Mapping and analyzing historical shoreline changes in Massachusetts

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ABSTRACT

Increases in coastal population and shoreline stabilization efforts have heightened the need for government agencies, coastal residents, and consultants to document and understand coastal change. One way to better understand trends in shoreline change and to make this information accessible is through the creation of databases and maps displaying historical shoreline positions and rates of change along the coast.

The U.S. Geological Survey, in conjunction with the Woods Hole Oceanographic Institution Sea Grant Program, partnered with the Massachusetts Office of Coastal Zone Management to update shoreline change maps and to analyze historical shoreline change in Massachusetts. We used historical shoreline positions to measure the erosion and accretion of the coast from the mid-1800s to 1994. We digitized a new high-water shoreline from recent orthophotographs and added the new shoreline to a pre-existing historical shoreline position database. We conducted a statistical analysis of the database to identify patterns of erosion and accretion and to make quantitative estimates of the rates of shoreline changes. Such rates provide information that can be used to understand the magnitude and trends of shoreline changes and can also provide a basis for various coastal zone management strategies. We produced maps, data tables, and an explanatory user guide for distribution to coastal zone managers and coastal communities.

INTRODUCTION

Understanding coastal change has become increasingly important to the 78 coastal communities in Massachusetts. About half of Massachusetts' 6.2 million residents now live in the coastal zone, and the coastal population is growing rapidly. Erosion threatens beachfront houses and development along much of the state's 2400 km of shoreline, creating a critical need for the government and the public to have accurate, up-to-date information on shoreline change. Prior to this shoreline change update, however, Massachusetts' existing historical shoreline change database had not been updated since 1978. New maps and data displaying long-term and more recent trends of shoreline behavior increase the capability for sound decision-making and enhance public awareness of coastal change in Massachusetts.

To produce the necessary maps and data, we compiled historical shoreline positions in ArcInfo from a variety of map and aerial photograph sources. We generated 1:10,000 scale maps of the Massachusetts coast that display historical shorelines, rates of change, locations of rate-of-change measurements (transects), and orthophotographs. We also enhanced a Microsoft Access database created by Van Dusen (1996) that contains transects, dates, and rates of change; it can be used to perform spatial queries and to compile regional statistics and trends. The Massachusetts Office of Coastal Zone Management (MCZM) will distribute these maps, along with the data tables and a manual describing how to use the information, to regional government offices and coastal communities. These products will also be made available to the public through the Internet.

METHODS

Data Sources

Previous projects digitized and assembled historical shoreline data for the Massachusetts coast from 1842 to 1978 into ArcView GIS format (Benoit, 1989; O'Connell, 1997). Those

projects obtained shorelines from six different data sources: 1) National Ocean Service (NOS) topographic maps (T-sheets), 2) NOS hydrographic maps (H-sheets), 3) Federal Emergency Management Agency (FEMA) Flood Insurance Study topographic maps, 4) printed orthophotographs, 5) aerial photographs, and 6) digital orthophotographs. The early shorelines (1842 to 1950) were digitized exclusively from NOS T- and H-sheets. Shorelines from the 1970s were compiled by digitizing FEMA topographic maps, printed orthophotographs, and aerial photographs. These early data sets were digitized and placed into a GIS-compatible format using the Metric Mapping System (Clow and Leatherman, 1984; Benoit, 1989).

The aerial photography used to generate the 1994 orthophotographs has a nominal scale of 1:48,000 and was taken by the National Ocean Service in September and October of 1994. MCZM provided full-color digital mosaicked orthophotographs that have a resolution of one meter per pixel. We used these geographically-registered orthophotographs to digitize the 1994 shoreline directly within ArcView GIS software.

There are several possibilities for identifying a high-water shoreline. In most locations, we delineated the shoreline using the high-tide wrack line. However, due to the range in geomorphology along the Massachusetts coast, other delineations were sometimes more appropriate, such as the wet/dry interface, algal lines along rocky shores, vegetation changes in salt marshes, and the interface between seawalls and open water. Photographs of some areas, such as bleached-out sandy beaches, were difficult to interpret visually. In these cases, field checks and historical shorelines aided interpretation of the orthophotographs.

To verify the accuracy of orthophotograph rectification, we selected control points along the Massachusetts shore at easily recognizable sites, such as building corners and street intersections. We located these sites in the field and recorded the DGPS coordinates, which we then compared to orthophotograph coordinates. Results show that the orthophotographs comply with National Map Accuracy Standards (U.S. Bureau of the Budget, 1947).

Due to the variety of aerial photograph data sources and analytical techniques used to compile the shoreline positions described here, there are a number of potential sources of error that affect the accuracy of the shoreline positions shown on the shoreline change maps. Since much of the historical database had not been checked previously for geographic accuracy, the historical database was subjected to quality control review. The relatively high geographic accuracy and photographic detail of the 1994 orthophotographs, as evidenced by the accurate display of roads, buildings, and shoreline structures, allowed the identification of errors in the pre-1994 shorelines. Although the pre-existing data set was represented to comply with National Map Accuracy Standards, there are inevitably errors in any large spatial data set that more accurate data bring to light. Our analysis resulted in the removal of approximately 43 kilometers of poor-quality data that could have contributed to erroneous interpretations of shoreline change.

Analysis of the various sources of error suggests that the individual shoreline positions in our completed data set are generally accurate to within +/- 8.5 meters. Rates of shoreline change derived from these shorelines have a resolution of +/- 0.12 meters/year (Thieler et al., 2001).

Generating the 1994 Shoreline

We used the line tool in ArcView 3.2 to delineate shoreline segments for each orthophotograph at a scale of >= 1:2,000. After saving shapefiles of the 1994 shoreline segments for each orthophotograph, we used the ArcView Geoprocessing Wizard extension to merge all segments into a single shapefile containing the 1994 shoreline. We added the attributes "length" and "year" to the attribute table before using the Geoprocessing Wizard again to merge the 1994 shoreline with the shapefile of historical shorelines.

Some areas had highly migratory shorelines, such as barrier islands where the landward migration over the past 150 years exceeded the width of the island. To ensure that seaward shorelines would only be compared to other seaward shorelines, and not to any landward shorelines, it was necessary to create two edited versions of the shoreline coverages. One

coverage included only the seaward edge of migrating areas (for example, only the open-ocean side of a barrier island); the complementary coverage included only landward coasts (for example, only the bay side of a barrier island). This method enabled us to examine barrier island migration in addition to shoreline change.

Preparing the Workspaces

We used a suite of Arc Macro Language (AML) programs and a modified version of programs in the Digital Shoreline Analysis System (DSAS; Danforth and Thieler, 1992; Thieler and Danforth, 1994; Van Dusen, 1996) to pinpoint shoreline positions, cast orthogonal transects along the shoreline, compute a linear regression of the rate of shoreline change at each transect location, collect all of the rates and statistics into an INFO database, and create 1:10,000 scale maps. To achieve this it was necessary to establish a shore-parallel baseline and to create sequentially numbered workspaces containing data for each coastal area.

· To establish a point of reference for shoreline change measurement, we used the *buffer* command to draw baseline segments 50 meters landward of and parallel to the general trend of the shorelines. We used a combination of the ArcEdit commands *unsplit, grain*, and *spline* to modify the baseline, placing vertices at 20 meter intervals. Van Dusen (1996) described a similar approach using the *spline, generalize,* and *densify* commands.

We saved each baseline segment, typically about 7 kilometers long, in its own workspace along with a coverage containing the corresponding shorelines. Using polygon coverages, we clipped the larger shoreline coverages, thereby creating smaller coverages to reduce AML processing time.

Once all of the completed shoreline and baseline coverages were saved in the appropriate workspaces, we ran an AML to format the data for the transect-casting and rate calculation software. In each workspace, the AML created a frequency file listing of all of the shoreline years in that area. The AML then used this file with the *reselect* command to select arcs by their year attribute before using the *build* and *ungenerate* commands on the coverage. It also used the frequency file to create a file containing the date for each shoreline. It created formatted text files for the baseline and all shorelines using the generate files.

Digital Shoreline Analysis System

As described by Van Dusen (1996), the basic software used to determine shoreline rates-of-change was a modified version of the DSAS, developed by the U.S. Geological Survey (Danforth and Thieler, 1992). This software is comprised of two C programs. Using the formatted text files, the first program applied a baseline-vertex approach to cast orthogonal transects from each vertex on the baseline to the most seaward shoreline (Figure 1). The program also created a file that contained both the coordinates of points at which the transects crossed each shoreline, and the dates associated with each of those shoreline points. A second C program used this file to compute the rates of change between shorelines at each transect location and to collect all of the rates and statistics into an INFO database. The resulting output file includes four statistical measurements for each transect: the end point rate, average of rates, linear regression rate, and jackknife rate.
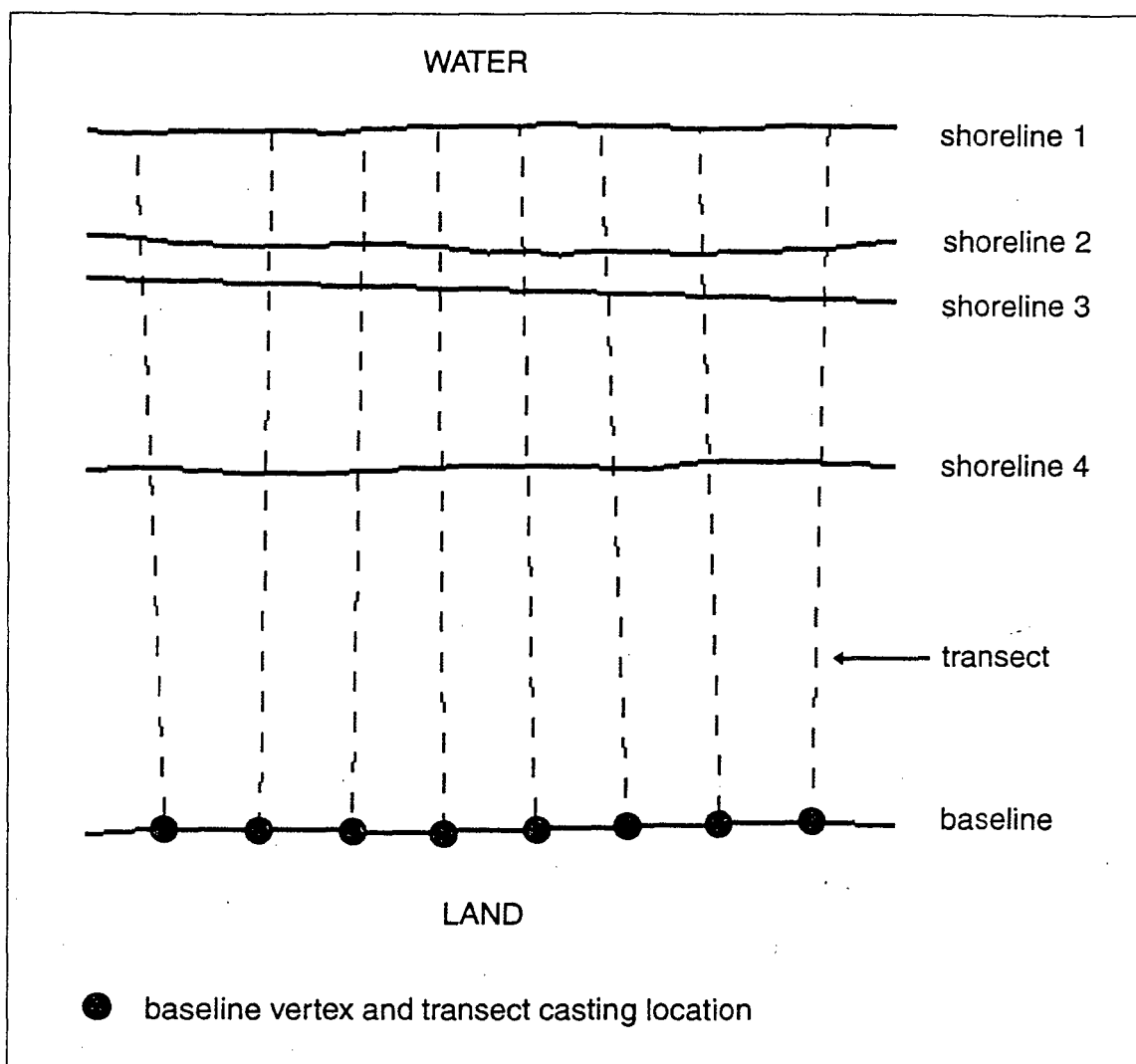
Figure 1. The transect casting scheme used to determine locations for the measurement of shoreline rates of change.

These rates of shoreline change (Dolan et al., 1991) were calculated by measuring the differences between shoreline positions through time along a given transect. The end point rate was calculated by dividing the distance of shoreline movement by the time elapsed between the oldest and the most recent shoreline. The average of rates method (Foster and Savage, 1989) involved calculating separate end point rates for all combinations of shorelines and then taking the average of all end point rates. A linear regression rate-of-change statistic was determined by fitting a least squares regression line to all shoreline points for a particular transect; the rate is the slope of the line. The jackknife rate was implemented as an iterative linear regression which calculates a linear regression fit to shoreline data points with all possible combinations of shoreline points, leaving out one point in each iteration. The slopes of the linear regression lines were averaged to yield the jackknife rate.

Compiling the Data

A suite of four AMLs formatted the output files from the two C programs for the maps and database. The first AML created a coverage of the transect lines with associated shoreline change rates. To do this, it built the transect coverage as lines with the *build* command and added

formatting symbols and values for the baseline and transect numbers to the attribute table for use in labeling transects on the maps. In order to determine angle and direction of the lines, it then built line and node topology and added coordinates of the transect nodes to the coverage's node attribute table. Next, it imported the data from files created by the rate-calculation program into the ArcInfo tables and established a relate in the workspace for the next step. After joining the area files to the transect attribute table for that area, the AML brought the related information and arcs to a new appended coverage.

At this point, all of the necessary map coordinates and rate-of-change statistics were calculated. A second AML made a database for export to Microsoft Access. This AML employed the *append* command to create a new coverage containing the transects for the area workspaces. It then used the *tics* option with the *append* command to renumber transects in the appended coverage with unique, sequential ID values. After building the line coverage, the AML added a new item to the attribute table to allow reselection of every other transect. It then deleted alternate transects, creating a 40 meter interval for display on the printed maps, and renumbered the transects for labeling in the database and on maps. It also utilized the *additem* and *join* commands to add the town names from a separate coverage to the transect coverage. The final routine sorted the transect coverage by baseline and transect numbers.

We used ArcMap to remove manually the poorly located transects that crossed inlets and jetties. After the manual edits, a third AML added items to the attribute table of the transect coverage and selects the attribute table in ArcTables. It used the ArcEdit command *unsplit* to combine the identification arcs in the transect coverage and then builds the transect line coverage. The AML then sorted the transects by transect number in ArcTables. After using the *copyinfo* command on the transect attribute table to create a data file, the AML used *dropitem* to delete attributes such as TNODE that are unnecessary for a user database. It then sorted this data file by transect number and used the *infodbase* command to create a database file. A final AML created the last files needed for the database by indexing the transects according to which map would display them. Using the *infofile* command, it created a DAT file for each map containing the transect number, town name, and town identification number. Finally, it used the *infodbase* command to copy this information into DBASE III+ files.

We imported the INFO database into Microsoft Access and converted it to a standalone application to improve users' ability to perform spatial queries and to compile regional statistics and trends. The database forms, reports, and macros were set up for an interactive display; only the tables needed to be replaced with the new database files and the transect coverage database. We used a macro to update the database with the new statistics and to calculate mean rates and bounding shoreline dates for each transect.

Map Production

The final project goal was to generate maps displaying shoreline change. We used an AML to format the maps with a legend and other explanatory information. This AML used the *reselect* command to draw shorelines with a different color for each era. It also used the command *relate add* to correlate the files created by the rate-calculation program to the existing relate environment, which was saved as an INFO file. The *readselect* command selected every other transect in the writefile of selected transects, and the ArcPlot commands *arcendtext* and *leadertolerance* allowed the transects to be labeled with the associated identification number and linear regression rate of change.

<center>RESULTS</center>

The series of programs described above produced an Access database that can be searched by map number, community name, or transect number. Transect statistics can be listed in a table or graphed in histograms. The tables and histograms can either be printed or viewed on screen (Figures 2 and 3).
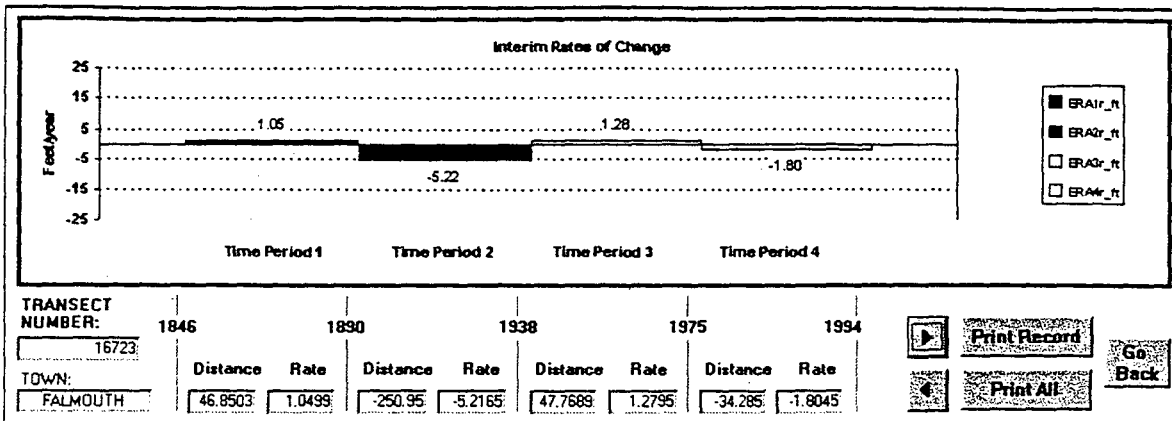
Figure 2. Sample histogram displaying the rate of change during each era at a particular transect.

MASSACHUSETTS HISTORIC SHORELINE CHANGE PROJECT — Transect Statistics for FALMOUTH

Transect Number:	First Time Period		Second Time Period		Third Time Period		Fourth Time Period		Net (overall) Time Period: Net Distance Change*	Summary Statistics: Long Term Annual Shoreline Change Rate~
	Distance*	Rate**	Distance*	Rate**	Distance*	Rate**	Distance*	Rate**		
16719	1846 94.32	2.13	1890 -443.11	-9.22	1938 -94.68	-2.56	1975 -82.84	-4.36	1994 1846 to 1994 -526.31	-4.17
16720	1846 -168.80	-3.84	1890 -196.72	-4.10	1938 -90.91	-2.46	1975 -79.00	-4.17	1994 1846 to 1994 -535.43	-3.58
16721	1846 -191.40	-4.36	1890 -192.29	-4.00	1938 -46.85	-1.29	1975 -113.98	-6.00	1994 1846 to 1994 -544.52	-3.48
16722	1846 -137.17	-3.12	1890 -212.04	-4.43	1938 -20.51	-.56	1975 -104.43	-5.51	1994 1846 to 1994 -474.15	-3.12
16723	1846 46.85	1.05	1890 -250.95	-5.22	1938 47.77	1.29	1975 -34.29	-1.80	1994 1846 to 1994 -190.62	-1.57
16724	1846 33.04	.75	1890 -241.08	-5.02	1938 10.01	.26	1975 -63.68	-3.35	1994 1846 to 1994 -261.71	-2.00
16725	1846 29.53	.66	1890 -232.15	-4.82	1938 6.10	.16	1975 -57.51	-3.02	1994 1846 to 1994 -254.03	-1.94
16726	1846 24.28	.56	1890 -211.68	-4.40	1938 -6.82	-.20	1975 -59.84	-3.15	1994 1846 to 1994 -254.07	-1.90
16727	1846 -5.02	-.10	1890 -177.59	-3.71	1938 -24.54	-.66	1975 -46.98	-2.46	1994 1846 to 1994 -254.13	-1.87
16728	1846 -17.68	-.39	1890 -162.40	-3.38	1938 40.88	1.12	1975 -72.90	-3.84	1994 1846 to 1994 -212.11	-1.44

Statistics for each interim time period show the distance difference and the derived rate of change. Summary statistics show the overall derived Long Term Annual Shoreline Change Rate.

* units in feet. ** units in feet/year. ~ determined using linear regression.

Figure 3. Sample transect listing produced by the Access database.

The programs also produced 91 ArcPlot files. The area maps of the Massachusetts coast are at a scale of 1:10,000 and display historical shorelines, transect locations, and long-term rates of change overlaid on the 1994 orthophotographs (Figure 4).

North River

7260:(-2.49)

7262:(-0.33)

7264:(-0.26)

7258:(-0.43)   7266:(-0.03)

7256:(-0.59)

7254:(-0.23)

7252:(3.12)   Fourth   7268:(-0.07)
                     Cliff   7272:(-0.10)

                                     7274:(-0.03)

                                     7276:(-0.03)

7250:(8.30)   7278:(-0.10)

                    7248:(6.82)   7280:(-0.13)

          7246:(0.36)   7282:(-0.13)

        7244:(-0.89)
          7242:(0.00)   7284:(-0.26)
          7240:(0.26)
                                     7286:(-0.30)
        7238:(-0.46)

Time Periods		7236:(-0.03)	7288:(-0.26)
— 1844 to 1890		7234:(0.62)	7290:(-0.16)
— 1892 to 1938		7232:(0.75)	7292:(0.03)
— 1948 to 1975	South River	7230:(0.46)	7294:(0.00)
— 1978 to 1982		7228:(-0.07)	
— 1994			7296:(-0.07)

7226:(0.18)

7224:(0.13)   7298:(0.10)

7222:(0.43)   7300:(0.13)

7220:(0.53)

Kilometers 0   1/2   1
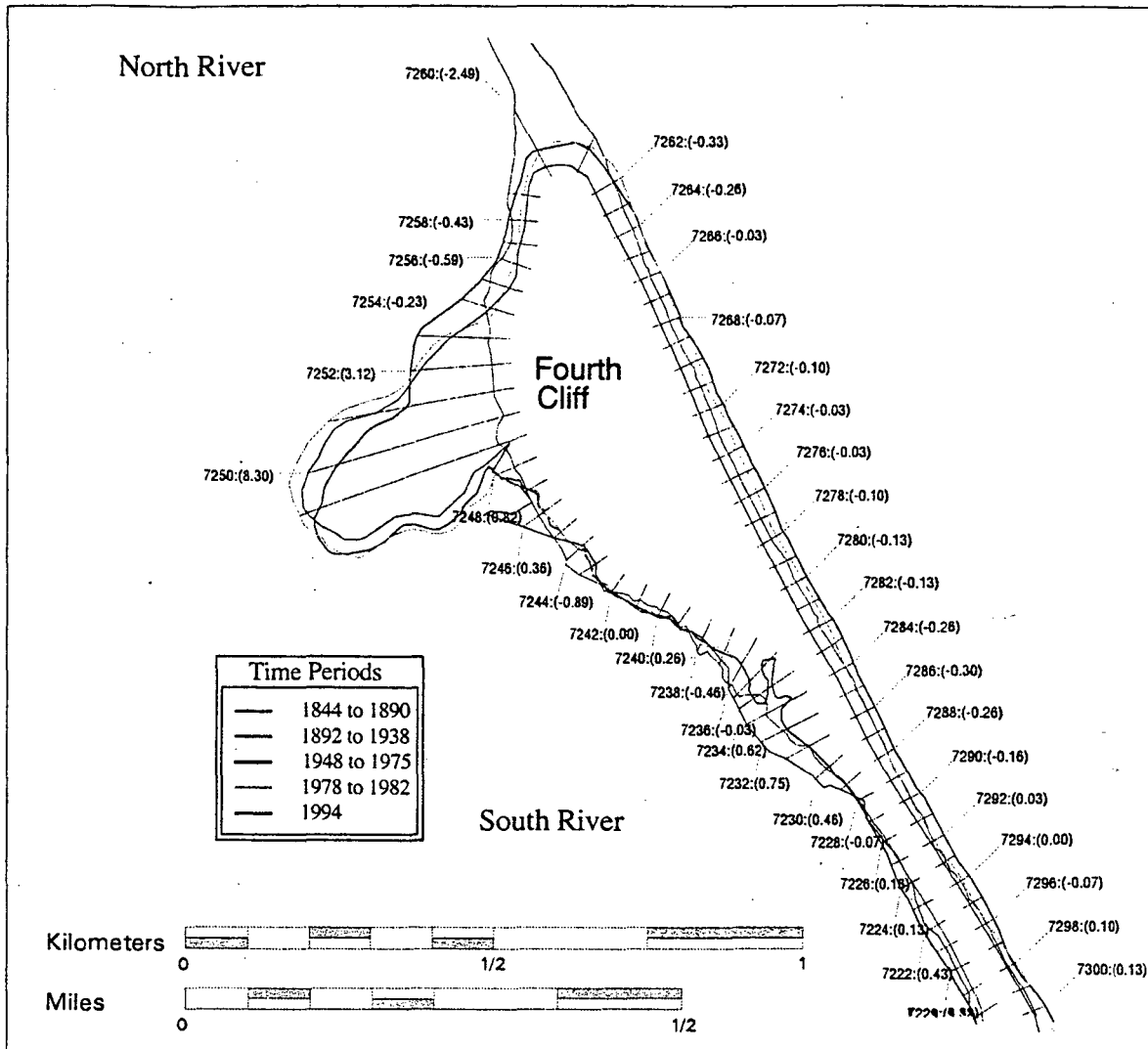
Miles 0   1/2

Figure 4. Enlarged section of a shoreline change map for Scituate, Massachusetts, displaying historical shorelines, transects, and linear regression rate. (For clarity at page size, the orthophotograph underlay is not shown.)

The resulting database and maps include a total of 30,354 transects spaced at 40 meters along the coast of Massachusetts. Linear regression rates indicate erosion at 68% of the transects, accretion at 30% of the transects, and no net change at 2% of the transect locations.

Both the highest and lowest linear regression rates, 15.2 meters per year of accretion and 12.9 meters per year of erosion, occur on Nauset Beach in Chatham, where the barrier island shoreline faces the open Atlantic Ocean.

Several coastal areas have nearly the same number of accreting areas as eroding areas, such as Hingham (47% eroding, 48% accreting) and Hull (50% eroding, 46% accreting). Both of these areas are located within 40 kilometers of Boston, are highly populated, and have a number of seawalls holding the shoreline in place.

Eroding transect locations predominate in Plum Island (74% eroding, 24% accreting), Truro (83% eroding, 15% accreting), Wellfleet (81% eroding, 18% accreting), and Barnstable (73% eroding, 25% accreting). All of these areas have exposed sandy beaches.

The number of accreting transect locations exceeds the number of eroding transect locations in Harwich (36% eroding, 63% accreting), which is shielded by Monomoy Island to the

southeast, and Manchester (40% eroding, 53% accreting), which is characterized by rocky cliffs interspersed with stretches of sandy beaches.

The maps and database serve many purposes and interests. For example, state and local government agencies use the historical rate-of-change data to manage and regulate coastal development. Developers and potential homebuyers can examine the maps to determine the stability of beachfront property. Residents can view post-storm erosion in the context of long-term shoreline variability. This information can also aid in evaluating past management efforts, such as the emplacement of seawalls, jetties, and groins that have influenced shoreline change.

MCZM distributes these maps, along with the database and a manual describing how to use the information, to regional government offices and coastal communities. These products will also be made available to the public on the Internet.

SUMMARY

This project addresses the increasing need to measure and document coastal change by combining established shoreline evaluation techniques with improved GIS applications. The resulting maps and database comprise a current and accessible source of information on coastal change in Massachusetts, including historical shorelines and shoreline change statistics. Massachusetts's coastal managers can continue to benefit from the database by updating the database with new shorelines and rerunning the suite of AMLs and C programs that calculate change and produce maps.

Academics, consultants, citizen groups, developers, and government agencies can use the map and data products described in this paper for a variety of purposes and interests. The database and maps have the potential to improve decisions concerning coastal management, residential and commercial development, and coastal research by making shoreline data comprehensible and available to a wide audience. The maps displaying shorelines and rates of change are visually appealing and quickly understood, particularly when overlaid on orthophotographs. More detailed information is readily available in an interactive database. If further modifications are desired, new modules can be incorporated into the current program and database structure. These methods and products are an excellent resource for anyone interested in coastal change, and they serve as a solid foundation for future applications.

ACKNOWLEDGEMENTS

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