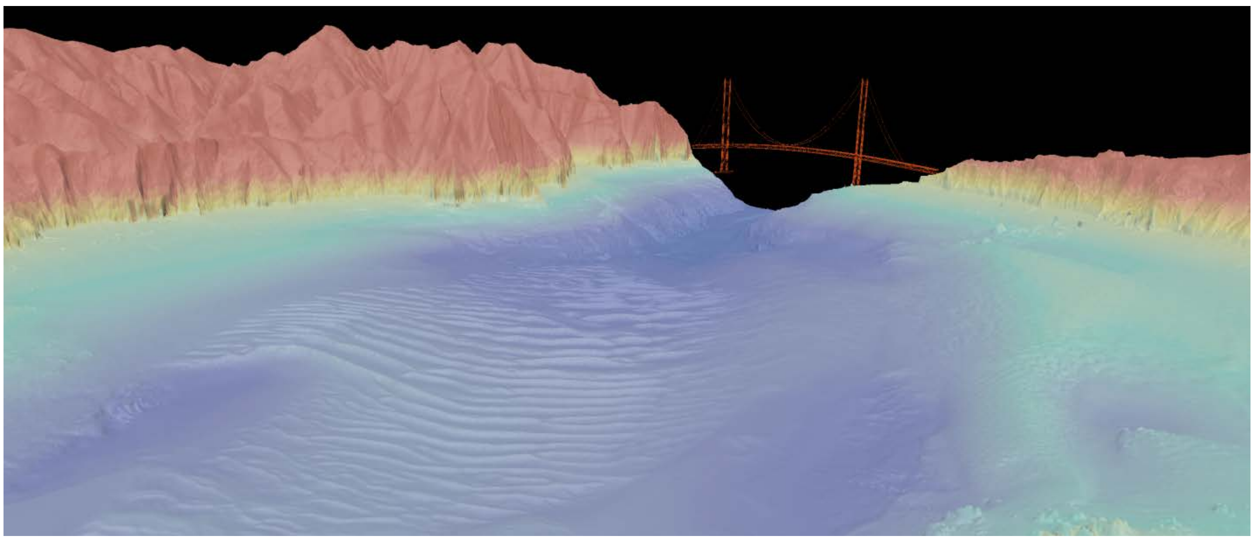
USGS
science for a changing world

A Seamless, High-Resolution Digital Elevation Model (DEM) of the North-Central California Coast



By Amy C. Foxgrover and Patrick L. Barnard

Data Series 684

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit *http://www.usgs.gov* or call 1–888–ASK–USGS

For an overview of USGS information products, including maps, imagery, and publications, visit *http://www.usgs.gov/pubprod*

To order this and other USGS information products, visit *http://store.usgs.gov*

Suggested citation:
Foxgrover, A.C., and Barnard, P.L., 2012, A seamless, high-resolution digital elevation model (DEM) of the north-central California coast: U.S. Geological Survey Data Series 684, 11 p. and data files. (Available at *http://pubs.usgs.gov/ds/684/*.)

Cover: Oblique 3-D perspective view of bathymetry and topography offshore of, and adjacent to, the mouth of San Francisco Bay, California. The view is looking toward the Golden Gate Bridge from a point over the Pacific Ocean, 4 kilometers southeast of the Golden Gate. Elevations in the scene are vertically exaggerated by three times.

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)

A Seamless, High-Resolution Digital Elevation Model (DEM) of the North-Central California Coast

By Amy C. Foxgrover and Patrick L. Barnard

Abstract

A seamless, 2-meter resolution digital elevation model (DEM) of the north-central California coast has been created from the most recent high-resolution bathymetric and topographic datasets available. The DEM extends approximately 150 kilometers along the California coastline, from Half Moon Bay north to Bodega Head. Coverage extends inland to an elevation of +20 meters and offshore to at least the 3 nautical mile limit of state waters. This report describes the procedures of DEM construction, details the input data sources, and provides the DEM for download in both ESRI Arc ASCII and GeoTIFF file formats with accompanying metadata.

Introduction

A seamless, 2-meter (m) resolution digital elevation model (DEM) was constructed for the open-coast region of the San Francisco Bay Area (outside of the Golden Gate Bridge), extending from Half Moon Bay to Bodega Head along the north-central California coastline (fig. 1). The goal was to integrate the most recent high-resolution bathymetric and topographic datasets available (for example, Light Detection and Ranging (lidar) topography, multibeam and single-beam sonar bathymetry) into a seamless surface model extending offshore at least 3 nautical miles (nmi) and inland beyond the +20 m elevation contour.

This work was undertaken as part of the Our Coast – Our Future (OCOF) Project, a collaborative research effort between the U.S. Geological Survey (USGS), the Gulf of the Farallones National Marine Sanctuary, PRBO Conservation Science, and the National Park Service. The goal of OCOF is to provide natural resource managers, local governments, and community members with science-based decision-support tools to plan for and respond to sea level rise and storm hazards along the stretch of California's outer coast extending from Half Moon Bay to Bodega Head (http://data.prbo.org/apps/ocof/).

This DEM was constructed to provide critical model boundary conditions (bathymetry and topography) necessary to predict the impacts of severe winter storms and sea level rise along this stretch of coast, using the Coastal Storm Modeling System (CoSMoS). This process-based modeling system was first applied along the coast of southern California (Barnard and others, 2009; Barnard and Hoover, 2010). CoSMoS can be run in real time or with prescribed scenarios, incorporating atmospheric forcing information (wind and pressure fields) with a suite of state-of-the-art physical process models (WaveWatch3, SWAN, XBeach, Delft3D) to enable detailed prediction of water levels, run-up, wave heights, and currents, ultimately predicting the spatial distribution of coastal flooding, inundation, and potential for erosion and cliff failure. The DEM was constructed to define the general shape of the nearshore, beach, and cliff surfaces as accurately as possible, with less emphasis on the detailed variations in elevation inland of the coast and on bathymetry inside harbors. As a result, this DEM should not be used for navigation purposes.

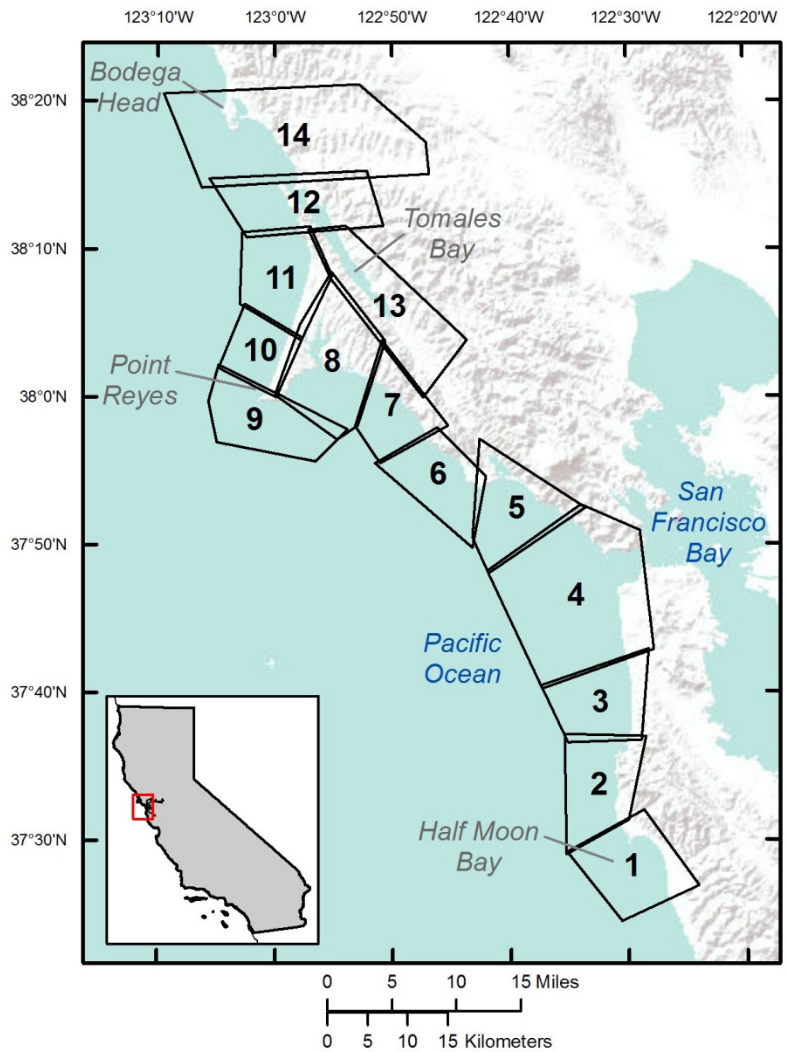


Figure 1. Extent of the north-central California coast digital elevation model (DEM) and the 14 constituent blocks.

DEM Construction Methods

The most recent high-resolution bathymetric and topographic datasets available were compiled to generate this DEM. The vast majority of topographic elevations used in the DEM were obtained from three aerial lidar surveys conducted in 2010. One was commissioned by the USGS, one by the California State Ocean Protection Council (OPC), and the third, the Golden Gate Lidar Project (GGLP), was managed by San Francisco State University. Bathymetry data in the DEM are primarily from multibeam bathymetric surveys conducted between 2006 and 2010 by the California State University, Monterey Bay (CSUMB) Seafloor Mapping Lab, and Fugro Pelagos, Inc., largely for the California Seafloor Mapping Project, a collaborative, multi-institutional campaign (http://seafloor.csumb.edu/csmp/csmp.html). Additional data sources that were included, but have relatively small spatial extents, include local beach and nearshore topographic elevation data obtained using all-terrain vehicles (ATV) and walking surveys, nearshore single-beam bathymetric data from personal watercraft surveys (PWC), and regional DEMs constructed by the National Oceanic and Atmospheric Administration (NOAA) Coastal

Services Center, the National Geophysical Data Center (NGDC), and the geographic information system (GIS) division of the Community Development Agency with the county of Marin. The extents of the individual input data sources are provided as a GIS shapefile, and detailed information on each dataset is provided as a downloadable spreadsheet.

To keep file sizes and processing times reasonable during construction, the study area was divided into 14 constituent DEMs, or blocks, each covering an alongshore distance of approximately 10 kilometers (km) (fig. 1; table 1). DEMs extend offshore to approximately the 3-nmi limit of California's state waters, and inland to at least the +20-m elevation contour. Each DEM block overlaps with the adjacent blocks by at least 250 m. While the lidar data could support a topographic DEM with a 1-m horizontal resolution, a resolution of 2 m was selected for the final DEM to match the resolution of the primary bathymetric datasets used in the project.

Table 1. Individual DEM names and locations comprising the north-central California coastal DEM, listed from south to north. [IDs for each DEM section are used in the file names and within GIS shapefiles]

ID	Geographic Vicinity	County
1	Half Moon Bay	San Mateo
2	Pacifica	San Mateo
3	Daly City	San Mateo
4	San Francisco Bar	San Francisco and Marin
5	Bolinas	Marin
6	Palomarin Beach	Marin
7	Wildcat Beach	Marin
8	Drakes Bay	Marin
9	Point Reyes	Marin
10	Point Reyes Beach	Marin
11	Abbotts Lagoon	Marin
12	Tomales Point	Marin
13	Tomales Bay	Marin
14	Bodega Bay	Marin and Sonoma

DEM Construction Overview

ArcGIS was the primary software used for DEM construction. For each individual DEM, the native datasets were mosaicked into a single grid to preserve the original surfaces as closely as possible. Prior to mosaicking, datasets were gridded and (or) resampled to 2-m resolution (if necessary), and their spatial extents were modified according to the following guidelines.

Datasets of comparable quality (for example, overlapping multibeam data), collected over the same time period, were not clipped. In these instances the overlapping regions were blended together using the "Blend" algorithm in the "Mosaic to New Raster" tool in Arc Toolbox. One exception to this is topographic lidar data along the shoreline. Since the nearshore is a very dynamic region that can be modified greatly by a single storm event, rather than blending multiple high-resolution datasets (which could produce unrealistic beach morphology), data from a single time period were selected for use. Where possible, we used data collected in the fall for nearshore elevations to minimize the potential of winter storm effects.

In overlapping regions where the quality of one dataset was clearly inferior to the other (for example, regional 10-m resolution DEMs overlapping with 2-m resolution lidar), the spatial extent of the inferior dataset was clipped so there was minimal overlap, typically 20 m. The overlapping regions were then smoothed together using the Blend algorithm. This range of overlap was found to be the most efficient for ensuring a smooth transition between datasets while minimizing the use of lower quality data. The spatial extent of each dataset used is included as a GIS shapefile. In addition, the areas of overlap were typically well outside of the dynamic coastal zone, which was generally covered by a single lidar pass, so any blending should have minimal impact in this important region.

DEM Construction Procedures

1. Divide study area into ~10-km alongshore segments

- Define DEM coverage area/polygon that extends ~10 km alongshore, from 3 nmi offshore to beyond the +20 m topographic contour inland
- Ensure that adjacent DEM coverage areas overlap by ~250 m

2. Acquire most recent or highest resolution datasets in DEM coverage areas (example in fig. 2)

- Lidar
- Multibeam bathymetry
- Local high-resolution beach topography (usually ATV-acquired) and nearshore bathymetry (usually PWC-acquired).

3. Fill gaps with older/lower resolution datasets

- Lower resolution DEMs - for example, NGDC's 10-m resolution tsunami inundation DEM, (Carignan and others, 2011) in Bodega Harbor
- Bathymetric data derived from single-beam bathymetry - for example, 1980s survey in Drakes Estero and 1998 bathymetry in Bolinas Lagoon

4. Convert all datasets into identical horizontal coordinate system, vertical datum, and grid resolution

- Horizontal coordinate system: UTM NAD83, Zone 10 North
- Vertical Datum: NAVD88
  - If different [usually Mean Lower Low Water (MLLW)], convert using local NOAA tide station information [http://tidesandcurrents.noaa.gov/ (last accessed December 12, 2011)] based on survey metadata
- Grid resolution: 2 m
  - If already gridded at less than 2 m, resample to 2-m using bilinear interpolation
  - If already gridded at greater than 2 m, export as xyz file, reimport xyz file as point data, create TIN (triangular irregular network), create 2-m grid from TIN using linear interpolation of the TIN triangles, and clip to survey extent
  - Ungridded:
    - Lower resolution surveys (for example, PWC-collected bathymetry): create TIN from points, then convert to 2-m grid using linear interpolation of the TIN triangles

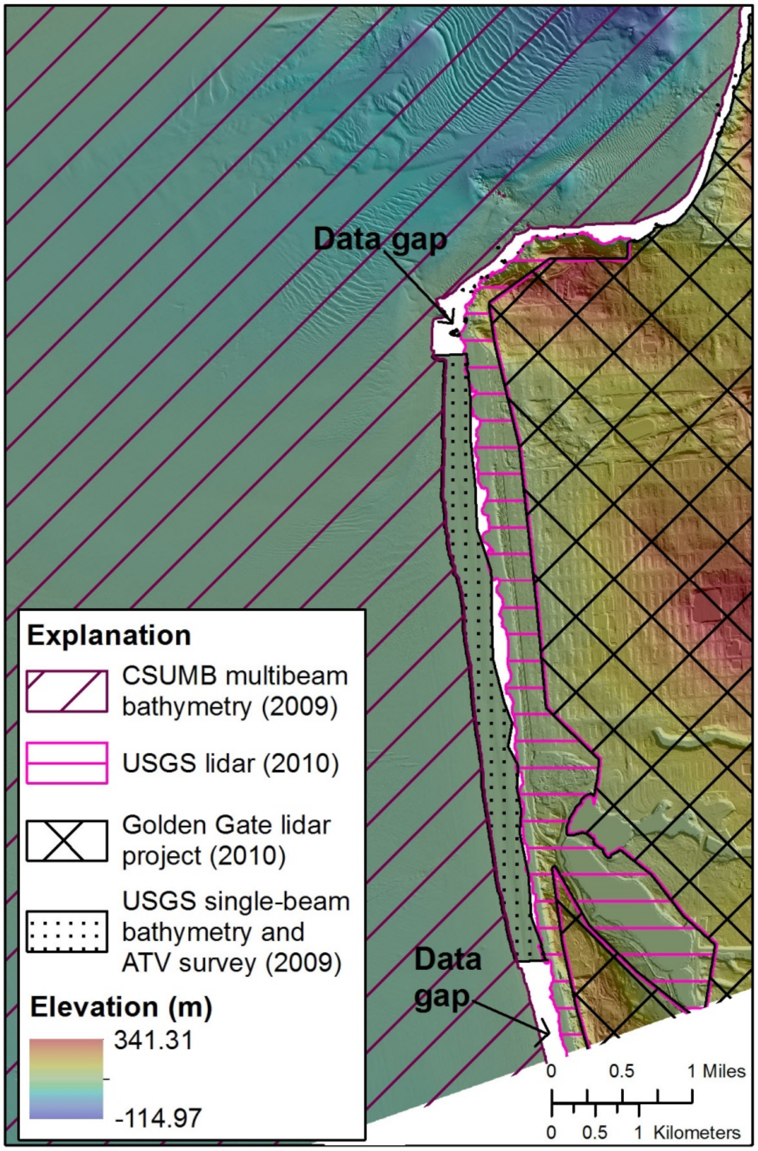


Figure 2. Areal extent of data sources used for the southern portion of digital elevation model (DEM) 4 in the vicinity of Ocean Beach, San Francisco, California. Abbreviations: CSUMB, California State University, Monterey Bay; USGS, U.S. Geological Survey; ATV, all-terrain vehicle; m, meter.

5. Clip datasets to DEM/coverage needs, if necessary

- Useful for data management and processing efficiency
- Necessary for very large datasets, such as countywide lidar datasets (for example, Golden Gate Lidar Project data)
- Remove ocean water surfaces and offshore rocky outcrops/islands
    - Aerial topographic lidar from 2010 was provided as bare-earth hydro-flattened DEMs. The breakline polygons provided with aerial lidar data were used to generate 2-m resolution grids of water surfaces over the ocean or tidal embayments where bathymetric data were to be inserted. This grid was used to mask out water surfaces in the topographic DEM using the “Set Null” tool in Arc Toolbox.

    - Hydro-flattened surfaces of small inland water bodies were retained in the final DEM. Since these areas are of less importance for this research, no attempt was made to obtain bathymetric depths for these inland ponds or lakes (for example, Lake Merced in San Francisco). Hydro-flattened features that were retained in the final DEM are provided in shapefile format.
    - Extract small islands and rocky outcrops from topographic lidar datasets using breaklines provided. These features are not included in the nearshore interpolation but are incorporated into the final DEM in step 8.

6. Manage overlapping datasets

- Datasets were allowed to overlap extensively only if they are from the same time period, of comparable quality, and not within the dynamic nearshore region; otherwise only minimal (~10-30 m) overlap was allowed to ensure smooth DEM transitions
- Low-resolution datasets "pushed" to 2-m resolution, such as personal watercraft data and regional DEMs, were clipped to minimal overlap with adjacent high-resolution datasets (usually multibeam and topographic lidar)
- Topographic lidar was clipped so that only a single dataset is used for the coastal zone. Where available, the USGS lidar is given highest preference in the nearshore zone because it was collected in the summer and fall of 2010, when beach morphology was least likely to be influenced by storm events. The Golden Gate Lidar Project data are used for all reaches landward of the USGS lidar coverage (roughly 10-m elevation and higher) and along the coastline where USGS lidar was not collected. The OPC lidar is present only in two small sections that are not covered by USGS or GGLP lidar (within DEM sections 1 and 14).

7. Fill in data gaps between high-resolution datasets

- If no high-resolution data are available between the offshore multibeam bathymetry and coastal topographic lidar in protected harbors/embayments, or in other areas where interpolation from surrounding datasets will create a surface unlikely to reflect actual bathymetry/topography accurately, fill in gaps with regional DEMs or other low-resolution datasets. Otherwise, interpolate across gaps.
    - Filling in harbors or embayments using regional DEMs/other low-resolution data:
        - Clip best available regional DEM or bathymetry to gap area, allowing only minimal overlap (~20 m) with adjacent high-resolution datasets
        - Export clipped grid as xyz file, reimport xyz data as points, create TIN, create 2-m grid from TIN, clip to gap extent
    - Interpolation across nearshore gaps:
        - Create preliminary DEM using Mosaic tool (fig. 3*A*) with the following settings:

          Coordinate System: UTM Zone 10 North
          Pixel Type: 32 Bit Float
          Cell Size: 2
          Mosaic Method: Blend
          Mosaic Color Map: Last
        - Create polygon of data gap(s) to fill within the preliminary DEM surface
        - Buffer the data gap polygon with a linear distance of 20 m using the Buffer tool in Arc Toolbox

- Clip preliminary DEM using the buffered polygon, export clipped grid as xyz file, reimport xyz data as points (fig. 3*B*), create TIN, create 2-m grid from TIN, clip to buffered gap extent

▪ Interpolation around perimeter of Bolinas Lagoon and Drakes Estero:

- Fill narrow gaps between bathymetry grids of Bolinas Lagoon and Drakes Estero and the nearest high-resolution topography using the same procedure as used above for interpolating across nearshore gaps.

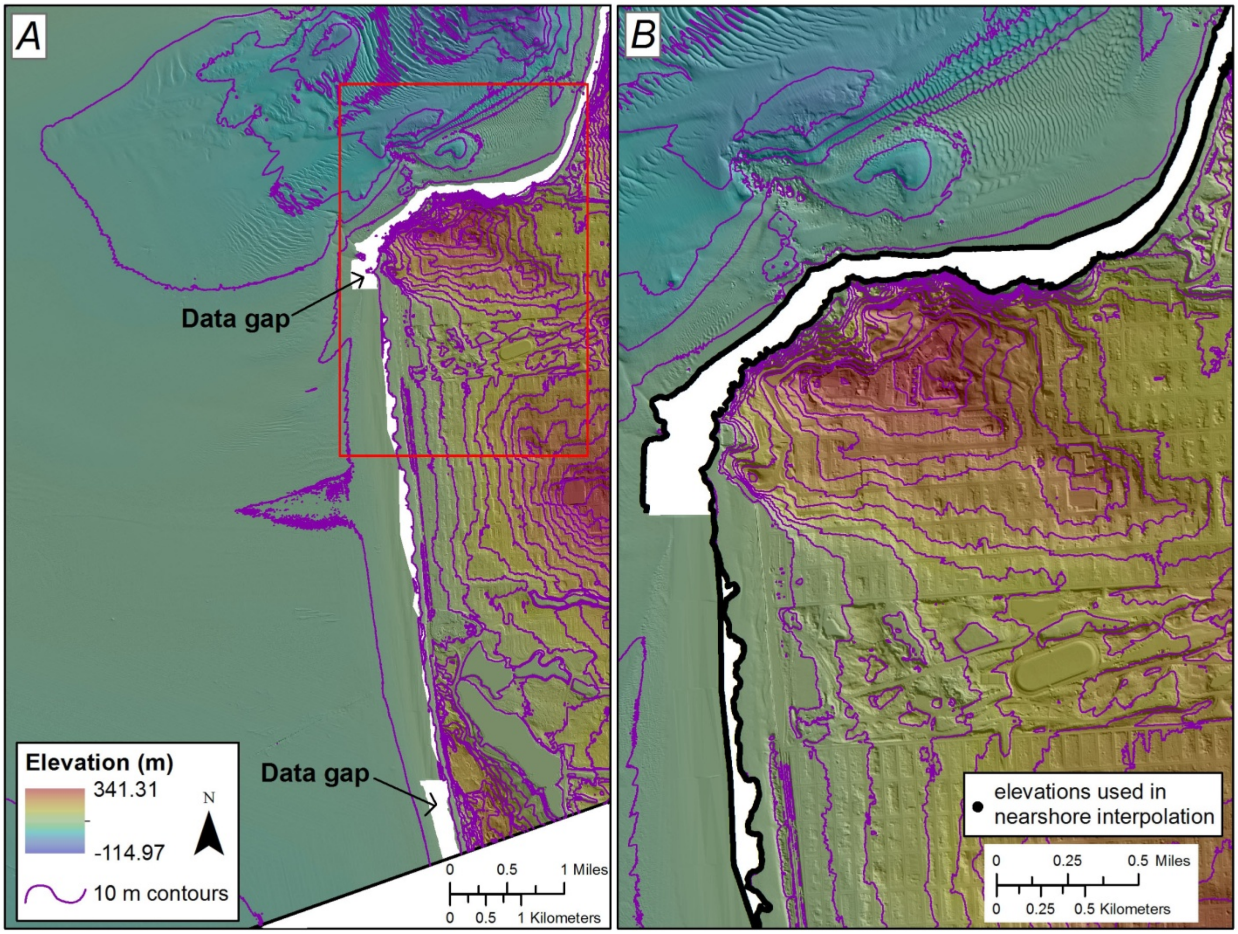


Figure 3. *A*, Preliminary digital elevation model (DEM) for southern portion of DEM 4 with data gaps present in the nearshore. *B*, Expanded view of red-outlined region in *(A)* showing points extracted for use in interpolating elevations across data gaps. Abbreviation: m, meter.

8. Compile final DEMs

- Load all datasets for DEM
- Verify all significant data gaps filled (few missing cells acceptable) in DEM coverage area
- Build interim DEM using Mosaic to New Raster tool in ArcGIS with same settings as noted above in Step 7
- Build final DEM using Mosaic to New Raster tool in ArcGIS. Input rasters used are the interim DEM from the previous step and a grid of lidar elevations for small islands and

rocky outcrops. Islands/outcrops are given priority in the mosaicking algorithm so that those elevations overwrite elevations from the nearshore interpolation.

- Clip output to DEM coverage area
- Create contours and plot cross-shore profiles to verify data quality and consistency (fig. 4)

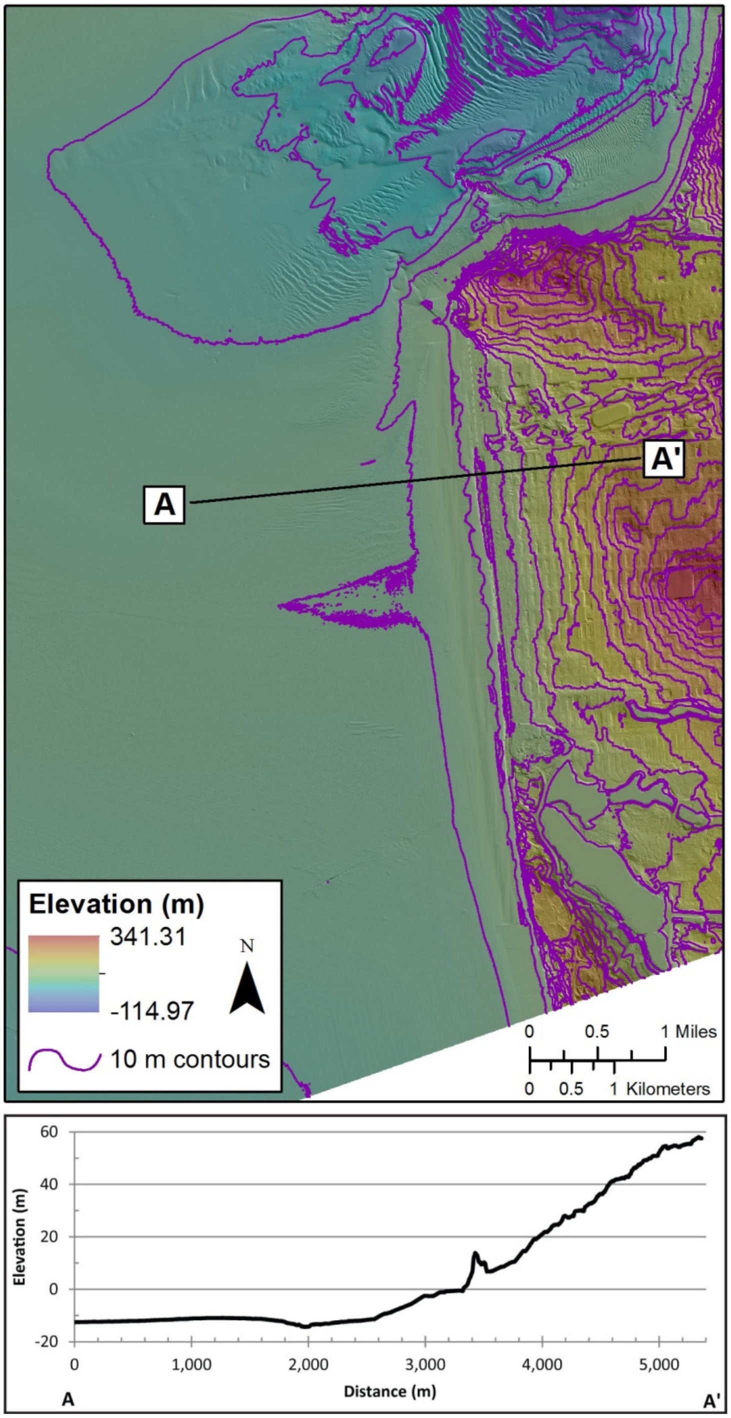


Figure 4. Final digital elevation model (DEM) for the southern portion of DEM 4 (top) and offshore-to-onshore elevation profile along section A-A’ (bottom). Abbreviation: m, meter.

DEM Accuracy and Limitations

Original data were preserved as much as possible by minimizing exporting, regridding, smoothing and (or) resampling during the DEM construction process. However, the vertical accuracy of the resulting DEM is only as good as the accuracy of the native data, which vary considerably. Vertical accuracy reported by the data-source agencies ranges from about ±9 cm root-mean-square error (RMSE) in open terrain for most of the lidar data to potentially greater than 1 m for older bathymetric data. The final DEMs have been reviewed and corrections have been applied for obvious anomalies, but we have not thoroughly analyzed the native datasets to determine whether the reported horizontal and vertical uncertainties are correct. We also assume that grids provided to us were constructed using appropriate techniques and in the proper resolution from cleaned point data. Users should contact the original data sources for inquiries about all metadata and related issues, such as data accuracy or consistency. No guarantee is given for the quality of any of the data. Users must carefully consider the inherent limitations and potential issues associated with these data when using these grids.

The coastal zone is an extremely dynamic environment. Single storms can modify local beach and nearshore elevations by more than 1 m and move elevation contours horizontally by tens of meters; seasonal and interannual changes also can significantly affect coastal bathymetry and topography. Because the datasets used for the DEM were obtained at different times (mostly from 2007 to 2010) and at different resolutions, we make no assurances regarding the local accuracy of the DEM surface. However, where possible, we used data collected in the fall to minimize the potential for winter storm effects.

DEM bathymetry in harbors and tidal embayments should be used with extreme caution. High-resolution multibeam data were available in the main channel of Bodega Harbor and the narrow portion of Pillar Point Harbor, between the inner and outer breakwaters, but the majority of bathymetry in harbors and subembayments was derived from lower resolution DEMs and (or) older single-beam bathymetric data. Therefore, harbors and tidal embayments may have the least accurate bathymetries in the DEM. This DEM was not constructed for navigation but to provide a representative surface to enable accurate physical process modeling of waves, tidal currents, beach morphology changes, and coastal flooding during an extreme storm. Therefore, any other uses of this data should be carefully considered given the above caveats.

The Digital Files

For all spatial data files the horizontal coordinate system is Universal Transverse Mercator (UTM), Zone 10 North, North American Datum of 1983 (NAD83). All elevations are relative to the North American Vertical Datum of 1988 (NAVD88) and all values (eastings, northings, and elevation) are in meters.

Each of the 14 DEMs is provided in both ESRI Arc ASCII and GeoTIFF file format. Arc ASCII files can easily be converted to ARC raster grids using the Arc Toolbox ASCII to Raster tool. Table 2 lists the individual file sizes along with some basic geospatial statistics of the final DEMs.

Table 2. Summary statistics for each DEM section.
[Abbreviations: km², square kilometers; m, meter;MB, megabytes]

DEM ID	Surface area (km^2)	Minimum elevation (m)	Maximum elevation (m)	Mean elevation (m)	Uncompressed file size (MB) GeoTIFF	Arc ASCII
1	108.3	-55.23	263.40	-7.40	74	403
2	105.9	-52.96	463.57	-0.36	62	270
3	108.8	-31.79	205.40	-4.61	46	292
4	314.6	-114.97	341.32	2.54	144	921
5	120.1	-32.99	604.54	25.45	69	417
6	92.6	-45.7	338.61	-4.68	53	342
7	86.2	-45.45	422.30	59.02	56	301
8	162.0	-57.67	409.21	34.93	123	561
9	99.3	-73.97	186.95	-47.11	37	327
10	61.6	-65.44	120.47	-26.67	33	201
11	104.0	-69.96	205.97	-18.90	61	281
12	127.9	-146.33	258.78	21.23	98	332
13	159.2	-16.62	429.76	94.56	159	891
14	317.3	-82.9	242.22	26.22	240	762

There are three polygon shapefiles: DEM_coverage_areas, DEM_source_data, and Hydro_flattened_water. The DEM_coverage_areas shapefile provides the DEM coverage polygons for all 14 DEMs (fig. 1). DEM_source_data outlines the boundaries for each of the native input datasets, with fields displaying key metadata such as data type, native resolution, and date collected. Hydro_flattened_water outlines the location of small lakes or ponds within the terrain that were assigned a hydro-flattened elevation during lidar post-processing. Elevations in these small areas reflect water surface elevations, not bathymetric elevations. Finally, there is a spreadsheet (NCenCA_DEM_Metadata.xls) that lists the primary metadata for all the datasets used in this project.

Polygon Shapefiles

DEM_coverage_areas.zip

DEM_source_data.zip

Hydro_flattened_water.zip

Spreadsheet

NCenCA_DEM_Metadata.xls, .xlsx, and .ods

Acknowledgments

Many thanks to Pat Iampietro (California State University Monterey Bay), Anne Sturm (U.S. Army Corps of Engineers), Brian Quinn (County of Marin), Dennis Hall (NOAA), Ellen Hines (SFSU), Carol Ostergren (USGS), Matt Brennan (ESA-PWA), and Bill Carmen (Bolinas Lagoon Restoration Project) for providing newly released data to support this project. Numerous multibeam datasets used in this study were acquired, processed, archived, and distributed by the

Seafloor Mapping Lab of California State University Monterey Bay. This project was funded by the Our Coast – Our Future Project and the USGS Coastal and Marine Geology Program. Thanks to Pete Dartnell and Dan Hoover for reviewing this report.

References Cited

Barnard, P.L., and Hoover, Daniel, 2010, A seamless, high-resolution, coastal digital elevation model (DEM) for southern California. U.S. Geological Survey Data Series 487, 8 p. and database, available at *http://pubs.usgs.gov/ds/487*/.

Barnard, P.L., O'Reilly, Bill, van Ormondt, Maarten, Elias, Edwin, Ruggiero, Peter, Erikson, L.H., Hapke, Cheryl, Collins, B.D., Guza, R.T., Adams, P.N. and Thomas, Julie, 2009, The framework of a coastal hazards model — A tool for predicting the impact of severe storms: U.S. Geological Survey Open-File Report 2009-1073, 21 p., available at *http://pubs.usgs.gov/of/2009/1073*/.

Carignan, K.S., Taylor, L.A., Eakins, B.W., Caldwell, R.J., Friday, D.Z., Grothe, P.R., and Lim, E., 2011, Digital elevation models of central California and San Francisco Bay: Procedures, data sources and analysis: NOAA Technical Memorandum NESDIS NGDC-52, 49 p. and datasets, available at *http://www.ngdc.noaa.gov/dem/squareCellGrid/download/741*.