



1.0 Study Area

1.1 Introduction

1.1.1 Study Purpose

The National Hurricane Program (NHP), an interagency group comprised of the Federal Emergency Management Agency (FEMA), the U.S. Army Corps of Engineers (USACE) and National Oceanic and Atmospheric Administration (NOAA) - National Weather Service (NWS) conducts assessments and provides tools and technical assistance to assist state and local governments in developing hurricane evacuation plans and managing evacuation operations. Through the hurricane evacuation study (HES) process, state and local governments are provided with a range of resources, including regional demographic data, maps, evacuation clearance times, and user-friendly evacuation models. These various data and tools are consolidated and summarized in the Technical Data Report (TDR) for the study area, designed to be the primary source of regional evacuation information for federal, state and local government officials.

The study area for the Massachusetts HES TDR includes the storm surge vulnerable communities within the counties of Barnstable (Barnstable, Bourne, Brewster, Chatham, Dennis, Eastham, Falmouth, Harwich, Mashpee, Orleans, Provincetown, Sandwich, Truro, Wellfleet, and Yarmouth), Bristol (Acushnet, Berkley, Dartmouth, Dighton, Fairhaven, Fall River, Freetown, New Bedford, Raynham, Rehoboth, Seekonk, Somerset, Swansea, Taunton, and Westport), Dukes (Aquinnah, Chilmark, Edgartown, Oak Bluffs, Tisbury, and West Tisbury), Essex (Beverly, Danvers, Essex, Gloucester, Ipswich, Lynn, Manchester, Marblehead, Nahant, Newbury, Newburyport, Peabody, Rockport, Rowley, Salem, Salisbury, Saugus, and Swampscott), Middlesex (Arlington, Belmont, Cambridge, Everett, Malden, Medford, Newton, Somerville, Waltham, Watertown, Winchester), Nantucket, Norfolk (Braintree, Brookline, Cohasset, Milton, Quincy, and Weymouth), Plymouth (Duxbury, Hingham, Hull, Kingston, Marion, Marshfield, Mattapoisett, Plymouth, Rochester, Scituate, and Wareham), and Suffolk (Boston, Chelsea Revere, and Winthrop) Counties. A map of the study area is depicted in Figure 1-1.

1.1.2 Funding

The Massachusetts HES and the completion of the representative TDR was funded by the Federal Emergency Management Agency (FEMA), in coordination with the United States Army Corps of Engineers (USACE) – New England District.

1.1.3 Authority

The authority for the USACE's participation in this study is Section 206 of the Flood Control Act of 1960, as amended (Public Law 86-645). FEMA's participation is authorized by the Disaster



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Relief Act of (Public Law 93-288). These laws authorize the allocation of federal resources for planning activities related to hurricane preparedness.

1.1.4 Coordination Information

FEMA is responsible for the overall program management of HESs funded through the NHP. Funding is provided from FEMA through an interagency agreement to the USACE, which in turn provides the more detailed, day-to-day management of each study effort. The USACE often engages technical experts to support their efforts and to undertake specific portions of the study process, such as the conduct of transportation analysis and evacuation modeling. State officials support FEMA and the USACE and work closely with the local emergency managers in the study area to ensure that their needs are addressed in the study process.

None of the states in the New England region have had the benefit of a full-fledged HES as prepared under the direction of the NHP. The NHP, through a USACE contract with Battelle, prepared a transportation analysis report and abbreviated transportation model (ATM) for the state of Maine in 2007. Additionally, Portsmouth, New Hampshire, commissioned a study of hurricane evacuation clearance times for the entire Seacoast Region of the State, which was completed in 2012. Furthermore, various states and local governments throughout the region have initiated their own hurricane related transportation analyses for their own specific jurisdictions, but no comprehensive effort that looks at all aspects of hurricane evacuation within an entire state or the New England region as a whole.

The NHP started the New England HES process in 2012 with the development of Storm Tide Atlases to map the maximum storm tide inundation for the entire New England area. In coordination with FEMA and the USACE, local government officials were then able to draft new evacuation zones, which are the basis for almost all other aspects of this HES. As the mapping was in its final stages of completion, this study effort commissioned a behavioral analysis for Rhode Island, as well as for Connecticut and Massachusetts, to determine the behavioral responses of the evacuating population in response to theoretical storms. Nonetheless, given recent scares from Earl in 2010 and Sandy in 2012, the behavioral analysis also included New Englander's actual responses during those events. The Transportation Analysis portion of the study effort was kicked off in January of 2014. The USACE and its consultants met with state and local officials to finalize evacuation zones and routes and to begin the process of demographic data collection for evacuation modeling. A final stakeholder meeting presenting the HES, ATM and the draft HURREVAC-ready clearance times was conducted in December 2015.



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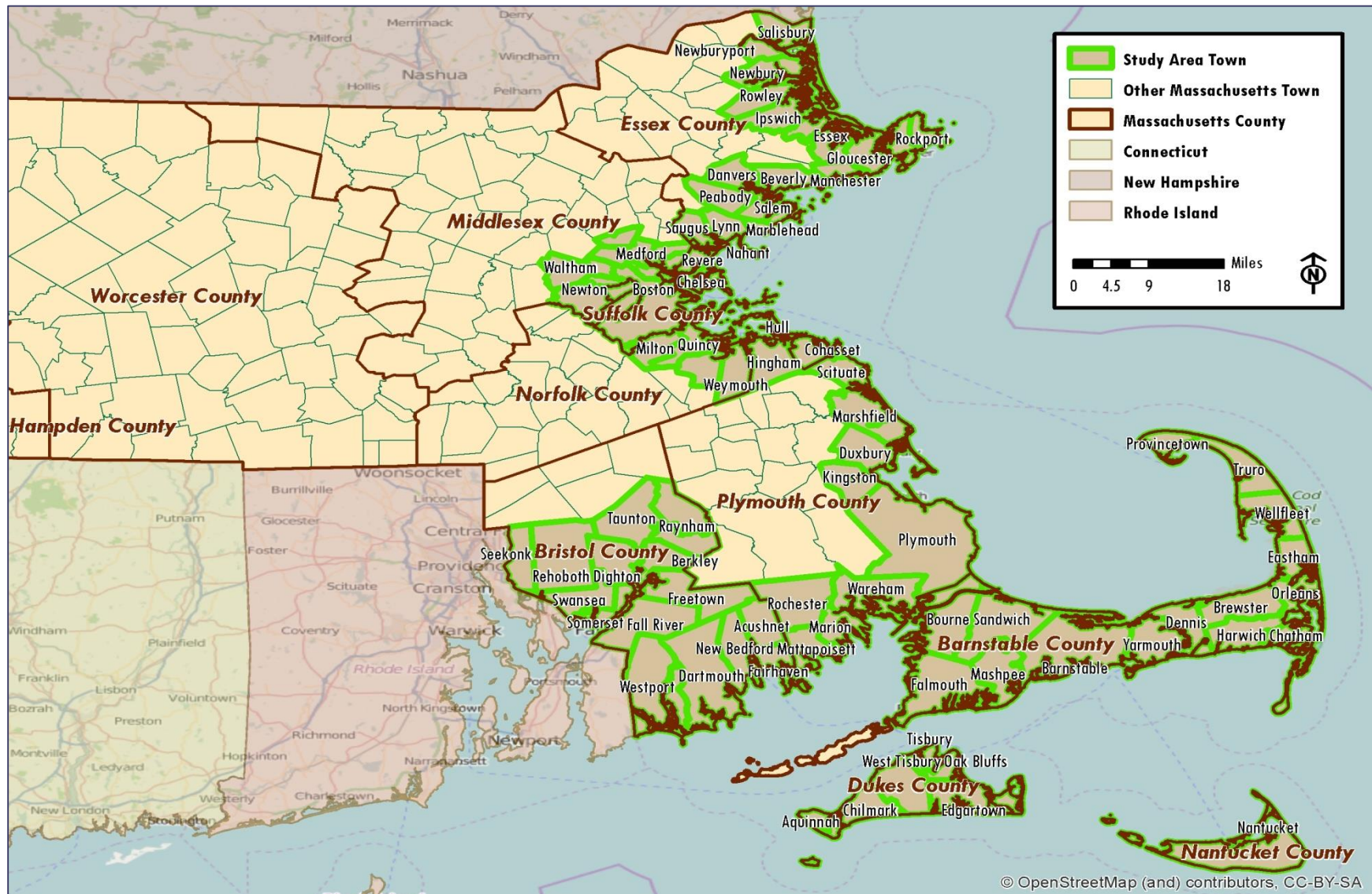


Figure 1-1: Map of Massachusetts HES TDR Study Area



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1.2 Description of Study Area

1.2.1 Geography

Massachusetts, located in the New England region of the northeastern U.S. is the seventh smallest state with an area of 10,555 square miles. Despite its small size, it features numerous distinctive regions. The large coastal plain of the Atlantic Ocean in the eastern section of the state contains Greater Boston along with most of the state's population, as well as the distinctive Cape Cod peninsula. To the west lies the rural-hilly region of Central Massachusetts and beyond that the Connecticut River Valley. Along the western border of Western Massachusetts lies the highest elevated part of the state, the Berkshire Mountains range.

The Massachusetts HES TDR study area includes the surge vulnerable communities of Barnstable, Bristol, Dukes, Essex, Middlesex, Nantucket, Norfolk, Plymouth, and Suffolk Counties. The proximity of these areas to the Atlantic Ocean, Massachusetts Bay, Narragansett Bay, Cape Cod Bay, Buzzards Bay, and numerous rivers make these areas susceptible to high winds, storm surge, and flooding should a storm threaten.

Barnstable County has a total area of 1,306 square miles, of which 394 square miles is land and 912 miles is water (U.S. Census Bureau). Barnstable County borders Plymouth County to the northwest; off Barnstable County's southern shore are Dukes County and Nantucket County. The Massachusetts HES TDR focuses on the fifteen coastal communities of Barnstable, Bourne, Brewster, Chatham, Dennis, Eastham, Falmouth, Harwich, Mashpee, Orleans, Provincetown, Sandwich, Truro, Wellfleet and Yarmouth within Barnstable County.

Bristol County has a total area of 691 square miles, of which 553 square miles is land and 138 square miles is water (U.S. Census Bureau). It is surrounded by Norfolk County (north), Plymouth County (east), Newport County, Rhode Island (southwest), Bristol County, Rhode Island (west), and Providence County, Rhode Island (northwest). The Massachusetts HES TDR focuses on the fifteen coastal communities of Acushnet, Berkley, Dartmouth, Dighton, Fairhaven, Fall River, Freetown, New Bedford, Raynham, Rehoboth, Seekonk, Somerset, Swansea, Taunton, and Westport within Bristol County.

Dukes County has a total area of 491 square miles, of which 103 square miles is land and 388 square miles is water (U.S. Census Bureau). It is the third smallest county by land area. It is surrounded by Barnstable County (northeast), Plymouth County (north), Bristol County (northwest), and Nantucket County (east). The Massachusetts HES TDR focuses on the six coastal communities of Aquinnah, Chilmark, Edgartown, Oak Bluffs, Tisbury, and West Tisbury within Dukes County.



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Essex County has a total area of 828 square miles, of which 493 square miles is land and 336 square miles is water (U.S. Census Bureau). It is surrounded by Rockingham County, New Hampshire (north), Suffolk County (south), Middlesex County (west), and Hillsborough County, New Hampshire (northwest). The Massachusetts HES TDR focuses on the eighteen coastal communities of Beverly, Danvers, Essex, Gloucester, Ipswich, Lynn, Manchester, Marblehead, Nahant, Newbury, Newburyport, Peabody, Rockport, Rowley, Salem, Salisbury, Saugus, and Swampscott within Essex County.

Middlesex County has a total area of 847 square miles, of which 818 square miles is land and 29 square miles is water (U.S. Census Bureau). It is the third largest county in Massachusetts by land area. It is surrounded by Hillsborough County, New Hampshire (north), Essex County (northeast), Suffolk County (southeast), Norfolk County (south), and Worcester County (west). The Massachusetts HES TDR focuses on the eleven coastal communities of Arlington, Belmont, Cambridge, Everett, Malden, Medford, Newton, Somerville, Waltham, Watertown, and Winchester within Middlesex County.

Nantucket County, an island 30 miles south of Cape Code, has a total area of 304 square miles, of which 45 square miles is land and 259 square miles is water (U.S. Census Bureau). It is the smallest county in Massachusetts by land area and second-smallest by total area. The Massachusetts HES TDR focuses on the entire island of Nantucket.

Norfolk County has a total area of 444 square miles, of which 396 square miles is land and 48 square miles is water (U.S. Census Bureau). It is the third smallest county in Massachusetts by total area. It is surrounded by Middlesex County (northwest), Suffolk County (north), Plymouth County (southeast), Bristol County (south), Providence County, Rhode Island (southwest), and Worcester County (west). The Massachusetts HES TDR focuses on the six coastal communities of Braintree, Brookline, Cohasset, Milton, Quincy, and Weymouth within Norfolk County.

Plymouth County has a total area of 1,093 square miles, of which 659 square miles is land and 434 square miles is water (U.S. Census Bureau). It is the third largest county in Massachusetts by total area. The communities of Hingham and Hull extend north of Norfolk County and face onto Massachusetts Bay, sharing a northern water boundary with Suffolk County. It is surrounded by Norfolk County (north), Barnstable County (southeast), and Bristol County (west). The Massachusetts HES TDR focuses on the eleven coastal communities of Duxbury, Hingham, Hull, Kingston, Marion, Marshfield, Mattapoisett, Plymouth, Rochester, Scituate, and Wareham within Plymouth County.

Suffolk County has a total area of 120 square miles, of which 58 square miles is land and 62 square miles is water (U.S. Census Bureau). It is the second smallest county in Massachusetts by



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land area and smallest by total area. Suffolk County has no land border with Plymouth County to its southeast, but the two counties share a water boundary in the middle of Massachusetts Bay. It is surrounded by Essex County (north), Norfolk County (south), and Middlesex County (west). The Massachusetts HES TDR focuses on the four coastal communities of Boston, Chelsea, Revere, and Winthrop within Plymouth County.

1.2.2 Geology and Topography

Despite Massachusetts's small size, it features wide variations in its landscape. In the northwestern portions of the state, it features rolling mountains compared to the coastal landscape found in the southeastern portions. Of specific interest to the Massachusetts HES TDR, are the landscape features found within the coastal study areas of Barnstable, Bristol, Dukes, Essex, Middlesex, Nantucket, Norfolk, Plymouth, and Suffolk Counties.

The Massachusetts coastline is deeply indented with bays, coves, and estuaries, separated by narrow promontories. Some of these form natural harbors that gave rise to the state's historic ports, including Newburyport, Gloucester, Salem, Boston, and New Bedford. The state has a few small barrier islands, the largest of which is Plum Island. The state's largest promontory is the Cape Cod peninsula. Its backbone is formed by glacial moraines, but much of its coastline has been shaped by the long shore drift of coastal sand, which forms many of its famous sandy beaches. To the south of Cape Cod, glacial moraines rise above the ocean surface to form the state's largest islands: Martha's Vineyard, Nantucket, the Elizabeth Islands, and Monomoy Island.

1.2.3 Bathymetry

Shallow water close to the shore tends to increase the magnitude of hurricane-induced storm surge, thus knowing the offshore bathymetry of the study area is extremely important. Massachusetts has a very distinct shape outlined by its many large bays along the Atlantic coast. The most significant bays are: Buzzards Bay, Cape Cod Bay, and the largest, Massachusetts Bay.

Buzzards Bay measures 28 miles long by 8 miles wide. Buzzard Bay's current configuration, a well-mixed central bay and fringing shallow drowned-river valleys, with their shallow depth, tidal action, and surface waves, promotes mixing of the estuarine waters to create a productive aquatic ecosystem.

Cape Cod Bay measures 604 square miles, stretching from Marshfield to Provincetown. Most of Cape Cod Bay is composed of glacially derived rocks, sands, and gravels. Generally, currents in Cape Cod Bay move in a counter-clockwise fashion, moving south from Boston, to Plymouth then east and then north to Provincetown. Since 1914, Cape Cod Bay has been connected to



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Buzzards Bay by the Cape Cod Canal, which divides the upper cape communities of Bourne and Sandwich.

Massachusetts Bay extends from Cape Ann (north) to Plymouth Harbor (south), a distance of approximately 42 miles. The northern shore of Massachusetts Bay is rocky and irregular; the southern shore is low, marshy, and sandy. Along the shores are a number of capes and headlands, and off the coast a number of small islands, especially in the entrance to Boston Harbor.

1.2.4 Demographics

The State of Massachusetts is the sixth smallest state by land area, the 14th most populous, and the third most densely populated. With a statewide population estimate of 6,745,408¹, a majority of the population lies in the state capital of Boston (Suffolk County). Other major communities within the Massachusetts HES TDR includes Worcester (Worcester County), Cambridge (Middlesex County), New Bedford (Bristol County), Quincy (Norfolk County), Lynn (Essex County), and Fall River (Bristol County). Table 1-2 summarizes the county demographics within the study area.

¹ "American Fact Finder, Massachusetts," U.S. Census, 2013 American Community Survey (ACS), 2014 Population Estimate, <http://factfinder.census.gov/>, (May 15, 2015).



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Table 1-1: Massachusetts HES TDR Demographics

Community	Census Data		Population Changes	
	2010	2015	(Number)	(Percent)
Acushnet	10,303	10,314	11	0.11%
Aquinnah	311	397	86	27.65%
Arlington	42,844	43,308	464	1.08%
Barnstable	45,193	44,944	(249)	-0.55%
Belmont	24,729	24,943	214	0.87%
Berkley	6,411	6,452	41	0.64%
Beverly	39,502	40,026	524	1.33%
Boston	617,594	629,182	11,588	1.88%
Bourne	19,754	19,729	(25)	-0.13%
Braintree	35,744	36,051	307	0.86%
Brewster	9,820	9,786	(34)	-0.35%
Brookline	58,732	58,738	6	0.01%
Cambridge	105,162	105,737	575	0.55%
Chatham	6,125	6,138	13	0.21%
Chelsea	35,177	36,222	1,045	2.97%
Chilmark	866	886	20	2.31%
Cohasset	7,542	7,935	393	5.21%
Danvers	26,493	26,899	406	1.53%
Dartmouth	34,032	34,313	281	0.83%
Dennis	14,207	14,168	(39)	-0.27%
Dighton	7,086	7,113	27	0.38%
Duxbury	15,059	15,126	67	0.44%
Eastham	4,956	4,945	(11)	-0.22%
Edgarton	4,067	4,135	68	1.67%
Essex	3,504	3,546	42	1.20%
Everett	41,667	42,092	425	1.02%
Fairhaven	15,873	15,952	79	0.50%
Fall River	88,857	88,811	(46)	-0.05%
Falmouth	31,531	31,591	60	0.19%
Freetown	8,870	8,923	53	0.60%
Gloucester	28,789	29,043	254	0.88%
Gosnold	75	135	60	80.00%
Harwich	12,243	12,223	(20)	-0.16%
Hingham	22,157	22,330	173	0.78%
Hull	10,293	10,319	26	0.25%
Ipswich	13,175	13,354	179	1.36%



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Table 1-1: Massachusetts HES TDR Demographics (continued)

Community	Census Data		Population Changes	
	2010	2015	(Number)	(Percent)
Kingston	12,629	12,673	44	0.35%
Lynn	90,329	90,788	459	0.51%
Malden	59,450	59,803	353	0.59%
Manchester	5,136	5,185	49	0.95%
Marblehead	19,808	19,958	150	0.76%
Marion	4,907	4,915	8	0.16%
Marshfield	25,132	25,307	175	0.70%
Mashpee	14,006	14,000	(6)	-0.04%
Mattapoissett	6,045	6,086	41	0.68%
Medford	56,173	56,607	434	0.77%
Milton	27,003	27,094	91	0.34%
Nahant	3,410	3,432	22	0.65%
Nantucket	10,172	10,224	52	0.51%
New Bedford	95,072	94,927	(145)	-0.15%
Newbury	6,666	6,732	66	0.99%
Newburyport	17,416	17,569	153	0.88%
Newton	85,146	86,241	1,095	1.29%
Oak Bluffs	4,527	4,563	36	0.80%
Orleans	5,890	5,877	(13)	-0.22%
Peabody	51,251	51,522	271	0.53%
Plymouth	56,468	56,965	497	0.88%
Provincetown	2,942	2,964	22	0.75%
Quincy	92,271	92,595	324	0.35%
Raynham	13,383	13,422	39	0.29%
Rehoboth	11,608	11,664	56	0.48%
Revere	51,755	52,534	779	1.51%
Rochester	5,232	5,299	67	1.28%
Rockport	6,952	7,040	88	1.27%
Rowley	5,856	5,914	58	0.99%
Salem	41,340	41,926	586	1.42%
Salisbury	8,283	8,396	113	1.36%
Sandwich	20,675	20,615	(60)	-0.29%
Saugus	26,628	27,051	423	1.59%
Scituate	18,133	18,181	48	0.26%
Seekonk	13,722	13,932	210	1.53%
Somerset	18,165	18,241	76	0.42%



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Table 1-1: Massachusetts HES TDR Demographics (continued)

Community	Census Data		Population Changes	
	2010	2015	(Number)	(Percent)
Somerville	75,754	76,945	1,191	1.57%
Swampscott	13,787	13,862	75	0.54%
Tisbury	3,949	3,995	46	1.16%
Swansea	15,865	15,951	86	0.54%
Taunton	55,874	55,953	79	0.14%
Truro	2,003	1,731	(272)	-13.58%
Waltham	60,632	61,321	689	1.14%
Wareham	21,822	22,086	264	1.21%
Watertown	31,915	32,352	437	1.37%
Wellfleet	2,750	3,012	262	9.53%
West Tisbury	2,740	2,628	(112)	-4.09%
Westport	15,532	15,587	55	0.35%
Weymouth	53,743	54,366	623	1.16%
Winchester	21,374	21,621	247	1.16%
Winthrop	17,497	17,763	266	1.52%
Yarmouth	23,793	23,726	(67)	-0.28%
Total:	2,861,354	2,888,947	27,593	0.96%
Sources: U.S. Census State and County QuickFacts				



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Table 1-2: Massachusetts HES TDR Demographic and Housing Data by Community

Community	2015 Population	Permanent Occupied Housing Units	Mobile Home Units	Vacation / Seasonal Units	Tourist Units
Acushnet	10,314	3,938	195	21	-
Aquinnah	397	145	3	345	-
Arlington	43,308	19,172	7	94	100
Barnstable	44,944	19,118	58	5,761	2,456
Belmont	24,943	9,734	10	68	-
Berkley	6,452	2,122	17	18	-
Beverly	40,026	16,058	19	121	112
Boston	629,182	257,353	252	3,054	18,986
Bourne	19,729	7,856	163	2,218	541
Braintree	36,051	13,853	-	42	206
Brewster	9,786	4,368	-	3,134	836
Brookline	58,738	25,095	27	247	511
Cambridge	105,737	44,271	11	604	3,563
Chatham	6,138	3,092	8	3,891	504
Chelsea	36,222	12,172	-	30	128
Chilmark	886	398	19	1,188	-
Cohasset	7,935	2,857	27	86	-
Danvers	26,899	10,775	190	65	1,315
Dartmouth	34,313	11,329	64	665	-
Dennis	14,168	6,909	216	7,911	928
Dighton	7,113	2,481	9	23	-
Duxbury	15,126	5,368	-	345	-
Eastham	4,945	2,383	-	3,321	502
Edgarton	4,135	1,794	-	3,258	279
Essex	3,546	1,419	-	124	35
Everett	42,092	15,700	15	24	-
Fairhaven	15,952	6,705	40	474	2
Fall River	88,811	38,437	49	100	82
Falmouth	31,591	14,096	118	7,113	804
Freetown	8,923	3,181	-	54	-
Gloucester	29,043	12,595	20	1,298	339
Gosnold	135	39	3	174	-
Harwich	12,223	5,614	32	4,156	287
Hingham	22,330	8,531	34	113	-



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Table 1-2: Massachusetts HES TDR Demographic and Housing Data by Community (continued)

Community	2015 Population	Permanent Occupied Housing Units	Mobile Home Units	Vacation / Seasonal Units	Tourist Units
Hull	10,319	4,642	-	800	105
Ipswich	13,354	5,535	-	276	39
Kingston	12,673	4,681	241	129	-
Lynn	90,788	33,478	33	75	-
Malden	59,803	23,813	109	39	50
Manchester	5,185	2,167	-	120	-
Marblehead	19,958	8,205	41	312	20
Marion	4,915	1,899	-	432	-
Marshfield	25,307	9,592	149	1,096	-
Mashpee	14,000	6,115	110	3,408	164
Mattapoissett	6,086	2,522	-	640	-
Medford	56,607	22,985	12	79	157
Milton	27,094	9,305	-	59	-
Nahant	3,432	1,550	-	65	-
Nantucket	10,224	4,232	147	6,725	462
New Bedford	94,927	38,702	58	117	3
Newbury	6,732	2,619	-	239	15
Newburyport	17,569	7,688	-	251	61
Newton	86,241	31,564	26	306	894
Oak Bluffs	4,563	1,989	47	2,208	161
Orleans	5,877	2,943	50	2,049	291
Peabody	51,522	21,425	778	85	742
Plymouth	56,965	21,455	634	2,537	611
Provincetown	2,964	1,778	11	2,390	1,128
Quincy	92,595	40,800	27	292	569
Raynham	13,422	4,889	361	14	273
Rehoboth	11,664	4,121	-	28	-
Revere	52,534	20,757	164	146	227
Rochester	5,299	1,836	-	20	-
Rockport	7,040	3,253	-	773	301
Rowley	5,914	2,176	-	27	-
Salem	41,926	18,091	-	134	219
Salisbury	8,396	3,487	232	718	63
Sandwich	20,615	7,753	-	1,289	292



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Table 1-2: Massachusetts HES TDR Demographic and Housing Data by Community (continued)

Community	2015 Population	Permanent Occupied Housing Units	Mobile Home Units	Vacation / Seasonal Units	Tourist Units
Saugus	27,051	10,479	94	21	337
Scituate	18,181	6,877	51	874	-
Seekonk	13,932	5,147	15	25	405
Somerset	18,241	7,117	10	59	104
Somerville	76,945	32,602	-	89	332
Swampscott	13,862	5,550	-	94	-
Tisbury	3,995	1,806	37	1,129	307
Swansea	15,951	6,112	-	53	-
Taunton	55,953	22,364	697	52	155
Truro	1,731	829	25	1,675	1,024
Waltham	61,321	23,956	19	122	1,243
Wareham	22,086	9,179	932	2,404	-
Watertown	32,352	14,908	16	64	-
Wellfleet	3,012	1,485	293	2,995	314
West Tisbury	2,628	1,197	47	951	-
Westport	15,587	6,176	13	779	130
Weymouth	54,366	22,692	122	145	-
Winchester	21,621	7,732	-	67	-
Winthrop	17,763	7,900	-	68	-
Yarmouth	23,726	11,197	17	5,412	2,388
Total	2,888,947	1,172,312	7,229	95,100	46,102

Sources: U.S. Census 2009-2013 American Community Survey 5-Year Estimates.

1.3 Historical Hurricane Activity

Given the relatively high latitude of the entire New England coastline, it would be surprising to some people how frequently tropical cyclones have visited the region, some storms even attaining major (Category 3) hurricane status. Nonetheless, the area is subject to Atlantic basin hurricanes that originate as tropical waves that form off the coast of Africa. Also known as Cape Verde storms, these events are named for the islands from where many of these waves first coalesce into tropical cyclones. These tropical waves traverse the Atlantic Ocean, intensify as they come in contact with the Gulf Stream, and many get entrained in the jet stream, which carries them at relatively high forward speeds to the coast of New England. In fact, those hurricanes that originate off the Southeastern U.S. and Mid-Atlantic states can present local



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officials in New England with the added challenge of having to plan, order and execute an evacuation with very little lead time. Figure 1-2 below displays the number of tropical systems that have come within 100 nautical miles of the New England area from 1851 to 2008.

The New England Coast is very familiar with hurricanes and tropical storms. According to the NOAA Historical Hurricane Track Database from 1851 to the present, of the 47 tropical cyclones (tropical storm and above) that have come within 100 statute miles of the Southern New England coast, 19 were hurricanes, three of them major (Category 3 and above). The most active decade for tropical cyclone activity was the 1880s with a total of 7 tropical events, but the 1860s, the 1950s and the 1960s were also busy with four storms each. With a search radius of 150 nautical miles the total number of tropical cyclones balloons to 74, many of which were just off shore, but close enough to possibly warrant some degree of protective actions in response to their approach. A few of the major storms to impact the area, including a few not included in the above database, are described in more detail below.

The Great Colonial Hurricane (GCH) – August 1635: The storm was estimated to have been a Cape Verde-type hurricane, probably a Category 4 or 5 hurricane that was likely a Category 3 when it made landfall in the vicinity of eastern Long Island and Connecticut and Rhode Island. Reportedly the area between Providence, Rhode Island, and the Piscataqua River in New Hampshire was seriously impacted by this storm with some evidence of damage still apparent fifty years after its occurrence.

According to the accounts of Governors William Bradford of the Plymouth Bay Colony and John Winthrop of the Massachusetts Bay Colony, the community of Plymouth and surrounding areas suffered severe damage with houses blown down and large sections of the woods completely toppled by the winds. Elsewhere in eastern Massachusetts widespread wind damage was reported as was the destruction of the Plymouth Colony's Aputuxet Trading Post, near the

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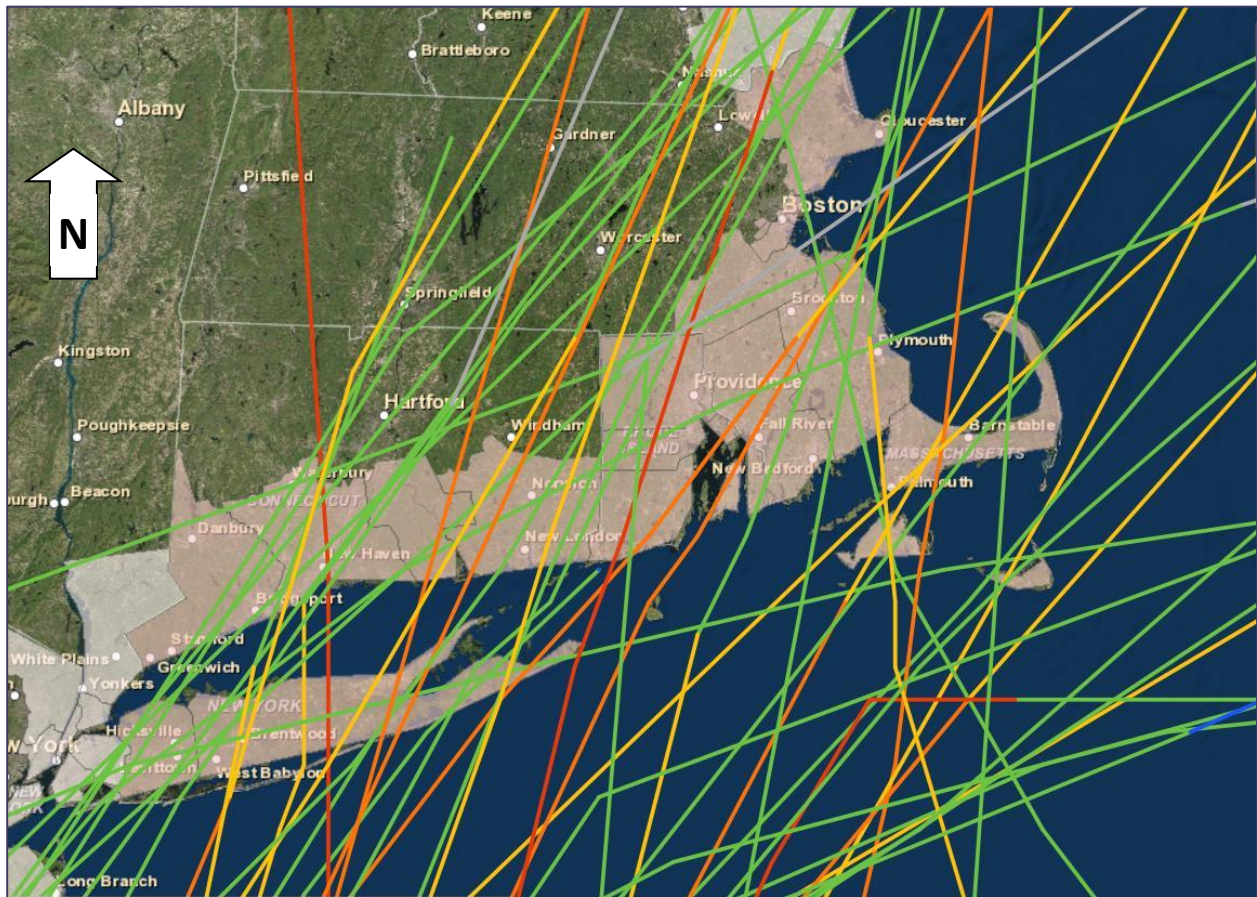


Figure 1-2: Tropical Systems impacting New England (1851 – 2008) (Image created using the National Oceanographic and Atmospheric Administration (NOAA) Coastal Services Center’s Historical Hurricane Tracker, <http://coast.noaa.gov/hurricanes>)

present-day site of Bourne. The Boston area did not suffer from the tide as did areas just to its south. The nearest surge swept over the low-lying tracts of Dorchester, ruining the farms and landscape.

Based on recent analysis, the storm tide in Narragansett Bay was assessed to approximately 14 feet above normal tide with values as high as 22 feet reported in other locations in New England. According to Brian Jarvinen, once the director of the National Hurricane Center’s SLOSH surge modeling program and charged with re-evaluating past historical storms for determining storm tide flooding potential, indicated that based on his analysis of the data and subsequent recreation of the storm, the GCH is probably the most intense New England hurricane in recorded history.



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The 1804 Snow Hurricane – October 1804: The tropical cyclone, which was probably spawned near Puerto Rico, proceeded up the eastern U.S. seaboard until it impacted the New England region as a Category 2 hurricane. Of interest with this particular storm is that the hurricane was assessed to be at its peak intensity when it was over Massachusetts and that it was responsible for generating widespread snow, up to three feet in some areas, throughout the New England region as it progressed northeastward. Along the coast, Salem recorded 7 inches of rain and winds from the storm blew the steeple off the famous Old North Church in Boston.

The Great September Gale of 1815 – September 1815: This event was the first major storm to hit the New England region in 180 years (see the GHC citation above), and was assessed to be a Category 3 when it came ashore. Although it made landfall around Old Saybrook, Connecticut, its storm surge had huge impacts on Narragansett and Buzzards Bay, where reportedly its geography was permanently altered by the impacts of the hurricane, as well as at the wharves in Boston, where many boats were sunk and destroyed. In Dorchester, just south of Boston, the local historian William Diana Orcutt reported the storm destroyed the bridge between his community and Milton over the Neponset River as well as the first parish meeting house. Noah Webster, who weathered the storm in Amherst, Massachusetts reported that the winds decimated many orchards and cider mills, as well as toppled entire groves of various hardwood trees and coated everything with a layer of salt.

1849 Hurricane – October 1849: A hurricane that was first reported off the coast of North Carolina made landfall in Massachusetts on October 6th and caused 143 deaths. It is the second most deadly hurricane in Massachusetts history after the 1938 Great New England Hurricane described below.

1869 Hurricanes – September and October 1869: In September a Category 3 hurricane (number 6) followed by the Saxby Gale hurricane in October struck southeastern Massachusetts. Hurricane 6 was a compact storm when it made landfall somewhere around Narragansett Bay and it passed just west of Boston as a Category 1, downing many trees, causing heavy damage and producing heavy rainfall there. One confirmed casualty in Massachusetts was attributed to the passing of the storm. Hurricane 10, also known as the Saxby Gale, passed just east of Martha's Vineyard and crossed Cape Cod on October 4th. Although it reportedly visited heavy damage across New England, the brunt of its destruction was felt along the Bay of Fundy in Canada.

The Great New England Hurricane of 1938 – September 1938: This Category 5, which has also been dubbed "The Long Island Express", made landfall on September 21, 1938 and was the first major hurricane to strike New England since 1869. The Blue Hill Observatory, outside of Boston,



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measured sustained winds of 121 mph, with gusts of 186 mph. Providence, Rhode Island reported sustained winds of 100 mph, gusting to 125 mph. Storm tides of 18 to 25 foot tides were reported as far east as Cape Cod with 8 feet of water reported in Bourne and Falmouth and five feet in Buzzards Bay. Narragansett Bay experienced a destructive storm surge of 12 to 14 feet. The hurricane's heavy rains of 3 to 6 inches combined with the effects of the frontal system produced rainfall of 10 to 17 inches causing severe flooding, particularly in areas of Western Massachusetts and along the Connecticut River. The widespread destruction resulting from this storm included 600 casualties, 1,700 injuries, and over \$400 million in damages (including 9,000 homes and businesses lost and 15,000 damaged). Damage to the southern New England fishing fleet was catastrophic, as over 6,000 vessels were either destroyed or severely damaged.

The Great Atlantic Hurricane – September of 1944: Beginning as a tropical wave in the Lesser Antilles it gained strength as it raked along the Mid-Atlantic and New England states. When it made landfall near Point Judith, RI, it was traveling at 47 miles an hour. This hurricane affected the New England region just six years after the 1938 Hurricane, but was said to have only caused about one-third the damage of that storm due to its lesser intensity at landfall and its acute angle of approach, which diminished its storm tide impacts. Although there are few specific reports of damage and impacts in New England, it did cause significant destruction along the Delmarva and New Jersey Coastlines. Nonetheless, Cape Code experienced more than \$5 million (in 1944 dollars) in damage, most of it attributable to Cape Cod can be attributed to lost boats, as well as fallen trees and utility impacts. The storm all along its track caused heavy and abundant rainfall with parts of coastal Massachusetts receiving up to 8 inches of rain.

Hurricane Carol – August 1954: Hurricane Carol was among the worst tropical cyclones on record to affect the New England region. It developed from a tropical wave near the Bahamas on August 25, 1954, and slowly strengthened as it moved northwestward, eventually making landfall on Long island, New York, and Clinton, Connecticut at the peak of its intensity.

Prior to its arrival, Carol caused the evacuation of over 20,000 people off of Cape Cod. Upon arrival, the storm produced a storm surge of up to 14.4 feet in New Bedford harbor, and over 6 inches of rain fell throughout New England. The wind also had a hand in contributing to the losses suffered by Massachusetts during Carol, destroying 800 homes and causing some degree of damage to another 3,350. Wind damage in the Boston area was reported to be extensive, even destroying the spire to the Old North Church which was repaired after the 1804 hurricane. In the aftermath of the storm, at least 15 deaths were attributed to Carol and damage costs were estimated to be \$175 million. Consequently, President Eisenhower declared Massachusetts a federal disaster area which provided up to \$1.5 million in financial aid. Due to



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the damages and overall impacts in Massachusetts and the entire New England area, Carol had the distinction of being the first named storm to be permanently retired from the revolving list of hurricane names.

Hurricane Edna – September 1954: Arriving in the New England Region of just eleven days after Hurricane Carol, it made landfall 100 miles to the east of that storm and therefore impacted eastern Massachusetts while leaving the rest of southern New England relatively unscathed. The storm traversed eastern Cape Cod and the islands during a rising high tide with recorded peak wind gusts of up to 120 mph; consequently storm surges of 6' were common throughout the impacted region. Edna also contributed an additional 5 to 7 inches of rain to Carol's previous 6 inches which resulted in major inland flooding. The storm was responsible for over 2 deaths and \$40 million in damage across the region.

Hurricane Diane – August 1955: Originally a Category 2 storm, by the time Hurricane Diane reached New England, it was an extratropical storm. Nonetheless, it produced heavy rainfall dropping 19.75 inches of rain in Westfield, Massachusetts, the maximum amount recorded in the U.S. for this particular storm. Flooding occurred across much of southern Massachusetts, from its border with New York toward Worcester all the way east to the ocean. Most streams in the western part of the state overflowed their banks with rapidly moving water, whereas in the southeast with its relatively flat topography, streams flooded large areas along their courses over long periods of time. In the aftermath, the flooding from Diane resulted in 12 deaths statewide and caused \$110 million in damages.

Hurricane Gloria, 1985. Hurricane Gloria made landfall in Milford, Connecticut on September 27, 1985 as a Category 1 storm. As it continued northeastward through New England, it became extratropical over Maine on the 28th. In spite of arriving during low tide, it did cause severe beach erosion along the New England coast, as well as the loss of many piers and coastal roads. There was a moderate storm surge of 5.9 feet above normal high tide in New Bedford, Massachusetts. The storm left over 500,000 people in Massachusetts without power. It dropped up to 6 inches of rain causing many flooding issues in the region. Hurricane Gloria was responsible for 8 casualties and \$900 million in damages. The name 'Gloria' has been retired.

Hurricane Bob, 1991. Hurricane Bob made landfall in New England near Newport, Rhode Island on August 19, 1991 as a Category 2 storm. It travelled across southeastern Massachusetts towards the Gulf of Maine, causing the most significant amount of damage in Massachusetts. The storm spawned major evacuations on Cape Cod that lead to a reported 11 mile backup of vehicles trying to cross the US 6/Sagamore Bridge, as well as the opening of nine shelters in that



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region.² Peak winds in excess of 100 mph were recorded in the communities of Brewster and Truro on Cape Cod. There were 4 different reports of tornados as Bob came ashore. New Bedford and Woods Hole recorded peak storm tides of 5.8 feet, but damage was heaviest from Buzzards Bay east to Cape Cod where at least 61 houses were destroyed. A number of south-facing beaches on the islands of Nantucket and Martha’s Vineyard lost 50 feet of beach to erosion. Up to 7 inches of rain was reported to have fallen throughout New England, with 7.06 inches officially recorded in Westfield, MA. Hurricane Bob knocked out power to over 500,000 customers in the state including all of Cape Cod, some of them for up to five days. Ultimately, the storm was responsible for 1 fatality and approximately \$1 billion in total damages for Massachusetts, and \$2.5 billion in overall damages. The name ‘Bob’ has been permanently retired.³

Hurricane/Tropical Storm Earl, 2010. Hurricane Earl the storm made its closest approach to Massachusetts, passing roughly 90 mi (150 km) southeast of Nantucket as a tropical storm. Before making landfall in Nova Scotia as a Category 1 storm with 75 mph winds it brought high winds of up to 58 mph and heavy rains with 5.17 inches recorded in Yarmouth, MA. Based on the responses provided for the Behavioral Analysis performed for this study (See Chapter 4), only 14.5 percent of those living in the cat 1/2 evacuation zones heard notice that they must evacuate, and only 3% indicated they actually did so. Interestingly, in the Category 3/4 zone, 14% indicated that they heard some notice to evacuate and 3.5% said they actually did. There were reports of downed trees and power lines in Eastern Massachusetts. Hurricane Earl was responsible for five casualties including one in Massachusetts, as well as for \$20,000 in damages for the state of the \$18 million tallied in the U.S.⁴

Hurricane/Tropical Storm Irene, 2011. Hurricane Irene was a Category 3 hurricane in the Bahamas before eventually weakening to a tropical storm in New England. The storm did not make a direct landfall in New England, but traveled inland through Connecticut and into western Massachusetts and Vermont on August 28, 2011. Despite this inland track, wind and heavy rains impacted the New England area causing 1 casualty (in Massachusetts) and over 100 injuries. Some parts of New England received 9-10 inches of rainfall which caused major flooding and road and bridge washouts. Strong winds took down trees and power lines, causing over 670,000 power outages. The Westfield and Deerfield Rivers rose 20 and 15 feet

² Michael Specter (August 20, 1991). "[Hurricane Rakes New England](#)". Washington Post. Retrieved April 23, 2010.

³ "New England Hurricanes of Note," Massachusetts Emergency Management Agency, <http://www.mass.gov/eopss/agencies/mema/hazards/hurricanes/new-england-hurricanes-of-note.html>, (May 14, 2015).

⁴ John P. Cangialosi, "Tropical Cyclone Report, Hurricane Earl", (National Hurricane Center, 13 January 2011), http://www.nhc.noaa.gov/data/tcr/AL072010_Earl.pdf, (May 15, 2015)



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respectively in one hour, attaining flood levels not seen since 1955 and 1938 (see Hurricane Diane and Yankee Clipper references above). Hurricane Irene's impacts were most evident in the hill communities and western portions of Massachusetts, for which the damage assessments estimated that over 525 homes were destroyed or suffered major damage. Across the East Coast, Hurricane/Tropical Storm Irene caused over \$15 billion in damages. The name 'Irene' has been retired.

Hurricane Sandy, 2012. Hurricane Sandy was a Category 3 hurricane near Cuba before weakening into a tropical storm/post-tropical cyclone. While the storm made final landfall in Atlantic City, New Jersey on October 29, 2012, Massachusetts and the rest of New England still felt the impacts of Sandy due to the size of the massive storm. Cape Cod and Buzzards Bay both recorded wind gusts of up to 83 mph. Portions of southern New England experienced significant damage from coastal flooding with entire dune systems destroyed in some communities and nearly 500,000 power outages, 300,000 of which were in Massachusetts. Damage across the East Coast from Sandy is estimated at over \$65 billion. The name 'Sandy' has been retired.⁵

1.4 Major Analyses

1.4.1 General

The Massachusetts HES was initiated in 2011 and was completed in 2015 with the publication of the TDR. It consists of several related analyses that develop technical data concerning hurricane hazards, vulnerability of the population, public response to evacuation advisories, timing of evacuations, and sheltering needs for various hurricane threat situations. The major analyses are briefly summarized in the following paragraphs. Detailed descriptions of the analyses and the methodologies of each are contained in subsequent chapters of this report.

1.4.2 Hazards Analysis

The hazards analysis determines the timing and magnitude of wind and storm surge hazards that can be expected from hurricanes of various categories, tracks, and forward speeds. The Sea, Lake, and Overland Surges from Hurricanes (SLOSH) numerical model is used by the National Hurricane Center (NHC) to compute the wind speeds and surge heights. The SLOSH output is also used to map storm tide inundation limits that are then used by state and local to delineate evacuation zones. The Hazards Analysis is presented in more detail in Chapter Two.

⁵ "New England Hurricanes of Note," Massachusetts Emergency Management Agency, <http://www.mass.gov/eopss/agencies/mema/hazards/hurricanes/new-england-hurricanes-of-note.html>, (May 14, 2015).



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1.4.3 Vulnerability Analysis

Utilizing the results of the hazards analysis, the vulnerability analysis identifies those areas, populations, and facilities that are vulnerable to specific hazards under a variety of hurricane threats. For this HES, hurricane evacuation zones were delineated for each community in the study area from the SLOSH storm tide inundation limit maps prepared during the Hazards Analysis phase. Population data was used to determine the vulnerable population within each evacuation zone. Further discussion on all aspects of the Vulnerability Analysis is provided in Chapter Three.

1.4.4 Behavioral Analysis

This analysis determines the expected response of the population threatened by various hurricane events in terms of the percentage of the population expected to evacuate, probable destinations of evacuees, public shelter use, and utilization of available vehicles. The methodology used to develop the behavioral data relied on telephone sample surveys of the general population within the study area and interviews with local emergency managers. A behavioral study was completed in 2013 for the Massachusetts HES after Hurricane Sandy (2012). A presentation of the Behavioral Analysis can be found in Chapter Four.

1.4.5 Shelter Analysis

The shelter analysis presents an inventory of public shelter facilities, capacities of the shelters, and shelter demand for each jurisdiction. Emergency management offices and the American Red Cross (ARC) furnished shelter names, capacities, and other details for their shelter inventory. Shelter demands for the Massachusetts HES were calculated using behavioral analysis data. Chapter Five contains information on the Shelter Analysis.

1.4.6 Transportation Analysis

The principal purpose of the transportation analysis is to: 1) determine the time required to evacuate the vulnerable population (clearance times); and 2) evaluate traffic control measures that could improve the flow of evacuating traffic. Complete details on the Transportation Analysis are presented in Chapter Six.

1.4.7 HURREVAC/Decision Tools

HURREVAC is a hurricane evacuation decision-support tool that uses clearance times in conjunction with NHC advisories to assist local officials in arriving at a decision to evacuate or not, as well as when those evacuations, when warranted, should begin. More information on this program may be found at the HURREVAC web-site at www.hurrevac.com. Chapter Seven describes the HURREVAC computer program.