Historic eelgrass trends in Salem Sound, Massachusetts

Final Report

By

Massachusetts Division of Marine Fisheries

Submitted to

Massachusetts Bays National Estuary Program

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Introduction

Seagrass loss is a global phenomenon (Orth et al. 2006, Short et al. 2006a, Short et al. 2014) correlated to habitat degradation, climate change, and direct physical impact. In Massachusetts, large declines of eelgrass extent in coastal salt ponds and estuaries are thought to be related to the eutrophication of those water bodies, for example, on Cape Cod (Costa et al. 1992) and in Boston Harbor (Taylor 2013). Eutrophication can result in decreased light penetration due to phytoplankton blooms and higher levels of sulfide in the sediment due to oxygen depletion; both of these effects are detrimental to eelgrass (Goodman et al. 1995, Holmer and Bondgaard 2001). Salem Sound, an urban estuary north of Boston Harbor, includes the inner harbors of Salem, Marblehead, Danvers, Manchester, and Beverly Harbors as well as an outer Sound region separated from Massachusetts Bay by a ring of islands. Salem Sound is fringed with eelgrass meadows, some of which have been stable for decades and are considered relatively pristine, while others are in decline, particularly in inner harbor areas such as Salem Harbor. Tidal amplitude (2.7 m/9 ft) and flushing capacity of greater Salem Sound are thought to help reduce the influence of nutrients (Chase et al. 2002). However, eutrophication affects localized areas of the Sound including Salem Harbor (Hubeny et al. 2017a). In order to better understand the spatial trends and stressors of eelgrass throughout Salem Sound, this project assessed temporal trends in eelgrass extent through high resolution interpretation of historic photos (1930's to 2012) and acoustic mapping of existing eelgrass (2016). The project also started to consolidate records of variables that could be potential causative factors of localized eelgrass loss.

The specific objectives of this project are to:

1. Calculate eelgrass extent in Salem Sound aerial photography from all study years at a scale of 1:1,000 with at least two patchiness classes.
2. Identify if meadows were absent, or new meadows found, in 2016 based on acoustic analyses.
3. Explore potential variables that could explain eelgrass trends by consolidating available records for a) air and water temperature; b) turbidity and light; c) water quality; c) weather, wind and storms; d) boating, dredging, and construction impacts; and e) other biotic factors such as wasting disease and bioturbation.
4. Make recommendations to prevent loss and/or improve habitat.
5. Write a MA Division of Marine Fisheries (DMF) Technical Report which will be available online along with relevant project data and shapefiles.
6. Present findings at a local stakeholder meeting and relevant conferences.

An additional objective of the project is to provide access to the original imagery and data streams relevant to eelgrass growth and decline for future analyses. This final report is being submitted with files listed in Appendix A. Online access to project data and shapefiles is expected within six months and a DMF Technical Report thereafter.

Background

Eelgrass

Zostera marina L. (eelgrass) is a submerged marine flowering plant. It is primarily perennial but some annual and mixed annual-perennial varieties exist (Jarvis and Moore 2015). Rhizomes, which are subterranean stems aiding in propagation and food storage, grow horizontally in the sediment branching at nodes. In *Z. marina* all growth originates from one terminal meristem. As the rhizome grows it produces a node supporting the growth of two clumps of roots. In some cases a lateral, clonal shoot grows from the node. Lateral shoots form their own meristem and eventually become a unique terminal shoot. Terrestrial plants that grow similarly include bamboo, rhubarb and asparagus. During the summer growing season, new leaf growth is initiated approximately every 10-14 days (Gaeckle and Short 2002). Lateral expansion of the meadow edge has been documented in the range of 12.5 to 16 cm/yr (5 to 6.3 in/yr) (Neckles et al. 2005, Olesen and Sand-Jensen 1994). The leaves range in size from 15 cm (6 in) to 1.5 m (5 ft) in height and persist for about one month before being shed from the parent plant. *Z. marina* needs approximately 9-30% of the light available at the water's surface for photosynthesis to occur (Dennison et al. 1993; Kenworthy et al. 2014). Other marine primary producers such as algae can grow at light levels of only 1% of surface light (Kemp et al. 2004, Zimmerman et al. 1997). The primary nutrient uptake is through the roots, but leaves can also absorb nutrients from the water column.

At the onset of favorable temperature and light conditions in the spring, eelgrass grows rapidly both through lateral clonal growth as well as sexual reproduction from seeds that germinated over the fall and winter. High summer temperatures slow growth but growth resumes in the fall as temperatures decrease. In the first growing season, a seedling can produce a terminal shoot and 2-12 lateral shoots. In the winter, growth is slow and only short leaves remain in most meadows. Generally in the second growing season some plants will differentiate into a reproductive shoots and flower but the spatial and temporal extent of flowering can vary due to biotic and abiotic forces. Seeds are dispersed either locally by dropping and sinking in the vicinity of the parent shoot, or more broadly by the shoot detaching and floating for a month or more (Källström et al. 2008) before the seeds sink to the bottom. The reproductive shoot dies in the process, but seed "rafting" on the buoyant shoot can disperse seeds as far as 150 km (>90 miles) (Källström et al. 2008). Individual shoots live for approximately two years, but meadows can sustain themselves for hundreds or even thousands of years (Reusch et al. 1999).

Z. marina is broadly distributed in the northern hemisphere. It is found on both coasts of the United States. On the Pacific coast it ranges as far south as the Baja peninsula and as far north as northern Alaska. On the Atlantic coast it ranges from North Carolina to Canada. Salem Sound is near the middle of the geographic range. The optimal temperatures for different life history stages of eelgrass range from 10-25°C (50-77°F) (Table 1).

Table 1. Optimal temperature ranges for Z. marina at different life history stages

Life history stage	Temp (°C)	Temp(°F)	Source
Adult growth	13.7-16.9°C	60°F	Lee et al. (2007)
Seed germination	10-15°C	50-59°F	Abe et al. (2008)
Seedling growth	20-25°C	68-77°F	Abe et al. (2008)
Mortality	Sustained >25°C	Sustained >77°F	Greve et al. (2003) Reusch et al. (2005)

Eelgrass requires more light as temperature increases (Ewers 2013), and photosynthesis and respiration rates increase with increased temperature (Lee et al. 2007). Since respiration responds more strongly than photosynthesis to temperature increases, productivity declines at certain temperature increases (Marsh et al. 1986).

Z. marina has a minimal light requirement between 9-30% of surface light in measurements taken globally, with 18.6% measured in Woods Hole, MA (Dennison et al. 1993; Kenworthy et al. 2014). It needs at least 35% to avoid suffering light-limiting morphological impacts such as reductions to below-ground carbon storage capacity (Ochieng et al. 2010). Low light conditions have been shown to drive eelgrass plants to allocate more energy to above-ground photosynthetic tissue and less energy to the development of below-ground biomass. In addition, plants that are experiencing light stress may be rapidly metabolizing remaining carbohydrate reserves in the rhizome, further depleting them (Colarusso 2006). This can exacerbate impacts from storms as plants with low below-ground structure may be ripped up more easily. Any factors that decrease light reaching the eelgrass leaves, including phytoplankton blooms, suspended sediments, cloudy days, smog, epiphytic coverage, and depth could have a detrimental effect on eelgrass. Decreased light availability is the primary threat to eelgrass consistently identified in the eelgrass literature. Water clarity is closely correlated with the depth distribution of eelgrass; in less turbid waters eelgrass grows to greater water depths. Light levels are not typically measured with sufficient temporal or spatial resolution to truly understand the impact acute and chronic light limitation may have on the distribution of eelgrass. A month-long turbidity event was shown to cause die-off of an eelgrass bed in Chesapeake Bay (Moore et al. 1997), illustrating the potential sensitivity of eelgrass to acute events. Moore et al. (1996) reported eelgrass loss when total suspended sediment (TSS) was 15-40 mg/L, Gallegos and Kenworthy (1996) reported no eelgrass deeper than 1 meter water depth if TSS >15 mg/L, and Kemp et al. (1983) reported no eelgrass growth at light attenuation coefficient >2/m. It has also been reported that eelgrass growing in more organic and eutrophic conditions requires higher light conditions to overcome the stressors in those environments compared to eelgrass growing in less degraded waters (Kenworthy et al. 2014). There is evidence that eelgrass can adapt to different light conditions by mechanisms such as changing leaf area (Dennison 1979), leaf production rates (Dennison and Alberte 1982) shoot density, plant weight and node production (Ochieng et al. 2010).

Studies have also linked eelgrass loss to nutrient loading, since nutrient enrichment increases algal and epiphytic growth, reducing the light available to the plant (Twilley et al. 1985, Costa 1988, Valiela et al. 1992) (Fig 1). Increases in ambient nutrient levels are also associated with a shift from a vegetation community dominated by eelgrass to dominance of macroalgae, phytoplankton or epiphytes (Short et al. 1993). Short et al. (1993) found eelgrass shoot density decreased with increasing nutrient loading and organic content of sediment, and decreases in available light. Latimer and Rego (2010) reviewed studies on nitrogen (N) and seagrass in southern New England and found N loading in excess of 50 kg/ha/yr has a significantly deleterious effect on eelgrass, and eelgrass disappeared where N was 100 kg/ha/yr or greater. Bohrer et al. (1995) reported eelgrass in Cape Cod estuaries at N loading rates of 1.6-64 kg/ha/yr but no eelgrass in embayments with N loading of 390-450 kg/ha/yr. Leo et al. (1994) attributes losses of large eelgrass meadows in Boston Harbor to nutrient loading. However, other studies have found healthy eelgrass meadows in Massachusetts Bay (north of Cape Cod) in embayments with high nitrogen loading (Lent et al. 1998) and studies done by Udy and Dennison (1997a,b) in Australia attributed seagrass morphological differences to light or other environmental variables since there was no correlation with proximity to nutrient sources.

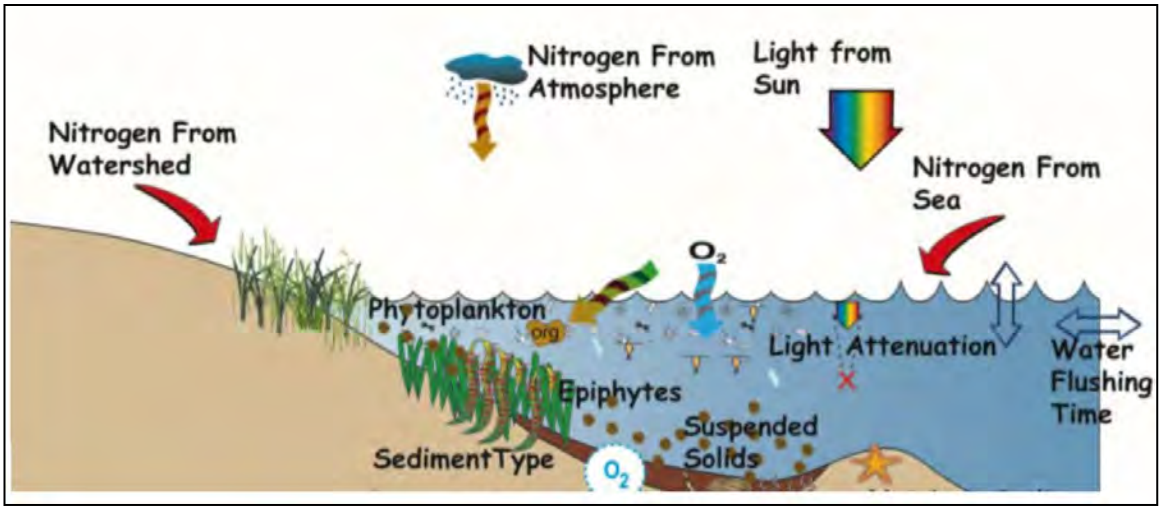


Figure 1. Conceptual diagram of threats to seagrass derived from nutrient enrichment. Source: J. Latimer, EPA. Reproduced with permission from http://www.gulfofmaine.org/2/wp-content/uploads/2014/03/eutrophication.pdf.

Physical features of an embayment such as exposure, slope and tidal range are also significantly related to eelgrass meadow morphometric characteristics (Lent et al. 1998). For example, more exposed meadows develop a more patchy and mounded form than meadows in more protected embayments and very few meadows with a northeast exposure (the direction of significant storms) are found in Massachusetts Bay (Lent et al. 1998).

Historically, eelgrass was valued as house insulation in the North Atlantic region due to its high silicon content (Moe 2014). Eelgrass harvesting was a thriving commercial industry for nearly 50 years until the advent of synthetic insulation products (Wyllie-Echeverria and Cox 1999). Dead or uprooted, floating eelgrass was harvested along the shore and on walls designed to intercept dead eelgrass as it floated to shore (Moe 2014); live plants were not cut or harvested. Eelgrass is no longer used or harvested commercially. Modern use of eelgrass is limited to using dead eelgrass collected from the beach as mulch and compost material.

Salem Sound

The Salem Sound embayment is surrounded by the towns of Manchester, Beverly, Danvers, Peabody, Salem and Marblehead, and is located approximately 14 miles (36 km) northeast of Boston Harbor

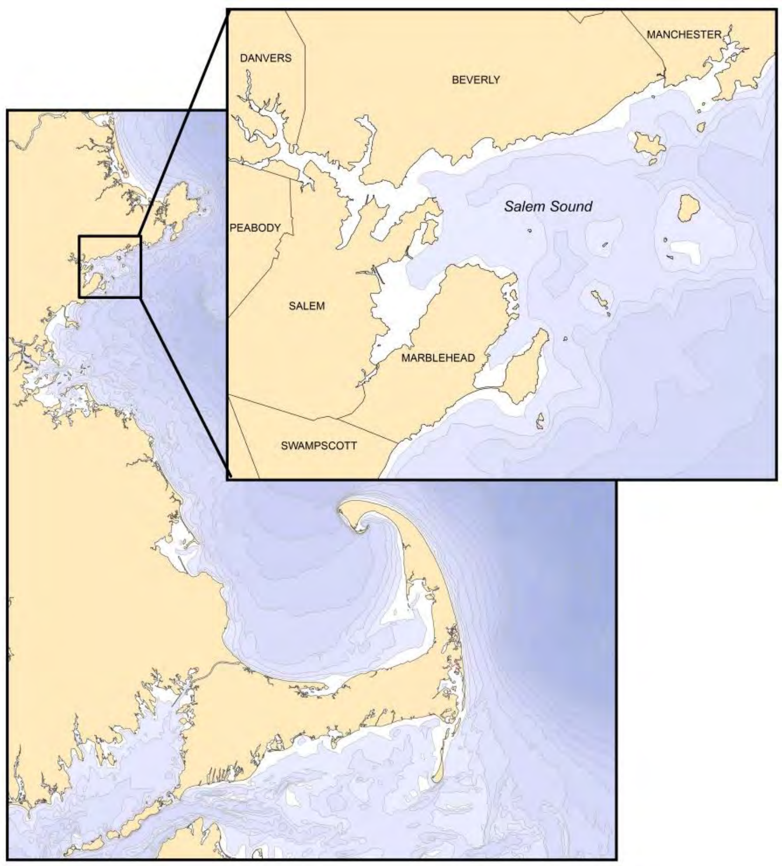


Figure 2. Site Locus

(Fig 2). Its seaward boundary is generally defined as an imaginary line drawn from Marblehead Light northeast to the southwestern point on Bakers Island, Beverly, and from the northwest point on Bakers Island to Gales Point, Manchester (MADEP 2012) (Fig 3). The Danvers River is the primary riverine input into the estuary, collecting water from tributaries including the North, Crane, Waters, Bass and Porter Rivers. The much smaller Sawmill Brook empties into inner Manchester harbor. Other smaller freshwater tributaries flow through Beverly, Salem and Marblehead harbors.

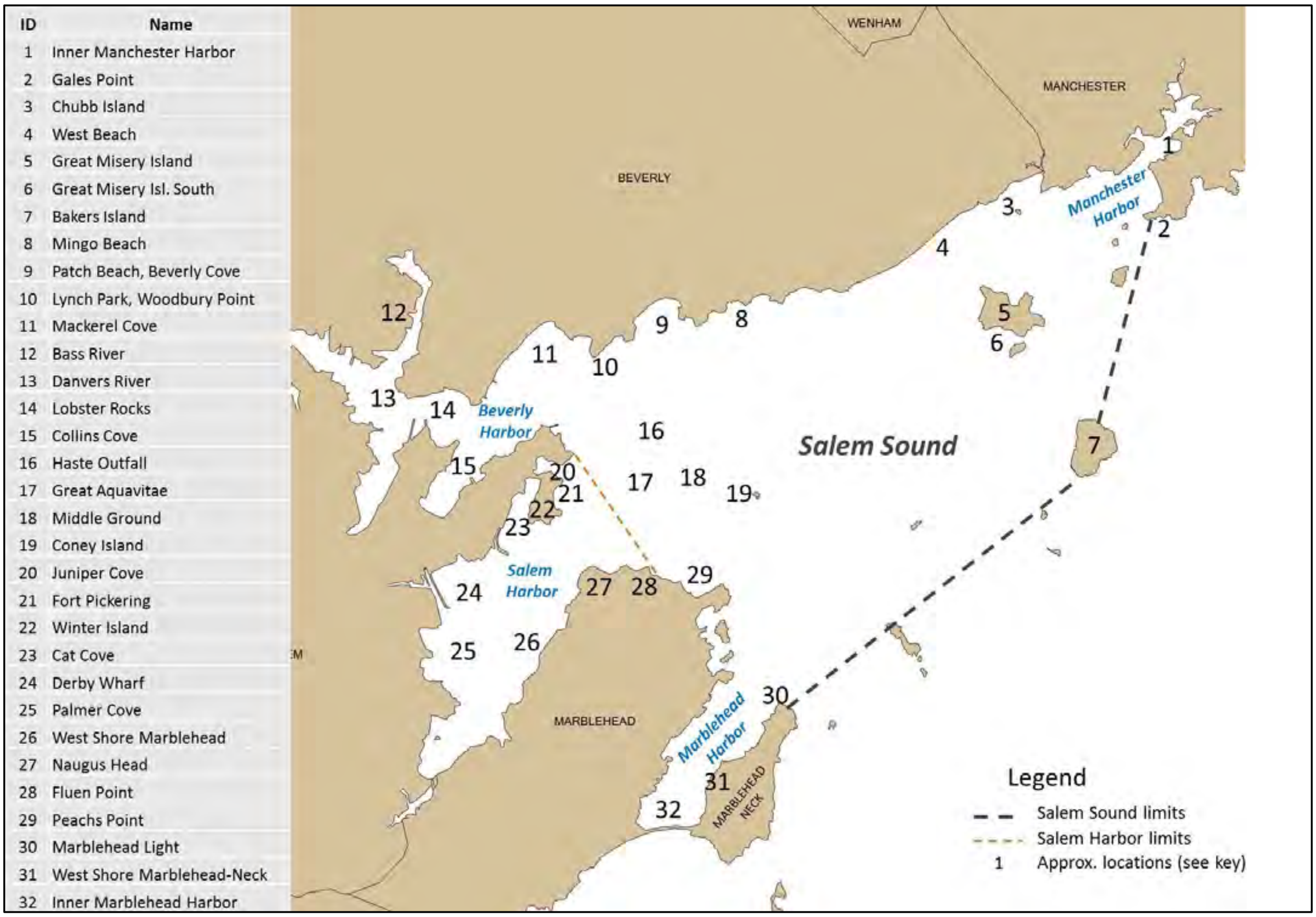


Figure 3. Locations of relevant landmarks

Salem Sound is a 36.3 km^2 (14 mi^2) embayment with a mean depth of 9.15 m (30 ft) at mean high water (Jerome et al. 1967). Semi-diurnal tides with a mean amplitude of 2.75 m (9 ft) provide substantial flushing from the adjacent Massachusetts Bay (Chase et al. 2002). Approximately 70% of the total water volume is exchanged with each tidal cycle (Chase et al. 2002). The shoreline is characterized by intermittent sandy beaches and large bedrock out-croppings. Subtidal sediment throughout the embayment varies from fine silts to cobbles. Several rocky islands define the eastern extent of Salem Sound and afford some level of storm protection.

The Salem Sound region supported Native Americans for thousands of years prior to colonial settlement in the early 17th century. Over the next two centuries, the region was a center for maritime commerce, fisheries, and industry. Population and land use boomed between the mid-19th to mid-20th century during the industrial revolution. Numerous textile mills, leather tanneries, and metal plating shops used the rivers for industrial waste disposal, power, and/or cooling (sources within Chase et al. 2002). The tanneries fell into decline after World War II coincident with the construction of a coal-fired power plant with seawater cooling in 1952. Both of these changes are evident in the sediment record, since tannery metal concentrations in sediment cores decrease steadily after World War II and fly ash contamination increases (Hubeny et al. 2017b). The power plant was expanded in 1972. It continued to release fly ash and to discharge heated water into the harbor until it was dismantled in 2014 and replaced by a natural-gas fired power generating facility in 2017.

Prior to 1905, all raw sewage was discharged directly to rivers and shallow nearshore areas. In 1905, the Haste Outfall pipe was constructed for raw sewage discharge from Peabody and Salem to Great Haste Island. In 1925, the South Essex Sewerage District (SESD) was established and the sewerage collection expanded. In 1978, sewage treatment was upgraded from raw to primary treatment (screening). In 1998, an additional upgrade to secondary treatment was constructed and a diffuser added at the Haste Outfall. The majority of sewage disposal within the embayment occurs through SESD, but a smaller secondary treatment plant has discharged to Manchester Bay from an outfall approximately 2,000ft northeast of Misery Island, within Salem Sound, since 1998.

Other pollution sources to Salem Sound include residential septic systems and stormwater impacts from Route 128. The highway corridor runs close to shore and across several tributaries to Salem Sound. Intensive retail and residential development along the corridor has followed, and the high level of impervious surface exacerbates stormwater runoff impacts. Water-based activities including marinas, mooring areas, yacht clubs and a commercial shipping terminal also contribute to pollution loads entering Salem Sound. The legacy of industrialization and organic loading has been captured in the sediment. Embayment sediment sampling in the 1980s found contaminants originating from industrial point sources and the burning of fossil fuels (Edwards and Kelcey 1989; NOAA 1988 in Chase et al. 2002). Due to high levels of mercury, polychlorinated biphenyls (PCBs) and polyaromatic hydrocarbons (PAHs), Salem Sound became known as a polluted estuary. These contaminants are still measurable both in sediment cores and surface sediments. Although the concentrations of pollutants have diminished considerably in surface sediment, some pollutants still exceed sediment quality guidelines (Hubeny et al. 2017b). Organic loading has also been greatly reduced, but not to pre-historical background or pre-Industrial conditions (Hubeny et al. 2017b). Currently, the primary water quality impairment in the Sound is bacteria (MADEP 2012), an indicator of stormwater runoff pollution.

The eelgrass history of Salem Sound is less well-known. DMF has a monitoring station at the meadow off of West Beach in Beverly (Fig 3) at a stable and persistent meadow, which has tracked eelgrass health seasonally since 2008 according to international SeagrassNet protocols (Short et al. 2006b). DMF has also planted eelgrass at four sites within Salem Harbor: Fort Pickering in 2012, Juniper Cove in 2012, Middle Ground in 2012, 2014, and 2015, and Woodbury Point in 2011 and 2012. Fort Pickering and Juniper Cove plantings did not succeed. The earliest attempt to map the extent of eelgrass Salem Sound-wide was accomplished by MA Department of Environmental Protection (DEP) in 1995 using photo-interpretation methods optimized for eelgrass mapping. Additional mapping by DEP occurred in 2001, 2006 (Salem Harbor only), and 2012. DEP's mapping methods involve collecting high-resolution aerial photography at particular flight specifications that optimize visibility of eelgrass (Costello and Kenworthy 2011). Collected images were then examined and eelgrass polygons drawn on acetate transparent film using a binocular stereoscope (1995), or drawn digitally onto scanned (2001) or digital

(2006, 2012) images in ESRI ArcGIS software. DEP field-verified a subset of the drawn eelgrass polygons using underwater photos and videos at points throughout each embayment. The minimum eelgrass mapping unit used by DEP was 0.1 acres (C. Costello, MA DEP, pers. comm.).

Acreage calculated using DEP's mapped eelgrass polygons of Salem Sound show 691 acres of eelgrass in 1995 and 566 acres in 2012, an overall decline of 18% (Table 2). Most of the decline occurred between 1995 and 2001 when 24% eelgrass loss was observed in analysis of the imagery. Between 2001 and 2012 an increase of 7% was observed. Within Salem Harbor, a large loss (88 acres) was documented between 1995 and 2001 (Table 3). The Salem Harbor loss accounted for half of the overall loss of eelgrass in Salem Sound.

Table 2. DEP eelgrass acreage per study year based on calculated area of polygons. (In 2006/7 only Salem Harbor was studied.)

Study Year	Acreage, Salem Sound	Acreage Change	Percent Change
1995	691	---	---
2001	528	-163	-24%
2012	566	+38	+7%

Table 3. DEP eelgrass acreage per study year based on calculated area of polygons for Salem Harbor only.

Study Year	Acreage, Salem Harbor	Acreage Change	Percent Change
1995	109	---	---
2001	21*	-88	-81%
2006/7	36	+15	+71%
2012	21	-15	-41%

**Very poor image quality in Salem Harbor*

Methods

In order to generate maps of eelgrass spatial extent at multiple time steps, this project utilized aerial photos collected by the DEP Eelgrass Mapping Project, MA Department of Transportation (DOT), DMF, and the United States Department of Agriculture (USDA). Photos publicly available on Google Earth and Bing Maps were reviewed and used when additional context was needed. The imagery was augmented by an acoustic survey and collection of groundtruthing data in August 2016. Other survey data (DMF 2013 acoustics, AECOM surveys) were incorporated to provide more context in the gaps between DEP mapping years. In order to consider potentially causative factors of eelgrass trends, stakeholder input was solicited and relevant biotic and abiotic variable datasets were analyzed.

Photo Acquisition and Interpretation

DEP Photos and Groundtruthing

Aerial imagery for analysis was obtained from the DEP's Wetlands Conservancy Program. Each image set had a different storage protocol based on the available technologies when collected. The 1995 imagery was not available from DEP in hard copy prints, negatives or digital files and was deemed missing from their archive. The 2001 images were available as mosaiced but non-georeferenced digital raster files (.TIFF) of scanned 10"x10" negatives and as original 10"x10" negatives. We georeferenced the raster images in ArcGIS 10.3 using the Georeference toolkit with 2014 USDA aerial images for ground control points. The 2006 and 2012 imagery were available as georeferenced digital files. The 2006 database was an individual GeoTIFF and the 2012 database was a single geodatabase containing individual GeoTIFFs. DEP also provided a shapefile of their field verification point data collected from 1994 to 2013.

DOT Photos

The DOT Survey Department maintains a photo archive of all aerial imagery collected for state transportation projects. Copies of aerial photos were obtained after an email request. DOT fly-overs have standard data collection protocols based on the project, however they do not match the flight standards to optimize eelgrass visibility. We acquired 281 images of Salem Sound dated between 1931 and 1978. Many were black and white and taken at various elevations. We examined all photos and identified and georeferenced a subset in ArcGIS 10.3 for determining the historic presence of eelgrass.

DMF Photos

DMF conducted aerial photo surveys of Salem Sound in September 2010 and August 2014 in a partnership with LightHawk to collect aerial imagery of eelgrass monitoring sites and mooring fields. These flights and the cameras used on the flights did not have standard data collection protocols and the images were not georeferenced.

USDA Photos

We utilized USDA National Agriculture Imagery Program (NAIP) aerial photography downloaded from the USGS EarthExplorer website as GeoTIFFs. We used their bulk-downloader program to acquire the five tiles that make up Salem Sound (4207025_se, 4207025_sw, 4207026_ne, 4207026_se, 4207034_nw). Images have a resolution of 1-meter or better and were collected to provide a high resolution base layer for assessing land boundaries during the agricultural growing season. Flights did not target low tide conditions which are optimal for eelgrass visibility, but do target an appropriate time of year. The Salem Sound imagery was collected in July 2014.

Photo analysis

Originally we intended to re-delineate the eelgrass meadows at each time step. However, after some experimentation we were reluctant to revise DEP's eelgrass polygons since we were unable to groundtruth our photo-interpretation of each time step and the potential to mischaracterize areas was high. For example, areas that appeared heavily vegetated were actually comprised of algae or rocks based on DEP groundtruth data, and conversely some areas that appeared bare were vegetated with very short or very sparse grass (Fig 4). DEP's groundtruthing point-data were a critical component of drawing the polygons.

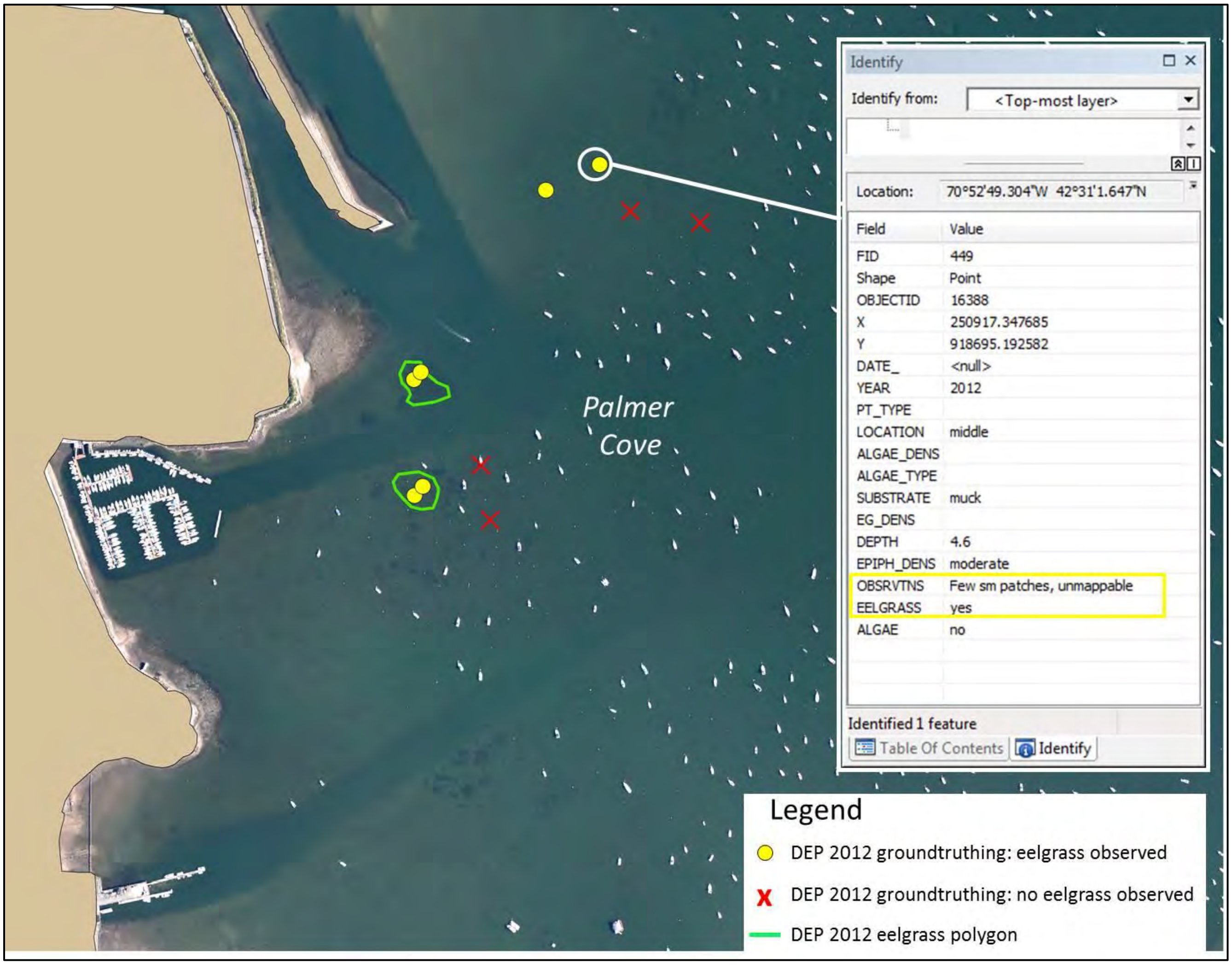


Figure 4. 2012 DEP aerial photograph of Palmer Cove, Salem with 2012 DEP field verification points. The attribute data for the circled point shows that sparse eelgrass ("few sm patches") is present but was not included in the 2012 DEP polygon.

Instead of redelineating the eelgrass polygons, we used the existing DEP polygons from each time point combined with DMF, USDA and Google Earth images in conjunction with groundtruthing data to classify the eelgrass polygons (or portions thereof) into "Dense," "Sparse," "Questionable Mapped," and "Questionable Unmapped" categories as follows:

- "Dense" classifications are continuous meadows and large patches that appeared to have greater than 50% aerial coverage within the bed (when comparing dark, vegetated areas to sandy areas).
- "Sparse" classifications are for polygons that appeared to have less than 50% aerial coverage.
- "Questionable Mapped" classifications are for polygons that had field point data that did not identify eelgrass or eelgrass was not visible in aerial photos.
- "Questionable Unmapped" classifications are for areas that appeared vegetated in aerial photographs but lacked field-verification points, or had positive field-verification points in areas not drawn by DEP (e.g. areas below DEP's 0.1ac Minimum Mapping Unit).

With a mapped polygon in view, we first determined if the polygon accurately portrayed the dark vegetated areas observed in the underlying aerial image. If eelgrass presence was questionable, field verification point data were queried to help understand the conditions in a bed. If field verification data were not available for a questionable area, best professional judgment was used to categorize the area utilizing information about the surroundings, the mapped habitat history of the area in question, and other available aerial images. While DEP's field verification point data occasionally affected our classification if information such as algae, rock presence, or notes about the eelgrass density were present, there were several instances where the field verification point data did not accurately reflect DEP's drawn polygons or underlying conditions as seen in the imagery.

Within each polygon we classified Dense and Sparse eelgrass polygons and assessed the surroundings for Questionable Mapped and Questionable Unmapped areas. A new shapefile with the classified eelgrass polygons was produced for each year. Photo-interpretation was performed for all years we were able to obtain imagery: 2001, 2006, and 2012.

Aerial photography from DOT was used to verify historical presence or absence of particular beds, USDA and DMF imagery were used to supplement the DEP imagery. When using imagery without corresponding groundtruthing data, assumptions were made. For example, dark submerged areas that appeared to be vegetated with the characteristic appearance of eelgrass, and/or were mapped at any time as eelgrass, were assumed to be eelgrass at the time that photo was collected.

DMF Acoustic Mapping

In August 2016, we conducted acoustic mapping surveys in Salem Sound, targeting beds mapped by DEP from 1995 to 2012, two of DMF's transplanting sites, and other sites of interest. We used a GPS integrated Humminbird 698SI 455 kHz side scan sonar and 83/200 kHz dual beam downward-looking bathymetric sonar with a transducer mounted off the port-side of a 20' Maritime Skiff (Fig 5). No layback corrections were made. Side scan sonar data were processed for water column removal and slant range and beam angle corrections with SonarTRX Pro and then exported as GeoTIFF mosaics. In the side scan sonar mosaic, eelgrass has a characteristic pattern which, after groundtruth verification, can be used to delineate eelgrass spatial extent (Fig 6).

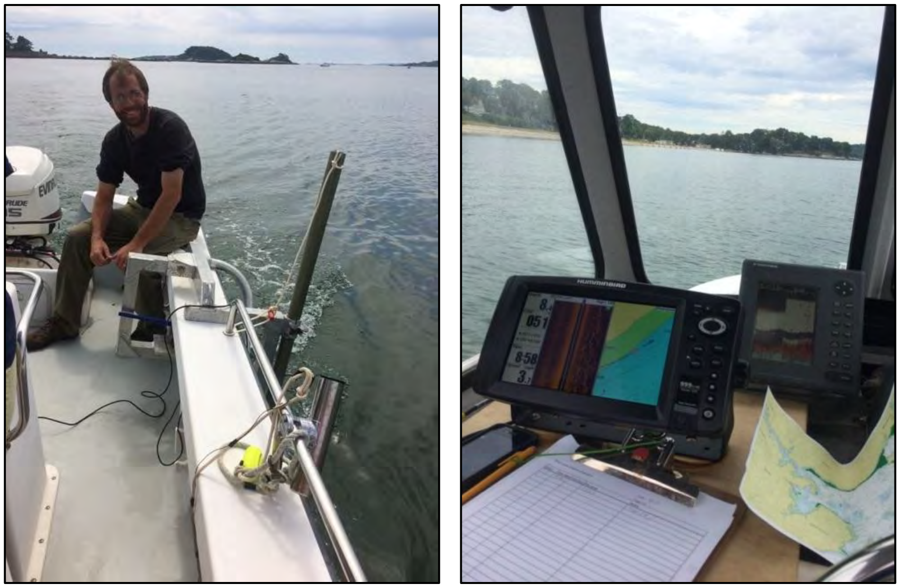


Figure 5. Mounting (left) and topside display (right) of Humminbird side scan sonar.

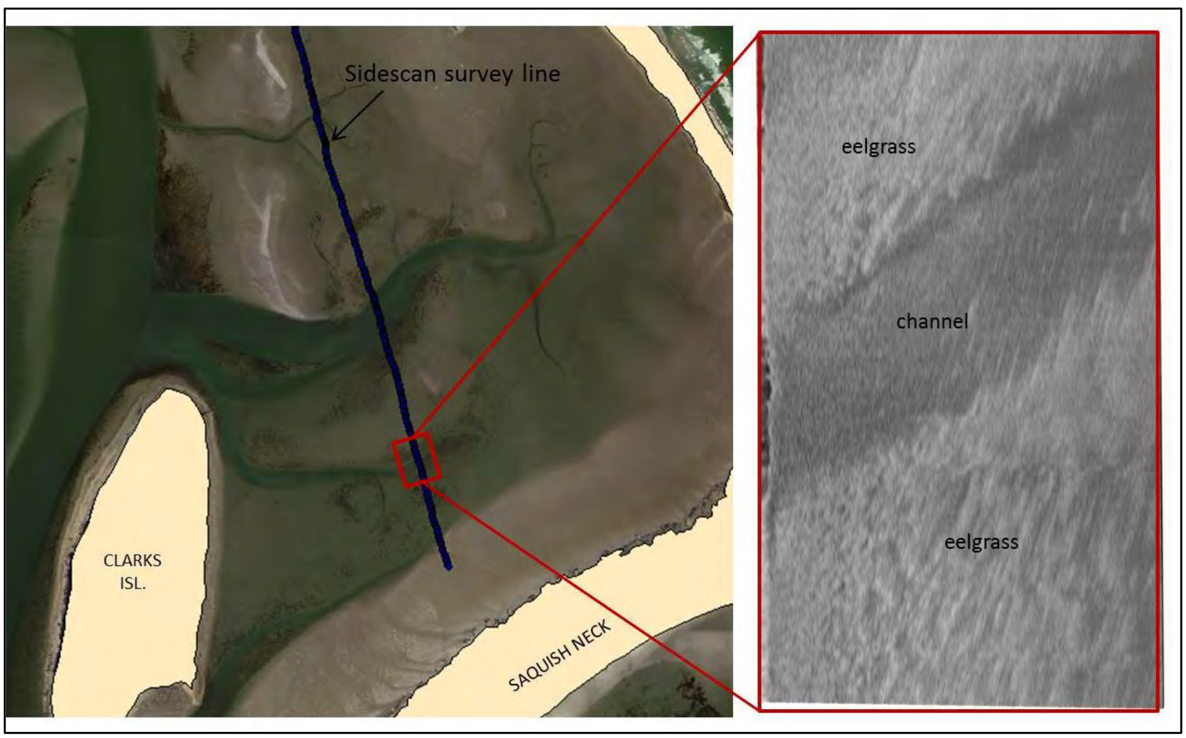


Figure 6. Example of side scan image output. Imagery from Duxbury Bay, MA.

Groundtruthing was done after the acoustic survey using an Aqua-Vu reeled towable live-feed underwater camera (Fig 7a). Sites targeted for groundtruthing were selected based on DEP eelgrass maps and real-time observations of the Humminbird display. The submersible camera allowed confirmation of eelgrass presence or absence (Fig 7b-d). In shallow or clear locations, eelgrass was observed by looking over the side of the survey vessel to confirm eelgrass presence (e.g. inner Marblehead and Manchester Harbors).

The acoustic survey was not designed to include 100% coverage of the embayment or 100% of the individual beds due to the large area of interest and time constraints. We therefore generally ran diagonal zigzag transects across each bed (Fig 8) in an effort to collect edge and middle-of-bed sidescan imagery. To fill in the gaps, we used 2014 USDA aerial photography in ArcGIS to help locate eelgrass and draw polygons. The combined area of all polygons was calculated to provide the 2016 estimated acreage of eelgrass. Density categories were not delineated as part of this estimate.

Figure 7. A) Aqua-Vu camera, B, C) imagery captured in vegetated areas, D) imagery captured in an un-vegetated area. Imagery from Salem Sound, MA.

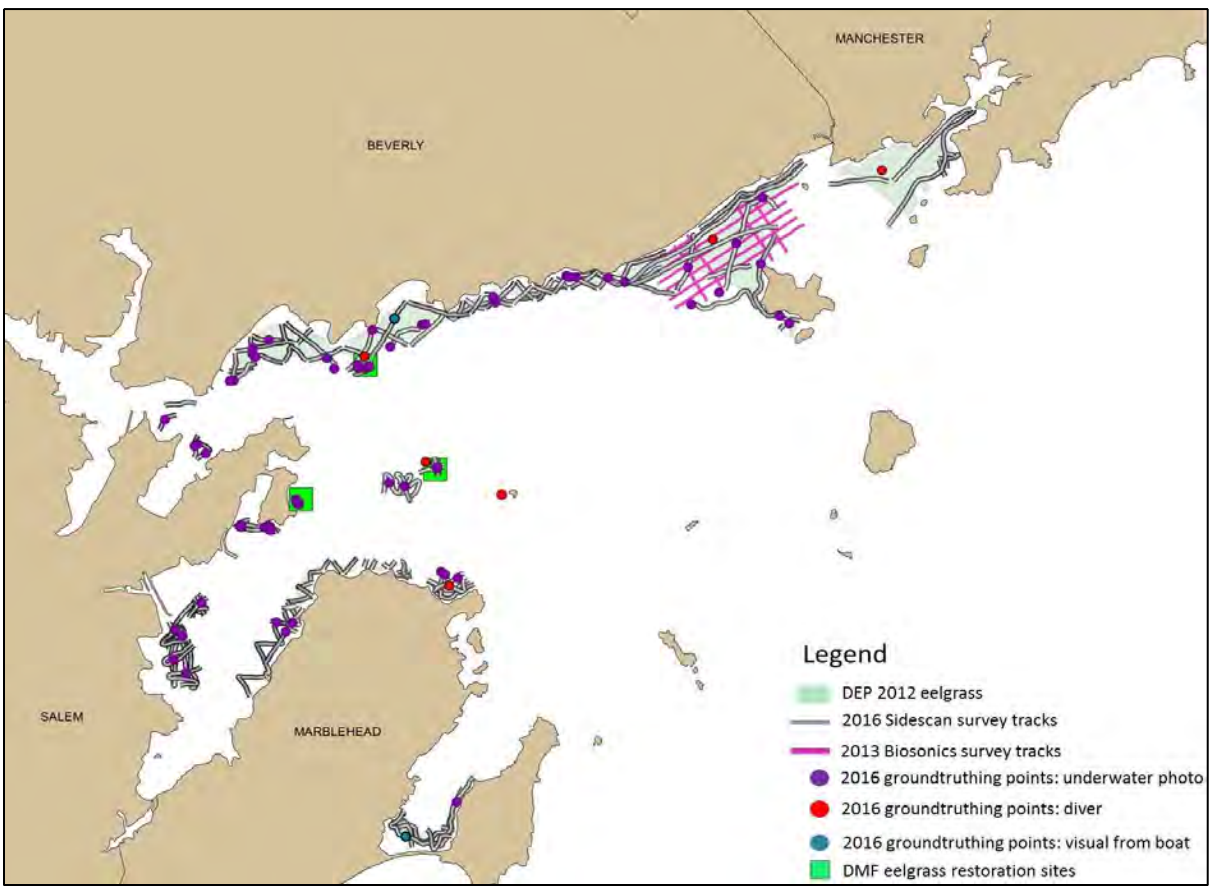


Figure 8. Acoustic survey tracks and groundtruthing locations that targeted DEP 2012 eelgrass areas and DMF restoration sites. Other areas targeted include DEP 1995 beds in Beverly and Salem harbors.

Meadows were also identified opportunistically at two sites: the Coney Island meadow was found while conducting unrelated dive work, and at Great Aquavitae when boat operators noticed eelgrass signatures on the Humminbird display while transiting to the Middle Ground transplant site.

DMF acoustic surveys conducted in 2010 and 2013 with a Biosonics DT-X instrument at the West Beach SeagrassNet site were used to groundtruth the DEP aerial photography, as well. The Biosonics DT-X digital echo sounder has a 420-kHz, 6° split-beam transducer. The transducer was attached to a pole mount on the port side of a 20' Maritime Skiff. For the surveys in 2010, the transducer was set up to generate pulses (pings) at 5 pings per second (pps) with a duration of 0.4 milliseconds (ms). At a sound speed of 1500 m/s and a pulse duration of 0.4 ms the vertical resolution of the echosounder is 0.3 meters (speed of sound/2 * pulse duration). In 2013, we used 10 pps and a pulse duration of 0.1 ms to test the theoretical vertical resolution of 0.08 meters. The data collection threshold was -130 dB. A WAAS-enabled handheld Garmin GPS76 was used for positioning. The external antenna was mounted directly on top of the transducer pole mount. The stated horizontal accuracy of this unit is within 3 m (Garmin 2015). The horizontal resolution of the echosounder varied based on speed from 1.5 m (at 3 knots) to 3.1 m (at 6 knots). The Biosonics .dt4 datafiles were processed using EcoSAV software version 1.0. The signal processing algorithm was developed specifically to detect seagrasses with hydroacoustic echosounders (Sabol and Merton 1995). EcoSAV produces measurements of plant height, percent coverage, and bottom depth by averaging the 5 and 10 Hz acoustic signals between each 1-Hz DGPS reporting cycle (Sabol et al. 2002).

Stakeholder Interviews

Throughout this study, stakeholders were engaged to identify datasets and provide information about activities and trends in Salem Sound. Stakeholders were identified by their affiliation with a municipal agency (harbormasters, conservation commission agents, shellfish constables), federal or state agency (EPA, CZM, DEP), or local watershed association or non-governmental agency (NGO) (e.g. Salem Sound Coastwatch (SSCW), Audubon), academic institutions (Salem State University, Northeastern University, Landmark School, Endicott College), commercial and recreational users of Salem Sound, or as recommended by other stakeholders. Informal information collection consisted of emails, phone and in-person interviews with individuals. One in-person stakeholder workshop was held on March 9, 2017 at SSCW to provide mapping results and facilitate a group discussion regarding trends and stressors (meeting attendance list and minutes in Appendix B). The meeting had 24 attendees. In addition to the stakeholder workshop we also presented at the Underwater in Salem Sound lecture series at the Abbot Public Library in Marblehead on April 26, 2017, which was open to the public and attended by roughly 85 people.

Biotic Stressors

Research on biotic (wasting disease, predation / bioturbation) and abiotic (temperature, light and water quality, physical impacts) stressor variables was examined in order to consider potential causes of loss.

Wasting disease

Wasting disease is a pathogenic infection thought to be caused by the slime mold *Labyrinthula zosterae* and responsible for the die-off of up to 90% of the seagrass on the U.S. eastern seaboard in the 1930's. Locally, Dr. Randall Hughes at Northeastern University is researching eelgrass genetics and wasting disease in MA waters. She was interviewed for current information about wasting disease in Salem Sound. Her doctorate student, Forest Schenck, sent data from a survey of prevalence and severity of infections of the third leaf of 120 shoots per site (10 shoots in 12 $0.25x0.25m^2$ quadrats evenly spaced approximately 2m apart along two transects running parallel to shore) conducted on 9/19/2016 at West Beach, Dorothy Cove (Nahant), Lynch Park (Beverly), and Niles Beach (Gloucester). DMF has collected qualitative observations of wasting disease at our SeagrassNet site off West Beach in Beverly since 2008. The Massachusetts Office of Coastal Zone Management (CZM) monitored wasting disease as part of an eelgrass study at Palmer Cove and West Beach in 2003 and 2004 (Wilbur 2005).

Predation

Several bird species directly consume eelgrass and numerous other organisms feed on its epiphytes, including lacuna snails (*Lacuna vincta*), green crabs (*Carcinus maenus)* and various shrimps and amphipod species. DMF collects qualitative data on snail grazing and green crab presence at numerous restoration and monitoring sites in Salem Sound. Salem Sound Coastwatch with CZM's Marine Invader Monitoring and Information Collaborative (MIMIC) program also has several dock and intertidal sampling sites throughout Salem Sound, and DMF has a MIMIC site at the West Beach eelgrass bed. CZM provided all MIMIC data for Salem Sound in an excel spreadsheet.

Abiotic Variables

Temperature

Regional air temperature trends were summarized using the Mass EEA Climate Adaptation Report (MAEEA 2011) and Blue Hill Observatory reports from 1851-2016 (BHO 2016) for a previous eelgrass report (Ford & Carr 2016). In-water datasets more local to Salem Sound were used for analysis (Fig 9).

- DMF's Climate Change database
  - SeagrassNet A and C are two bottom temperature stations maintained by DMF's Habitat Program located at the SeagrassNet monitoring site just off West Beach, Beverly within an eelgrass bed. Two Hobo pendants are deployed on the seafloor at roughly 3 m (10 ft) and 4 m (13 ft) mean low water (MLW) depth collecting temperature data hourly from 2008-2016. These data were used to determine if the optimal temperature range of eelgrass (10-25°C) was exceeded. They were also used to calculate monthly average bottom water temperature from 2008-2016. Months with <20 days of data were excluded from the monthly average analysis. This data could not be used for annual average analysis or for seasonal onset analysis since many years did not have a complete dataset. All months had at least 5 years of data collection, but not all months in all years had continuous data. Since there were fewer than 5 years with calculable annual and summer averages, these trends were not analyzed.
  - DMF's Recreational Saltwater Fishing Program maintains a bottom temperature station in Beverly Harbor at 7 m (23 ft) depth MLW with year-round monitoring every two hours using a Hobo pendant. These data were used to compare annual, summer, and monthly average bottom water temperature and seasonal onset from 2004-2012 in months and years with complete data.
- NERACOOS Website (NERACOOS 2017)
  - Massachusetts Bay buoy, NERACOOS A01, is owned and operated by Dr. Neal Pettigrew at the University of Maine. We calculated and analyzed annual, summer, and monthly average surface (1 m depth) water temperature and seasonal onset from 2002-2016.

We calculated and analyzed annual average bottom (50 m depth) water temperature from 2002-2016.

    - Outer Boston Harbor buoy, NOAA 44013, is owned and operated by the National Data Buoy Center. These data were used to compare annual, summer, and monthly average surface (1 m depth) water temperature and seasonal onset from 2003-2016.
    - Inner Boston Harbor buoy, NOAA CO-OPS station 8443970, is owned and operated by NOAA National Ocean Service. These data were retrieved from NOAA's Tides and Currents website (NOAA NOS 2017). These data were used to compare annual, summer, and monthly average surface (1 m depth) water temperature and seasonal onset from 1998-2016.

- Data obtained by not analyzed
    - The DMF Shellfish Sanitation Database has eight sites in Salem Sound that were sampled for surface water temperature in 2008 and 2011. Sampling was not continuous and was not coincide with a specific tidal stage so we did not analyze these data. Since all Designated Shellfish Growing Areas have been closed since the 1970's, a closure frequency history was not done.
    - Salem Sound Coastwatch provided water column temperature data collected from six stations in greater Salem Sound between May 2010 and May 2011 by Salem Sound Coastwatch and Salem State University. Due to the short time series, these data were not analyzed.
    - EPA provided data collected by their coastal nutrient criteria and trend monitoring study conducted in 2010 and 2011 from the OSV Bold (July 2010 and August 2011) and supplemented by sampling by the EPA's New England Regional Laboratory. This project collected water column temperature. Due to the short time series, these data were not analyzed.

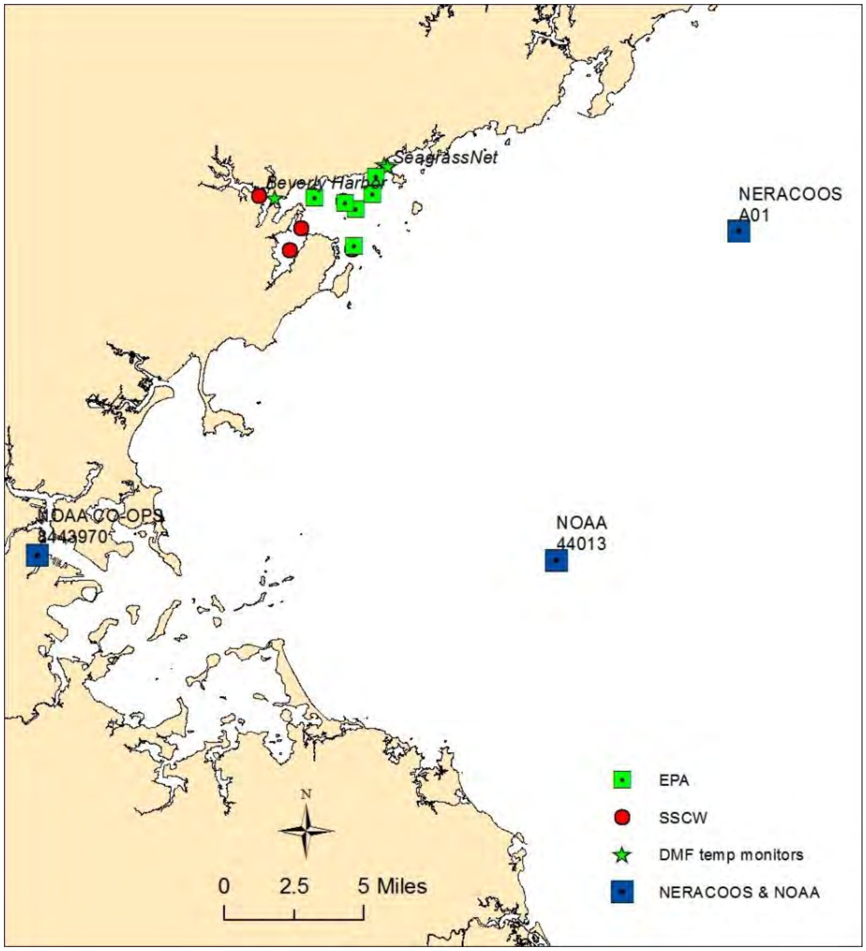


Figure 9. Sampling stations monitored for temperature by Salem Sound Coastwatch (SSCW), EPA, DMF, NERACOOS, and NOAA.

In addition to comparing annual, summer, and monthly averages year to year, seasonal onset was examined using data from the DMF Beverly Harbor Station, the NERACOOS Massachusetts Bay station, and the NOAA Inner and Outer Boston Harbor stations. Jerome et al. (1967) stated, "Finfish did not frequent the shoal waters of the shore sampling stations in large numbers until surface water temperatures reached 50°F." Therefore, spring seasonal onset was defined as the Julian Day that the daily average water temperature reached 50°F (10.4°C) and stayed at or above 50°F. Conversely, winter seasonal onset was defined as the date the daily average water temperature reached 49°F and stayed at or below 49°F (9.4°C). A linear regression through time was applied to individual average temperature datasets and the seasonal onset datasets. A t-test was used to determine if there was a statistically significant linear relationship at a 0.1 significance level. This is similar to the method used to analyze temperature trends in Buzzards Bay with volunteer monitoring data (Rheuban et al. 2016).

Light availability and water quality

Several variables influence light penetration in the water column, including precipitation and streamflow, phytoplankton blooms, and suspended sediment. The most direct measurement of light penetration is the amount of photosynthetically active radiation (PAR) in the water, quantified as µmol photons/m^2/second, which is a measure of the photosynthetic photon flux density (PPFD). This absolute measurement can be used to calculate the light extinction coefficient, Kd. Generating a Kd curve allows the determination of light at various depths which can help elucidate if light conditions are suitable for eelgrass. Dennison et al. (1993) compiled data that show suitable Kd values ranging by location from $0.28/m^2$ in Woods Hole, MA to $1.21/m^2$ in Denmark. DMF and EPA have conducted sampling with Li-Cor PAR sensors at several sites throughout Salem Sound. DMF's Li-Cor data logger, model number LI-1400, was coupled with an LI-192 underwater quantum sensors and a topside sensor. The underwater sensor is attached to a 2009S Lowering Frame which is lowered into the water column using an attached cable and monitored for proper depth using an attached transect tape. PAR measurements were collected at the SeagrassNet monitoring site off West Beach, Beverly (10 readings over 6 days) and at eelgrass restoration sites in Beverly (Woodbury Point (12 readings over 3 days)) and Salem (Fort Pickering (1 reading over 1 day), Middle Ground (5 readings over 2 days), Juniper Cove (7 readings over 2 days)) (Fig 10) at various field visits between 2011 and 2016. Sampling took place during the summer growing season and between 10 am and 2 pm. Li-Cor sampling at the SeagrassNet site generally took place within two hours of low tide, and restoration site sampling tended to take place within two hours of high tide, unintentionally. PAR, secchi and YSI measurements were collected by EPA at three stations within Salem Sound in 2010 and five stations in 2011. Stations were located near the SESD Great Haste outfall (SS-6), near the West Beach eelgrass bed (SS-5), outside of the harbors of Beverly (SS-4), Manchester (SS-3), Marblehead (SS-1) and in the center of the embayment (SS-2) (Fig 10). No PAR sites were located in inner harbor areas.

From 2008-2016, DMF deployed two continuous underwater HOBO pendants (model UA-002-64) that measure temperature and light (in $lumens/ft^2$) at the shallow (3 m/10 ft MLW) and deep (4 m/13 ft MLW) SeagrassNet monitoring stations in the eelgrass bed off West Beach, Beverly and a reference HOBO stationed on land. Percent light reaching the seafloor was calculated by comparing the reference HOBO measurements to the underwater measurements using the following formula:

$$Light_{seafloor} = Light_{inwater} / Light_{ref}$$

The mean daily percent light at the shallow and deep monitoring stations was calculated and trimmed down to the hours of peak solar irradiance (10 am to 2 pm) (Hirst et al. 2008, Macdonald 2015, sources in Dowty and Ferrier 2009). Deployments occurred seasonally; the data were filtered to remove no data records, and records beyond the initial two weeks of deployment were discarded due to potential algal fouling effects. The light data were plotted to determine which seasons have the clearest water and to compare the magnitude of light loss between the shallow and deep stations. It should be noted that HOBO loggers have a range of spectral sensitivity and do not collect all light wavelengths, therefore the percent light calculation is an underestimate of the actual whole-spectrum percent light reaching the bed.

We also assembled reports and datasets specific to Salem Sound for variables relevant to light penetration, including datasets that provided related water quality information (e.g. bacteria, nutrients, turbidity). The data locations are in Figure 10 and the data source descriptions are as follows:

- Salem Sound Coastwatch provided salinity, temperature, dissolved oxygen, and pH data collected using a YSI water quality sonde at six stations in greater Salem Sound between May 2010 and May 2011 by Salem Sound Coastwatch and Salem State University. This project also collected surface and bottom samples for chlorophyll *a* and nutrients which were analyzed at the University of New Hampshire (UNH) Water Quality Analysis Laboratory.

- EPA provided conductivity, salinity, temperature, dissolved oxygen, fluorescence, optical backscatter, and PAR data using a water quality sonde at six stations in greater Salem Sound for their coastal nutrient criteria and trend monitoring study conducted in 2010 and 2011 from the OSV Bold (July 2010 and August 2011) and supplemented by sampling by the EPA's New England Regional Laboratory (July and September 2011). Water samples were analyzed for chlorophyll *a* and nutrients at the Chesapeake Biological Laboratory. These studies are described in more detail in Liebman (2010 and 2011). These data were filtered for stations in the greater Salem Sound area. EPA also collected data in June, August, September, and October 2012; these data were analyzed by EPA.
- From EPA's Storage and Retrieval and Water Quality Exchange (STORET) database, we downloaded Mass Department of Public Health (DPH) *Enterococcus* abundance and station location data. These data were filtered for stations in Essex County. These samples were collected from 2003 to 2011 between the end of May (roughly May 20) and the beginning of September (roughly the first week of September). Samples were collected from stations on average every 2 days during the sampling season. These samples were analyzed to determine which stations had values over the safe swimming threshold of 104 colony forming units per 100 mL (cfu/100 mL).
- From MassGIS we downloaded the locations of DEP Watershed Planning Program water quality monitoring from 1994-2014. The data are described as follows: "Approximately twenty-four hundred unique predominantly surface water stations in this datalayer have been visited sometime between 1994 and 2014. Each station, stored as a single point in the layer, represents a location where general field characteristics were observed, where in-situ probe measurements were made, or where discrete water quality samples were collected by WPP staff or their agents" (MA DEP 2014). These stations were located in the higher reaches of tributaries so we did not request or analyze these data.
- From DMF Shellfish Sanitation and Management Program we received Designated Shellfish Growing Area fecal coliform data. This dataset also included temperature and salinity. Sampling was not continuous and did not coincide with a specific tide stage so we did not analyze these data.
- Monthly average precipitation data were downloaded from the National Weather Service Cooperative Observer Program station in Marblehead, MA (NOAA 2017). No USGS stream gage data were available for streams entering Salem Harbor. Mass DCR also had rainfall data located in Beverly (http://www.mass.gov/eea/agencies/dcr/water-res-protection/water-data-tracking/rainfall-program.html and http://www.mass.gov/eea/agencies/dcr/water-res-protection/water-data-tracking/monthly-water-conditions.html) that were not analyzed in this study.
- Two historic point sources of pollution were SESD and Salem Harbor power plant. Both have water quality monitoring datasets. It was outside of the scope of this study to collect and analyze those datasets.

Turbidity and secchi depth data from EPA and SSCW were plotted to examine seasonal and tidal water clarity trends. We calculated a secchi depth/total depth index to determine which stations have more light reaching the seafloor. The chlorophyll *a* data were plotted to determine which seasons and tides have the lowest chlorophyll *a* concentrations and to compare surface and bottom concentrations. We used depth and spatial distribution of stations to describe patterns in light availability in the greater Salem Sound area.

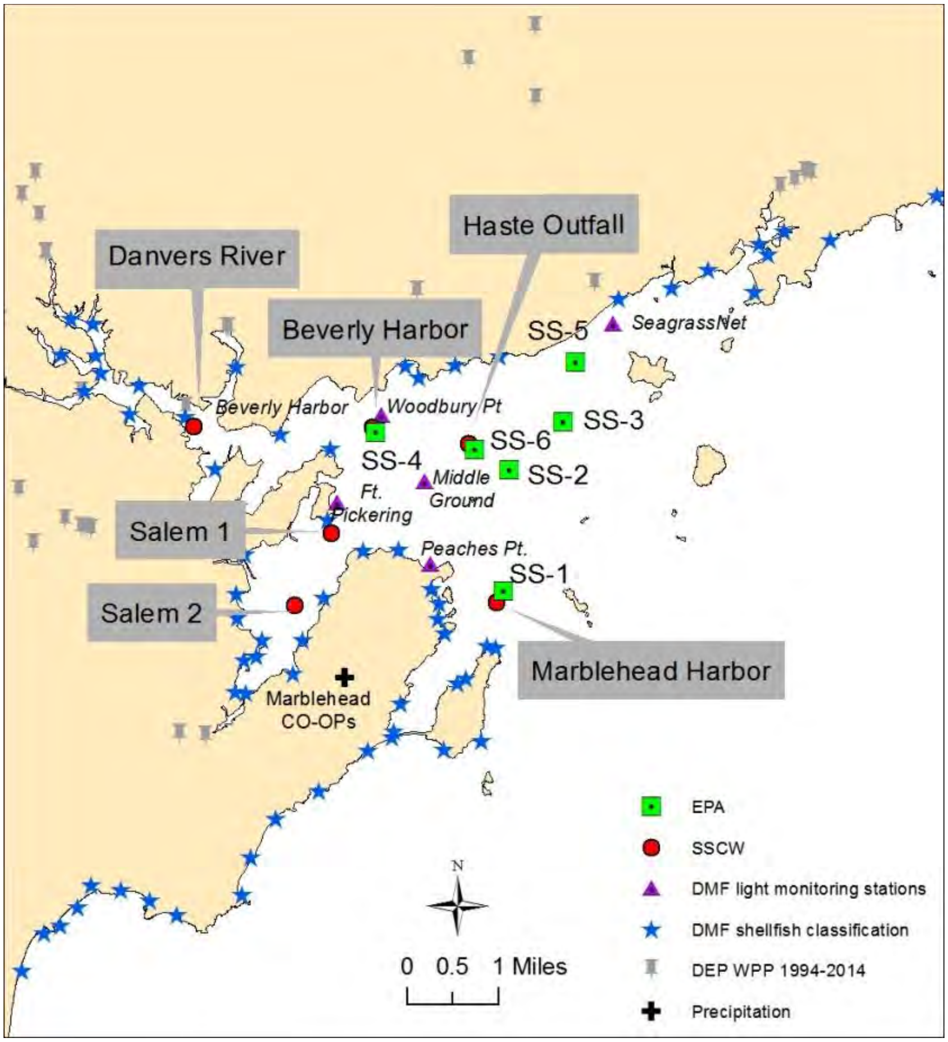


Figure 10. Sampling stations monitored for water quality-related variables including precipitation and light.

To assess potential trends in water quality, we used *Enterococcus* data collected by DPH to compare the number of days above the threshold of 104 cfu/100mL for each station by year. Precipitation data from the National Weather Service were also tested for significant correlations between year and monthly average and annual average precipitation. For the bacteria and precipitation data, a t-test was used to determine if there was a statistically significant linear relationship at a 0.1 significance level.

Acute turbidity events were described using a search of Google Earth imagery and interviews with harbormasters to identify examples.

Physical impact

Direct physical impact to eelgrass plants can occur as a result of alterations in wind speed and direction that affect waves and currents. A regional characterization of wind speed and direction was used to set the regional context (Knorr 2013).

A variety of more localized activities can result in direct and indirect physical impacts. We assessed information on the following factors:

- Boating: We conducted interviews with harbormasters and did a visual assessment of overlap of eelgrass with boating routes (Starbuck and Lipsky 2013), marinas, and mooring fields using Google Earth imagery. An approximation of moorings located within eelgrass beds was done by viewing Google Imagery from Aug 2013 and Sept 2014 (e.g. imagery collected during the active boating season) and counting moorings that overlap with known existing beds.
- Dredging location and frequency: We contacted Mass DEP, Mass CZM and discussed with stakeholders. A count and map of dredging projects within Salem Sound since 2006 was provided by CZM.
- Coastal construction: DMF Technical Review database was queried for in-water work reviewed in various permitting processes within Manchester, Beverly, Danvers, Salem and Marblehead. The number of projects by project type and habitat type were summarized.
- Fishing Gear: literature referencing fishing and fishing gear was reviewed, primarily Jerome et al. (1967) and Chase et al. (2002). There are no aquaculture licenses in Salem Sound.
- Wind speed and direction (local): annual and daily wind speed and direction averages and average annual wind gusts were downloaded from the NERACOOS website for the Massachusetts Bay (Mass Bay) buoy, NERACOOS A01, and the Outer Boston Harbor buoy, NOAA 44013 (Fig 9). These buoys are owned and operated by Dr. Neil Pettigrew, U Maine and the National Data Buoy Center, respectively. We also calculated the number of days the maximum daily wind speed was ≥ 22 knots, monthly from 2001-2016. Twenty-two knots is the threshold for "Strong Breeze" on the Beaufort Wind Scale. At this speed, larger waves from 2.4-4 m (8-13 ft), whitecaps, and more spray are common. We tested for significant linear relationships between year and average annual wind speed, direction, gusts, and number of days/month ≥ 22 knots using linear regression analysis. A t-test was used to determine if there was a statistically significant linear relationship at a 0.1 significance level. The wind direction is recorded as relative to true north.
- Ice: No quantifiable source of ice data (extent, timing) was identified. Inquired with harbormasters and stakeholders about their observations.

Results

DEP Photos & DMF Acoustic Mapping

The resulting acreages from photo-interpretation of DEP's 2001, 2006 and 2012 aerial surveys and from DMF's 2016 acoustic mapping are shown in Tables 4 and 5 and Figure 11. Across all three years, DMF's estimates are higher than DEP's. In both 2001 and 2012, there is more dense than sparse grass embayment-wide. Dense and sparse grass comprised 40% and 27% of the total, respectively. To determine if the eelgrass is becoming significantly more dense or sparse, a bed density ratio was calculated according to the following formula:

Dense (ac)/Sparse (ac) = Bed density ratio

Less than 3% of the eelgrass mapped by DEP was classified as Questionable Mapped; meadows where DEP mapped eelgrass and DMF questioned the designation. Questionable Unmapped classifications, which are areas where DEP did not map eelgrass but DMF did, were frequent and cumulatively very large, comprising 28%, 62% and 33% of the embayment total in 2001, 2006 (Salem Harbor only) and 2012 respectively (Fig 11).

Table 4. Results of DEP and DMF photo-interpretation and acoustic mapping (2016) in eelgrass acreage.

Eelgrass extent, acres	1995	2001	2012	2016
Dense	691	310	343	722
Sparse	(included in dense)	202	224	(included in dense)
Questionable Mapped	not assessed	15	3.11	not assessed
Questionable Unmapped	not assessed	201	280	not assessed
DMF Total Estimate	---	713	847	722
DEP Total Estimate	691	528	566	---
Bed density ratio		1.53	1.53	

Table 5. Results of DEP and DMF photo-interpretation and acoustic mapping (2016) in eelgrass acreage for Salem Harbor only.

Eelgrass extent, acres	1995	2001*	2006	2012	2016
Dense	---	0	8	2	---
Sparse	---	21	26	16	---
Questionable Mapped	---	0	0.3	3	---
Questionable Unmapped	---	33	56	26	---
DMF Total Estimate	---	54	90	48	51
DEP Total Estimate	109	21	36	21	---

*very poor imagery

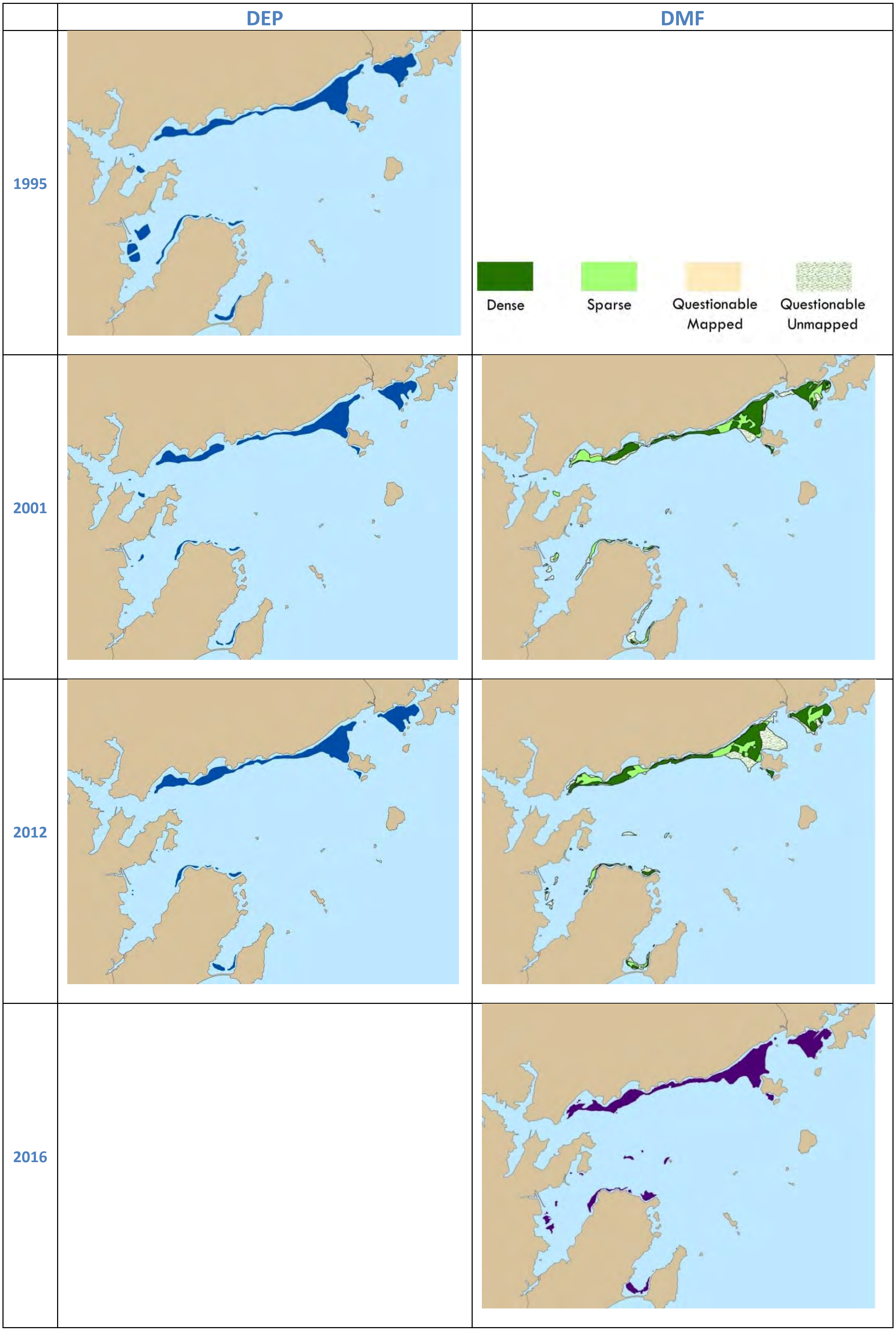


Figure 11. Results of photo-interpretation for 1995, 2001 and 2012, and combined 2016 acoustic survey/photo-interpretation. In 1995 and 2016 density classes were not assessed as there was no DEP imagery for those years.

While total acreage has been fairly stable embayment-wide (roughly 700 acres in 1995 and 2016), there were localized losses. Beds were completely lost in Collins Cove, Lobster Rocks, Marblehead, Hawthorne Cove, and inner Manchester Harbor since 1995 (Fig 11 and Appendix D). In Salem Harbor, there have been large reductions in individual bed size and extent since at least 1995. Based on historical imagery and NOAA charts (dated 1964), most of the shallow waters of inner Salem Harbor had eelgrass at some point prior to 1995. Now Salem Harbor has relatively small remnant beds in Palmer Cove, Derby Wharf, Cat Cove, and Winter Island; some of these beds are no longer mapped by DEP since they are below DEP's minimum mapping unit. A bed in Hawthorne Cove was present in 2006 (DMF analysis) but is thought to be gone now. Eelgrass gains were dominated by improved mapping of the deep edge between West Beach and Great Misery Island during the 2016 acoustic survey, which was corroborated by the Biosonics mapping work that DMF conducted in 2013. The 2013 survey confirmed that eelgrass extended beyond the DEP 2012 polygon and verified the existence of patchy regions in the center of the bed (Fig 12). Additional gains were attributed to the opportunistic identification of beds not previously mapped at Great Aquavitae and Coney Island, and the restoration of a bed a Middle Ground. There is no evidence of substantial eelgrass expansion. The DOT aerial images showed beds present as far back as 1931 along the Beverly coastline, and other beds that have lost acreage since the 1950s including Salem Harbor (Fig 13) and parts of Manchester Harbor (Fig 14). A detailed assessment for each bed and harbor is in Appendix D.

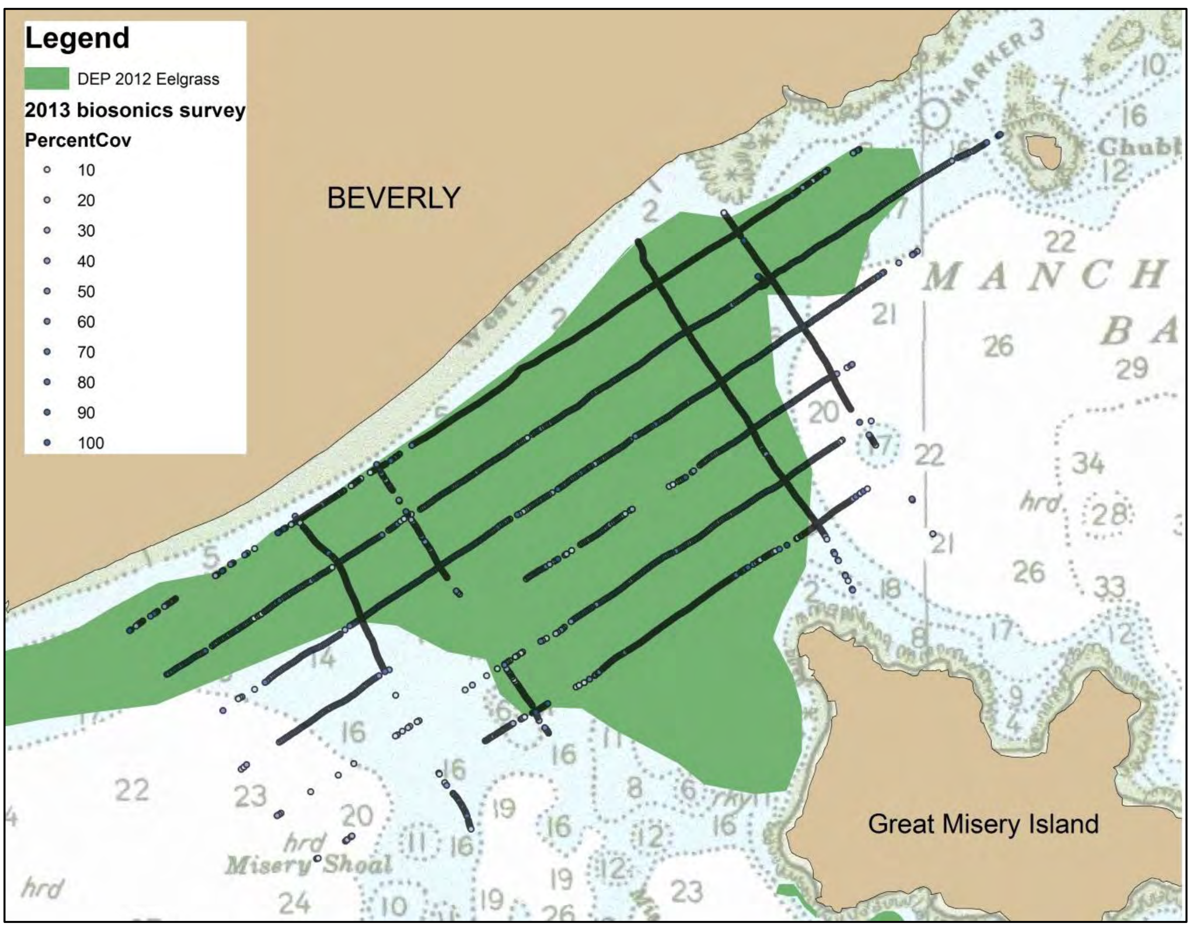


Figure 12. Map of 2013 Biosonics survey results at West Beach, Beverly where each dot is a sonar ping that detecting eelgrass presence and percent cover.

Figure 13. Aerial imagery of Cat Cove, Salem Harbor from 1954 (DOT) and 2012 (DEP) showing approximate eelgrass edge (yellow).

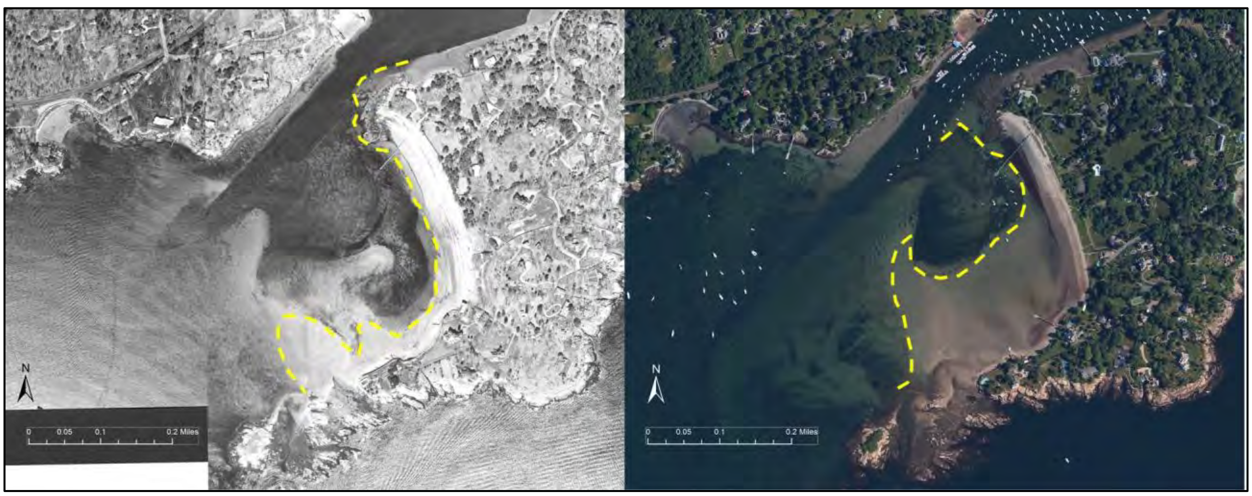


Figure 14. Aerial imagery of Manchester Harbor from 1957 (DOT) to 2014 (USDA) showing approximate eelgrass edge (yellow).

Historical accounts of mapping and/or sampling in Salem Sound include the following:

- In 1967, as part of an estuarine study and report of Salem Sound, DMF conducted a marine vegetation survey (Jerome et al. 1967). The report does not include any mention of eelgrass, though it existed in the embayment at that time. This omission is due to the sampling methods used in the survey, which involved sampling algae from shore at shallow intertidal areas and trawled samples from limited subtidal sites.
- A follow-up study done by Chase et al. (2002) noted eelgrass beds off Beverly Cove. Eelgrass was found in both the trawl and beach seine surveys at this location. This site overlaps with the DEP 1995 eelgrass polygons.
- Eelgrass morphology was studied by Wilbur et al. (2005) at West Beach and Palmer Cove, and by Lent et al. (1998) at West Beach, Mingo Beach and Beverly Cove.
- Eelgrass beds have been mapped by coastal construction applicants as part of various permitting processes (e.g. AECOM for the SESD pipeline, discussed herein).

Biotic variables

Wasting disease

Several wasting disease data points exist for Salem Sound, but none have long time series. Wilbur et al. (2005) monitored eelgrass at West Beach, Beverly and Palmer Cove, Salem Harbor and noted trace (0-1%) to low (2-30%) levels of wasting disease at both sites in 2004. DMF has noted trace levels since the onset of monitoring the West Beach meadow in 2008 (DMF unpublished data). Lent et al. (1998) monitored eelgrass at three Beverly sites (West Beach, Mingo Beach and Beverly Cove) in addition to six other Massachusetts Bay sites and found a low incidence of wasting disease across all meadows, but found two of the three highest average levels at Mingo Beach and Beverly Cove. Mingo Beach had mean wasting disease indices of 8% with a mean maximum percent wasting disease of 33.9%. Beverly Cove had mean wasting disease indices of 4% with a mean maximum percent wasting disease of 27%. Forest Schenck reported that at West Beach, 69% of shoots showed signs of wasting disease with an average percent cover of lesions of 8% and at Lynch Park/Woodbury Point 30% of shoots showed signs of wasting disease with an average percent cover of lesions of 4% (Forest Schenck, Northeastern University, pers. comm.). Short et al. (1993) reported mass mortalities where mean incidence was greater than 8%. Based on the continued long-term presence of healthy eelgrass off Mingo Beach, Beverly Cove, and West Beach based on DEP and DMF mapping and monitoring, any potentially deleterious effects of wasting disease are not thought to be of concern in these locations. It is thought that there is a sustainable level of wasting disease that a healthy bed can endure without measureable impacts to extent or density (Forest Schenck, Northeastern University, pers. comm.). In addition to wasting disease metrics, interactions with other variables should be considered. Bull et al. (2012) found that wasting disease can interact with higher water temperatures to limit the growth of eelgrass.

Predators

Lent et al. (1998) found incidence of herbivory by snails at Beverly monitoring sites was within the range of values previously reported at Gloucester and Boston sites by Chandler et al. (1996)(1-12% of leaf area). Herbivory tended to be concentrated in the "optimal growth zone" (e.g. not the shallowest or deepest parts of the bed) and was positively correlated with eelgrass density. The Beverly sites had the highest incidences of herbivory of all sites in this study. DMF has noted snail grazing since the onset of monitoring at West Beach since 2008. Typically, observed snail abundance peaked in July and October monitoring (DMF unpub. data).

Green crab foraging and bioturbation have been associated with eelgrass loss in other New England embayments (Neckles 2015). Green crabs have been observed by Salem Sound Coastwatch during MIMIC sampling at each of nine intertidal sampling sites since the onset of monitoring in 2008. Similarly, DMF has documented green crabs at the West Beach eelgrass meadow since monitoring began in 2008 with no observable trends in population size or evidence of impacts to the meadow. DMF also regularly observes burrowing behaviors of lobsters, native cancer crabs and green crabs at eelgrass reference and restoration sites in Salem Sound (DMF unpub. data). The only substantial invasive species changes observed in Salem Sound by the MIMIC program are the detection of European rockpool prawn (*Palaemon elegans*) in 2010 and a potential expansion of existing European Oyster (*Ostrea edulis*) populations after 2012. Neither species is expected to significantly affect eelgrass due to habitat preferences and diet.

Salem Sound also supports birds that graze on eelgrass including brant and Canada geese, American wigeon, and redhead and black ducks. Grazing by a brant goose was documented at the DMF SeagrassNet site (T. Evans, DMF, pers. comm.). Salem Sound Coastwatch has conducted waterfowl surveys every winter since 2010 and some baseline survey data were collected by R. Buchsbaum in 1988. These data were not analyzed.

Abiotic variables

Temperature

Eelgrass optimal temperature

At the West Beach bed, long-term temperature records do not exceed the optimal eelgrass temperature range of 50-77°F (Fig 15, Table 1). These data were also reviewed by the regional SeagrassNet working group and they speculate that temperature is not likely a primary stressor at this site (Tay Evans, DMF, pers. comm.).

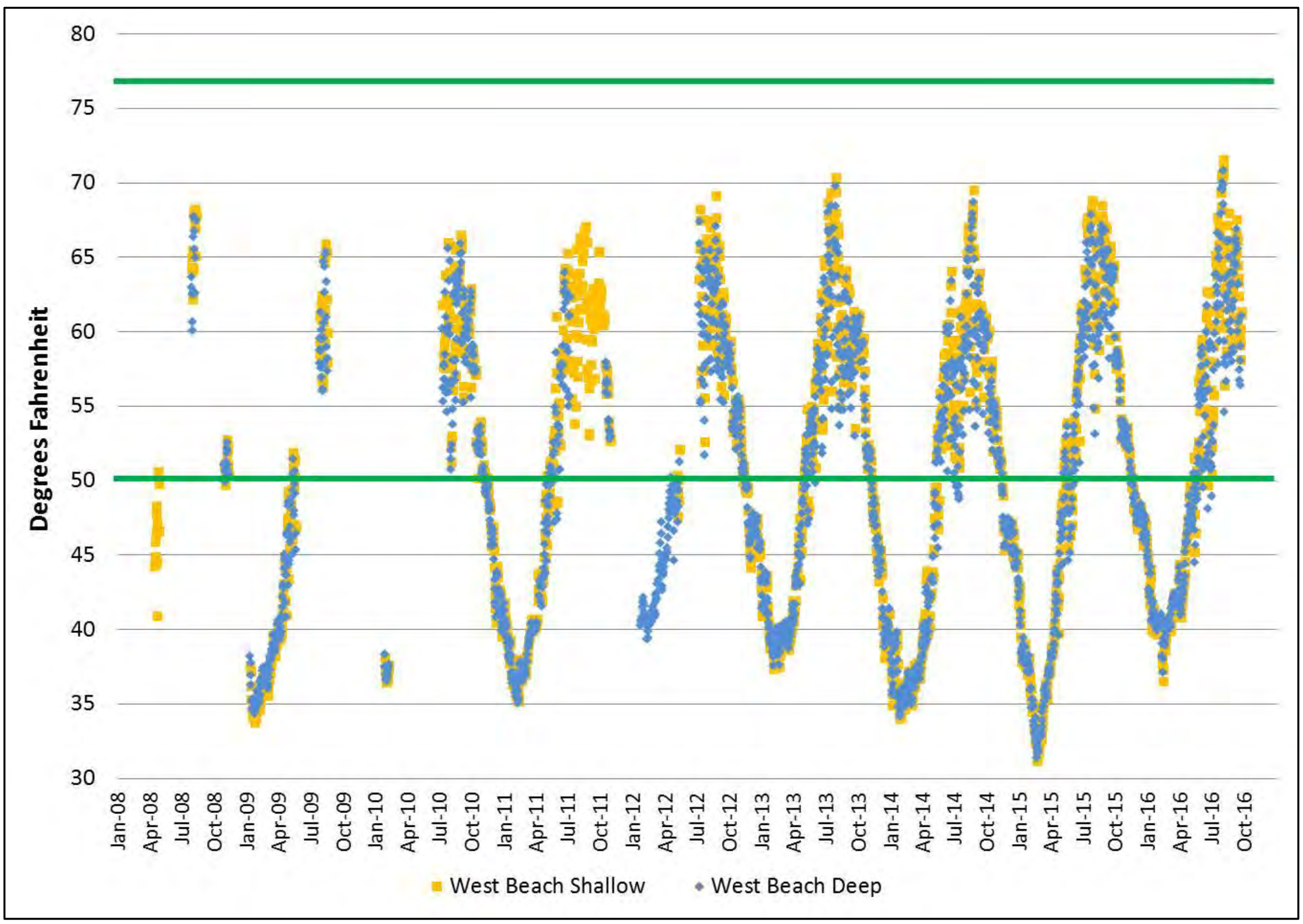


Figure 15. SeagrassNet average daily temperature data at the shallow and deep monitoring transects. The upper and lower optimal temperature limits (50-77F, Table 1) are shown in green.

Annual and summer averages

The average annual water temperature at Outer Boston Harbor and Mass Bay showed significant warming over time and Inner Boston Harbor showed significant cooling over time (Fig 16, Table 6). The cooling trend is found in the longest dataset, and is driven by a very high average temperature in 2002 driven by a strong El Niño episode. Record temperatures and drought were documented globally (Waple and Lawrimore 2003). Summers (Jun, Jul, Aug) are warming significantly in four of five datasets: Outer Boston Harbor, Mass Bay surface, Mass Bay bottom, and Beverly Harbor (Table 6).

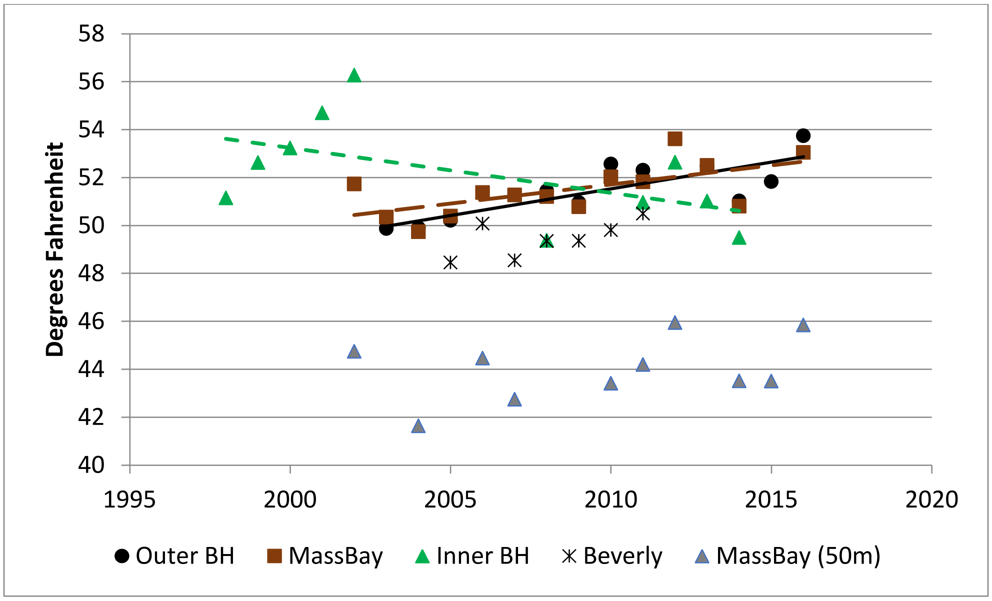


Figure 16. Annual average temperatures over time. Significant trends are indicated by trend lines (outer BH, Mass Bay, and Inner BH).

Table 6. Linear model results for changes in temperature over time at six stations.

Station	Outer Boston Harbor (surface)		Mass Bay (surface)		Inner Boston Harbor (surface)		Beverly Harbor (bottom)		SeagrassNet A (bottom)		SeagrassNet C (bottom)	
Years	2002-2016		2002-2016		1997-2015		2004-2012		2009-2016		2009-2016	
Month	slope (°F/yr)	p-value	slope (°F/yr)	p-value	slope (°F/yr)	p-value	slope (°F/yr)	p-value	slope (°F/yr)	p-value	slope (°F/yr)	p-value
Jan	+0.2	0.02										
Feb	+0.2	0.02			-0.3	0.07						
Mar							+0.6	0.02				
Apr												
May	+0.2	0.002	+0.3	0.008			+0.7	0.003				
Jun							+0.5	0.01	-0.8	0.03	-0.8	0.01
Jul	+0.2	0.06	+0.2	0.03								
Aug	+0.2	0.02					+0.5	0.02	+0.67	0.06		
Sep	+0.2	0.06			-0.3	0.06	+0.6	0.05				
Oct	+0.2	0.01					+0.95	0.09				
Nov	+0.3	0.0001	+0.2	<0.0001	-0.2	0.03						
Dec	+0.3	0.005	+0.2	0.02								
Summer	+0.2	0.03	+0.1	0.09			+0.5	0.0003	n.a.		n.a.	
Annual	+0.2	0.002	+0.14	0.01					n.a.		n.a.	

Values with a p-value >0.1 not reported since results not considered significant. n.a. indicates fewer than 5 years of data were available, so trends were not analyzed.

The monthly average water temperature analyses showed that November had the strongest linear increase in Outer Harbor and Mass Bay (Fig 17). Most months are increasing in most datasets, but decreases of 2-3°F were found at Inner Boston Harbor and 8°F degrees at the SeagrassNet site (Table 6).

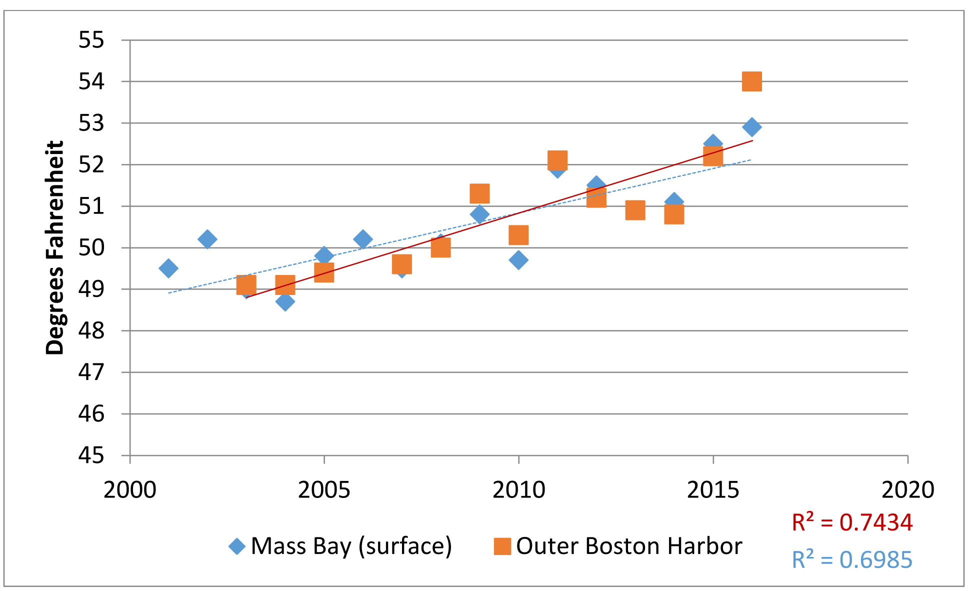


Figure 17. Mass Bay and Outer Boston Harbor average November temperatures.

Seasonal onset

For the stations in Inner Boston Harbor, Outer Boston Harbor, Mass Bay surface, and Beverly Harbor, we tested for significant differences between the onset of spring and winter over time. At Outer Boston Harbor, Mass Bay, and Beverly Harbor we found earlier springs and later winters. Inner Boston Harbor showed later springs and earlier winters (Table 7).

Table 7. Onset of spring and winter water temperatures

		Spring onset			Winter onset		
Station	**Years**	**Direction**	**Magnitude**	**p-value**	**Direction**	**Magnitude**	**p-value**
Outer Boston Harbor (surface)	2002-2016	Earlier spring	11 days/decade; late May to mid-May	0.02*	Later winter	17 days/decade; mid Nov to early Dec	0.002*
Mass Bay (surface)	2002-2016	Earlier spring	10 days/decade; late May to mid-May	0.01*	Later winter	17days/decade; mid Nov to early Dec	<0.001*
Inner Boston Harbor (surface)	1997-2015	Later spring	5 days/decade; early May to 1 wk later	0.27	Earlier winter	7 days/decade; late Nov to mid Nov	0.11
Beverly Harbor (bottom)	2004-2012	Earlier spring	18 days/decade; early June to mid-May	<0.001*	Later winter	2 days/decade; early Nov to mid Nov	0.7

**Significant*

Light availability and water quality

PAR data

Data from stations within Salem Sound were used to conduct a local-scale analysis of in-water light availability and assess other factors that could influence light availability in the embayment. Li-Cor and HOBO data were collected by DMF at the SeagrassNet monitoring site off West Beach and at several eelgrass restoration sites in Beverly (Woodbury Point) and Salem (Middle Ground, Juniper Cove). The SeagrassNet site percent light ranged between 18 and 24% (based on PAR) between sampling in 2011, 2014 and 2016 with a Kd of 0.30. In 2012, all restoration sites sampled had greater than 15% light (based on PAR) at the canopy and Kd values between 0.41 to 0.47 (Fig 18).

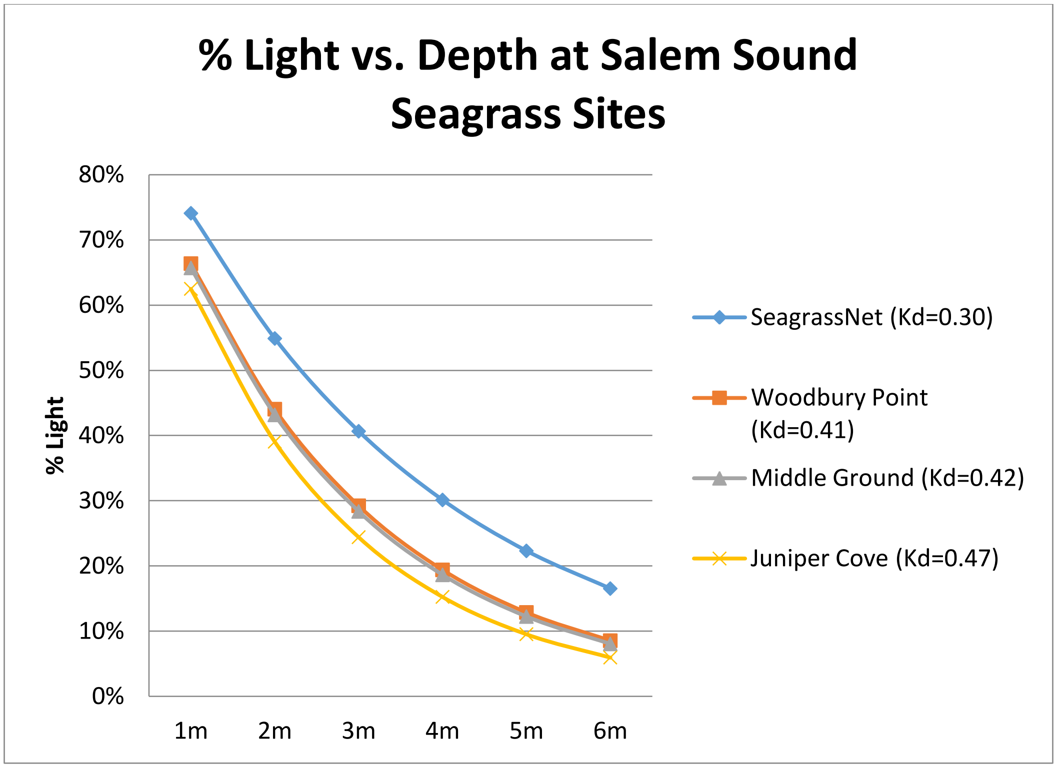


Figure 18. Light extinction curves for sites in Salem Sound.

EPA also measured light extinction and found a strong relationship between light extinction and intensity of impact at eelgrass beds (Liebman 2013) (Fig 19).

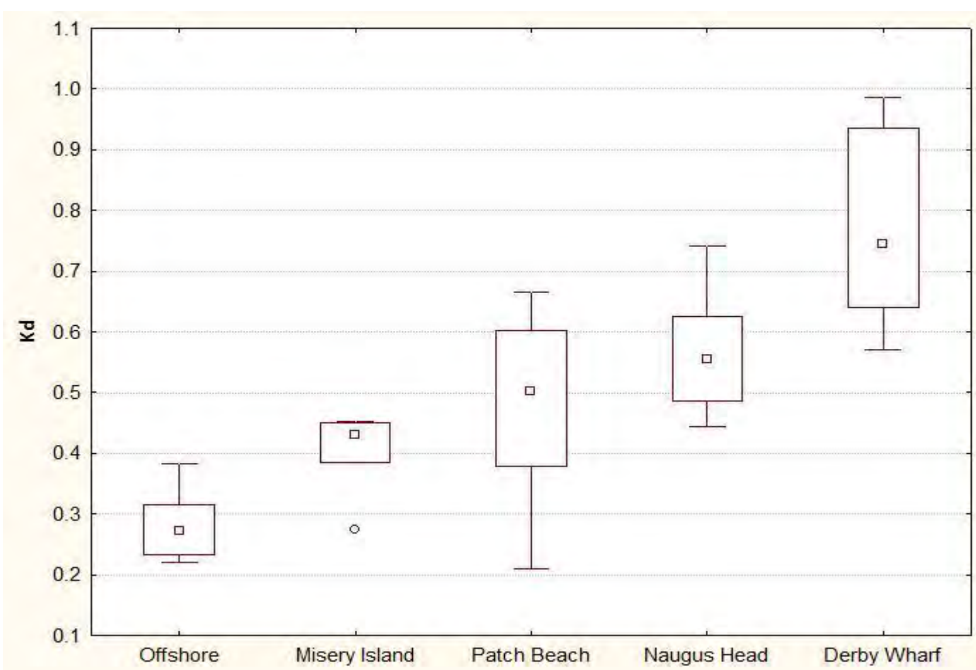


Figure 19. Light extinction compared to intensity of impact at eelgrass beds (from Liebman 2013). Figure reproduced with permission.

HOBO light data

The continuous logging at the SeagrassNet station occurred at a shallow station (Site A, 3 m/10 ft MLW) and a deeper station (Site C, 4 m/13 ft MLW). There were higher light levels at the shallow station and conditions are clearest in the wintertime and most turbid in the summertime (Fig 20).

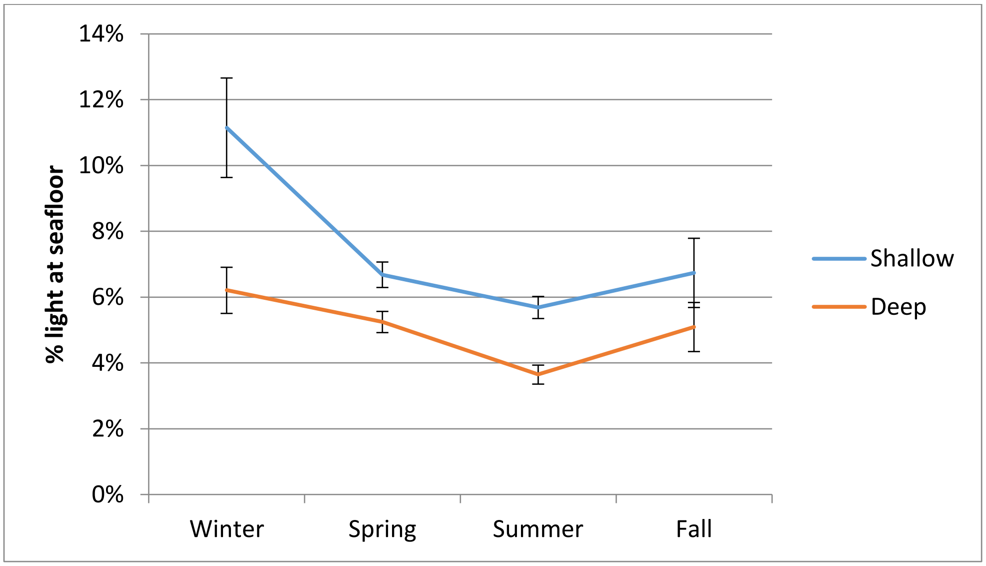


Figure 20. Percent light at the top of the canopy, averaged for each season, plotted with standard error bars.

Turbidity and secchi depth data

Deeper stations have deeper secchi depths (Fig 21). But the shallower stations have higher index values, meaning that light is getting to the bottom at Salem 2, Danvers River, and Beverly Harbor (Fig 22). Late spring and summer had the lowest secchi index values (no winter data) (Fig 22).

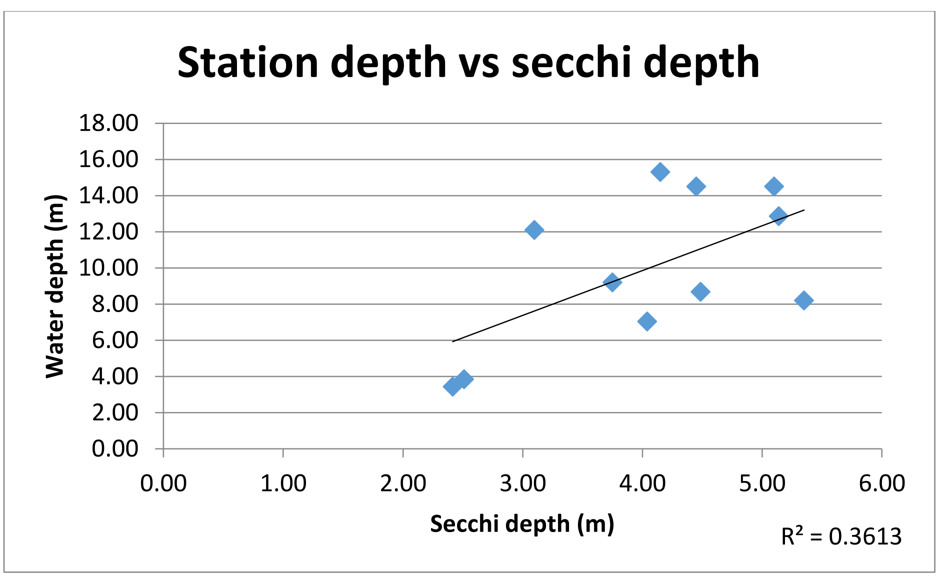


Figure 21. Station depth vs. secchi depths using both EPA and SSCW monitoring data (2010/2011).

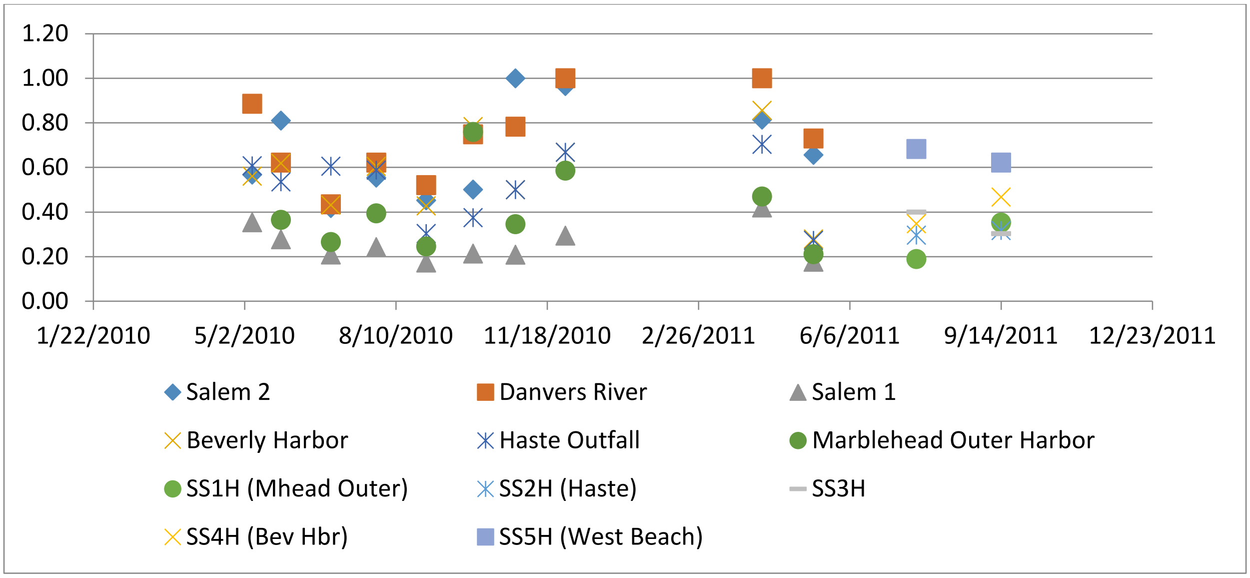


Figure 22. Secchi index (secchi depth/station depth) for both EPA and SSCW stations in Salem Sound.

We compared secchi depth measurements taken at low tide with high tide (2.75 m/ 9 ft mean tide range). Some stations were clearer at low tide; some were clearer at high tide. Differences were on the order of 0.5 meters (Table 8).

Table 8. Secchi depth measurements low tide vs. high tide. Negative values mean water clarity was clearer at low tide, positive values mean water clarity was clearer at high tide.

Row Labels	SS1	SS2	SS3	SS4	SS5
07/20/2011	-0.6	-0.5	0.1	-0.7	
09/14/2011	-0.5	0.4	0.4	0.7	-0.2

Chlorophyll *a*

The chlorophyll *a* data were consistent across the datasets with values in the 0-6.5 µg/L range (Figure 23). Concentrations were higher in fall sampling (note there was no sampling between November and May).

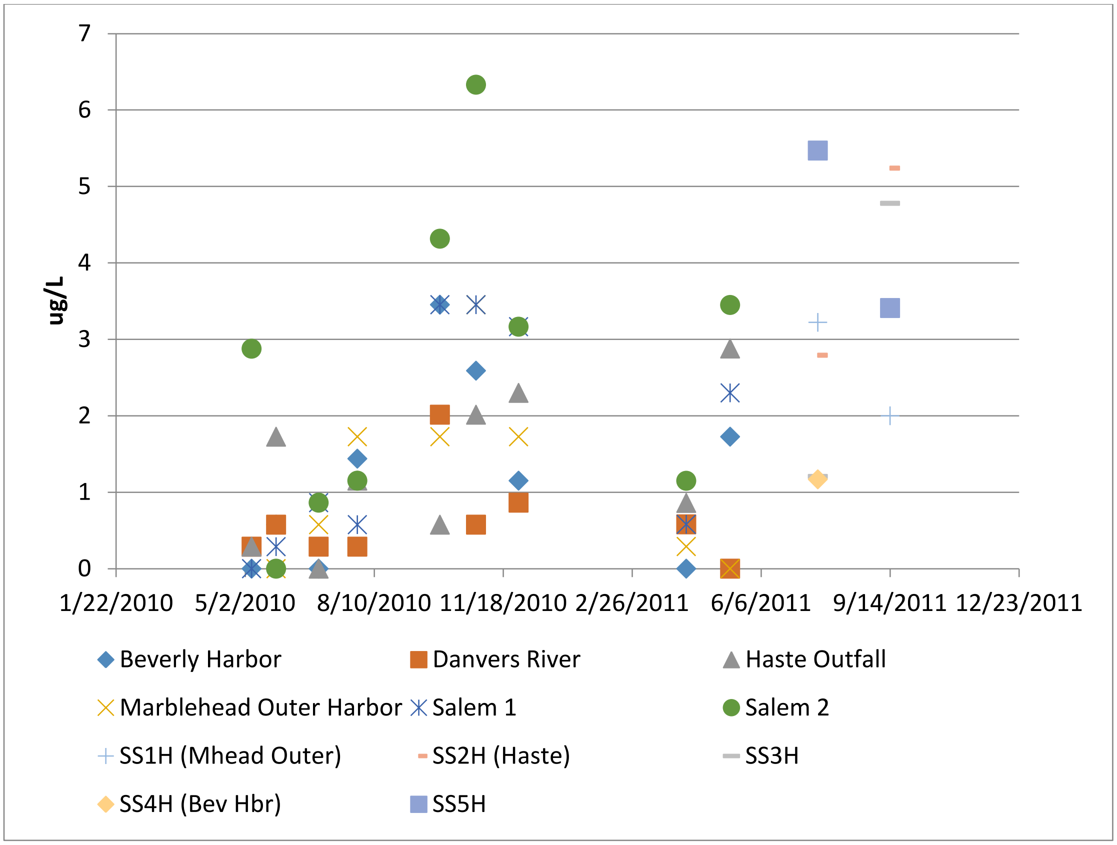


Figure 23. Surface chlorophyll *a* samples from both Salem Sound Coastwatch and EPA monitoring.

Chlorophyll *a* values were higher at the bottom than at the surface except at Salem 2 (Table 9).

Table 9. Surface vs. bottom chlorophyll *a* concentrations. Negative values mean more chlorophyll *a* at the seafloor, positive values mean more chlorophyll *a* at the surface.

Surface-bottom	5/7/2010	5/26/2010	7/28/2010	9/30/2010	10/28/2010	11/30/2010	4/9/2011	5/13/2011
Beverly Harbor	-0.58	-0.29	-1.15	1.15	-1.73	-0.29	-0.86	-2.01
Danvers River	-0.29	0.58	-0.58	0.58	-1.15	-2.59	-0.86	-0.86
Haste Outfall	-3.17	1.44	0	-1.44	-1.73	-2.02	-0.29	-1.44
Marblehead Outer Harbor	0	0	-0.29	0	2.30	1.15	-2.59	-4.03
Salem 1	-0.86	0	-0.58	0.29	1.44	1.44	-0.86	-1.61
Salem 2	2.88	-0.86	-1.44	0.58	1.44	1.44	0.57	-1.44

We compared total chlorophyll *a* measurements taken at low tide with high tide (2.75 m/9 ft mean tide range). Most stations had less chlorophyll *a* at low tide, but the differences were small (Table 10).

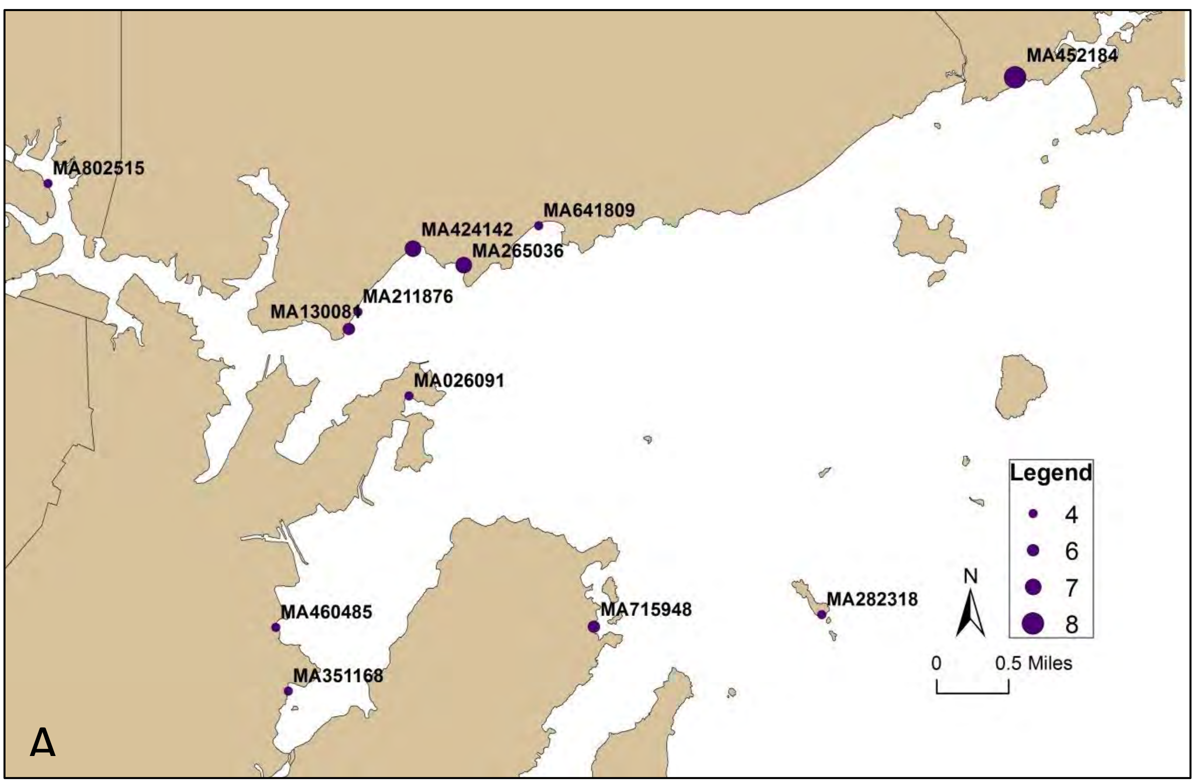
Table 10. Chlorophyll *a* concentrations low tide vs. high tide. Negative values mean less chlorophyll *a* at high tide, positive values mean more chlorophyll *a* at high tide.

	SS1	SS2	SS3	SS4	SS5
7/20/2011	-0.60	0.89	0.15	1.27	-0.23
9/14/2011	-0.20	1.72	1.09	0.65	2.06

Bacteria

Salem Sound is classified by DEP as a Pathogen-Impaired estuary based on pathogen Total Maximum Daily Load (TMDL) sampling at dozens of sites throughout the individual harbors and tributaries (MADEP 2012, 2014). There are 21 segments impaired for indicator bacteria in the embayment. Primary bacteria sources include stormwater runoff, failing septic systems, pet and animal waste, and illicit sewer connections. DEP prioritized nearly 20 segments in Salem Sound as needing more monitoring and rectification of the source of pathogens, including tributaries, public swimming areas and numerous segments with potential illicit discharges.

Enterococcus data were available at 36 stations in Salem Sound from 2003-2011. Five stations (MA452184, MA715948, MA424142, MA265036, MA130081) had six or more days/summer when the station measurement exceeded 104 cfu/100 mL, the single sample water quality standard for safe swimming (MA 105CMR445 2017). Stations MA424142 and MA802515 had the highest measured concentrations (24,000 cfu/100 mL in 2009 and 2007, respectively). There was no clear spatial pattern associated with high concentrations of bacteria (Fig 24).



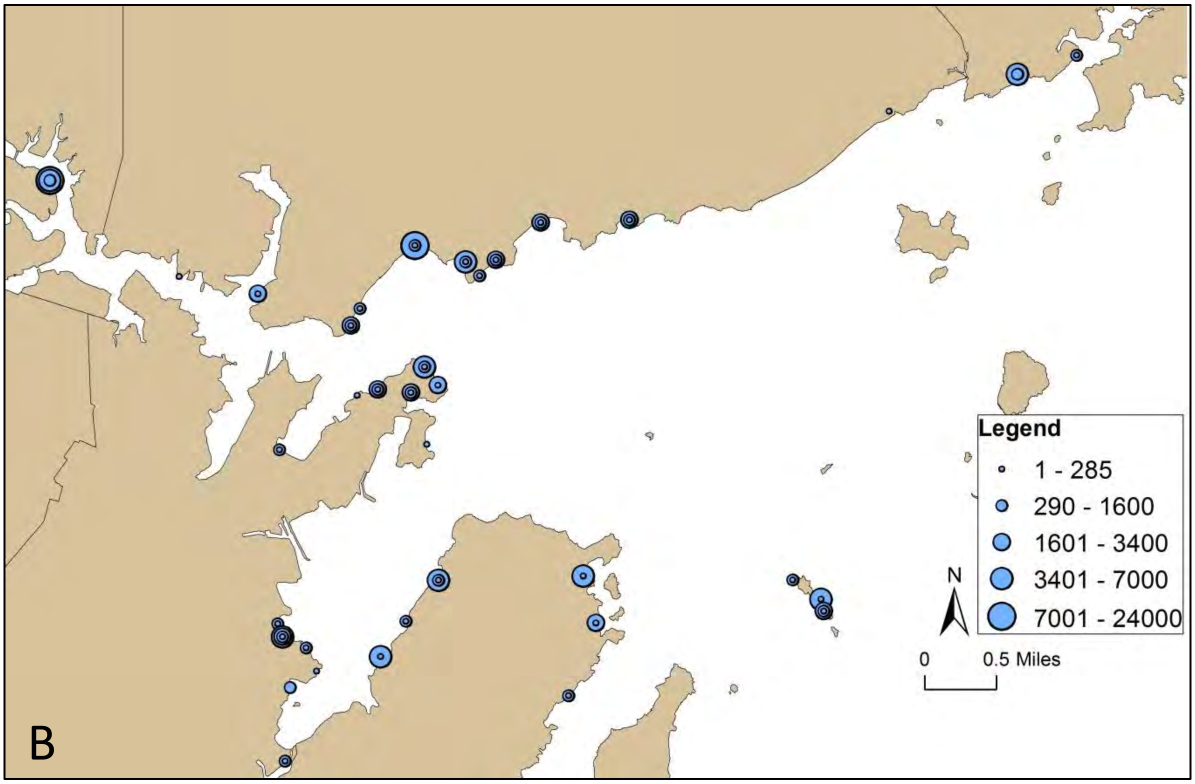


Figure 24. A) Maximum number of days/year a station exceeded the safe swimming threshold between 2003-2011. B) *Enterococcus* station data from 2003-2011 in cfu/100mgL.

Over time, there has been an increase in the number of days per summer when the safe swimming threshold is exceeded (Fig 25).

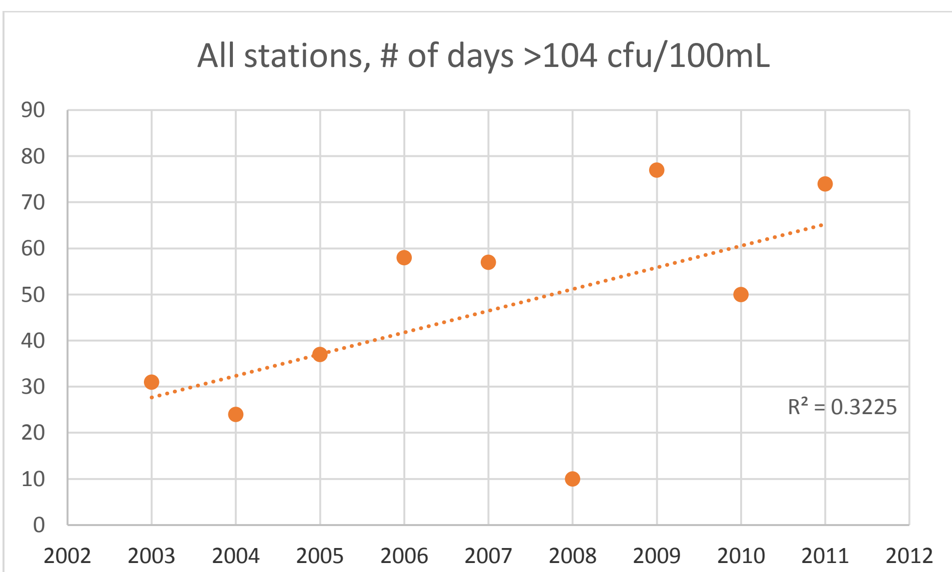


Figure 25. Number of days when *Enterococcus* safe swimming threshold is exceeded shown.

The DMF Shellfish Program also monitors bacterial water quality (via fecal coliform). Pollution from sewage beyond safe shellfish consumption levels led to most shellfish growing areas in Salem Sound being designated as Prohibited to the harvest of shellfish in 1925 and all were closed by 1971. Most recently, water samples collected in 2016 demonstrated that water quality still does not meet standards for either commercial or recreational harvest (D. Winkler, DMF, pers. comm.).

Precipitation

There was no significant trend in annual average precipitation from 1985-2016 at the Marblehead CO-OPs station. In June and December there were positive trends that were significant at a 0.1 level. In September and November there were negative trends that were significant at a 0.1 level. The magnitude of differences was small, between 0.05-0.17 inches from the start to the end of the time series (Table 11).

Table 11. Annual average precipitation by month from 1985-2016, Marblehead

	n	Min(in)	Max(in)	Mean(in)	SD	slope	p-value
Jan	30	0.02	0.31	0.12	0.06	-0.0007	0.59
Feb	32	0.03	0.28	0.12	0.06	0.0015	0.16
Mar	32	0.02	0.53	0.15	0.10	0.0007	0.71
Apr	32	0.03	0.42	0.14	0.09	-0.0010	0.57
May	31	0.02	0.53	0.12	0.09	0.0005	0.78
Jun	32	0	0.37	0.14	0.09	0.0031	0.07*
Jul	32	0.03	0.25	0.12	0.06	0.0003	0.80
Aug	32	0.03	0.31	0.12	0.07	-0.0010	0.45
Sep	32	0.04	0.28	0.12	0.08	-0.0024	0.09*
Oct	32	0.01	0.37	0.15	0.09	0.0027	0.14
Nov	32	0.03	0.3	0.14	0.07	-0.0026	0.04*
Dec	31	0.04	0.29	0.14	0.06	0.0024	0.05*
Annual	32	0.09	0.17	0.13	0.02	0.0003	0.41

**Significant*

Acute Turbidity Events

Turbidity is caused by both phytoplankton blooms and sediment suspension. Hubeny concluded that phytoplankton blooms dominate the suspended sediment load in Salem Sound (Hubeny et al. 2017a). Acute turbidity events are poorly documented but can be linked to storms and anthropogenic impacts such as coastal construction activities that disturb the seafloor. Google Earth imagery was used to document a turbidity event along the west shore of Marblehead in 2000 (Fig 26). It is not clear what caused this turbidity event.

Figure 26. Turbidity event along the west shore of Marblehead, Salem Harbor. Google Earth 2000 image.

A turbidity plume around the work area of the 2015 SESD pipeline trenching project was also documented using Google Earth imagery (Fig 27). In October 2013, prior to the trenching project that would extend from Cat Cove to the west shore of Marblehead, SESD measured eelgrass in the planned trenching area and adjacent 100-meter buffer area to either side of the centerline. The 2013 survey found a small patch (<13 square feet (sf)) within the construction footprint, and several larger beds (54,752 sf) in the buffer area. They also identified a bed off Cat Cove (AECOM 2013, Appendix E, "Area 3") where DMF found only bare rocky bottom in the 2016 acoustic mapping. During construction, which occurred in 2015, a turbidity plume extended past the turbidity curtain into the mapped eelgrass areas (Fig 27). A post-construction eelgrass survey in October 2015 found that the small eelgrass patches closest to the work area were absent but numerous new small patches emerged resulting in an overall increase in eelgrass in the survey area, and SESD concluded no permanent impact to eelgrass (Appendix E, AECOM 2015). DMF acoustic mapping in 2016 did not identify any eelgrass patches in the area SESD surveyed along the west shore of Marblehead in the Naugus Head meadow (Appendix E, Areas #5 through #12), however there is a chance the acoustic survey missed these areas if density was too low for detection. While there are differences in the mapping of small patches between the SESD survey and the DMF acoustic survey, the larger continuous eelgrass meadow polygons drawn by both surveys do align closely. The pipeline trench and backfill areas resulting from the pipeline replacement were apparent in the sonar imagery (Fig 28).

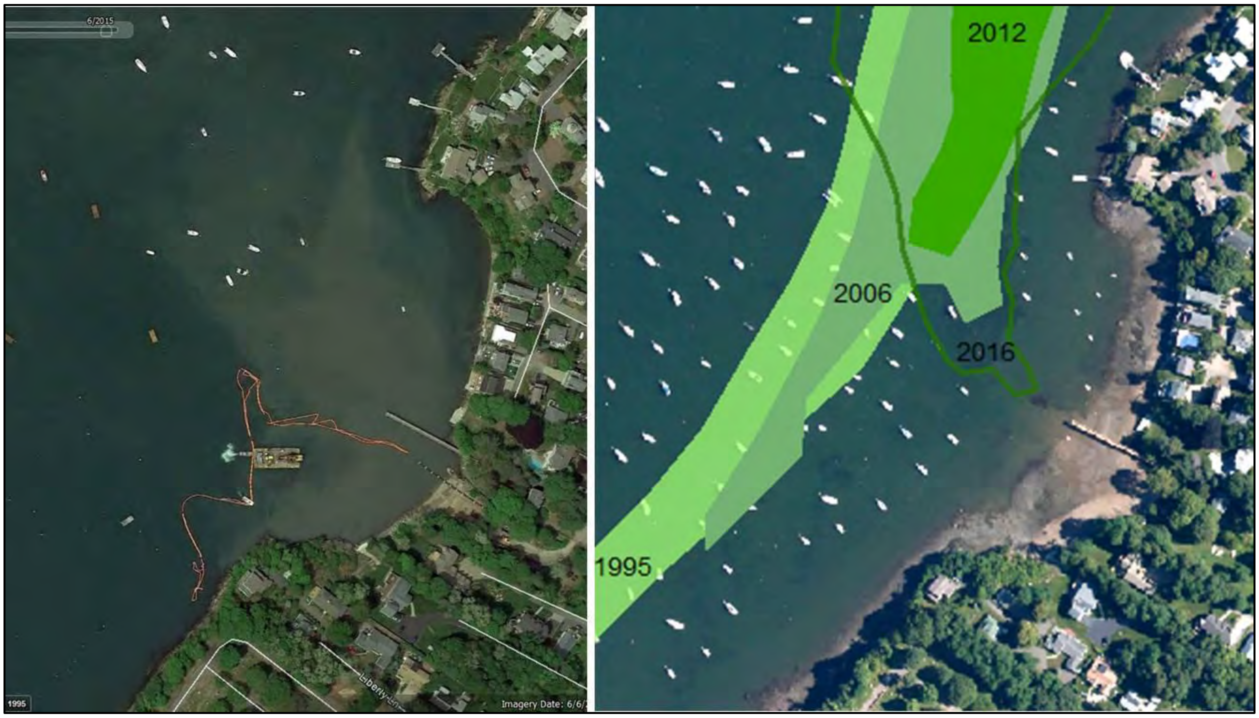


Figure 27. Turbidity plume caused by 2015 SESD trenching work (left) within historic and existing eelgrass areas

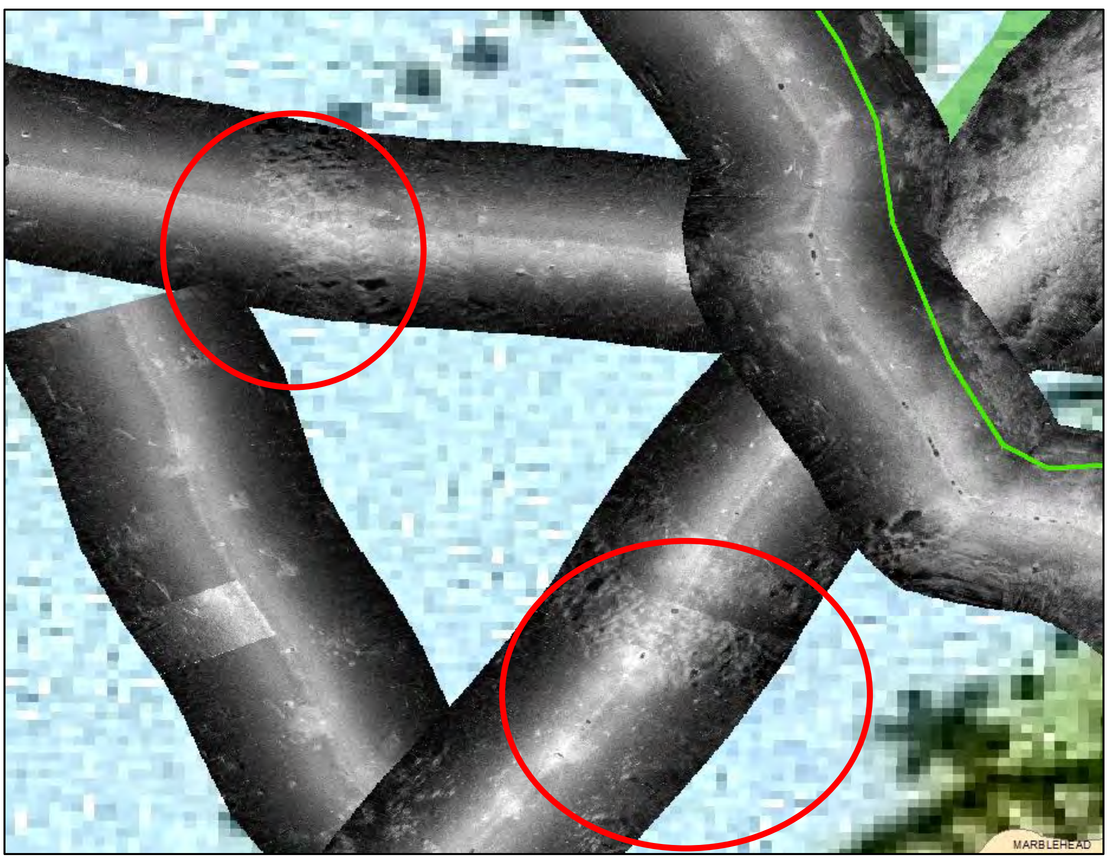


Figure 28. SESD pipeline trench and backfill areas (red circles) detected in the sidescan survey data (grey swath lines) near the 2016 eelgrass area (green line).

Physical impact

In 1997 a total of 5,605 assigned boat moorings and registered slips were reported by the harbormasters of Manchester, Beverly, Danvers, Salem and Marblehead (Chase et al. 2002). In 2017, harbormasters reported that the number of boat moorings and slips in these towns has increased to 6,600, an 18% increase in 20 years. Marblehead and Manchester experienced the greatest increases (45%, 26% respectively) and Beverly experienced a loss of moorings and slips (-24%) (Table 12). Impacts to eelgrass caused by boating include direct loss of habitat from moorings and docks, shading from boats or related structures, propeller and keel scouring, and increased turbidity. Specifically, direct loss of eelgrass occurs where the anchor or mooring block is placed in eelgrass and the chain scours the seafloor during tidal changes, creating a circular or oblong scar that is visible in aerial imagery. Based on 2013 and 2014 Google Earth imagery, we estimate that 400-500 moorings are currently located within mapped eelgrass beds in Salem Sound. In Manchester, mooring monitoring studies have found that the average mooring scar size is 40-50 m^2 (Evans 2012, DMF unpub. data), resulting in an estimated 4-6 acres of eelgrass loss from mooring scars in the 2013-2014 time frame.

Table 12. Number of moorings and boat slips by town

	Manchester	Beverly	Danvers	Salem	Marblehead	Total
1997	670	765	810	1370	1990	5605
2016	841	580	750	1541	2888	6600
Change	26%	-24%	-7%	12%	45%	18%

Another potential source of direct physical impact is permitted coastal alteration projects, including commercial and residential developments, marine pipelines, marinas, and dredging. Since 2006, there have been at least 20 dredging projects either completed or currently underway throughout the embayment (B. Boeri, Mass CZM, pers. comm.). DMF’s Technical Review database recorded nine dredging projects reviewed in Salem Sound between 2013 and 2016. Other notable projects identified in DMF’s database between 2013 and 2016 include hard shoreline projects like seawalls (33 projects), docks and piers (22), and placement of fill (7). In the same time period, numerous projects were reviewed that would specifically have impacts to eelgrass (12 projects), coastal bank (48), intertidal (42) and streams (12). These counts represent projects that DMF reviewers commented on in the permitting phase; if or when the projects were completed is not recorded.

Motor boat use associated with recreational boating activity overlaps with eelgrass in Salem Sound. Transit routes cross eelgrass meadows in shallow and deep areas, with the heaviest concentration entering each of the harbors (Fig 29).

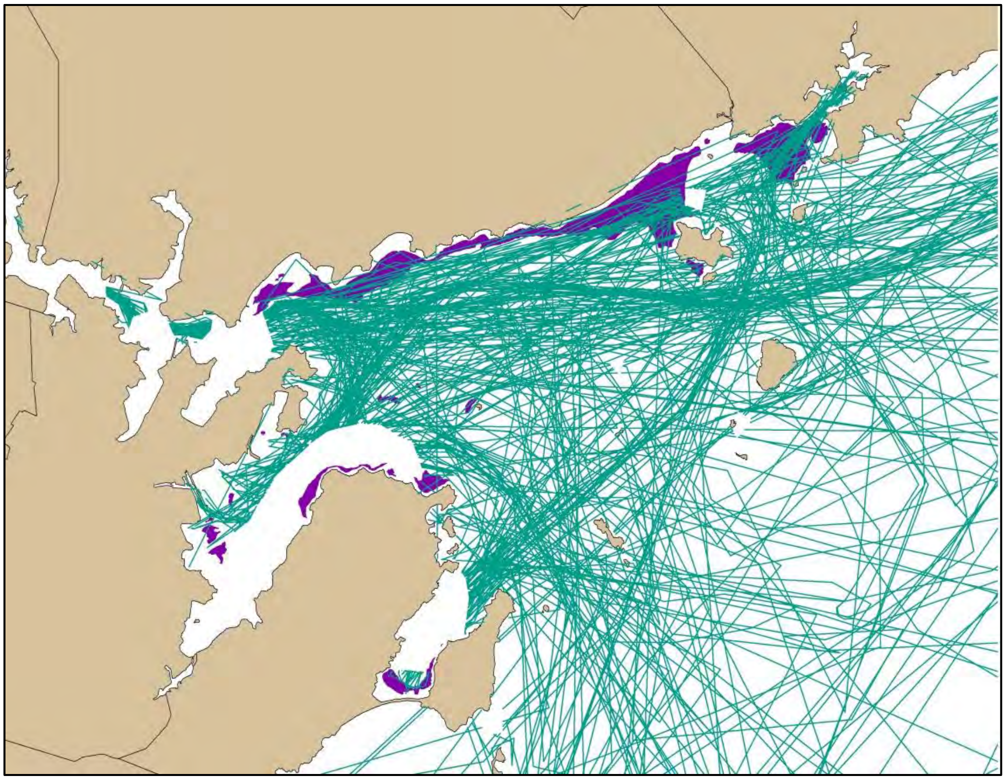


Figure 29. NROC recreational boater route data (2012) overlaid on 2016 DMF eelgrass layer.

In addition, fishing activity overlaps eelgrass beds. There is a long history of commercial and recreational fishing in Salem Sound. Target species include lobster, mackerel, striped bass, sea urchin and others, using a variety of gears including rod and reel, traps, purse seines, weirs, and trawls (Chase et al. 2002). There are no available spatial data regarding the distribution of fishing activity. DMF has observed active and derelict fixed gear (lobster pots) within the SeagrassNet site at West Beach and throughout Salem Sound. In some cases, lobster gear is thought to have contributed to failure of eelgrass transplant plots planted for restoration, such as at Fort Pickering (Evans et al. 2013). Mobile gears such as otter trawls are prohibited from Salem Sound year-round under the DMF Inshore Net Regulated Areas and Mobile Gear Regulated Areas. No commercial marine aquaculture activity has occurred in Salem Sound in the past 20 years (C. Schillachi, DMF, pers. comm.). Shellfish harvest has been prohibited in much of the embayment since the 1920s (D. Winker, DMF, pers. comm.).

Wind could also be causing physical impacts in the Sound by affecting turbidity, circulation, and eelgrass bed exposure. We looked at changes in average annual wind speed and at the average number of wind events each to determine if either is changing over time. There was no significant change in annual wind speed or direction since 2000 (Fig 30). There was a significant, but small, increase in average annual wind gusts at Mass Bay (from about 13.5 to 14.0 kts) (Fig 31).

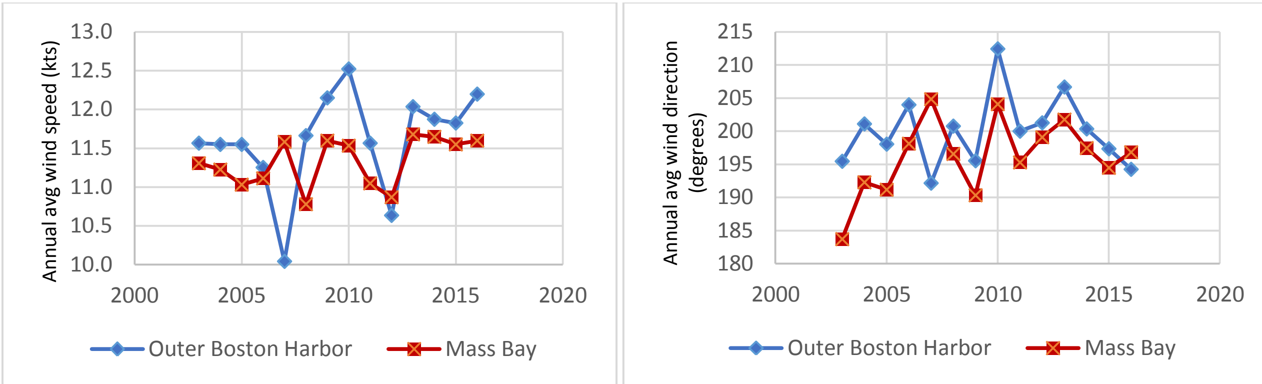


Figure 30. NERACOOS buoys annual average wind speed (kt) (left) and annual average wind direction (degrees) (right) from 2003-2016.

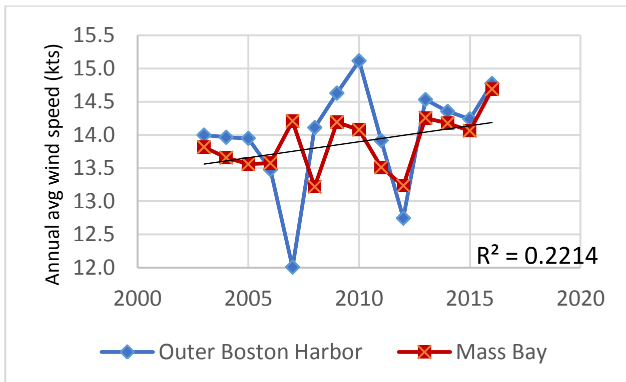


Figure 31. NERACOOS buoys annual average wind gust (kt) from 2003-2016. The trendline is for the Mass Bay station where a significant increase was measured.

To test if any month was getting increasingly windy, we compared the monthly average wind speed per month over time. There were no significant results with average monthly wind speeds. June had an increase in the average wind gust speed over the time series for the Outer Boston Harbor station (n=14, p=0.09), and May had a decrease in the average wind gust speed over the time series for the Mass Bay station (n=14, p=0.1). We also filtered the data to look at trends in high wind events, defined as a day with a maximum wind speed ≥22 knots. We found significant increases in the number of days/month with high wind events at the Mass Bay station in January, February, March, and November. February saw the greatest increase in number of days with wind events, from about 10 days/month to 20 days/month. We found a significant decrease in May, when the number of wind event days went from 6 days/month to 1 day/month. The results were significant only at the Mass Bay station but trends at Outer Boston Harbor were the same (Table 13).

Table 13. Monthly average wind speed changes over time (2003-2016)

	n	Min	Max	Mean	SD	slope	p-value
Jan	12	9	22	15.9	4.19	0.52	0.04*
Feb	12	8	21	14.8	4.13	0.70	0.002*
Mar	12	6	15	10.4	3.12	0.37	0.05*
Apr	13	3	10	6.5	2.37	0.13	0.40
May	12	1	7	3.3	1.83	-0.26	0.02*
Jun	13	0	3	1.6	1.26	0.07	0.37
Jul	15	0	2	0.5	0.64	0.03	0.42
Aug	16	0	7	1.1	1.78	0.10	0.30
Sep	16	0	4	2.1	1.24	0.01	0.85
Oct	15	2	11	7.6	3.22	0.16	0.41
Nov	15	3	17	9.8	3.86	0.38	0.08*
Dec	15	7	22	14.0	5.13	0.11	0.71

Ice and icebergs have the potential to scour eelgrass. We were unable to quantify changes in ice presence over time. Several harbormasters and stakeholders noted heavy ice events in some years (e.g. 2015) while in other years icing is minor, which is consistent with other embayments queried (Ford and Carr 2016). One boater documented extensive icing in 2004 in Marblehead Harbor (Appendix C). Some losses have occurred in areas most likely to experience contact with ice (e.g. shallow fringes along the eastern shores (in relation to the water) of Salem and Marblehead; shallow inshore bed at the mouth of Beverly Harbor), so it is possible that ice plays a role in localized losses, however no information is available regarding the timing and severity of ice events.

Discussion

Mapping

Since the 1995 eelgrass imagery was not available to re-examine and only Salem Harbor was mapped in 2006, the only coincident time points in the DEP and DMF analyses are 2001 and 2012. In that timeframe, DEP measured an eelgrass gain of 38 acres (7%) and DMF found a gain of 134 acres (19%). No changes in bed density patterns were observed between 2001 and 2012, however, it is possible that major density changes occurred prior to 2001 as evident in the historical DOT imagery especially in Salem and Manchester harbors. The large discrepancy between DMF and DEP areal coverage is attributed to differences in the resolution and minimum mapping units used. DEP generally only maps beds >0.1 ac and does not include small isolated patches or highly patchy areas in some cases. DMF's goal for this project was to identify any and all eelgrass visible using any of the available methods, with no minimum mapping unit. In spite of these differences, both assessments found an increase in overall eelgrass extent between 2001 and 2012. The majority of this increase is likely attributed to very poor image quality, and therefore difficulty implementing photo-interpretation methods, in 2001 (especially in Salem Harbor) compared to excellent image quality in 2012.

To determine eelgrass trends between 2012 and 2016, we compared our analysis of the aerial photography DEP collected in 2012 with in-water acoustic work and opportunistically available aerial photography collected in 2016. We found 125 fewer acres in 2016 than in 2012 (a 15% loss). Unfortunately, differences in the mapping methods between the two time points make it impossible to determine if this was an actual loss of eelgrass. The 2012 DMF eelgrass estimate was 847 acres compared to DEP's 566 acres (Table 2). The additional 280 acres in the DMF analysis came from more liberal mapping of areas with insufficient groundtruthing, as well as including areas that had DEP groundtruthing data identifying lower density or patchy eelgrass areas. For example, at West Beach, three 2012 DEP groundtruthing points found patchy eelgrass extending to the east beyond the eelgrass bed boundary delineated by DEP and the aerial imagery showed lower density eelgrass to the west that fell below their minimum mapping unit. The presence of grass in this area was further corroborated by DMF's 2013 Biosonics mapping exercise. DMF's 2012 photo-analysis redrew the boundary to include the groundtruthing points and the lower density eelgrass, increasing the size of this bed by 164 acres (Fig 31). For the 2016 acoustic survey, we targeted the 2012 DEP meadow boundaries so this meadow was not comprehensively mapped with side scan, and since it is a deeper bed, aerial imagery of this bed was poor. So this "expansion area" is not included in the 2016 acreage estimate, and we are not confident that any true loss occurred here between 2012 and 2016. Based on a thorough examination of the mapping data sources, it is more likely that the extent of eelgrass has remained stable, and differences are attributed only to mapping methods.

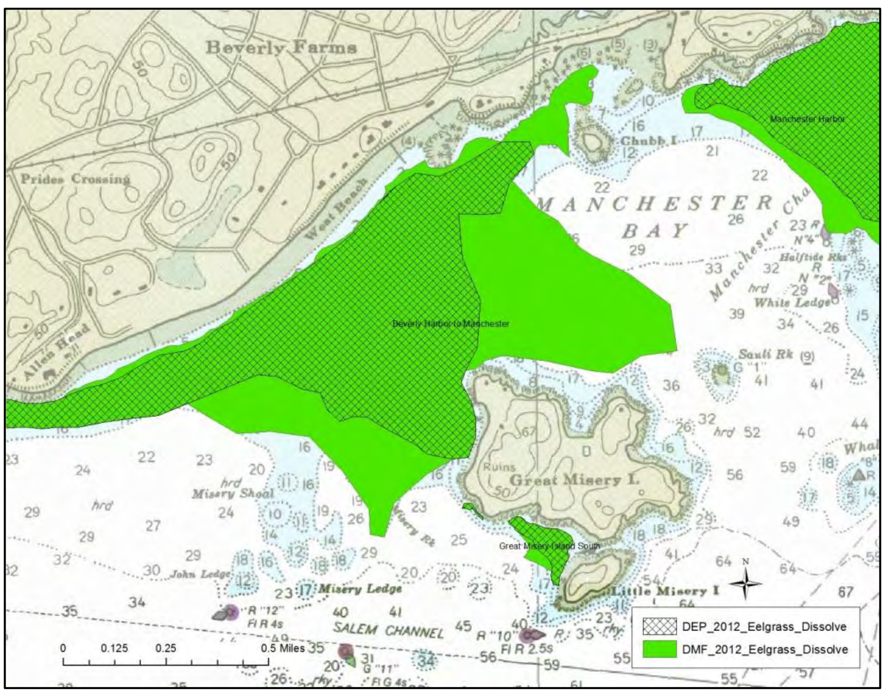


Figure 31. Mapping differences between DMF and DEP at the northern end of the Beverly Harbor to Manchester bed near West Beach.

By examining the beds on an individual basis we determined that losses are occurring in inner harbor areas including Salem Harbor, Beverly Harbor (Collins Cove), Danvers River, Lobster Rocks, inner Manchester Harbor, and Marblehead Harbor. Salem Harbor has seen the most substantial losses in eelgrass. NOAA charts from 1964 and aerial imagery as far back as the 1930's suggests that the shallow areas of Salem Harbor were completely covered with eelgrass. A bed remains along the Naugus Head shoreline, though there are signs it is receding to the north. Remnant patches also remain in Palmer

Cove and near Winter Island. The edge recession of a relatively large bed in Marblehead Harbor and what appears to be the bifurcation of another large bed in inner Marblehead Harbor are concerning, as are complete losses in Collins Cove and Beverly Harbor.

There are changes (both losses and gains) in the extent of the beds in the outer harbor regions, including along the Beverly coast and outer Manchester Harbor. However, these changes appear consistent with natural bed expansion and contraction. Gains in eelgrass extent were also found in areas where never-before-mapped eelgrass beds were documented at Coney Island, Middle Ground, and Great Aquavitae. Some of these beds have likely been long-standing, but are only just now being documented.

Our mapping of the eelgrass spatial extent in Salem Sound suggests relative stability over the last decade, but notable localized eelgrass loss is masked in the calculation of net change which includes new beds and bed expansions.

Stressors

The biotic stressors on eelgrass include wasting disease and bioturbation by birds and invertebrates. Wasting disease is relatively well-documented in this area. Stakeholders and eelgrass experts that have study sites in Salem Sound did not identify wasting disease as a primary cause for concern. Wasting disease at a certain prevalence results in massive die-off of eelgrass, and we have no evidence of rapid embayment-wide losses. Lent found low levels of wasting disease overall, with the highest levels at Mingo Beach and Beverly Cove in 1998. Both DEP and DMF found expansion of the Beverly Cove bed in the most recent mapping, and Mingo Beach has remained relatively stable with only minor edge fluctuations over time. The effect of wasting disease in other areas is more difficult to discern. In Palmer Cove, Wilbur (2005) noted trace to low occurrence of wasting disease, and these beds are faring poorly. At this time, we can't quantify the significance of the effect of wasting disease as it relates or compounds other stressors, especially in the inner harbor areas.

Eelgrass loss due to predation has not been measured over time. We have not observed or heard reports of large-scale grazing impacts as has been noted as a cause of rapid loss in other systems, such as from Canada geese (Rivers and Short 2007). Stakeholders did not identify bioturbation by birds or crabs, such as the green crab, as a particular concern.

Although increases in regional water and air temperatures are apparent, temperature records in the outer harbor do not exceed temperature thresholds for eelgrass, so there is no evidence at this stage to suggest temperature stress in the Salem Sound region. Since eelgrass is in the middle of its geographic range, we expect eelgrass to be fairly resilient to increasing temperatures, to a point. We are concerned that in the inner harbors even slight increases in temperature could increase the risk for hypoxic conditions due to the increased organic content of the sediment, resulting in more stress to those plants. Also, an increase in water temperature and a seasonal change of earlier spring temperatures and later winter temperatures could add stress by altering the population of eelgrass predators or otherwise affecting eelgrass physiology.

Some evidence suggests that light availability is a limiting factor for eelgrass in the inner harbor areas of Salem Sound. Eelgrass loss is primarily occurring in inner harbor areas. These areas have more rapid light extinction (Fig 19) and documented turbidity events. Although secchi depths were not consistently shallower in inner harbor areas (Fig 22), we expect this is an artifact from non-continuous sampling. A strong relationship between light extinction and eelgrass impact was found by EPA (Liebman 2013) (Fig 19).

What is driving the light limitation is less clear. It is probable that the inner harbor beds are more affected by physical disturbances that reach the sediment (e.g. dredging, boating) since these activities are concentrated in the inner harbors compared to the broader Sound, and the sediment is muddier (Hubeny et al. 2017a), has a higher organic content and is more contaminated (Hubeny et al. 2017b) than in outer areas. Resuspension of sediments in mooring fields and urban runoff also contribute to turbidity at varying frequencies, although marine phytoplankton is thought to be the dominant source of particulate matter in the water column in Salem Harbor (Hubeny et al. 2017a). The frequency and severity of phytoplankton blooms increase when nutrient loading creates eutrophic conditions. Greater Salem Sound is well-flushed, and is not considered nutrient stressed. Menzie-Cura (1996) estimated the Salem Harbor nitrogen loading rate of 17 kg/ha/yr and considered it non-eutrophic and recent TMDL assessments did not trigger nutrient impairment thresholds (MassDEP 2014). However, it is possible that inner harbor areas are more nitrogen stressed than outer harbor areas. Riverine inputs including nitrogen from upstream non-point sources may be concentrated due to limited circulation in inner harbors (the total nitrogen loading estimate for the Crane, North, Porter, and Waters Rivers is 45 MT/yr (Chase et al. 2002)). The highest bacterial concentrations are found in inner harbors, suggesting increased water quality impairment of inner harbor areas. It appears that non-point source pollution continues to degrade water quality over time despite the reduction in industrial point-sources. The increasing trend in the number of days per summer where bacteria concentration exceeds safe swimming thresholds is evidence of ongoing water quality degradation in and near Salem Sound. Inner harbor eelgrass beds are highly vulnerable to complete loss due to continued degraded water quality and exposure to acute turbidity events observed in the inner harbor.

The outer sound regions, including Middle Ground, the north shore of Marblehead, and the Beverly coastline, have eelgrass beds that are a mix of sparse and dense and generally have less epiphytic coverage and appear healthier relative to the health of the inner harbor beds. Water clarity in the outer sound is better relative to the harbors, exhibiting higher secchi depths and light extinction curve data (Figs 19, 22). Light monitoring measured 18-25% of surface light reaching the bottom which meets the 18% minimal light requirement for eelgrass (Dennison et al. 1993) but is lower than the 35% light level suggested to be optimal to maintain below-ground storage capacity (Ochieng et al. 2010). Also, Kenworthy et al. (2014) identified that beds growing in high quality habitat areas require less light for growth.

Light is not the only factor influencing eelgrass bed shape and size. Geomorphology and sediment movement are strongly linked to eelgrass extent (Lent et al. 1998). As visible in aerial photographs, the bed near Gale's Point in Manchester Harbor appears to be heavily influenced by shifting sands. A hurricane prevented successful replanting of eelgrass in Beverly (T. Evans, DMF, pers. comm.), so it is reasonable to assume that sediment movement is an important influence along the Beverly coast and at Middle Ground. Average wind speeds and directions are not changing linearly, but some months do have more days with higher average wind speeds. This increase in energy in the system may have implications for sediment movement and mixing that could positively or negatively impact eelgrass.

Boating activity, dredging, and the installation/use of moorings is a prominent source of eelgrass impact in Salem Sound. Approximately 400-500 moorings are located within known eelgrass beds, which create a cumulative eelgrass loss of up to 5 acres based on mooring impact studies DMF has conducted in Manchester. Boating activity itself also plays a role in localized eelgrass losses through direct removal of eelgrass from propeller scouring, grounding, and anchoring. The greatest eelgrass losses are occurring in highly utilized and space-restricted areas of the Sound. As boating continues to expand in this area, its impact on the health and extent of eelgrass may deserve further assessment so as not to underestimate its potential significance.

There were several datasets that could not be analyzed within the scope of this study that deserve further attention. Work done by the DEP TMDL program, Haste Outfall studies, records of precipitation, the more recent years of the Beverly Harbor temperature dataset, Salem Harbor power plant, and hydrodynamic models including particle distribution (e.g. Krahforst et al. 2001) all deserve additional attention to inform our understanding of the sources of stress on eelgrass in Salem Harbor. Hubeny et al. (2017a) has started to assess the influence of turbidity caused by either eutrophication, dredging, or run-off, and additional work is warranted.

Conclusion

In Salem Sound, we found extremely resilient yet highly vulnerable stands of eelgrass as well as some of the most robust and healthy eelgrass beds in Massachusetts. Loss over time is occurring in the inner harbors and is likely driven primarily by compromised water quality and light availability, though loss is aggravated by physical impacts associated with boating activity and physical disturbance. Temperature is increasing regionally, but we do not have evidence of direct or indirect stress caused by rising temperature. Higher temperatures can improve conditions for algae blooms (Rheuban et al. 2016) leading to decreased light. We also do not have evidence of predators being a stressor to eelgrass at this point in time. To better protect and understand eelgrass we recommend the following:

- Continuing efforts to reduce and eliminate point and non-point pollution (stormwater upgrades, vessel pumpouts, rain gardens, wetland restoration within the watershed to enhance retention and filtration of stormwater);
- Preventing direct physical impacts to eelgrass (such as by moving mooring fields out of eelgrass, marking eelgrass and channels to ensure boaters and fishing gears remain out of eelgrass beds, allowing no major silt-producing activities within 100 feet of eelgrass);
- Developing an annual eelgrass mapping protocol for the embayment so that changes in extent and condition can be documented. The assessment must be done with repeatable methods, involving multiple tiers of mapping (aerial imagery, acoustic groundtruthing, diver surveys);
- Requiring eelgrass surveys for any construction projects within or near current or historically mapped eelgrass areas, or areas suitable for growth. Publicly available polygons should be used as only a guide and not an exhaustive compilation of eelgrass beds;
- Dredging should not occur in eelgrass or in a buffer zone of at least 100 feet from the eelgrass edge to account for turbidity. Use of silt curtains and turbidity monitoring should be incorporated into Best Management Practices;
- Further study of: year-round light and water quality in Salem Harbor and reference sites; wasting disease, epiphyte load, shoot density, nitrogen content, and sediment toxicity at the established seagrass monitoring station at West Beach and at a second location within an inner harbor system; circulation and residence time as a factor impacting the harbors; physiological research focused on photosynthesis and respiration rates, growth rates, and starch storage to

help determine restoration potential; and eelgrass seeding to determine if it is a cost effective restoration or bed maintenance technique.

- There is some evidence that converting chain moorings to conservation moorings can help minimize eelgrass impacts in existing mooring fields when equipment is properly sized and maintained (DMF 2016). However not all embayments are suitable for these moorings, which can be just as impactful as chains if not installed and maintained correctly (DMF 2016), or if utilized as a mechanism to increase mooring densities in confined areas.
- We recommend archiving DEP hard copy prints and negatives as digital, georeferenced maps through a partnership with MassGIS, state archives, and DEP. The georeferenced images we utilized for this project will be available on the DMF website.

Acknowledgements

This work would not have been possible without the support of the Massachusetts Bays National Estuary Program. The acoustic field work was conducted with help from Steven Voss, Kate Ostrikis, Tay Evans, and Mark Rousseau (DMF). Without the cooperation of Michael McHugh and Charlie Costello (DEP), we would not have been able to repeat their photo-interpretation. Joe Costa (Buzzards Bay National Estuaries Program) provided valuable advice on photo-interpretation and digitization. Our group of stakeholders who are the stewards of this embayment system included harbormasters, shellfish wardens, natural resource managers, and non-profit coordinators. They provided abundant information about the region and provided helpful ideas to move this project forward. Thank you to Brad Hubeny (SSU), Barbara Warren (SSCW), Forest Schenck (NEU), and Matt Liebman (EPA) for providing data for analysis, and a special thank you to Barbara Warren for hosting us at two meetings. This report was improved with the editorial assistance of Matt Liebman, Prassede Vella (MassBays), Barbara Warren, Tay Evans, and Mark Rousseau.

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APPENDIX A

LIST OF ASSOCIATED FILES, AVAILABLE SEPARATELY

- DMF eelgrass polygons with patchiness categories (.shp and .kmz)
  - 2001
  - 2006
  - 2012
- DMF acoustic mapping survey eelgrass polygons, 2016 (.shp and .kmz)
- DEP aerial imagery (geoTIFF)
  - 2001
  - 2006
  - 2012
- DEP groundtruthing waypoints (.shp)
- SSCW Lecture Series Presentation given on 4/26/17 (.pdf or .jpg)

APPENDIX B

STAKEHOLDER MEETING MINUTES

Salem Sound Eelgrass Study

Stakeholder Meeting
March 9, 2017
Salem Sound Coastwatch 9:30-11:30 a.m.

ATTENDEES

Name	Email	Affiliation
Barbara Warren		MassBays/SSCW
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Tay Evans	Tay.evans@state.ma.us	MassDMF
Alex Pzeny		
Dave Pelletier		
Forest Schenck		NEU (Randall Hughes student)
Randall Hughes		NEU
Alyssa Novak		UMass Boston
Bion Pike		Manchester Harbormaster
		Salem Harbormaster
		School teacher
Laurie Kennedy		MassDEP (TMDL program)
Phil Colarusso		EPA
Matt Liebman		EPA
Robert Buchsbaum		MassAudobon
Rebecca		Consultant (wastewater)
Chris Bertoni		Salem Con Comm
Gary M.		
Noah		Hawthorne Marina
Brad Hubeny		Salem State University
Alan Young		Salem State University
Emily		Salem Sound Coastwatch

Powerpoint presentation by Jill Carr. Eelgrass losses confirmed in inner harbor areas – Salem Harbor, Beverly Harbor, Danvers River. Outer beds are relatively stable, though perhaps lees eelgrass between Curtis Point and Smith Point more recently. Our estimate is 700+ acres, DEP estimate is 500+ acres. Main cause of loss in inner harbor areas is likely due to poor water quality (Salem Harbor) and human disturbance (Salem Harbor and Beverly Harbor/Danvers River).

DISCUSSION

Issues raised that we should follow up on and/or make recommendations on are identified in bold.

Are differences between DEP and DMF estimates due to geolocation differences or difference in what is mapped as an area of eelgrass? We didn't talk about this much, but some thought needs to be given regarding the different eelgrass maps that are available (DEP, DMF, Ocean Plan).

Temperature—Consider using the hobo data to look at **# of days above a certain temperature**. (Phil)

Dredging—Follow up with Prassede/CZM about **dredging data**. Corps should have it too. Maybe project notifications. No one in the room knew more about how to extract this kind of data.

Invasives—There was a discussion about invasives and fouling organisms

- In a year with heavy Heterosiphonia japonica, no lobsters were landed in Manchester. (Bion)
- H. japonica has a new name. (Randall)
- Tunicates might be causing stress. Esp late summer/early fall when eelgrass stops dropping its leaves as much. More fouling in early fall. Phil C and Ted Maney have monitored Botrylloides on Martha's Vineyard and Juniper Beach, Salem Sound. Some presence, but not that much.
- SSCW lobster trap study, invasive/tunicates not a big problem, Diplosoma specifically mentioned. (Barbara)
- Predators, esp green crabs, didn't come up.

Wind—**Wind events definitely seem to be increasing, spring feels longer**. There are hydro models in this embayment. Look at? Reference?

Sedimentation – Shoaling in Palmer Cove because of wind. In Beverly, the area behind Monument Bar has scoured out.

Eutrophication – is an issue (fertilizers, pesticides). Phytoplankton causes turbidity (Barbara), Matt L is interested in this, can help put together information about this. Has done gradient work here. 2012 most recent. Nutrient pollution indicator index – Phil, Fred Short. Would be helpful to put Salem in context with rest of the state.

Ice – there is icing in some years. No specifics. Doesn't seem to be a concern with respect to eelgrass.

Boating – came up more in the context of moorings and anchoring. General disturbance from a variety of activities could be adversely affecting grass in Danvers River.

Manchester used to have a different boating channel. Eelgrass loss there could be anchoring or shoaling. Chris Bertoni will look into older aerials that the town had flown.

DEP WQ assessment and reporting – could use DMF assessment, data needs to be in MassGIS. (Laurie) As part of that, **rectifying the difference in meadow definition is needed**. (Phil)

One reason it's hard to connect events with eelgrass impacts is the lag in response.

Some points made about method – sidescan sonar sensitivity, density threshold, patch size, and depth characteristics of study area which could change sonar sensitivity if unit is fix-mounted on the vessel.

Product Chris B said she could use **explanation/brochure about why eelgrass is so important**. Why should we care? Include uniqueness of the area. Stable, long-lived grasses.

- Phil C. is hoping to do a travelling road show to teach Con Comms about eelgrass

- Emily made the point that information for boaters is needed. They usually want to do the right thing, but don't know about where the grass is or what the anchoring rules might be.

No suggestions that we are missing any data sources.

SUMMARY
Eelgrass acreage may be more than what DEP has reported due to the presence of deeper beds and finer scale mapping. Areas where eelgrass has been lost and is currently in poor health are inner harbor areas associated with water quality impairments. Impact of temperature and ecosystem changes over the longer term are of concern.

WHAT TO LOOK AT IN MORE DETAIL
Follow up with Matt Leibman about nutrient gradient work.

Carefully define how we delineated a meadow and directly compare to how DEP does.

Look at gale frequency.

Follow up with Phil Colarusso about critical thresholds for temp/light for eelgrass.

Better use of/connection to DEP waterbody assessment.

TO DO

ITEM	WHO/WHEN	NOTES
Send out minutes for review by DMF, SSCW, MassBays.	DMF as soon as possible	Need to be reviewed, edited, and finalized for inclusion in final report.
Follow up with Matt Liebman	DMF week of 3/20	
Follow up with Phil Colarusso	DMF week of 3/20	
Provide WQ data that might help – esp temp, fecal coliform	SSCW	
Write final report and consolidate and make available the data.	DMF	Goal is to finish report by end of April May.
Consider how to manage imagery and water quality data.	DMF, MassBays	For this project, data will be released on DMF website. Maybe MassBays too. Will probably happen in summer of 2016.

APPENDIX C

DOCUMENTED ICE EVENT:
http://www.chipford.com/marblehead_harbor_frozen.htm

Chip Ahoy

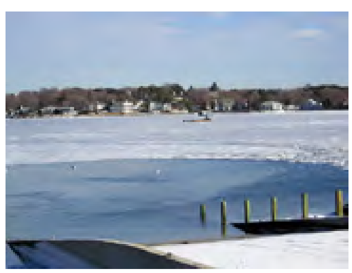
Chip Ford's 1974 Catalina 22 Restoration Project
Sail #3282 • Marblehead, Massachusetts

Marblehead Harbor Frozen Over
Jan. 21, 2004

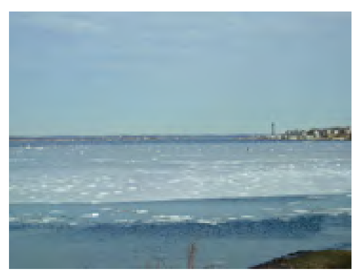
These photos were taken after two straight weeks of sub-zero Arctic temperatures and wind chill factors of -30° F and below.
Click on the thumbnail shots below for larger images.

Me, my diminishing woodpile, and a covered Chip Ahoy wintering in the background

From the Riverhead Beach boat ramp toward the mouth of the harbor.
(See this view in a warmer time.)



From the boat ramp toward Marblehead Neck.



From the boat ramp toward the harbor entrance (Marblehead Light).

The Riverhead Beach boat ramp and causeway to Marblehead Neck; Massachusetts Bay beyond.

Looking across the harbor to Marblehead Neck. (Note the roadway someone plowed across the ice.)

Looking across the harbor to the Neck. Think that Whaler's going to be moved anytime soon?

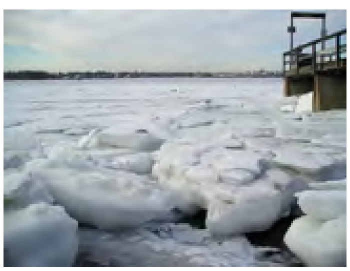
The Westside (Village Street) Town Dock & Mooring Area

Jan. 26, 2004

Click on the thumbnail shots below for larger images.

Off this town dock is where I keep Chip Ahoy moored in warmer months.

The ice runs all the way across Salem Harbor to the Salem power plant.



The town brings in the docks in the late fall, clearly for good reason. Remember, this is salt water!

Does the Arctic Circle look much different? All we need are penguins and a stray polar bear or two!

Panoramic view of Salem Harbor from Lafayette Street (Rte. 114) Salem/Marblehead line at the mouth of Forest River; Salem on left - Marblehead on right. (After opening, click box on lower-right to enlarge.)

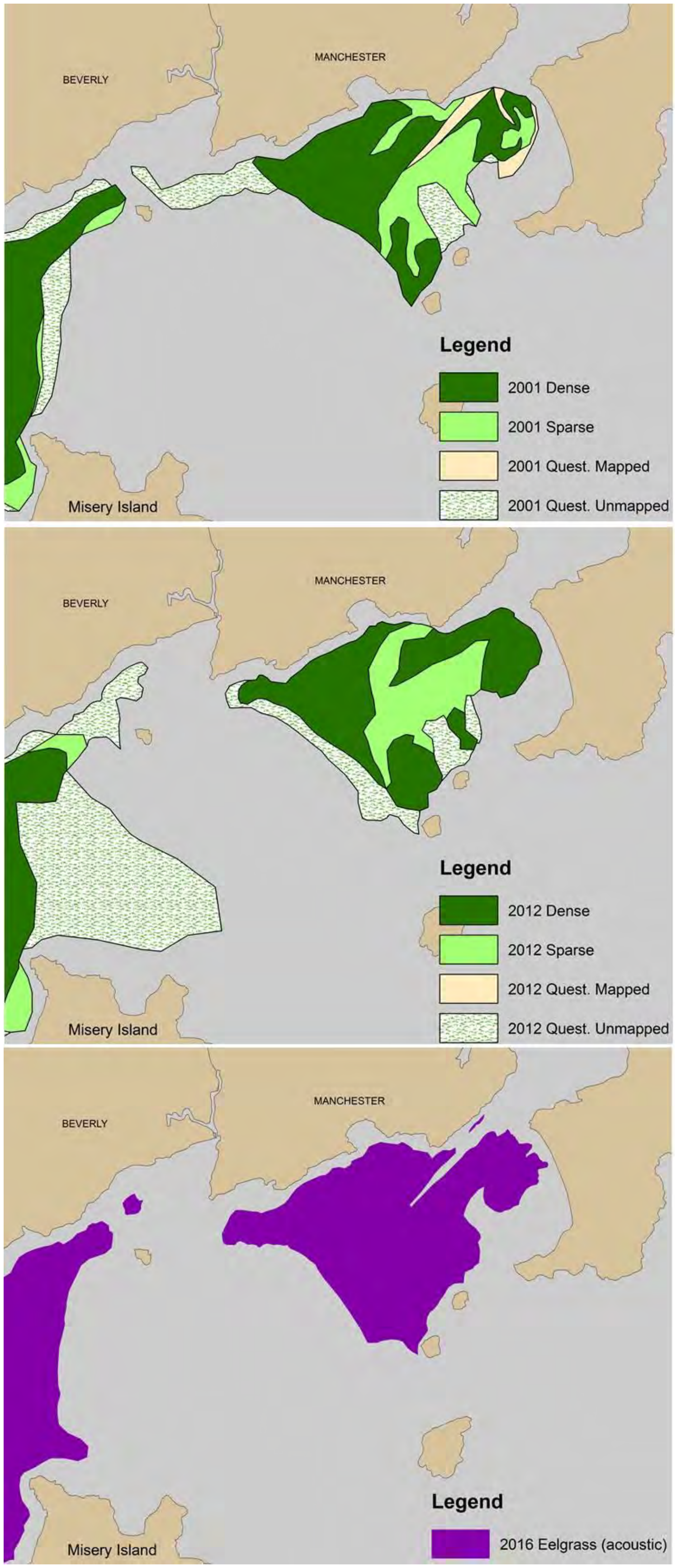
APPENDIX D

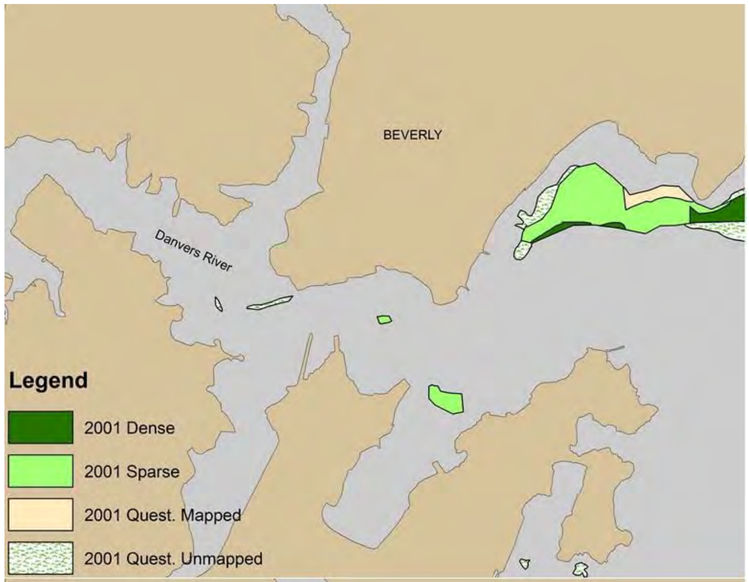
SUMMARY OF EELGRASS CHANGES FOR EACH EELGRASS MEADOW (TABLES) AND

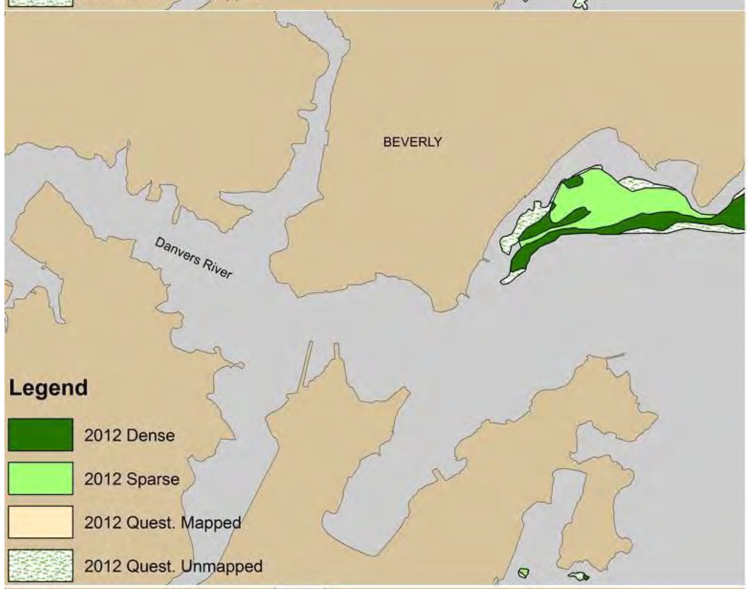
HARBOR-SPECIFIC MAPS (FIGURES)

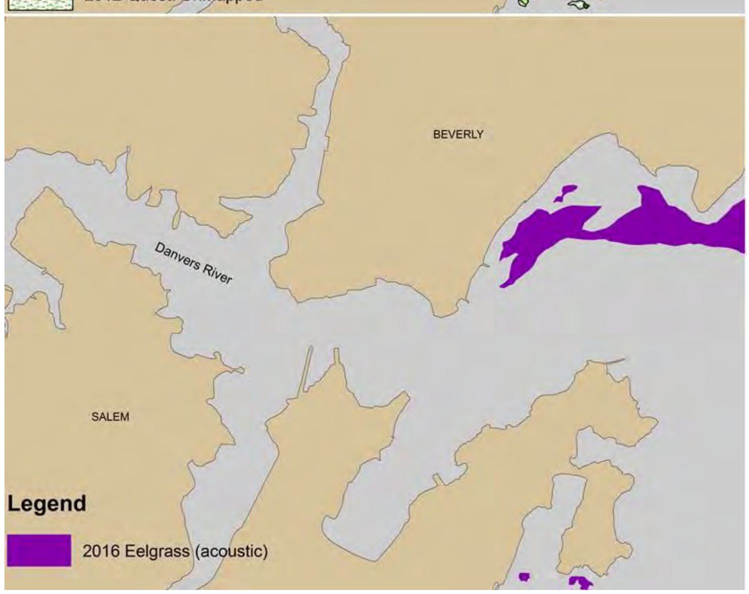
Name	DEP1995	DEP2001	DMF2001	DEP2012	DMF2012	DMF2016	Notes
Manchester Harbor	147.6	116.5	132.0	119.9	145.2	141.9	DMF acreage is consistently higher due to mapping of the deep edge and more liberal mapping of low density areas. Small bed inside of inner harbor lost between 1995 and 2001. Loss along Gales Point shoreline could be due to geomorphic/natural events but it is a popular boat anchoring area as well. Losses in the mooring field caused by scars and some fragmentation.
Great Misery Island South	5.7	6.8	6.8	6.5	8.0	8.4	Bed has become more dense since 2001. Small detached bed to north and west only mapped in 2012, groundtruthing showed low density bed. Was not found in 2016 acoustic survey.
Beverly Harbor to West Beach	387.1	361.6	458.0	391.6	582.5	462.0	This bed has been very stable. Big difference between DMF and DEP mostly due to higher resolution mapping of the deep edge, especially near West Beach; Some loss in Mackerel Cove, likely due to geomorphic/natural physical changes. The West Beach bed is one of the deeper meadows in Massachusetts, with a deep edge in at least 20' depth at mean low water. Most densities remained the same, but Beverly Cove became more sparse since 2001.
Danvers River			1.8				DEP found sparse grass during groundtruthing in 1996 but it was not mapped as a bed; no other mapping has been done since. Based on the DMF mapping methodology, the groundtruthing point from DEP was mapped in the 2001 analysis. DMF is interested in collecting more data from this area.
Lobster Rocks	1.4	0.7	0.7				Entire bed is now lost.
Collins Cove	8.9	5.0	5.0				Entire bed is now lost.
Fluen Point	1.6	0.8	2.0	0.9	1.9	2.0	Little change to the west, but on the east a detached bed has receeded since 1995 and disappeared. Higher 2016 estimate is due to mapping the deep and shallow edge at higher resolution.
Peachs Point	7.5	4.6	10.6	7.5	20.1	19.6	Little overall change. Larger DMF acreage was confirmed by 2012 aerial mapping and 2016 acoustic mapping. DMF is consistently larger due to mapping of the deep edge and more liberal mapping of low density areas.
Marblehead			9.1				This bed was along the east shore of Marblehead, and was detected in DEP groundtruthing data in 2008. It is not visible in aerial photos due to its depth and the presence of a mooring field. We think this bed was definitely present, but we don't know its current status since it hasn't been remapped since the 2008 groundtruthing.
Inner Marblehead	25.7	12.0	34.3	19.3	33.1	28.4	Some recession of deep edge since 2001, possibly due to mooring field, but bed is generally stable. Fragmenting and detachment along the northeast reach of the bed since 1995. DMF is consistently larger than DEP estimate due to mapping of the deep edge and more liberal mapping of low density areas. This bed extends along the Marblehead Neck shoreline.
Marblehead Light	0.2	0.1	0.1	0.2	0.2	0.2	Little change observed to this small bed.
Great Aquavitae					7.3	5.3	We think this bed was missed by DEP mapping due to its location in the central harbor near exposed rocks. It is a dynamic area with sand waves and a patchy bed. The reduction in acreage is likely real and probably due to natural morphological changes related to the high energy environment.
Middle Ground						0.8	This is a new bed from DMF restoration efforts, planted from 2013 to 2015.
Coney Island			1.7		2.3	4.2	This bed is difficult to map due to nearby rocks and algae, we think this bed is stable.
TOTAL	**585.8**	**508.1**	**662.1**	**545.9**	**800.5**	**672.9**	

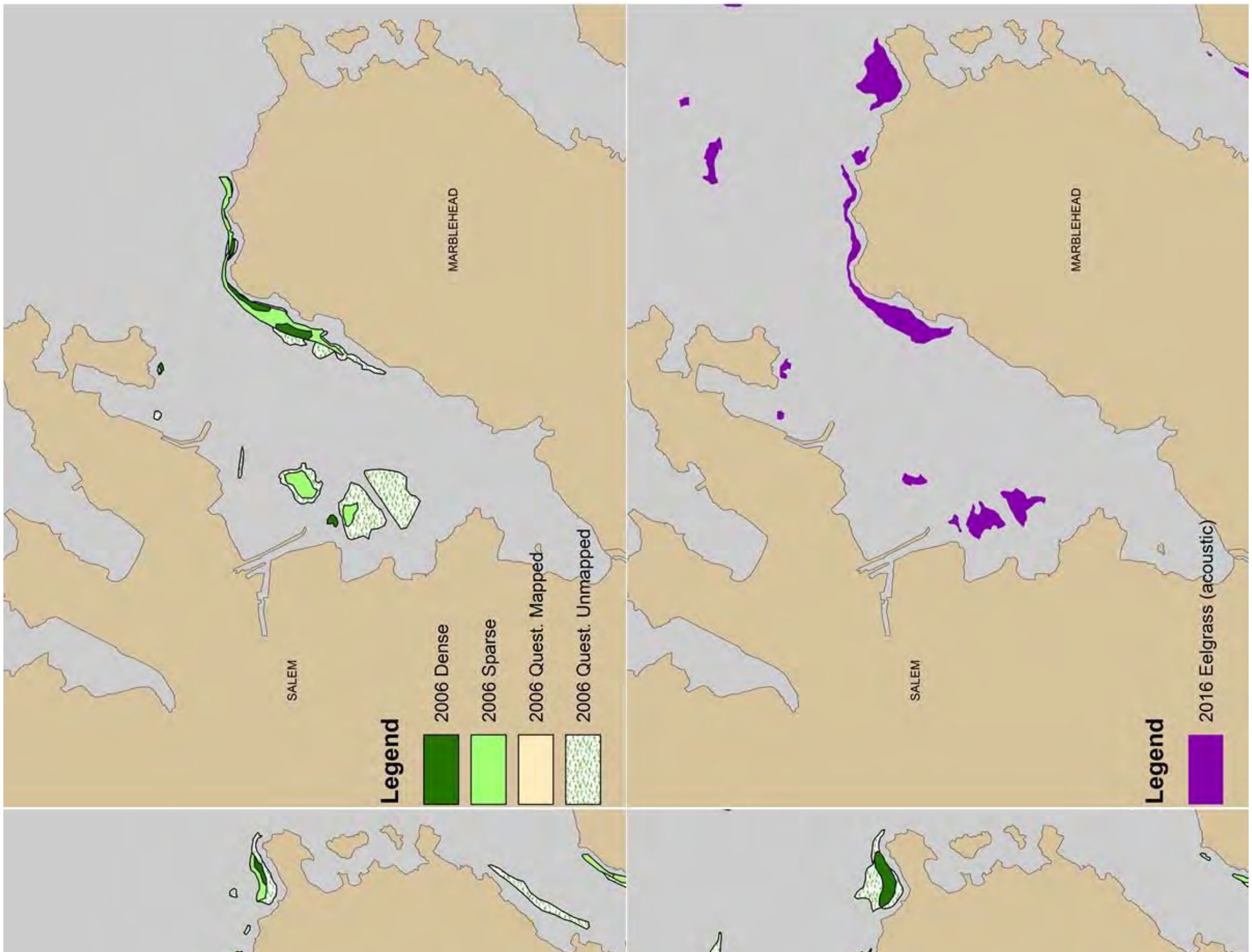
Salem Harbor	DEP1995	DEP2001	DMF2001	DEP2006	DMF2006	DEP2012	DMF2012	DMF2016	Notes
Hawthorne Cove					1.0				We think this bed was missed by DEP mapping since it is relatively small. It is clear in the aerial imagery, but there is no groundtruthing data. It is not seen after 2006 and it has not been acoustically mapped. We think this bed is lost.
Cat Cove			0.5		0.6	0.4	0.6	0.6	We think this bed was missed by DEP mapping in 1995, 2001, and 2006 since it is relatively small and the 2001 imagery is poor. Evidence of this bed at much greater extent is in historical aerial photos. This bed is apparent in the DEP 2006 and 2012 aerials. This bed historically connected to the Winter Island bed.
Winter Island			1.1	0.5	0.5	0.2	0.8	1.5	We think this bed was missed by DEP mapping in 1995 and 2001 since it is relatively small and the 2001 imagery is poor, though the bed is visible. Evidence of this bed at much greater extent is in historical aerial photos. This bed used to connect to the Cat Cove bed.
Palmer Cove 1 (southernmost)	18.1		4.1		20.4		6.3	8.2	This bed has substantially receded over time based on our review of aerial photos and NOAA charting. This bed is below the minimum mapping unit of DEP now but it can be seen in groundtruthing imagery and acoustics. Large difference between DMF 2001 and 2006 mapping due to poor '01 image quality. The bed still exists but has receded since 1995, when it was last mapped by DEP. This area is under substantial stress from high turbidity and boat activity.
Palmer Cove 2	19.9		4.7	2.6	19.7	0.4	5.5	8.9	Same as above, except this bed has been included in DEP's maps since 1995.
Palmer Cove 3 (northernmost)	1.0	0.5	1.5	1.0	1.0	0.4	0.8	1.0	This small bed did not disappear from DEP maps,and has remained around 1 ac in size since 1995 with fluctuations in edge extent and shape.
Derby Wharf	33.1	4.0	10.9	6.1	12.3		2.9	2.4	This bed has substantially receded since 1995, the largest loss in Salem Harbor. Development of a cruise ship port and dredging has occurred in this area. It is also under substantial stress from high turbidity and boat activity.
Naugus Head	33.2	15.7	29.8	25.7	34.2	19.0	25.9	26.6	This west shore portion of this bed has receded from south to north since 1995. The area experiences many of the stressors affecting the nearby Palmer and Derby Wharf beds. Along the point of Naugus Head there has also been recession of the deep edge.
Salem Hbr Total	**105.3**	**20.1**	**52.6**	**35.9**	**89.8**	**20.3**	**42.8**	**49.3**	


BEVERLY
MANCHESTER
Misery Island
Legend
2001 Dense
2001 Sparse
2001 Quest. Mapped
2001 Quest. Unmapped
BEVERLY
MANCHESTER
Misery Island
Legend
2012 Dense
2012 Sparse
2012 Quest. Mapped
2012 Quest. Unmapped
BEVERLY
MANCHESTER
Misery Island
Legend
2016 Eelgrass (acoustic)

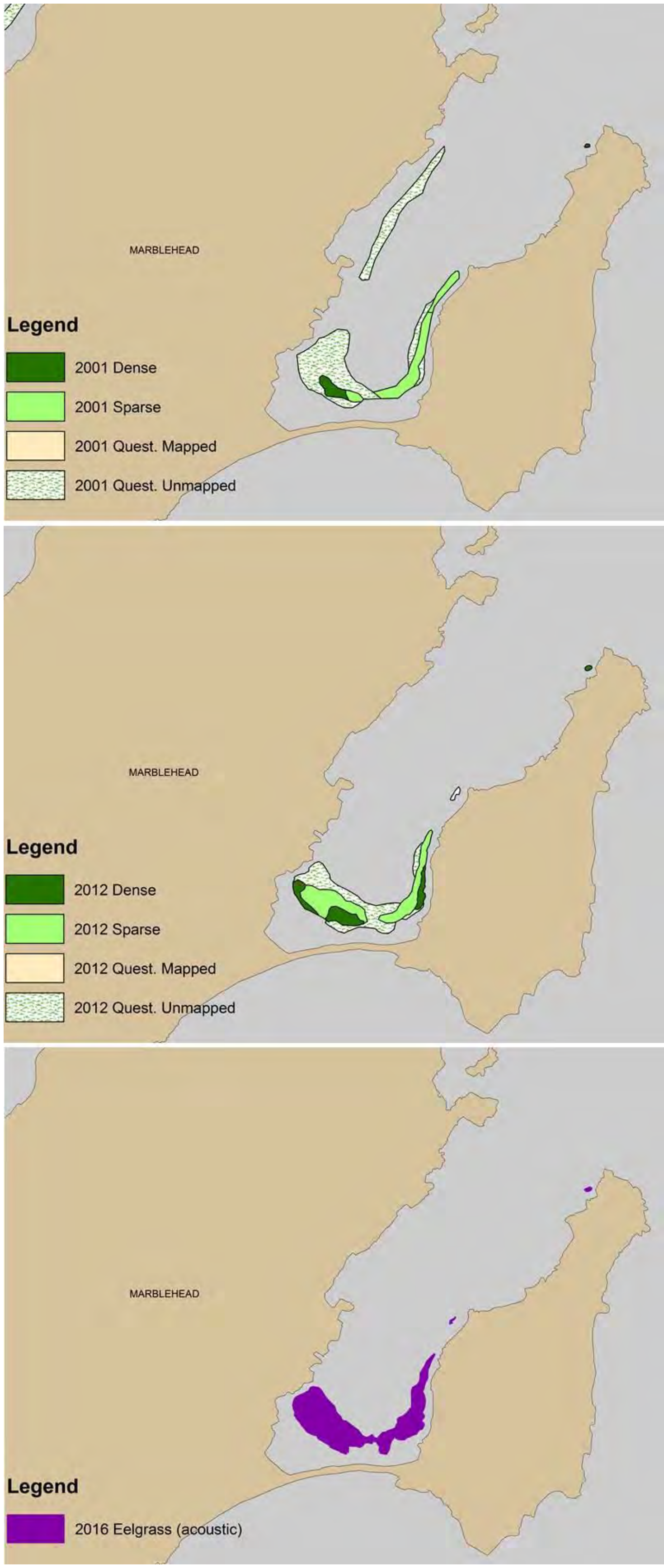

BEVERLY
Danvers River
Legend
2001 Dense
2001 Sparse
2001 Quest. Mapped
2001 Quest. Unmapped


BEVERLY
Danvers River
Legend
2012 Dense
2012 Sparse
2012 Quest. Mapped
2012 Quest. Unmapped


BEVERLY
Danvers River
SALEM
Legend
2016 Eelgrass (acoustic)



Legend
2001 Dense
2001 Sparse
2001 Quest. Mapped
2001 Quest. Unmapped
SALEM
MARBLEHEAD
Legend
2006 Dense
2006 Sparse
2006 Quest. Mapped
2006 Quest. Unmapped
SALEM
MARBLEHEAD
Legend
2012 Dense
2012 Sparse
2012 Quest. Mapped
2012 Quest. Unmapped
SALEM
MARBLEHEAD
Legend
2016 Eelgrass (acoustic)
SALEM
MARBLEHEAD


MARBLEHEAD
Legend
2001 Dense
2001 Sparse
2001 Quest. Mapped
2001 Quest. Unmapped
MARBLEHEAD
Legend
2012 Dense
2012 Sparse
2012 Quest. Mapped
2012 Quest. Unmapped
MARBLEHEAD
Legend
2016 Eelgrass (acoustic)

APPENDIX E

SESD PRE-CONSTRUCTION EELGRASS SURVEY MAPS

AND

SESD POST-CONSTRUCTION EELGRASS SURVEY MAPS

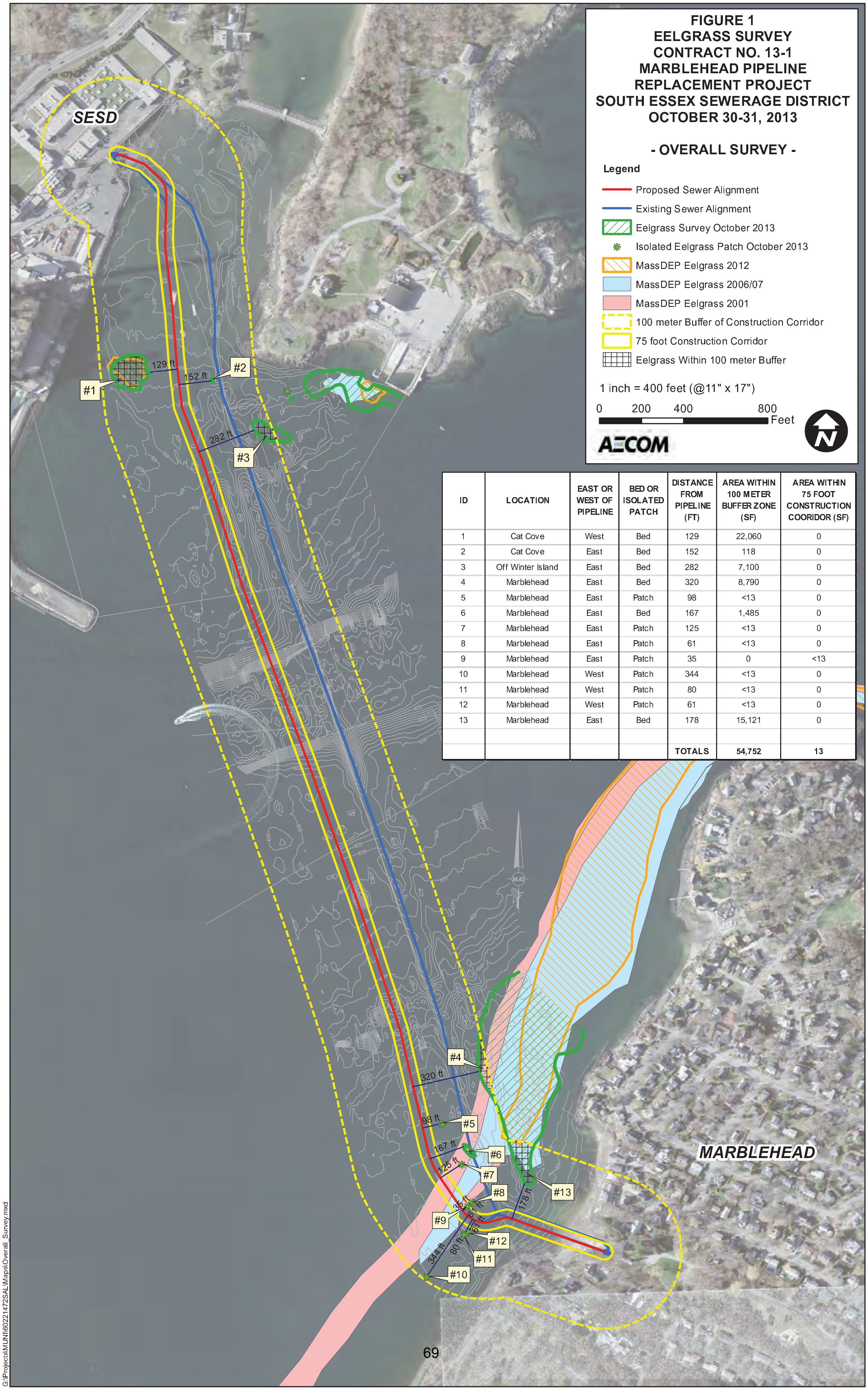


FIGURE 1
EELGRASS SURVEY
CONTRACT NO. 13-1
MARBLEHEAD PIPELINE REPLACEMENT PROJECT
SOUTH ESSEX SEWERAGE DISTRICT
OCTOBER 30-31, 2013

- OVERALL SURVEY -

Legend

- Proposed Sewer Alignment
- Existing Sewer Alignment
- Eelgrass Survey October 2013
- Isolated Eelgrass Patch October 2013
- MassDEP Eelgrass 2012
- MassDEP Eelgrass 2006/07
- MassDEP Eelgrass 2001
- 100 meter Buffer of Construction Corridor
- 75 foot Construction Corridor
- Eelgrass Within 100 meter Buffer

1 inch = 400 feet (@11" x 17")

0 200 400 800 Feet

AECOM

ID	LOCATION	EAST OR WEST OF PIPELINE	BED OR ISOLATED PATCH	DISTANCE FROM PIPELINE (FT)	AREA WITHIN 100 METER BUFFER ZONE (SF)	AREA WITHIN 75 FOOT CONSTRUCTION COORIDOR (SF)
1	Cat Cove	West	Bed	129	22,060	0
2	Cat Cove	East	Bed	152	118	0
3	Off Winter Island	East	Bed	282	7,100	0
4	Marblehead	East	Bed	320	8,790	0
5	Marblehead	East	Patch	98	<13	0
6	Marblehead	East	Bed	167	1,485	0
7	Marblehead	East	Patch	125	<13	0
8	Marblehead	East	Patch	61	<13	0
9	Marblehead	East	Patch	35	0	<13
10	Marblehead	West	Patch	344	<13	0
11	Marblehead	West	Patch	80	<13	0
12	Marblehead	West	Patch	61	<13	0
13	Marblehead	East	Bed	178	15,121	0
				TOTALS	54,752	13

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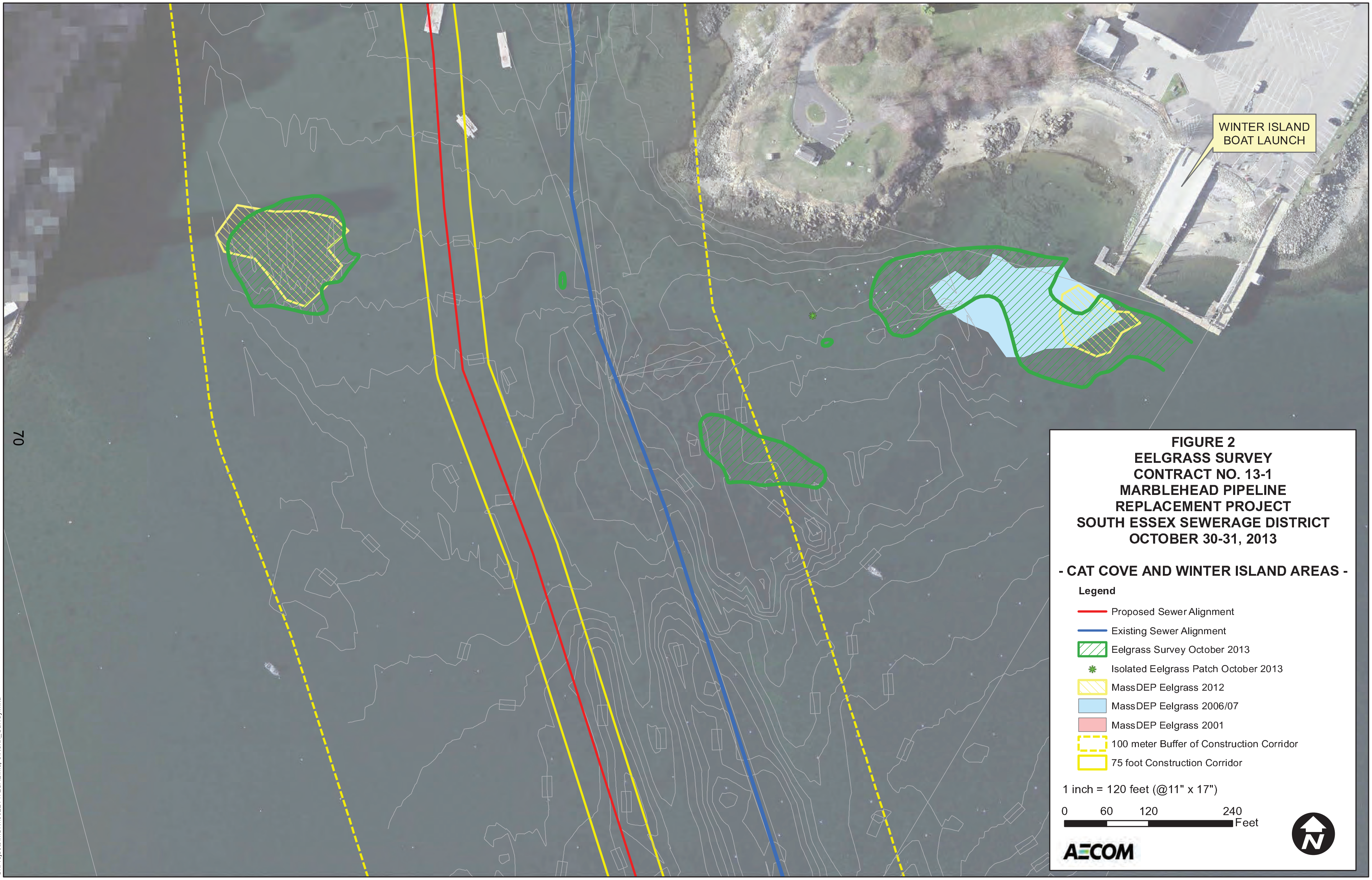

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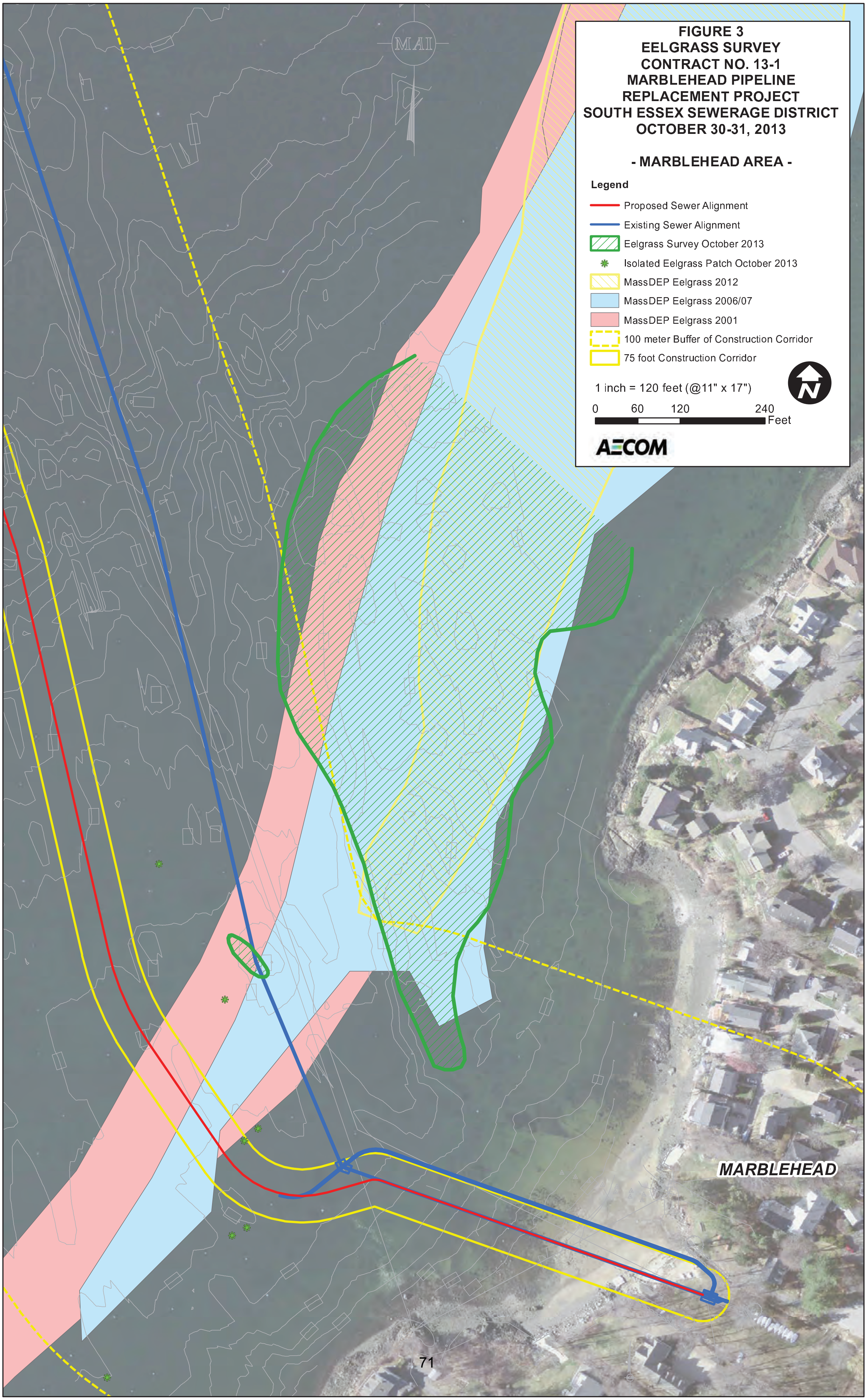
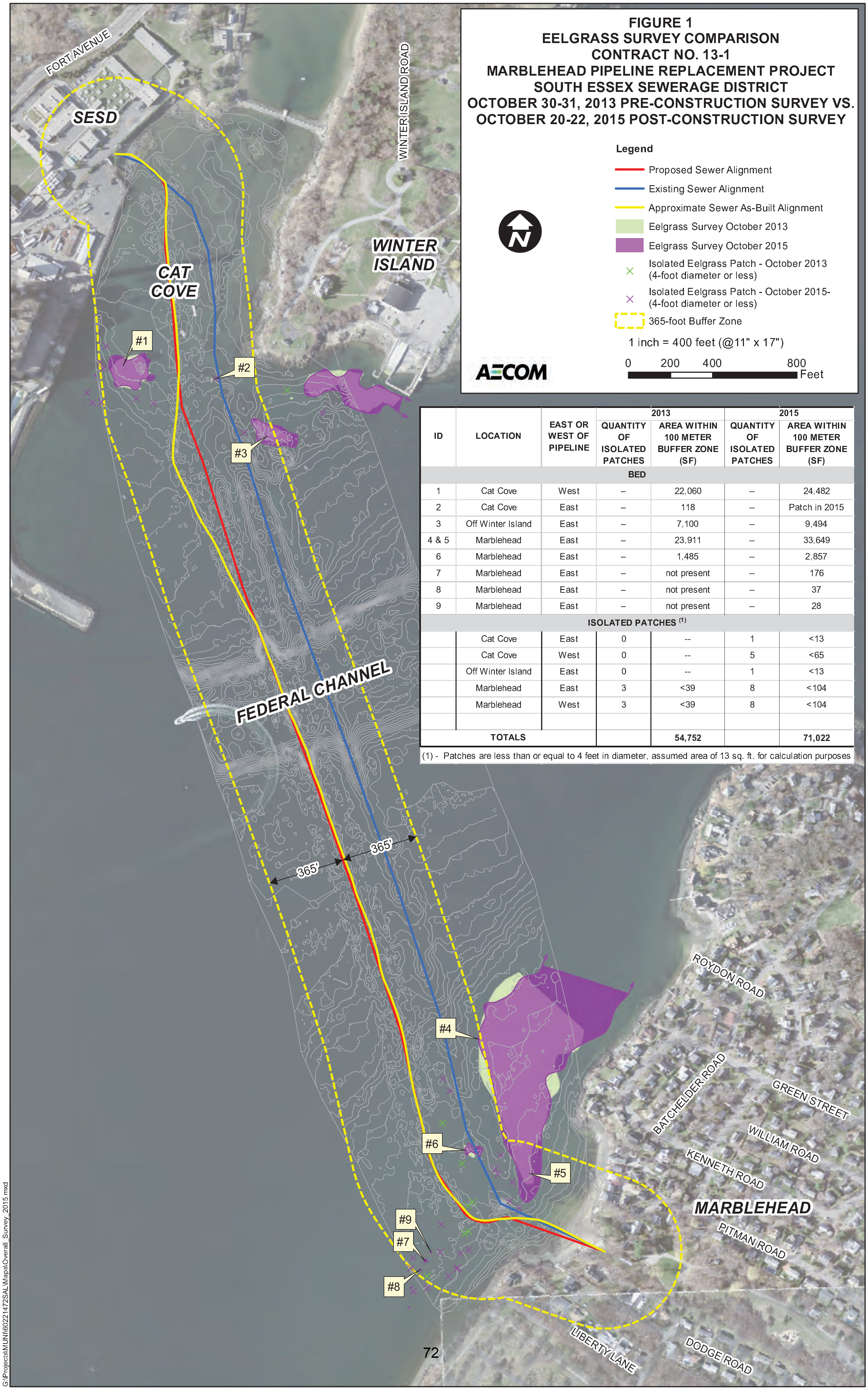


FIGURE 3
EELGRASS SURVEY
CONTRACT NO. 13-1
MARBLEHEAD PIPELINE
REPLACEMENT PROJECT
SOUTH ESSEX SEWERAGE DISTRICT
OCTOBER 30-31, 2013
- MARBLEHEAD AREA -
Legend
Proposed Sewer Alignment
Existing Sewer Alignment
Eelgrass Survey October 2013
Isolated Eelgrass Patch October 2013
MassDEP Eelgrass 2012
MassDEP Eelgrass 2006/07
MassDEP Eelgrass 2001
100 meter Buffer of Construction Corridor
75 foot Construction Corridor
1 inch = 120 feet (@11" x 17")
0 60 120 240
Feet
N
AECOM
MARBLEHEAD

FIGURE 1
EELGRASS SURVEY COMPARISON
CONTRACT NO. 13-1
MARBLEHEAD PIPELINE REPLACEMENT PROJECT
SOUTH ESSEX SEWERAGE DISTRICT
OCTOBER 30-31, 2013 PRE-CONSTRUCTION SURVEY VS. OCTOBER 20-22, 2015 POST-CONSTRUCTION SURVEY



ID	LOCATION	EAST OR WEST OF PIPELINE	2013 QUANTITY OF ISOLATED PATCHES	2013 AREA WITHIN 100 METER BUFFER ZONE (SF)	2015 QUANTITY OF ISOLATED PATCHES	2015 AREA WITHIN 100 METER BUFFER ZONE (SF)
BED						
1	Cat Cove	West	–	22,060	--	24,482
2	Cat Cove	East	–	118	--	Patch in 2015
3	Off Winter Island	East	–	7,100	--	9,494
4 & 5	Marblehead	East	–	23,911	--	33,649
6	Marblehead	East	–	1,485	--	2,857
7	Marblehead	East	–	not present	--	176
8	Marblehead	East	–	not present	--	37
9	Marblehead	East	–	not present	--	28
ISOLATED PATCHES (1)						
	Cat Cove	East	0	--	1	<13
	Cat Cove	West	0	--	5	<65
	Off Winter Island	East	0	--	1	<13
	Marblehead	East	3	<39	8	<104
	Marblehead	West	3	<39	8	<104
TOTALS				**54,752**		**71,022**

(1) - Patches are less than or equal to 4 feet in diameter, assumed area of 13 sq. ft. for calculation purposes

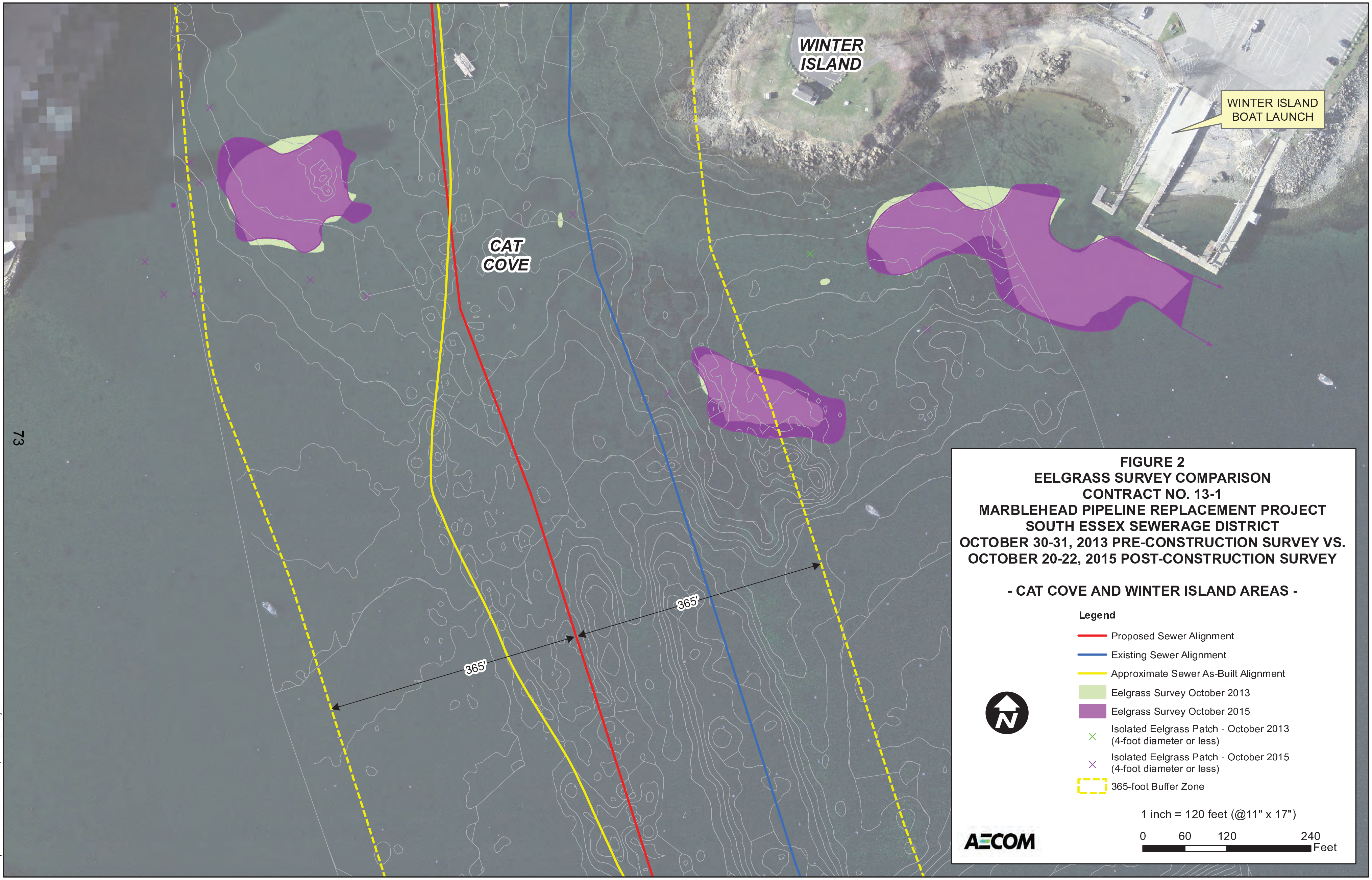


FIGURE 2
EELGRASS SURVEY COMPARISON
CONTRACT NO. 13-1
MARBLEHEAD PIPELINE REPLACEMENT PROJECT
SOUTH ESSEX SEWERAGE DISTRICT
OCTOBER 30-31, 2013 PRE-CONSTRUCTION SURVEY VS.
OCTOBER 20-22, 2015 POST-CONSTRUCTION SURVEY
- CAT COVE AND WINTER ISLAND AREAS -
Legend
Proposed Sewer Alignment
Existing Sewer Alignment
Approximate Sewer As-Built Alignment
Eelgrass Survey October 2013
Eelgrass Survey October 2015
Isolated Eelgrass Patch - October 2013 (4-foot diameter or less)
Isolated Eelgrass Patch - October 2015 (4-foot diameter or less)
365-foot Buffer Zone
1 inch = 120 feet (@11" x 17")
0 60 120 240 Feet
AECOM
WINTER ISLAND
WINTER ISLAND BOAT LAUNCH
CAT COVE
365'
365'
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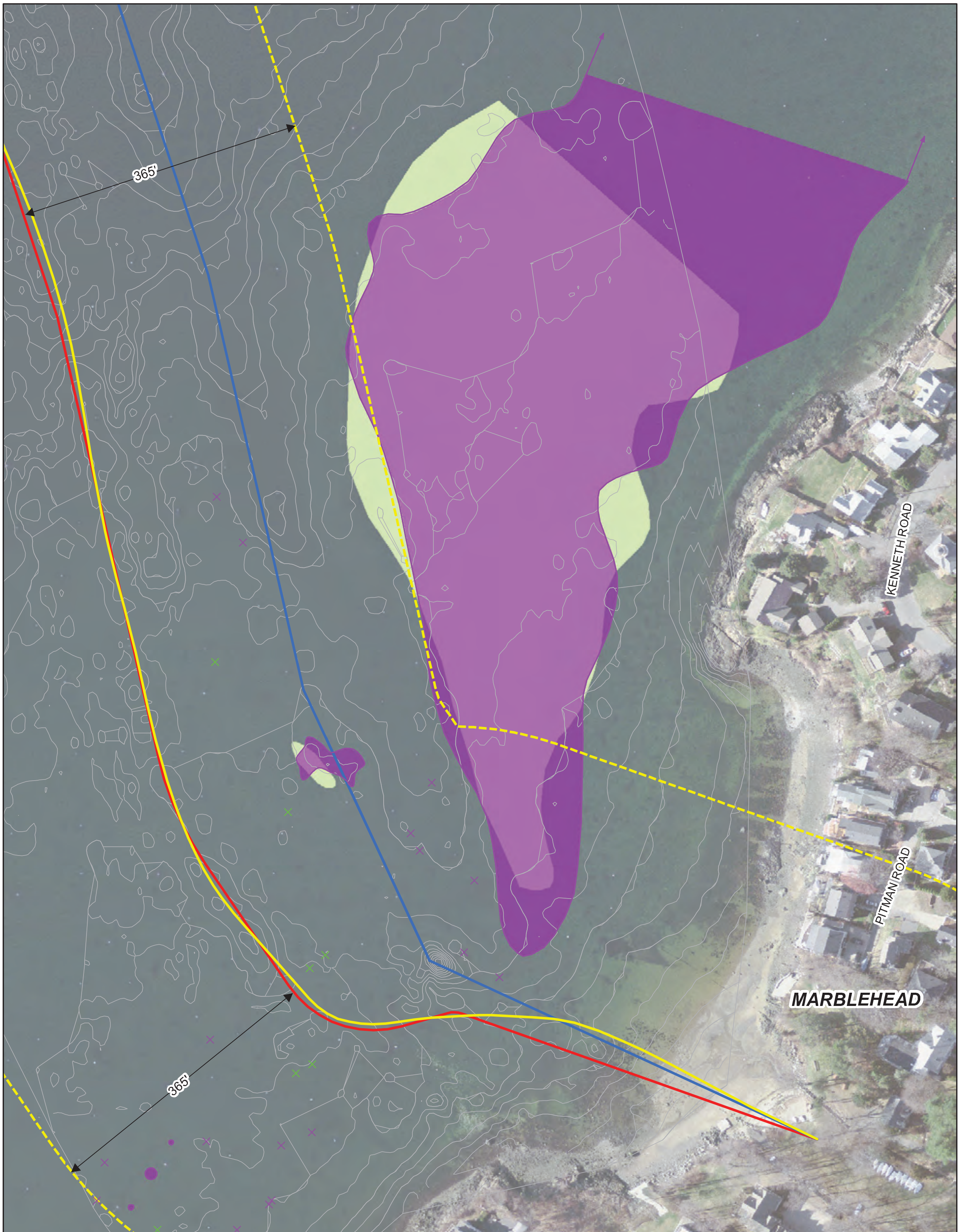

FIGURE 3
EELGRASS SURVEY COMPARISON
CONTRACT NO. 13-1
MARBLEHEAD PIPELINE REPLACEMENT PROJECT
SOUTH ESSEX SEWERAGE DISTRICT
OCTOBER 30-31, 2013 PRE-CONSTRUCTION SURVEY VS.
OCTOBER 20-22, 2015 POST-CONSTRUCTION SURVEY

- MARBLEHEAD AREA -

Legend

- Proposed Sewer Alignment
- Existing Sewer Alignment
- Approximate Sewer As-Built Alignment
- Eelgrass Survey October 2013
- Eelgrass Survey October 2015
- 365-foot Buffer Zone
- Isolated Eelgrass Patch - October 2013 (4-foot diameter or less)
- Isolated Eelgrass Patch - October 2015 (4-foot diameter or less)

AECOM

1 inch = 120 feet (@11" x 17")

0 60 120 240 Feet

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