & Bertness, 2005; Costa et al., 2020; Lawson et al., 2021; Levin et al., 2009; McClenachan et al., 2017; Timár et al., 2008; Zlinszky, 2010; Zlinszky & Timár, 2013).

When specified, the number of GCPs ranged from a minimum of four points to a minimum of thirteen points (Lawson et al., 2021; Timár et al., 2008; Zlinszky & Timár, 2013). Types of GCPs used include coordinate grids, historical buildings, fortresses, stable coastal rock features, and deep coastal channels.

Transformations

The type of transformation employed during georeferencing depends on the number of GCPs used and the overall scale of the raster and ground area. Types of transformations and minimum number of GCPs is shown in Table A2 (adapted from ArcGIS Pro) (ArcGIS Pro, n.d.).

ArcGIS Pro's guidance on georeferencing describes that polynomial transformations optimize global accuracy but do not guarantee local accuracy while spline transformations optimize local accuracy but not global accuracy.

Table 3B: Transformation Types and GCPs (Source: Tufts Team)

Transformation Type	Application	Minimum GCPs Required
Zero-order polynomial	Shifts raster, preserves straight lines	1
First-order polynomial	A.k.a. Affine transformation; shifts, scales, and rotates raster	3
Adjust	Optimizes for global least-square fitting and local accuracy	3
Projective transformation	Warps lines so they remain straight	4
Second-order polynomial	Bends or curves raster	6
Third-order polynomial	Bends or curves raster	10
Spline transformation	Rubber-sheeting method; optimizes for local accuracy but not global accuracy	10

The meta-analysis conducted by Schaffer and Levin recommends that analysts "use a 1st order polynomial transformation if the map covers a relatively small area so that the curvature of the Earth can be disregarded and when assuming no differential transformation of the historical." They further specify that, "as a thumb rule, when the grid lines are straight lines and are perpendicular to each other throughout the map, a 1st order polynomial transformation can be used." (Schaffer & Levin, 2015). These are seemingly contradictory practices from two trusted sources.

The reviewed HGIS papers employed a variety of transformations. A summary of the types of transformations used is shown in Table A3 below. Those who used different transformations on different maps did so to minimize the Root Mean Square Error (discussed in the following section).

Residual Errors

Once rasters are transformed, a residual error is returned by the GIS software and indicates the level of accuracy of the georeferencing and transformation. The residual error returned is typically the Root Mean Square Error (RMSE), which can be reported on the ground scale (e.g. in meters) or on the chart scale (e.g. in millimeters). The lower the RMSE, the more closely matched the GCPs and the more accurate the georeferencing.

Seven of ten studies reported residual errors for the georeferenced maps (Bromberg & Bertness, 2005; Costa et al., 2020; Lawson et al., 2021; Levin et al., 2009; Timár et al., 2008; Zlinszky, 2010; Zlinszky & Timár, 2013). Some reported errors on the map scale and some on the true scale. Six reported the Root Mean Square Error (RMSE) while one (Timár et al., 2008) stated only "residual error" without specifying the parameter or method, though it is assumed that the reported error was RMSE.
Where stated, average RMSEs ranged from 54-245 m on the ground and 0.5-1.1 mm on the map scale. The range across all papers was 3-708 m on the ground and 0.001-2.16mm on the map scale. A summary is shown in Table 3C.

Feature Analysis

Once the georeferencing process is complete, raster images are tied to coordinate systems and can be analyzed with modern GIS methods. The purposes of the reviewed papers were by and large to compare historical extents of features to current extents. This analysis took different forms: overlay, vectorization, and rasterization.

Overlay is used to visually compare two layers, but may not include mathematical or statistical analyses. Vectorization and rasterization can both be used to conduct statistical analyses, most typically comparing past and present areas. Table 3E below summarizes the feature analysis of these ten papers.

Table 3C: Transformations Employed in Papers (Source: Tufts Team)

Paper	1st Order Polynomial	3rd Order Polynomial	Spline	Projective
Bromberg & Bertness, 2005			X	
Costa et al., 2020	X		X	
Lawson et al., 2021	X			X
Levin et al., 2009	X		X	
Zlinsky, 2010		X		
Zlinsky & Timár, 2013		X		

Table 3D: RMSE Summary of HGIS Paper (Source: Tufts Team)

	Ground Scale (m)			Chart Scale (mm)		
Paper	**min**	**avg**	**max**	**min**	**avg**	**max**
Bromberg & Bertness, 2005	160	245	440			
Costa et al., 2020						0.5
Lawson et al., 2021						0.001
Levin et al., 2009	5	56.4	155.6	0.25	1.12	2.16
Timár et al., 2008*			200			
Zlinsky, 2010	3	140.8	707.9			
Zlinsky & Timár, 2013	3	140	708			

*not specified as RMSE

Table 3E: Feature Analysis Methods (Source: Tufts Team)

Paper	Overlay	Vectorize	Rasterize	Not Specified
(Birch et al., 2015)*				X
(Bromberg & Bertness, 2005)				X
(Costa et al., 2020)		X		
(Gimmi et al., 2011)		X		
(Lawson et al., 2021)^		X	X	
(Levin et al., 2009)		X		
(McClenachan et al., 2017)		X		
(Timár et al., 2008)	X			
(Zlinszky & Timár, 2013)		X		
(Zlinszky, 2010)		X		

*used the "'clip' function in ArcGIS" but did not specify whether they clipped in raster or vector form
^vectorized features, then rasterized to compare spatially

Time Horizon Combination of Historical Extents

Gimmi et al. and Levin et al. studied changes in wetlands over time. After vectorizing extents of each historical map, both studies combined a time period's vectorized wetlands extent with those of all successive time periods to create a representative "true" historical wetlands extent for that time period. Per findings from the wetlands history literature review, definitions of wetlands have changed over time. Earlier definitions are broader and include fewer wetlands than modern definitions. They may be subjective or somewhat arbitrary and have evolved to include more clear parameters, particularly after the U.S. Wetlands Protection Act of 1973. Early maps depicting wetlands, therefore, likely miss areas that would now be considered wetlands (e.g. based on the presence of vegetation species or soil moisture content). The practice of combining wetlands extents is based on the assumption that all wetlands existing in a time period also existed in the past but were not included in maps because of the broader definitions. Limitations to this assumption and practice are discussed in the Limitations section.

Variables/Metrics

The intent of employing the above feature analysis methods is to quantify changes from the historical maps' time periods to current time periods. Table 3F summaries the variables and metrics of interest in the reviewed papers.

Table 3F: Variables and Metrics of Interest (Source: Tufts Team

Paper	Variables/Metrics
(Birch et al., 2015)	area of land use chemical loadings
(Bromberg & Bertness, 2005)	area of salt marsh area of urban areas % change in salt marsh % change urban areas
(Costa et al., 2020)	# kelp forest observations Reliability index
(Gimmi et al., 2011)	landscape metrics mean distance to nearest patch
(Lawson et al., 2021)	coral cover coral fragmentation mangrove extent hardened shorelines
(Levin et al., 2009)	area of wetlands number of wetland bodies connectivity of wetlands
(McClenachan et al., 2017)	# coral observations Total area of coral Change in coral area
(Timár et al., 2008)	n/a
(Zlinszky & Timár, 2013)	water level of lake area of wetlands
(Zlinszky, 2010)	n/a

Limitations

The reviewed studies described limitations in two main categories: those pertaining to historical maps and HGIS methods and those pertaining to the subject matter, specifically water resources.

HGIS Limitations

HGIS is limited by many factors, three of which are succinctly summarized by Schaffer and Levin's meta-analysis:

> *"The first challenge relates to the accuracy of the field survey based on which the historical map was done. [...]*
>
> *The second challenge relates with how the world was perceived and interpreted. [...]*
>
> *The third challenge relates to errors which may be introduced during the process of map reproduction such as scanning, geo-referencing, digital data processing and digitization." (Schaffer & Levin, 2015)*

These three factors were mentioned throughout the ten HGIS studies. Historical maps are less accurate and less reliable than modern maps, mostly due to changes and precision in surveying and cartography (Bromberg & Bertness, 2005; Lawson et al., 2021; Schaffer & Levin, 2015; Zlinszky & Timár, 2013). Bromberg and Bertness state:

> *"Before the U.S. Geological Survey was formed in 1879, the quality and availability of historic data sets was unreliable. One exception is the early maps published by the U.S. Coast Survey, founded in 1834. Accurate maps containing land use data from before then are rare. Only starting in 1879 have scientists had access to consistent, highly detailed, and accurate maps." (Bromberg & Bertness, 2005)*

Maps are also biased by intended purpose: wetlands extents on a map may not be truly representative if the surveyor or mapmaker has little interest or expertise in wetlands, or the map's focus is on another subject (Bromberg & Bertness, 2005; Levin et al., 2009; Zlinszky & Timár, 2013). The artistic ability of the cartographer should be considered when deciphering symbology (Costa et al., 2020). Furthermore, context and details are often lost with time, including definitions of features, methods of cartography, methods of surveying, and levels of certainty (Costa et al., 2020; Lawson et al., 2021; Schaffer & Levin, 2015; Zlinszky & Timár, 2013).

As shown in the wide ranges of RMSEs, the georeferencing process can be subjective and subject to errors at many steps. Maps may be worn, scanning or digitizing may warp the original map, selected GCPs could be wrong or mismatched, and an inappropriate transformation can be chosen.

Subject Matter Limitations

As western scientific knowledge of the natural world has evolved, so too have understanding and classifications of ecologies and habitats. Wetlands specifically had broader definitions in the past than in modern day, and the content of historical maps is dependent on those definitions. Bromberg and Bertness, for example, describe:

> *"Definitions of wetlands have shifted over the years, making a consistent analysis over time difficult. In some studies, swamps refers to salt marshes (Shaler 1886), yet in others swamps refers exclusively to freshwater marshes (Wright 1907). The treatment of subtidal vegetation differs between surveys as well (Gosselink and Baumann 1980)." (Bromberg & Bertness, 2005)*

Gimmi et al., describe:

> *"For the Siegfried maps we found an instruction dating from 1873 in the Swiss Federal Archive in Berne that states that wet areas should be charted as soon as they could no longer be crossed on horseback (BA E27 22175). Wetland mapping on the modern National maps is based on aerial photograph interpretation. Wetlands are charted when typical wetland vegetation (e.g., reeds) is visible (pers. comm. swisstopo). This information suggests that modern instructions are less conservative; e.g., some of the wetlands depicted on modern maps could easily be crossed on horseback." (Gimmi et al., 2011)*

This inconsistency and broader past definition of wetlands led to two of the reviewed studies to combine a historic map's wetlands extents with later time periods under the assumption that wetlands existing in later time periods were present in previous ones (Gimmi et al., 2011; Levin et al., 2009). Though this assumption that wetlands could only decrease over time due to human activity may not hold true in all places, it allows for a consistent reconstruction of representative wetland extents over time that may be lost with evolving scientific understandings and surveying and cartographic techniques and standards.

Because the extent of the water resources studied in these papers vary by season or precipitation patterns, the survey season of the subject area has a large impact on the resulting maps. Surveys for available maps in different time periods may not have occurred in the same season or weather patterns could have varied greatly between periods, and these analyses are therefore more subject to errors or inconsistencies when comparing many maps across time (Costa et al., 2020).

Ideally, an HGIS study would include many maps of the same area in the same time period. These could all be analyzed and averaged for a historical extent of higher confidence, but this strategy is subject to map availability and accuracy. (Bromberg & Bertness, 2005).

Conclusions & Takeaways

HGIS methods for hydrological applications have strong potential for analysts to gain insights into past conditions to inform future climate resiliency scenarios. However, methods need to be chosen carefully because of the limitations of HGIS methods and historical understandings of hydrological subjects.

Schaffer and Levin detailed the following issues and guidelines common in HGIS that the forthcoming study on historical wetlands in the MAPC region will draw from:

- ➔ **Registration accuracy** is dependent on the GCPs chosen and the historical maps' relations to modern maps. Georeferencing should be done with graticules (coordinate grid lines or points) or recognizable features (triangulation points, mountain peaks, road intersections, prominent buildings). Where applicable, historical maps can be used to georeference other historical maps because they are more similar to each other than to modern maps.
- ➔ **Map generalization** depends on the scale of the historical map, the on-screen scale of the digitized map, and the scale of the screen. These can all impact the size, shape, and accuracy of the features when vectorizing. Analysts should make note of these different scales and use caution when interpreting the analysis.
- ➔ **Positional Accuracy** of features differs between feature types, particularly through time. Historic extents of rivers are the least accurate when compared to modern day, as river banks are constantly eroding and growing.
- ➔ **Attribute Accuracy** is dependent on the surveyor, map maker, and feature type. As previously discussed, the intent of the surveyor and map maker and artistic ability of the map maker heavily influence the resulting map. Further, features often do not have clear borders or symbols or are defined inconsistently between maps and time periods. It may be pertinent to group different categories of the same feature together where category definitions are uncertain.
- ➔ **Completeness of Information** depends on the scale of the map and map maker's expertise and intent. Other contemporary historical sources may be needed to contextualize the maps of interest.

These issues detailed in Schaffer and Levin's meta-analysis are further supported by conclusions drawn from and limitations described in the ten HGIS studies. The studies further inform that at least four GCPs should be used per map, and the first order polynomial transformation is most common and appropriate for maps at local scales but multiple transformations can be tested to minimize the RMSE. When possible, further research should be done on the methods used and context surrounding historical maps; some features shown on maps can be older than the map or copied from other maps and not part of novel surveys. Overall, the mid-1700s should be used as a starting point for HGIS studies. The mid-1800s are more useful starting points because surveying and cartography methods and technology were sufficiently advanced and were standardized around that time period, but maps from this time may not completely capture true historical extents as many ecological changes have already been made. (Earlier accurate maps of the US can be found, however, from the British Admiralty.)

Pertaining to subject matter, wetlands are generally underrepresented on historical maps when applying mapping standards, and the combination of time series approach may be appropriate to construct a representative historical extent. All types of wetlands can also be combined to alleviate concerns about differing definitions and symbology for types of wetlands. Lastly, consideration should be taken for the survey year and season, and research should be conducted on historical weather patterns—particularly precipitation—to inform interpretation of historical wetlands extents.

Appendix IV: GIS How-to Handbook

Step 1: Historical Map Georeferencing

Purpose: Align images of historic maps to a geographic coordinate system using ArcGIS Pro's georeferencing tool and guidance from Esri (Esri, n.d.).

A historical map was first added to the project's geodatabase in ArcGIS Pro as a .jpeg or TIFF file. Then, using the georeference tool, 20 or more control points were matched and tested for first order polynomial, third order polynomial, and spline transformations. The lowest RMSE was then chosen. A table of the transformations used and resulting RMSE values of all maps used is in Table 3D of the Appendix.

Step 2: Clip Georeferenced Maps to the Maximum Overlapping Extent

Purpose: Keep only the maximum intersecting extent of all historical maps used for a study area to ensure accuracy and comparability between layers.

Because each historical map may have different study areas, comparison between eras would be inaccurate if all extents were retained and vectorized. The relevant maps are first added to the same project document to visually assess their extents. The Clip Raster tool in ArcGIS is used to clip each raster to others in succession to obtain the maximum overlapping extent.

Step 3: Vectorize Historical Wetlands

Purpose: Create a polygon feature class of historical wetlands for each georeferenced historical map.

To initiate vectorizing, a new polygon feature class was created in the project's geodatabase with the following attribute fields (in addition to the native ObjectID, Shape, Shape_Length, and Shape_Area attribute fields automatically populated by ArcGIS Pro):

Table 4A: Historical Wetlands Attribute Fields and Types (Source: Tufts Team)

Field Name	Data Type	Description
MapYear	Short	Year the map was issued, e.g. 1893
MapMonth	Short	Month the map was issued, e.g. 6
SurveyYear	Short	Year the survey was conducted that map is based on, e.g. 1886
SurveyMonth	Short	Month the survey was conducted that map is based on, e.g. 8
SourceName	Text	Name of the map's source or creator, e.g. "USGS"
SourceURL	Text	URL of the map's source, e.g. "https://ngmdb.usgs.gov/ht-bin/tv_browse.pl?id=4f2f6898b8648c5094cd0aa60e086a8b"
Scale	Text	Scale of the original map, e.g "1:62500"
Notes	Text	Additional notes not captured by the other Fields

Step 3: Vectorize Historical Wetlands Continued

Purpose: Identify and delineate historical wetlands as vectorized polygons for each georeferenced historical map at an on-screen scale of 1:7000.

New features were created in the wetlands feature class by tracing polygons around wetlands symbology on the georeferenced historical map. The researchers aimed to maintain an on-screen scale of 1:7000 when vectorizing to maintain consistency in resulting features. The attribute fields were populated for all wetlands vectorized from the same historical map using the Calculate Field tool to fill in the same value for all polygons.

The process of vectorizing wetlands required establishing a standard operating procedure informed by the historical GIS methodology literature review and the Team's prior GIS experience. A few guidelines were employed to ensure consistency across spatial analysts and maps. Wetlands are not vectorized if the wetlands are cut off by the map's boundary, as they are incomplete and would affect the accuracy of future analyses. The research team vectorized over roads if the wetland clearly continued on the other side but did not vectorize through rivers, unless the river was small enough to only be symbolized on the map as a line rather than a channel. This decision is substantiated by the current wetlands shapefile classifying rivers as "Riverine" or "Estuarine and Marine Deepwater," i.e. not wetland. Lastly, the project generalized wetlands to include all types depicted - such as salt marsh or bog - because the analyzed historical maps did not have clear legends allowing us to distinguish between wetland types. Moreover, the scope and goal of this project do not necessitate differentiation.

Figure 4B below shows two examples of the historical map's original wetland and the resulting vectorized polygon, specifically how we vectorized over roads and generalized wetland types.

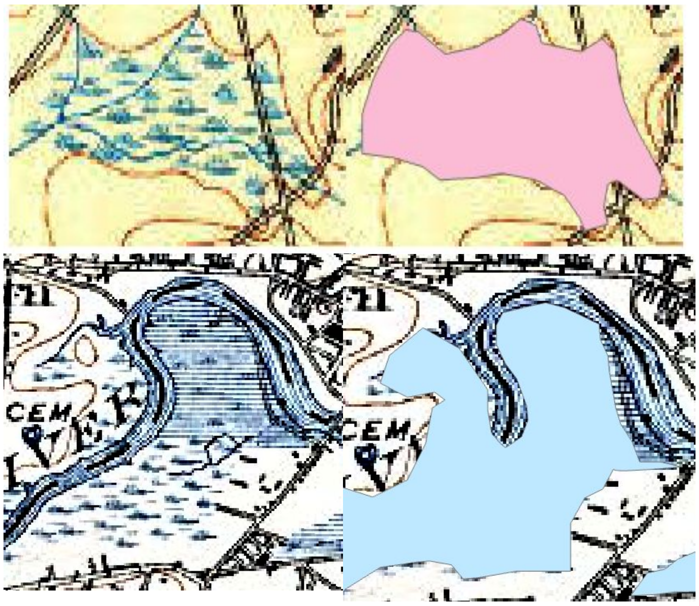

Figure 4A. Examples of the Wetlands Vectorized on the Historical Maps (Source: Tufts Team)

Step 4: Creation of Present Wetlands Extent Layer

Purpose: Create one feature class as a proxy for the present extent of wetlands for comparison with historical extent feature class in the following step.

In order to conduct a time horizon combination of historic wetlands extents, the project first needed to acquire and manipulate a feature class for the present-day extent of wetlands. The MassDEP's 2005 wetlands shapefile was used. This shapefile distinguishes between wetland types, such as cranberry bogs, salt marshes, and tidal flats. All wetland types present were selected (except for coastal wetlands which were deemed as not pertinent to this project's focus on inland flooding) and did not include any water bodies. The selected features were then exported to a new shapefile to use as the present extent of wetlands.

Step 5: Creation of Historical Wetlands Extent Layer

Purpose: Create a representative historical extent of wetlands for each time period using a time horizon approach.

Following methods employed in two of the HGIS papers reviewed in the previously discussed meta-analysis, this study uses a time horizon approach to merge past wetlands extents shown on historical maps with future ones to create representative past extents. This approach assumes that past definitions of wetlands are incomplete or inconsistent, resulting in broader and more conservative definitions and mapped extents of wetlands, and that wetlands present in later periods are also present in all prior periods. The earliest time period becomes the representative historical extent. In the case of historical maps of Boston, the 1903 map had substantially more wetlands depicted than the 1893 map despite being ten years later. This discrepancy substantiates the method of combining historic extents. The wetlands analyzed for Boston and the order of their combinations are shown in Figure 4B below.

Creating representative historical wetlands extents requires the use of several tools in ArcGIS Pro. The first is the Merge (Data Management) tool, which combines multiple input datasets into a new single output dataset. The resulting shapefile includes overlapping polygons from the two layers. To melt the boundaries between them, all features are selected and the Merge (Editor) tool is employed. This results in one multipart polygon of all wetlands. Separating this product into distinct polygons requires the Multipart to Single Part tool. This process is repeated for each combination of wetlands extents. The resulting representative historical wetlands layer of the earliest time period is compared to the extent of present-day wetlands in the same geographical region.

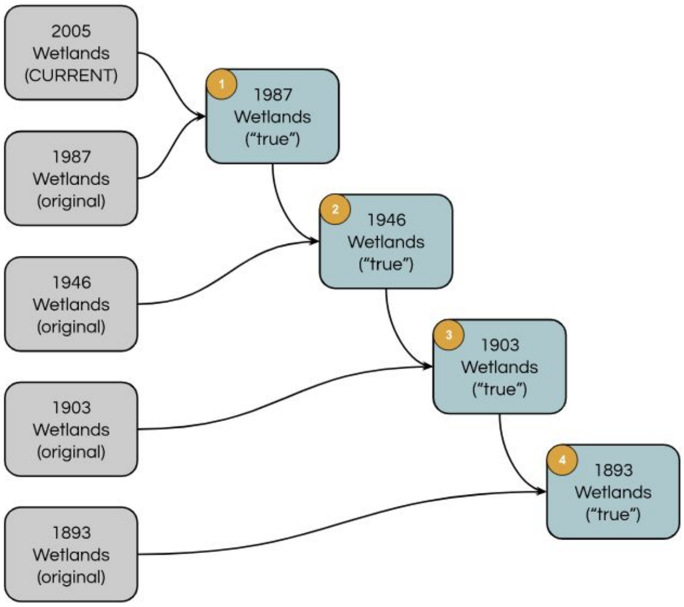

Figure 4B: Conceptual Diagram of Time Horizon Combination of Historical Maps (Source: Tufts Team)

Step 6: Determine Area Lost Between Historical and Present Wetlands Extent

Purpose: Visualize and calculate wetland loss between historical extent and present extent.

This final step in historical wetlands methodology compares the historical wetlands shapefile and cleaned current wetlands shapefile from the preceding steps. The two shapefiles are first mapped together to visually assess their relationship. Areas of interest are those that have historical wetlands and no current wetlands. Summary statistics are calculated on the ShapeArea column and a note is made on the minimum size of a reported wetland, the maximum size, and the total area covered by wetlands in the study area.

Appendix V: Flood Claim Analysis Statistical Figures

Histograms of Variables by Flood Claim Status

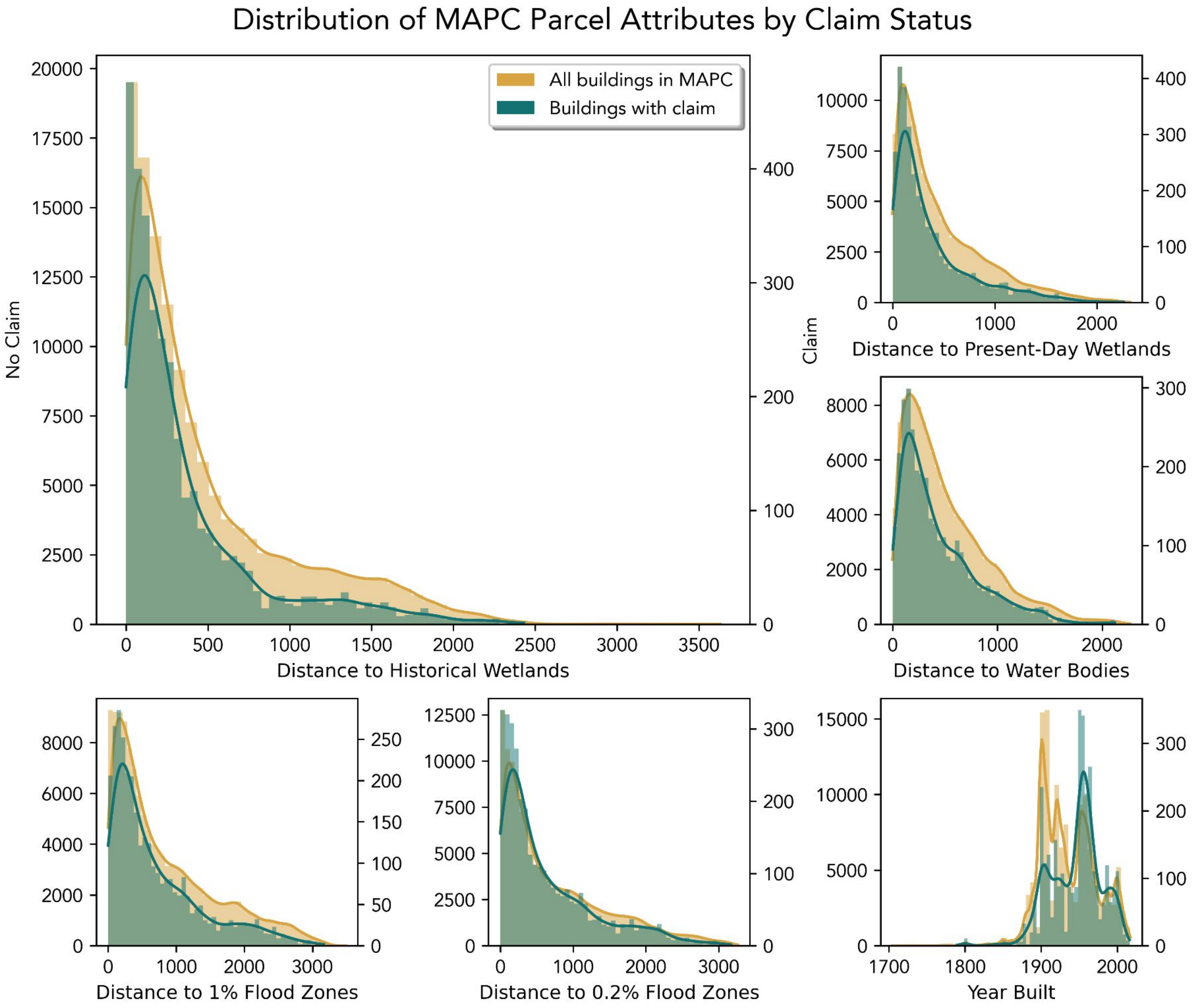

Figure 5A: Distribution of MAPC buildings' parcel attributes by claim status (Source: MAPC & Tufts Teams)
(distances are in meters)

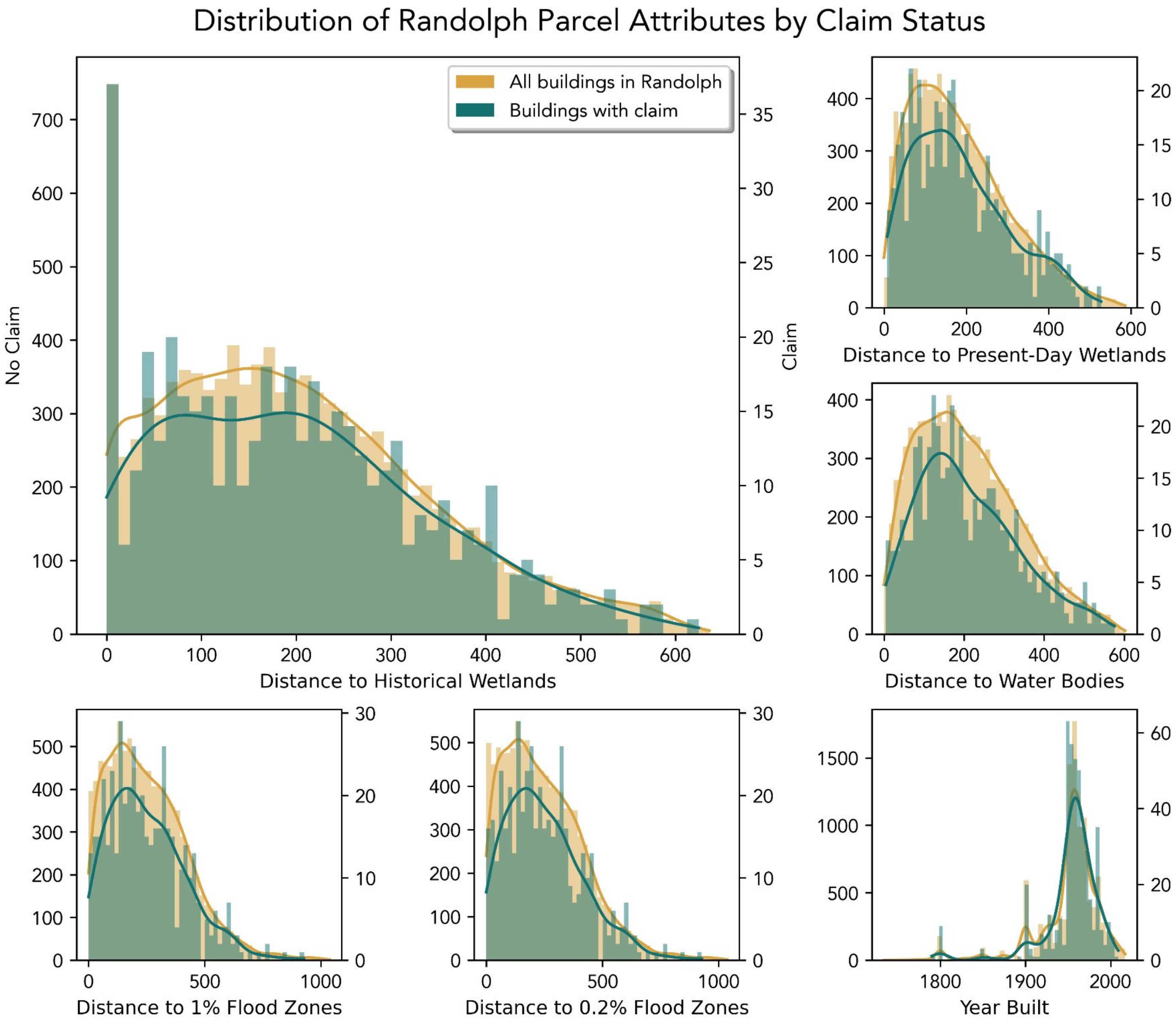

Figure 5B: Distribution of Randolph buildings' parcel attributes by claim status (Source: MAPC & Tufts Teams)
(distances are in meters)

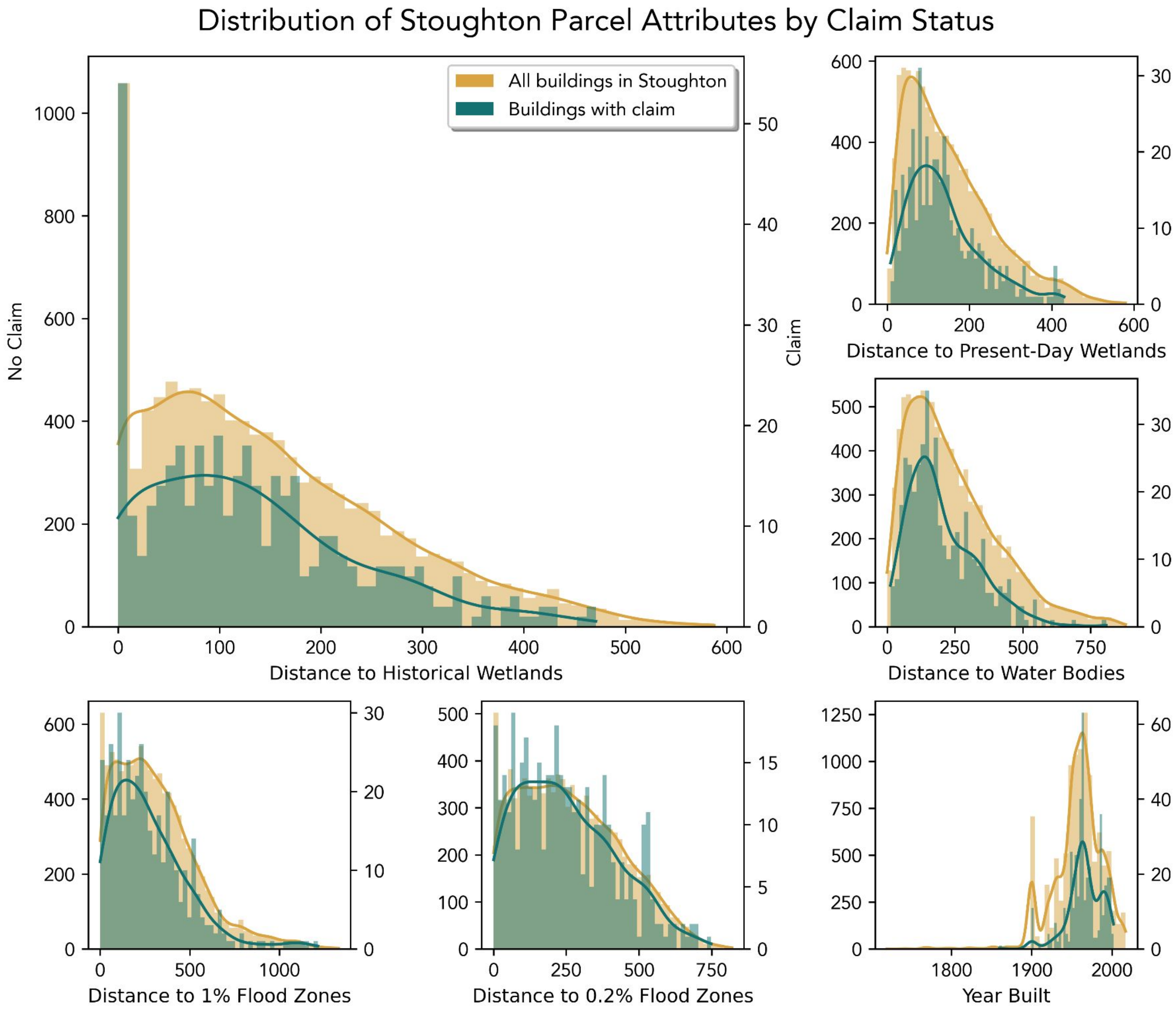

Figure 5C: Distribution of Stoughton buildings' parcel attributes by claim status (Source MAPC & Tufts Team)
(distances are in meters)

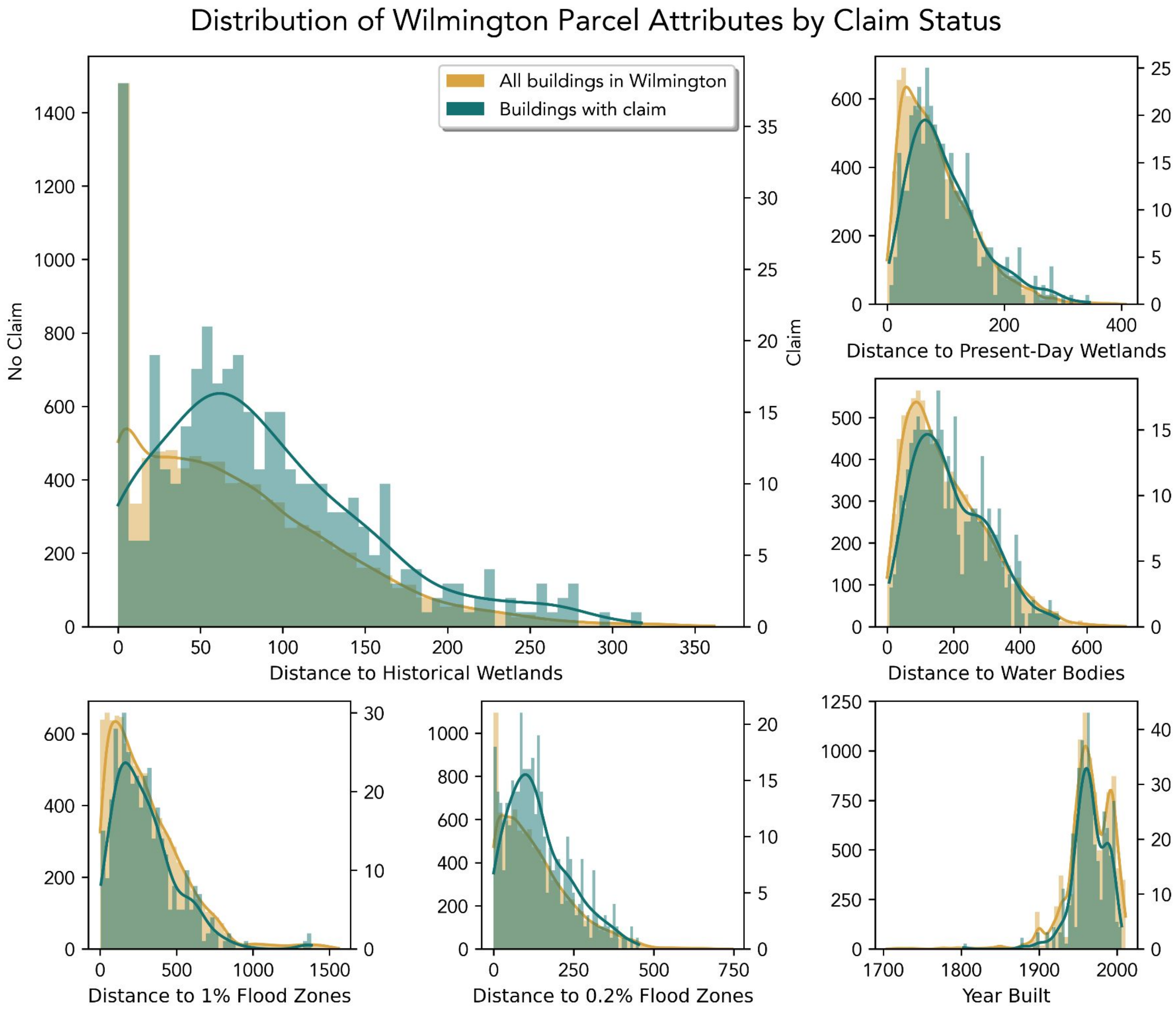

Figure 5D: Distribution of Wilmington buildings' parcel attributes by claim status (Source: MAPC & Tufts Team)
(distances are in meters)

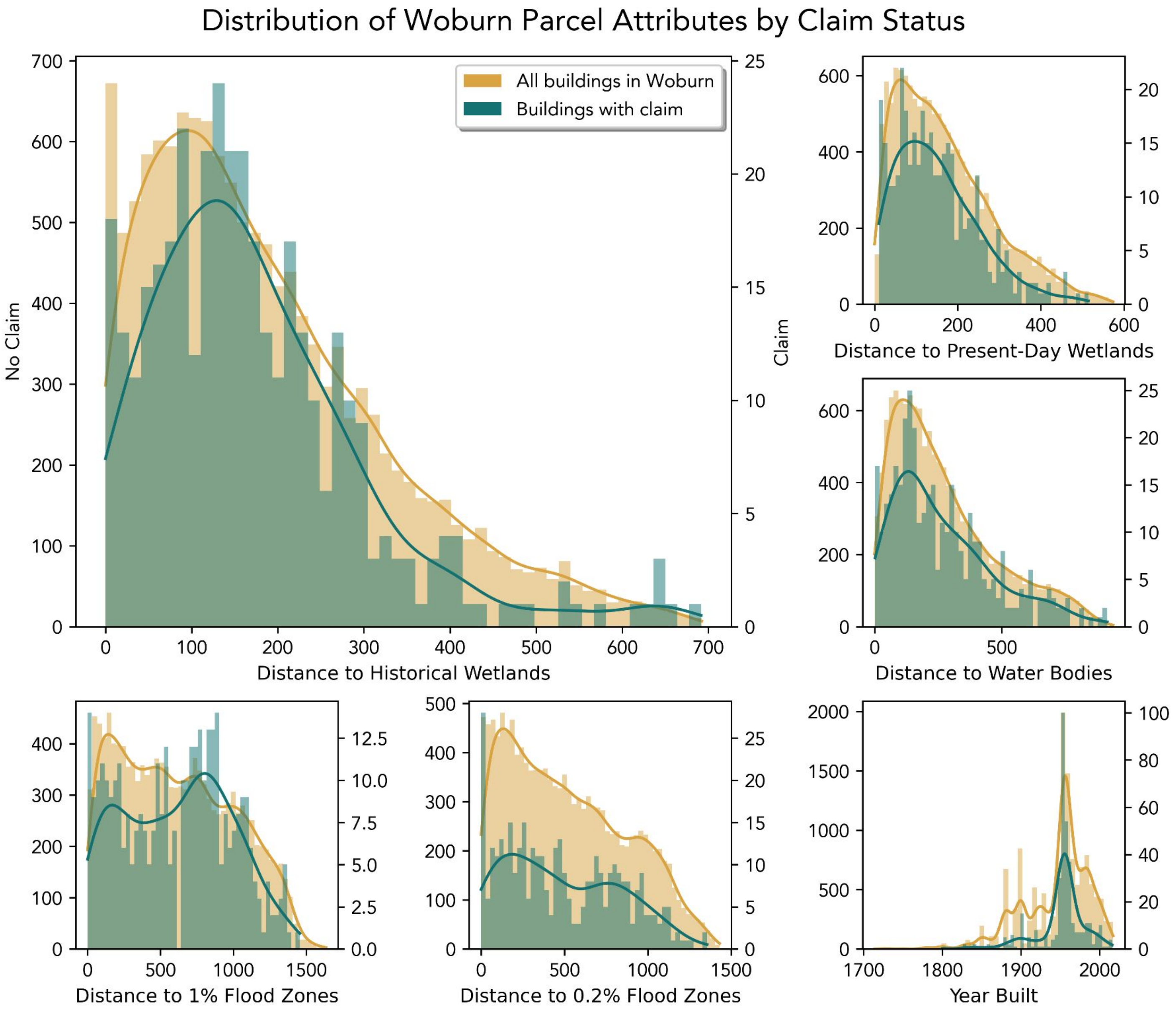

Figure 5E: Distribution of Woburn buildings' parcel attributes by claim status (Source: MAPC & Tufts Team)
(distances are in meters)

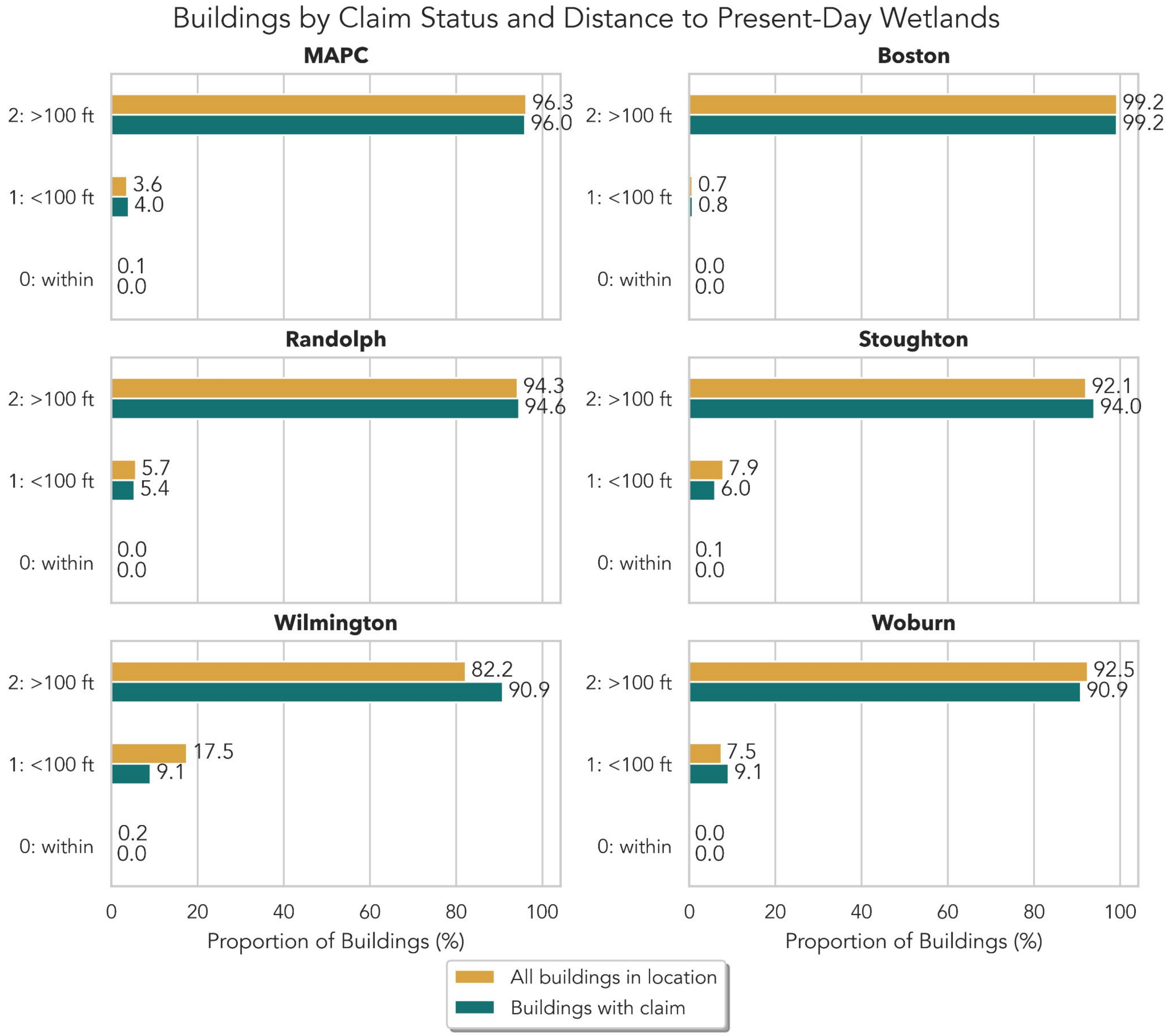

Figure 5F: Crosstab Bar Plot of Buildings by Claim Status and Distance to Present-Day Wetlands (Source: MAPC & Tufts Team)

Figure 5G: Crosstab Bar Plot of Buildings by Claim Status and Year Built (Source: MAPC & Tufts Team)