NOAA Technical Memorandum NESDIS NGDC- 13

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Contents

1. Introduction 1
2. Study Area 2
3. Methodology 2
   - 3.1 Data Sources and Processing 3
     - 3.1.1 Shoreline 4
     - 3.1.2 Bathymetry 6
     - 3.1.3 Topography 14
   - 3.2 Establishing Common Datums 16
     - 3.2.1 Vertical datum transformations 16
     - 3.2.2 Horizontal datum transformations 16
   - 3.3 Digital Elevation Model Development 16
     - 3.3.1 Verifying consistency between datasets 16
     - 3.3.2 Gridding of multibeam swath sonar data with MB-System 17
     - 3.3.3 Surfacing of bathymetric data 17
     - 3.3.4 Gridding the 1 arc-second Puerto Rico DEM 18
     - 3.3.5 Building the 1/3 arc-second DEMs 18
   - 3.4 Quality Assessment of the Grids 19
     - 3.4.1 Horizontal accuracy 19
     - 3.4.2 Vertical accuracy 19
     - 3.4.3 Slope maps and 3-D perspectives 19
     - 3.4.4 Comparison with source data files 24
     - 3.4.5 Comparison with NGS geodetic monuments 24
4. Summary and Conclusions 26
5. Acknowledgments 26
6. References 26
7. Data Processing Software 27

List of Figures

Figure 1. Overview of Puerto Rico region 1
Figure 2. Source and coverage of datasets used in compiling the Puerto Rico DEMs 3
Figure 3. Coastline datasets used in compiling the Puerto Rico DEMs 5
Figure 4. Mangrove and reef coverage along the southwest shore of Puerto Rico 5
Figure 5. Coverage of NOS hydrographic surveys in the Puerto Rico region 9
Figure 6. Coverage of SHOALS bathymetric LiDAR data used in compiling the Puerto Rico DEMs 10
Figure 7. Coverage of NOS bathymetric LiDAR surveys used in compiling the Puerto Rico DEMs 11
Figure 8. Source and coverage of multibeam sonar datasets used in compiling the Puerto Rico DEMs 13
Figure 9. Source and coverage of topographic datasets used in compiling the Puerto Rico DEMs 14
Figure 10. Detail of NED 1/3 arc-second DEM showing processing errors generated by USGS gridding algorithm 15
Figure 11. Histogram of the differences between NOS hydrographic survey H09491 and the 3 arc-second pre-surfaced bathymetric grid 18
Figure 12. Slope map of the 1/3 arc-second Fajardo DEM 19
Figure 13. Perspective view of the 1 arc-second Puerto Rico DEM 20
Figure 14a. Color image of the 1 arc-second Puerto Rico DEM 20
Figure 14b. Color image of the 1/3 arc-second San Juan DEM 21
Figure 14c. Color image of the 1/3 arc-second Fajardo DEM 21
Figure 14d. Color image of the 1/3 arc-second Guayama DEM 22
Figure 14e. Color image of the 1/3 arc-second Ponce DEM 22

Figure 14f. Color image of the 1/3 arc-second Mayagüez DEM 23
Figure 14g. Color image of the 1/3 arc-second Arecibo DEM 23
Figure 15. Histogram of the differences between one SHOALS bathymetric LiDAR survey and the Arecibo DEM 24
Figure 16. Location of NGS monuments and NOAA tide stations in the Puerto Rico region. NGS monument elevations were used to evaluate the Puerto Rico DEMs 25
Figure 17. Histogram of the differences between NGS monuments and the Ponce DEM 25

List of Tables

Table 1. Specifications for the Puerto Rico DEMs 2
Table 2. Coastline datasets used in compiling the Puerto Rico DEMs 4
Table 3. Bathymetric datasets used in compiling the Puerto Rico DEMs 6
Table 4. Digital NOS hydrographic surveys used in compiling the Puerto Rico DEMs 7
Table 5. NOS hydrographic surveys included in the NCCOS bathymetric DEM 9
Table 6. NOS bathymetric LiDAR surveys used in compiling the Puerto Rico DEMs 11
Table 7. USGS multibeam sonar DEMs used in compiling the Puerto Rico DEMs 12
Table 8. Multibeam swath sonar data used in compiling the Puerto Rico DEMs 12
Table 9. Topographic datasets used in compiling the Puerto Rico DEMs 14
Table 10. Relationship between Mean High Water and other vertical datums in the Puerto Rico region 16
Table 11. Data hierarchy used to assign gridding weight in MB-System 18

Digital Elevation Models of Puerto Rico: Procedures, Data Sources and Analysis

1. Introduction

In June 2007, the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed a series of bathymetric–topographic digital elevation models (DEMs) of Puerto Rico (Fig. 1) for the Pacific Marine Environmental Laboratory (PMEL), NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/). These nested DEMs (boundaries shown in Fig. 2) will be used as input for the MOST (Method of Splitting Tsunami) Model developed by PMEL to simulate tsunami generation, propagation and inundation. The DEMs were generated from diverse digital datasets in the region (source and coverage shown in Fig. 2) and will be used for tsunami forecasting and modeling, as part of the tsunami forecast system, SIFT (Short-term Inundation Forecasting for Tsunamis). This report provides a summary of the data sources and methodology used in developing a 1 arc-second DEM covering the entire island of Puerto Rico and 1/3 arc-second DEMs[1] centered on the major communities of Arecibo, Fajardo, Guayama, Mayagüez, Ponce and San Juan, Puerto Rico.



Figure 1. *Overview of Puerto Rico region. (image taken from http://earthquake.usgs.gov/regional/world/puerto_rico/puerto_rico_history.php)*

1. The Puerto Rico DEMs were built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems, such as UTM zones (in meters). At the latitude of Puerto Rico (18° N) 1/3 arc-second of latitude is equivalent to 10.25 meters; 1/3 arc-second of longitude equals 9.81 meters.

2. Study Area

The study area covers the island of Puerto Rico, located in the Caribbean Sea, with special emphasis on the coastal communities at risk from tsunamis. Puerto Rico covers 8,959 square kilometers with a population of almost 4 million people. The DEMs that cover this region extend well offshore into deeper water for the purpose of tsunami modeling (Fig. 2)

The island of Puerto Rico has three main physiographic regions: mountainous interior, coastal lowlands and a karst region. The mountainous interior covers 60% of the island with the highest peak, Cerro La Punta, reaching 1,338 meters. The coastal lowlands extend 13 to 19 km inward in the north and 3 to 13 km in the south. The karst region is located on the north side of the island.

San Juan, the capital of Puerto Rico, is located on the northeast coast and has one of the largest harbors in the Caribbean. San Juan covers 122 square kilometers with a population of 442,447 (2000 Census). The Bayamón River lies west of San Juan and empties into the Atlantic Ocean.

The city of Fajardo is located on the east coast of Puerto Rico, covering approximately 556 square kilometers, with a population of 40,712 (2000 Census). Home to the largest marina in the Caribbean, Fajardo provides access to the Virgin Islands to the east.

Guayama, known as "La Ciudad Bruja" (witch city) or "Pueblo de los Brujos" (city of witches), is located on the southeastern coast of Puerto Rico, and was founded in 1736 by Matías de Abadía. Nearby is the Jobos Bay National Estuarine Research Reserve, established in 1987, that consists of approximately 2,883 acres of mangrove forest and freshwater wetlands. The areas surrounding Guayama produce sugar, tobacco, coffee, and livestock.

Ponce is located on the southern coastal plain region of the island and has the second largest population in Puerto Rico. Ponce covers just over 500 square kilometers with a population of 186,475 (2000 Census). Previously a capital of the region for Spain, Ponce now provides a major shipping port for the Caribbean.

The city of Mayagüez is located on the west-central coast of Puerto Rico, covering 197.6 sq km, with a population of 104,557 (2000 Census). The Rio Grande de Añasco River lies to the north and the Guanajibo River to the south of Mayagüez. Both rivers empty into the Caribbean Sea from the west coast of Puerto Rico.

Arecibo, on the Puerto Rico northern coast, is home to one of the most important astronomical research facilities on Earth, the Arecibo Ionospheric Observatory, located in the mountains south of town. The observatory's massive dish is sited in a sinkhole larger in area than a dozen football fields and is tuned to detect the slightest sounds emitted from the farthest stars. This is the home base for NASA's 'SETI' (Search for Extra-Terrestrial Intelligence) project and, as such, holds great fascination for visitors.

3. Methodology

The Puerto Rico DEMs were developed to meet PMEL specifications (Table 1), based on input requirements for the MOST inundation model. The best available data were obtained by NGDC and shifted to common horizontal and vertical datums: World Geodetic System 1984 (WGS84) and Mean High Water (MHW), for modeling of 'worst-case scenario flooding', respectively. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1. Specifications for the Puerto Rico DEMs.

Grid Area	*Puerto Rico*	*Arecibo*	*Fajardo*	*Guayama*	*Mayagüez*	*Ponce*	*San Juan*
Coverage Area (W)	65°–68°	66.5°–67.1°	65.35°–65.9°	65.7°–66.4°	67.1°–67.6°	66.4°–67.1°	65.9°–66.5°
(N)	17°–19°	18.35°–18.8°	18.05°–18.6°	17.7°–18.05°	17.9°–18.6°	17.7°–18.05°	18.35°–18.8°
Grid Spacing	1 arc-second	1/3 arc-second					
Coordinate System	Geographic decimal degrees						
Horizontal Datum	World Geodetic System 1984 (WGS84)						
Vertical Datum	Mean High Water (MHW)						
Vertical Units	Meters						
Grid Format	ESRI ASCII raster grid						

3.1 Data Sources and Processing

Shoreline, bathymetric, topographic, and orthophotographic data (Fig. 2) were obtained from numerous federal and state government agencies, and universities, including: the U.S. Geological Survey (USGS); the NOAA National Ocean Service (NOS), National Geodetic Survey (NGS), Office of Coast Survey (OCS) and National Centers for Coastal Ocean Science (NCOOS); the Puerto Rico Planning Board (PRPB); the Puerto Rico Office of Management and Budget; and the University of Puerto Rico. Safe Software's (http://www.safe.com/) FME data translation tool package was used to shift datasets to WGS84 horizontal datum and to convert into ESRI (http://www.esri.com/) ArcGIS shape files. The shape files were then displayed with ArcGIS to assess data quality and manually edit datasets. NGDC's GEODAS software (http://www.ngdc.noaa.gov/mgg/geodas/) was used to manually edit large xyz datasets. Quick Terrain Modeler (http://www.appliedimagery.com/) was used to evaluate and edit the NOS bathymetric LiDAR surveys. Vertical datum transformations to MHW were accomplished using FME, based upon data from NOAA tide stations at San Juan and Magueyes Island (http://tidesandcurrents.noaa.gov/). VDatum (http://nauticalcharts.noaa.gov/csdl/vdatum.htm) was not available for this area.

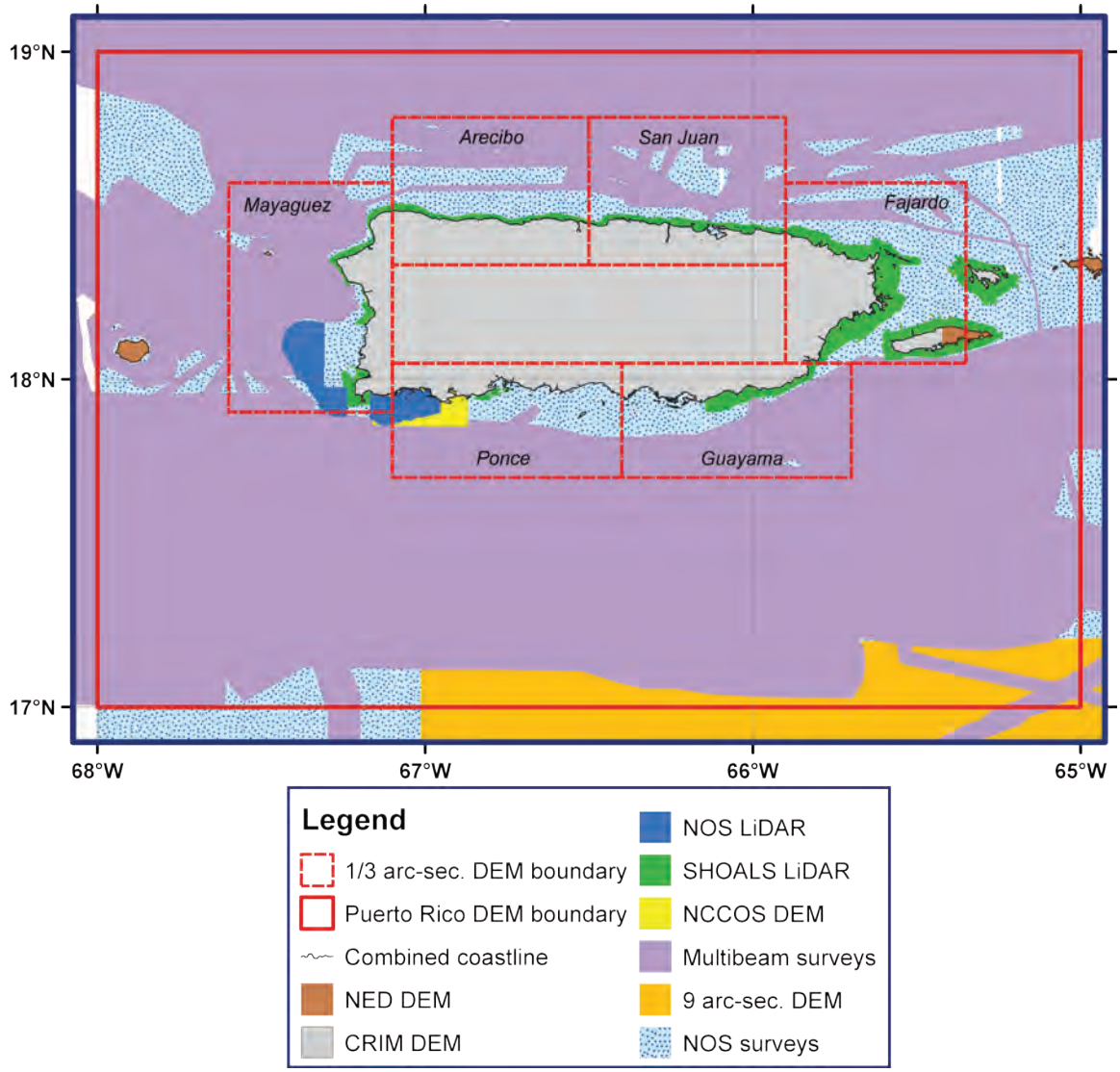


Figure 2. *Source and coverage of datasets used in compiling the Puerto Rico DEMs (boundaries in red).*

3.1.1 Shoreline

Digital shorelines were obtained from the Puerto Rico Planning Board and the National Oceanic and Atmospheric Administration (Table 2). The differences between the coastlines are largely qualitative and are due mainly to mangrove swamps portrayed as either landward or seaward of the coastline. As areas of dense mangrove coverage are known to strongly dissipate tsunami energy, it is important to make the distinction as to where the coastline lies relative to these areas.

Table 2: Coastline datasets used in compiling the Puerto Rico DEMs.

Source	*Area*	*Description*	*URL*
Puerto Rico Planning Board	Island of Puerto Rico	Digitized from aerial photos	http://www.crimpr.net/
NOAA National Geodetic Survey	Culebra, Vieques and other islands	Digitized NOS shoreline maps	http://www.csc.noaa.gov/shoreline/data.html
NOAA Office of Coast Survey	Mona and Desecheo islands	Extracted from NOS nautical charts	http://nauticalcharts.noaa.gov/csdl/ctp/cm_vs.htm

1) **Puerto Rico Planning Board digitized coastline of the main island of Puerto Rico**

This coastline was provided to NGDC by Dewberry and Davis, Inc. It was digitized by the Puerto Rico Planning Board (PRPB) from 1995 aerial photos as part of the "Centro de Recaudación de Ingresos Municipales (CRIM), Land Information System Project" between 1996 and 1998. Dewberry and Davis, Inc. received the coastline in multiple pieces, by USGS quadrangle, which they merged together and checked against orthometric photographs for accuracy. It was also degraded from a scale of 1:2,000 to 1:5,000.

2) **Vectorized shoreline derived from NOS shoreline maps**

This shoreline dataset represents a vector conversion of NOS shoreline (T-sheets) maps and CAD-based Standard Digital Data Exchange Format (SDDEF) data. It was created by the NOAA National Geodetic Survey (NGS) as part of its ongoing mission to map the coastline of the United States. The NOAA Coastal Services Center developed the procedures used in this project and was responsible for project oversight.

3) **NOS nautical charts extracted vector shoreline**

This coastline was extracted from NOS nautical charts using software developed by the NOAA Office of Coast Survey, Coast Survey Development Laboratory, Cartographic & Geospatial Technology Program. It is referenced to mean high water, NAD83 in non-projected geographic coordinates and based on 1:10,000 to 1:80,000 scale charts.

After analysis of the available coastlines, the vector shoreline generated from orthometric photos by the Puerto Rico Planning Board obtained from Dewberry and Davis, Inc, was chosen for the main island. Surrounding islands were added from the NOAA, NOS, OCS Extracted Vector Shoreline and the NOAA, NOS Digitized Coastline using ESRI ArcEdit. This "combined coastline" (Fig. 3) defines the mangrove-sea interface, encompassing mangrove areas around the island, except for the La Parguera area between 66.98º and 67.13º west (Fig. 4). The combined coastline was converted to point data for use as a coastal buffer for the bathymetric pre-surfacing algorithm (see Section 3.3.2) to ensure that interpolated bathymetric values reached "zero" at the coast. It was also provided to the U.S. Geological Survey for their use in developing a 1/3 arc-second National Elevation Dataset (NED) DEM for Puerto Rico (see Section 3.1.3).

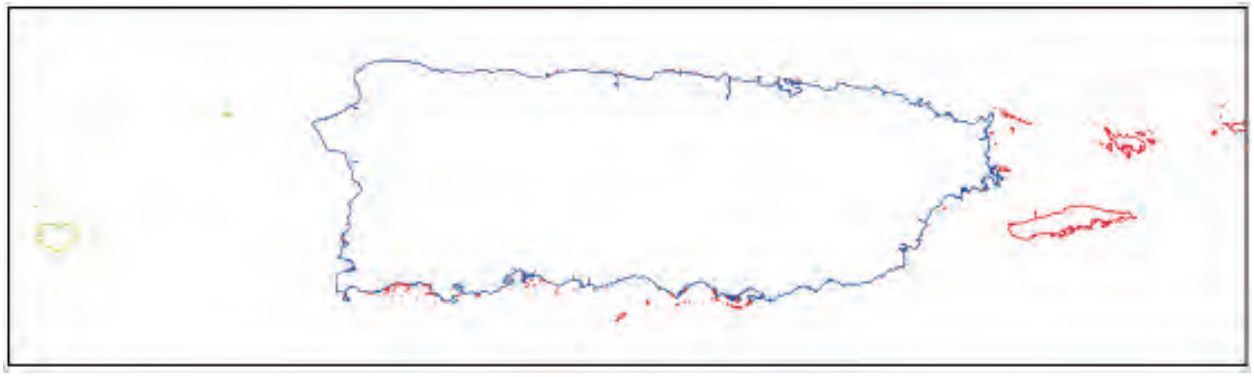


Figure 3. *Coastline datasets used in compiling the Puerto Rico DEMs. PRPB coastline (blue); NOS shoreline maps (red); and NOS nautical charts (green).*

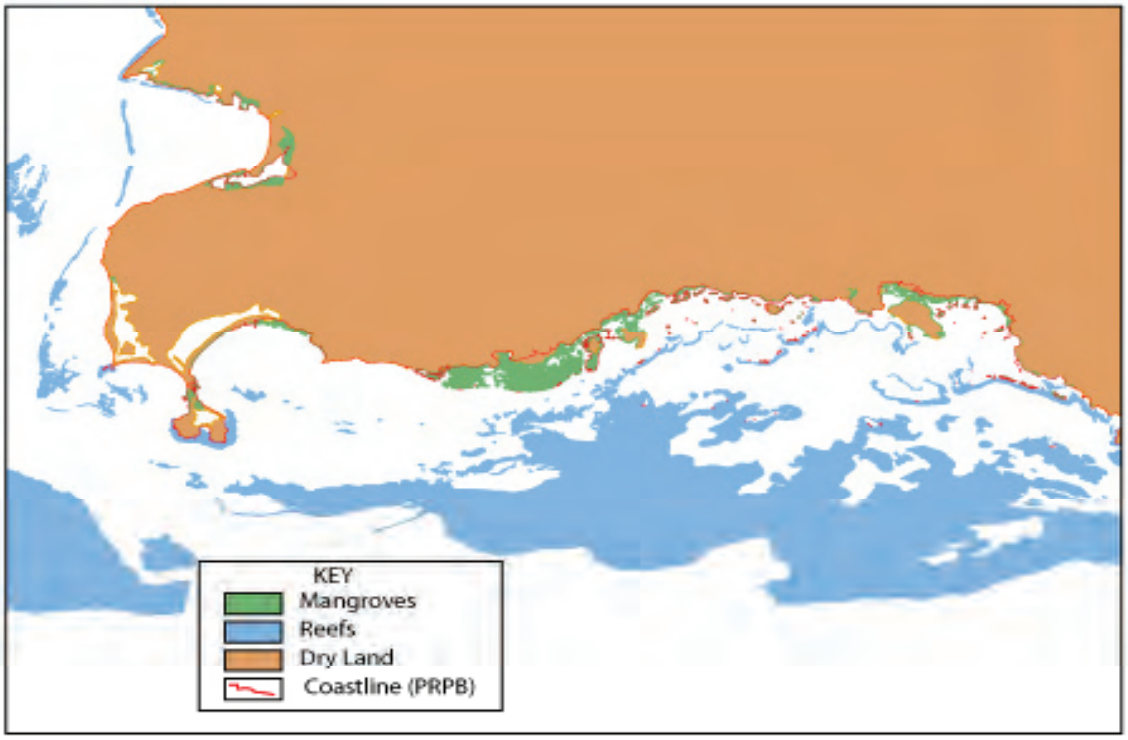


Figure 4. *Mangrove and reef coverage along the southwest shore of Puerto Rico. The green box represents the Parguera mangrove area, which is not encompassed by the PRPB coastline. This area is characterized by an extensive development of coral reefs, seagrass beds, and mangrove forests. (Graphic from NCCOS Biogeography Program, 2001)*

3.1.2 Bathymetry

Bathymetric datasets used in the compilation of the Puerto Rico DEMs (Table 3) included: 114 NOS hydrographic surveys; seven NOS bathymetric LiDAR surveys; U.S. Army Corps of Engineers SHOALS coastal LiDAR surveys; a 5 meter cell-size bathymetric DEM derived from NOS hydrographic survey data and scuba depths off the southwest coast of the island of Puerto Rico; DEMs derived from deep water multibeam sonar surveys collected by the U.S. Geological Survey; multibeam swath sonar files archived at NGDC and Lamont Doherty Earth Observatory; and a 9 arc-second DEM compiled from seafloor predicted topography data and General Bathymetric Chart of the Oceans (GEBCO) bathymetric contours.

Table 3. Bathymetric datasets used in compiling the Puerto Rico DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum*	*Original Vertical Datum*	*URL*
NOS	1900 to 2001	Hydrographic survey soundings	Ranges from 10 meters to 3 kilometers (Varies with scale of survey, depth, traffic and probability of obstructions)	Early Puerto Rico Island Datum, Puerto Rico Datum, NAD27 geographic, NAD83 geographic	MLW, MLLW	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NCCOS	2004	DEM of NOS soundings and scuba depths	5 meter DEM	WGS84 geographic	MLLW	http://coastalscience.noaa.gov/
JALBTCX	2001	SHOALS bathymetric LiDAR	5 meter posting	NAD83 US Virgin Islands, Puerto Rico State Plane	MLLW	
NOS	2006	bathymetric LiDAR	1 meter posting	NAD83 UTM Zone 19	MLLW	
USGS	2004–2007	DEMs of multibeam sonar surveys	1 to 5 arc-seconds	NAD83 UTM Zone 19	MSL	
NGDC, LDEO	1985–2005	Multibeam swath sonar files	Varies with depth	WGS84 geographic	MSL	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html and http://www.marine-geo.org/
NGDC	2005	DEM of Smith and Sandwell Predicted Topography combined with GEBCO contours.	9 arc-second	WGS84 geographic	MSL	http://topex.ucsd.edu/marine_topo/ and http://www.bodc.ac.uk/projects/international/gebco/gebco_digital_atlas/gda_development/

1) NOS hydrographic surveys

A total of 114 NOS hydrographic surveys were used in building the Puerto Rico DEMs (Table 4; Fig. 5). The survey data were originally vertically referenced to either mean lower low water or mean low water and horizontally referenced to Early Puerto Rico datum, Puerto Rico datum, NAD27 geographic and NAD83 geographic. Data point spacing for the surveys ranges from about 10 meters in shallow to up to 3 kilometers in deep water.

Table 4. Digital NOS hydrographic surveys used in compiling the Puerto Rico DEMs.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum*
F00279	1985	1:5,000	MLLW	Puerto Rico Datum
H02468	1904	1:5,000	MLW	Early PR Island Datums
H02469	1900	1:10,000	MLW	Early PR Island Datums
H02472	1900	1:5,000	MLW	Early PR Island Datums
H02490	1909	1:40,000	MLW	Early PR Island Datums
H02491	1909	1:10,000	MLW	Early PR Island Datums
H02492	1905	1:10,000	MLW	Early PR Island Datums
H02536	1901	1:20,000	MLW	Early PR Island Datums
H02537	1901	1:20,000	MLW	Early PR Island Datums
H02555	1902	1:10,000	MLW	Early PR Island Datums
H02582	1905	1:20,000	MLW	Early PR Island Datums
H02584	1902	1:20,000	MLW	Early PR Island Datums
H02585	1902	1:10,000	MLW	Early PR Island Datums
H02633	1903	1:20,000	MLW	Early PR Island Datums
H02634	1903	1:20,000	MLW	Early PR Island Datums
H02640	1903	1:40,000	MLW	Early PR Island Datums
H02672	1904	1:40,000	MLW	Early PR Island Datums
H02673	1904	1:20,000	MLW	Early PR Island Datums
H02674	1904	1:20,000	MLW	Early PR Island Datums
H02676	1909	1:60,000	MLW	Early PR Island Datums
H02677	1904	1:20,000	MLW	Early PR Island Datums
H02678	1904	1:20,000	MLW	Early PR Island Datums
H02686	1904	1:10,000	MLW	Early PR Island Datums
H02690	1904	1:10,000	MLW	Early PR Island Datums
H02803	1906	1:40,000	MLW	Early PR Island Datums
H02804	1906	1:20,000	MLW	Early PR Island Datums
H02871	1907	1:20,000	MLW	Early PR Island Datums
H02876	1909	1:20,000	MLW	Early PR Island Datums
H02877	1909	1:20,000	MLW	Early PR Island Datums
H02883	1907	1:20,000	MLW	Early PR Island Datums
H02934	1908	1:20,000	MLW	Early PR Island Datums
H02935	1908	1:20,000	MLW	Early PR Island Datums
H02936	1908	1:20,000	MLW	Early PR Island Datums
H02937	1908	1:20,000	MLW	Early PR Island Datums
H02938	1908	1:20,000	MLW	Early PR Island Datums
H03004	1909	1:20,000	MLW	Early PR Island Datums
H04205	1921	1:20,000	MLW	Early PR Island Datums
H04725	1927	1:10,000	MLW	Early PR Island Datums
H04742	1927	1:10,000	MLW	Early PR Island Datums
H06556	1940	1:10,000	MLW	Early PR Island Datums
H08637	1962	1:10,000	MLW	Puerto Rico Datum
H08638	1962	1:10,000	MLW	Puerto Rico Datum
H08639	1969	1:5,000	MLW	Early PR Island Datums
H08780	1967	1:20,000	MLW	Early PR Island Datums
H08811	1964	1:10,000	MLW	Puerto Rico Datum
H08812	1967	1:20,000	MLW	Puerto Rico Datum
H08813	1964	1:5,000	MLW	Puerto Rico Datum
H08814	1964/65	1:10,000	MLW	Early PR Island Datums
H08848	1965	1:5,000	MLW	Puerto Rico Datum
H08849	1965	1:5,000	MLW	Puerto Rico Datum
H08862	1965	1:5,000	MLW	Early PR Island Datums
H08877	1966	1:5,000	MLW	Early PR Island Datums
H08880	1966	1:20,000	MLW	Early PR Island Datums
H08985	1968	1:10,000	MLW	Early PR Island Datums
H08986	1968	1:10,000	MLW	Early PR Island Datums
H08987	1968	1:10,000	MLW	Early PR Island Datums
H08988	1968	1:10,000	MLW	Puerto Rico Datum

H08989	1968	1:20,000	MLW	Early PR Island Datums
H09029	1969	1:100,000	MLW	Early PR Island Datums
H09031	1969	1:5,000	MLW	Puerto Rico Datum
H09032	1969	1:5,000	MLW	Early PR Island Datums
H09033	1969	1:20,000	MLW	Early PR Island Datums
H09034	1969	1:20,000	MLW	Early PR Island Datums
H09110	1970	1:5,000	MLW	Early PR Island Datums
H09119	1970	1:10,000	MLW	Early PR Island Datums
H09120	1970	1:5,000	MLW	Early PR Island Datums
H09135	1970/71	1:10,000	MLW	Early PR Island Datums
H09183	1971	1:10,000	MLW	Early PR Island Datums
H09186	1971	1:10,000	MLW	Early PR Island Datums
H09190	1971	1:10,000	MLW	Early PR Island Datums
H09264	1972	1:10,000	MLW	Early PR Island Datums
H09265	1972	1:10,000	MLW	Early PR Island Datums
H09266	1972	1:20,000	MLW	Early PR Island Datums
H09267	1972/75	1:10,000	MLW	Early PR Island Datums
H09270	1967	1:40,000	MLW	NAD27 geographic
H09271	1972	1:10,000	MLW	Early PR Island Datums
H09272	1972	1:10,000	MLW	Early PR Island Datums
H09273	1972	1:20,000	MLW	Early PR Island Datums
H09278	1972	1:100,000	MLW	Early PR Island Datums
H09463	1975	1:125,000	MLW	Early PR Island Datums
H09485	1975	1:10,000	MLW	Early PR Island Datums
H09486	1975	1:20,000	MLW	Early PR Island Datums
H09490	1975	1:5,000	MLW	Early PR Island Datums
H09491	1975	1:5,000	MLW	Early PR Island Datums
H09517	1975	1:20,000	MLW	Early PR Island Datums
H09587	1976	1:125,000	MLW	Early PR Island Datums
H09595	1976	1:100,000	MLW	Early PR Island Datums
H09596	1976	1:10,000	MLW	Early PR Island Datums
H09597	1976	1:10,000	MLW	Early PR Island Datums
H09601	1976	1:10,000	MLW	Early PR Island Datums
H09602	1976	1:10,000	MLW	Early PR Island Datums
H09603	1976	1:10,000	MLW	Early PR Island Datums
H09604	1976	1:20,000	MLW	Early PR Island Datums
H09605	1976	1:20,000	MLW	Early PR Island Datums
H09607	1976	1:10,000	MLW	Early PR Island Datums
H09608	1976	1:10,000	MLW	Early PR Island Datums
H09609	1976	1:5,000	MLW	Early PR Island Datums
H09610	1976	1:20,000	MLW	Early PR Island Datums
H09616	1976	1:10,000	MLW	Early PR Island Datums
H09617	1976	1:10,000	MLW	Early PR Island Datums
H09618	1976	1:20,000	MLW	Early PR Island Datums
H09992	1982	1:80,000	MLW	Early PR Island Datums
H09993	1982	1:80,000	MLW	Early PR Island Datums
H10073	1983	1:10,000	MLLW	Puerto Rico Datum
H10074	1983	1:80,000	MLLW	Puerto Rico Datum
H10076	1983	1:80,000	MLLW	Puerto Rico Datum
H10077	1983	1:10,000	MLLW	Puerto Rico Datum
H10078	1983	1:20,000	MLLW	NAD27 geographic
H10083	1983	1:80,000	MLLW	Puerto Rico Datum
H10505	1993	1:5,000	MLLW	NAD83 geographic
H10506	1993	1:5,000	MLLW	NAD83 geographic
H11033	2001	1:5,000	MLLW	NAD83 geographic
H11034	2001	1:5,000	MLLW	NAD83 geographic
H11036	2001	1:5,000	MLLW	NAD83 geographic

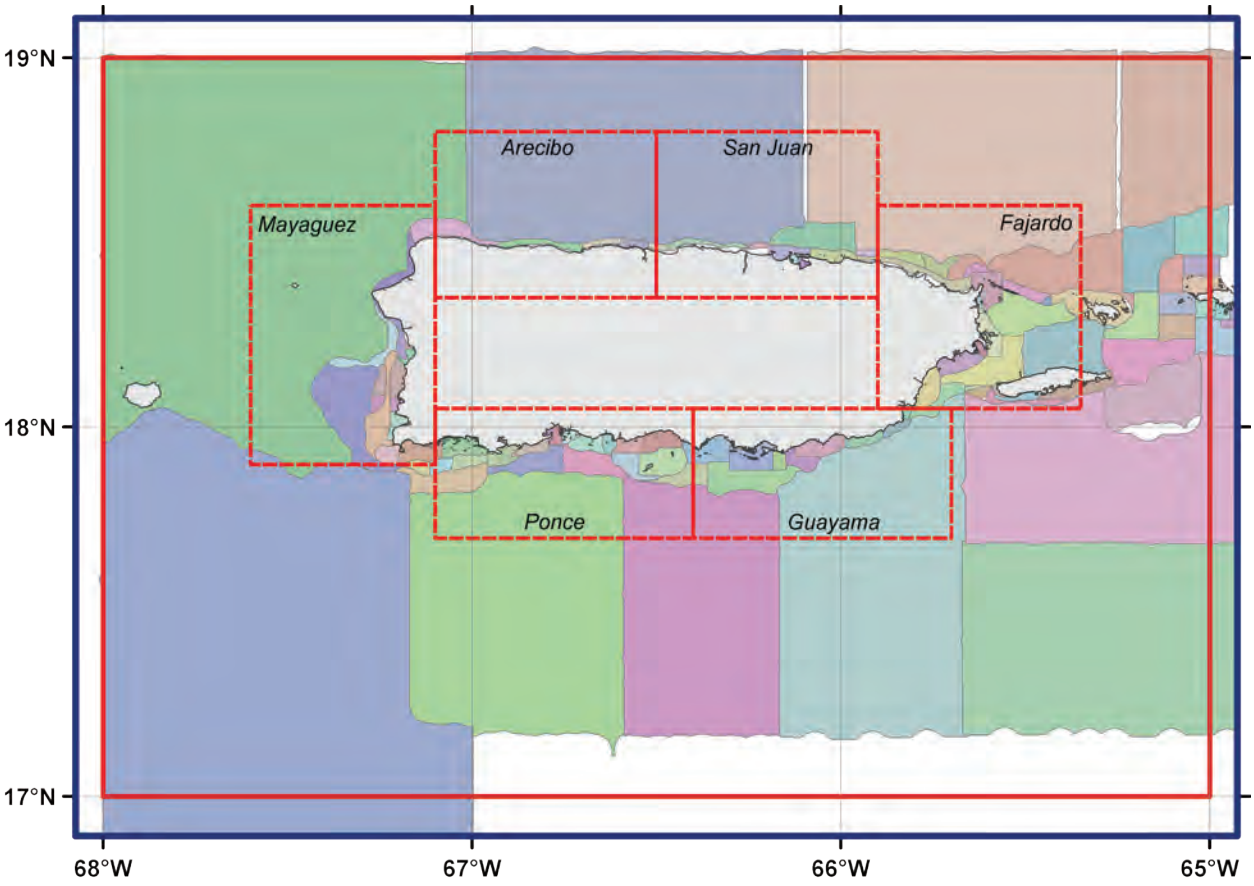


Figure 5. *Coverage of NOS hydrographic surveys in the Puerto Rico region. DEM boundaries in red.*

2) NOAA National Centers for Coastal Ocean Science (NCCOS) DEM

NOAA's National Ocean Service (NOS), National Centers for Coastal Ocean Science (NCCOS), Biogeography Team provided a 5-meter bathymetric DEM derived from NOS hydrographic surveys (Table 5) and depths collected by Biogeography Team SCUBA divers. SCUBA depths were used to fill gaps inshore of the NOS survey data. The DEM was generated using a triangulated interpolated network (TIN) with ESRI ArcView® 3D Analyst software. All reef crests were given a depth of 0.3 meters. Model validation using an independent set of bathymetric data revealed an average error of less than 0.3 meters. TIN models were then converted into raster maps (spatial resolution = 5 x 5 m). After conversion of this grid to MHW and WGS84, depth values were compared to NOS hydrographic survey and SHOALS LiDAR data in the same area and were within ~ 0.5 meters in most areas.

Table 5. NOS hydrographic surveys included in the NCCOS bathymetric DEM.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum*
H02676	1909	1:60,000	MLW	Early PR Island Datums
H08984	1968	1:10,000	MLW	Early PR Island Datums
H08985	1968/69	1:10,000	MLW	Early PR Island Datums
H08986	1968	1:10,000	MLW	Early PR Island Datums
H08987	1968	1:10,000	MLW	Early PR Island Datums
H08988	1968	1:10,000	MLW	Puerto Rico Datum
H08989	1968	1:20,000	MLW	Early PR Island Datums
H09029	1969	1:100,000	MLW	Early PR Island Datums
H09033	1969	1:20,000	MLW	Early PR Island Datums
H09119	1970	1:10,000	MLW	Early PR Island Datums
H09120	1970	1:5,000	MLW	Early PR Island Datums
H09183	1971	1:10,000	MLW	Early PR Island Datums

3) SHOALS LiDAR data

Dr. Aurelio Mercado-Irizarry at the University of Puerto Rico provided NGDC with bathymetric SHOALS[2] LiDAR data collected by the Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX). The 2001 survey encircles the islands of Culebra and Vieques, and most of Puerto Rico, except its southern coast. Data coverage spans from the shoreline to several kilometers offshore at 5 meter spacing (Fig. 6). The data were positioned using post-processed kinematic GPS and National Geodetic Survey monuments.

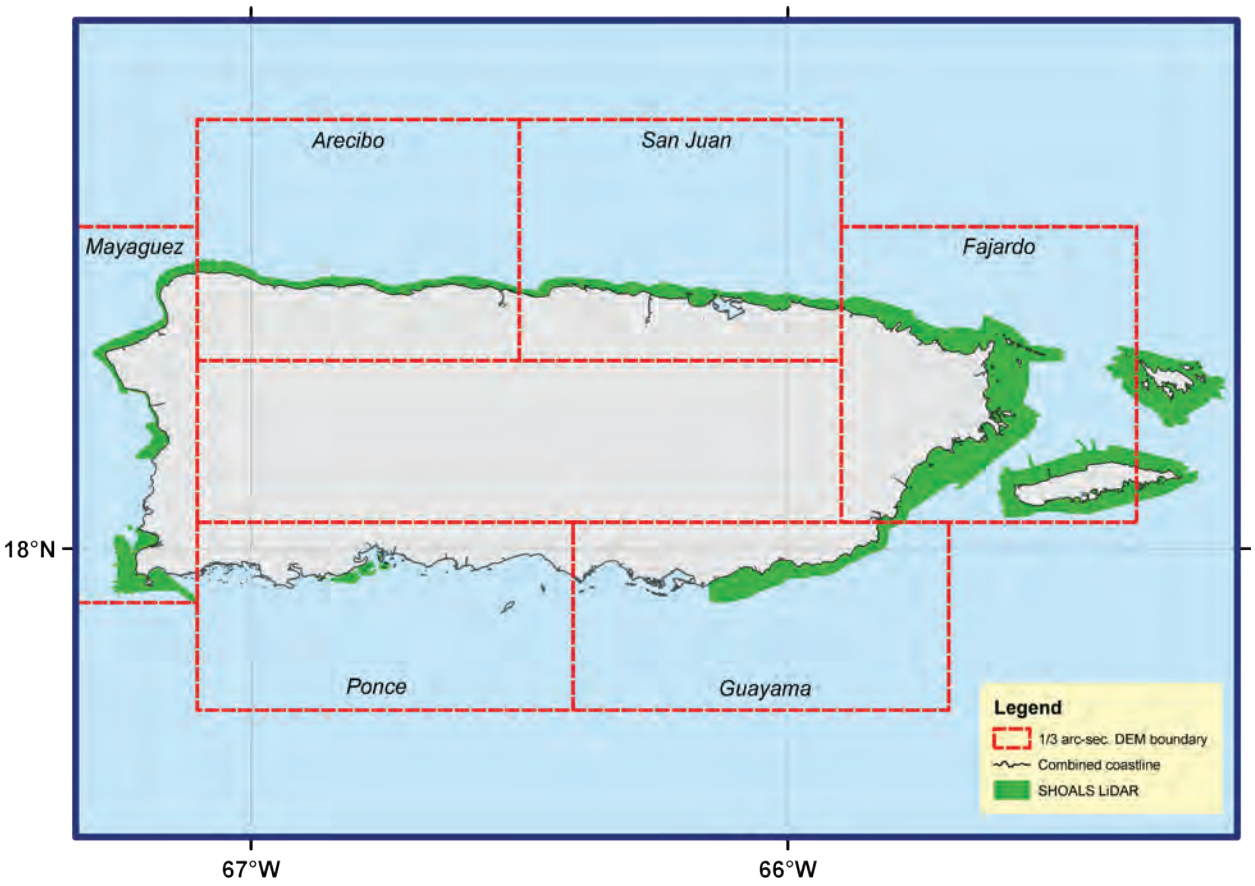


Figure 6. *Coverage of SHOALS bathymetric LiDAR data used in compiling the Puerto Rico DEMs.*

2. These data were collected by the SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey) system, which consists of an airborne laser transmitter/receiver capable of measuring 400 soundings per second. The system operates from a deHavilland DHC-6 Twin Otter flying at altitudes between 200 and 400 meters with a ground speed of about 100 knots. The SHOALS system also includes a ground-based data processing system for calculating acurate horizontal position and water depth. Lidar is an acronym for LIght Detection And Ranging. The system operates by emitting a pulse of light that travels from an airborne platform to the water surface where a small portion of the laser energy is backscattered to the airborne receiver. The remaining energy at the water's surface propogates through the water column and reflects off the sea bottom and back to the airborne detector. The time difference between the surface return and the bottom return corresponds to water depth. The maximum depth the system is able to sense is related to the complex interaction of radiance of bottom material, incident sun angle and intensity, and the type and quantity of organics or sediments in the water column. As a rule-of-thumb, the SHOALS system should be capable of sensing bottom to depths equal to two or three times the Secchi depth. [Extracted from metadata.]

4) NOS LiDAR bathymetry

In 2006 NOS conducted bathymetric LiDAR surveys covering the southwestern portion of Puerto Rico (Table 6; Fig. 7). Data collection was conducted using the LADS Mk II Airborne System, data processing using the LADS Mk II Ground System and data visualization, quality control and final products using CARIS (http://www.caris.com/). Most of the survey data have been archived at NGDC in UTM Zone 19 and MLLW datums, with soundings extracted using CARIS software; four surveys have not been processed to date. The data were subsequently evaluated and edited with QT Modeler, and transformed to WGS84 and MHW using FME software.

Table 6. NOS bathymetric LIDAR surveys used in compiling the Puerto Rico DEMs.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Vertical Datum*	*Original Horizontal Datum*
H11557	2006	1:10,000	MLLW	NAD83 UTM Zone 19
H11558	2006	1:10,000	MLLW	NAD83 UTM Zone 19
H11559	2006	1:10,000	MLLW	NAD83 UTM Zone 19
H11563	2006	1:10,000	MLLW	NAD83 UTM Zone 19
H11565	2006	1:10,000	MLLW	NAD83 UTM Zone 19
H11566	2006	1:10,000	MLLW	NAD83 UTM Zone 19
H11567	2006	1:10,000	MLLW	NAD83 UTM Zone 19

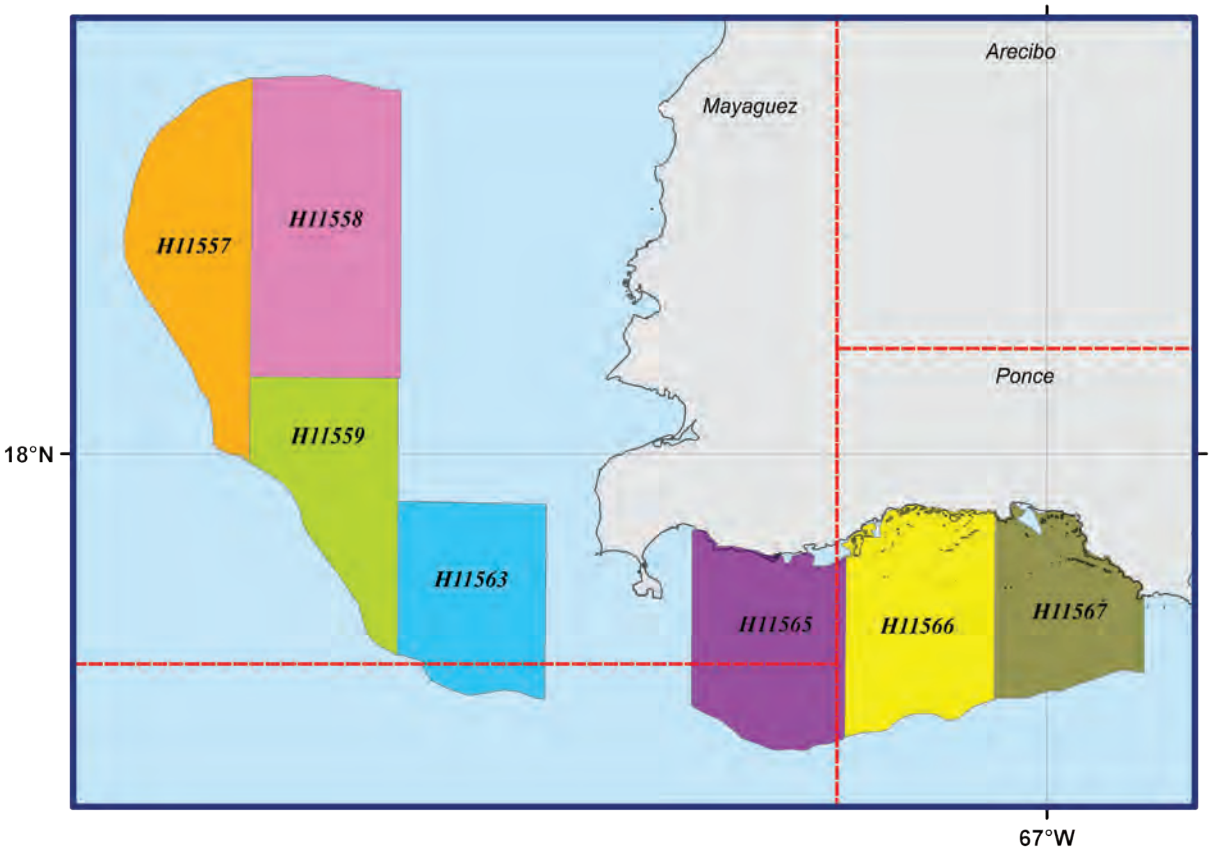


Figure 7. *Coverage of NOS bathymetric LiDAR surveys used in compiling the Puerto Rico DEMs.*

5) DEMs of USGS multibeam swath sonar surveys

Uri ten Brink and Jason Chaytor with the U.S. Geological Survey provided NGDC with DEMs of proprietary multibeam swath sonar surveys that their team has recently conducted around Puerto Rico (Table 7; Fig. 8). DEMs were referenced to NAD83 UTM Zone 19 and MSL. NGDC resampled the 5 arc-second DEMs to 3 arc-seconds, using ArcGIS, for use in building a preliminary 3 arc-second bathymetric surface (see Section 3.3.3). See ten *Brink and Smith (2003)*, *ten Brink, et al. (2004)*, and *Carbó et al. (2005)* for details on research discoveries related to these surveys.

Table 7. USGS multibeam sonar DEMs used in compiling the Puerto Rico DEMs.

DEM ID	*Year of Survey*	*Cell Size*	*Vessel*
HE-05019	2005	5 arc-seconds	Hesperis
NF0704	2007	1 arc-second	Nancy Foster
RB0604	2006	5 arc-seconds	Ron Brown
RB0605	2006	5 arc-seconds	Ron Brown

6) Multibeam swath sonar surveys

The original sonar files from multibeam swath sonar surveys and transits in the Puerto Rico region (Table 8; Fig. 8) were downloaded from the NGDC multibeam database (http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html) and from the Marine Geoscience Data System database (Carbotte, et al., 2004; http://www.marine-geo.org/). All sonar data were in WGS84 and MSL datums. Data were processed, evaluated, and edited using the MB-System software package (http://www.ldeo.columbia.edu/res/pi/MB-System/), an NSF-funded share-ware software application specifically designed to manipulate multibeam sonar data. Several cruises (C2907, EW9706, EW0105 and EW0301) had frequent anomalous values and showed significant discrepancies with other cruises, the USGS multibeam sonar DEMs and NOS hydrographic surveys: these cruises were not used in building the Puerto Rico DEMs.

Table 8. Multibeam swath sonar data used in compiling the Puerto Rico DEMs.

Cruise ID	*Year of Survey*	*Source*	*Vessel*	*Sonar System*	*Cruise Type*
AT04L04	2001	NGDC	Atlantis	SeaBeam 2100	Transit
C2605	1985	NGDC	Conrad	SeaBeam	Transit
EW9501	1995	MGDS	Ewing	Atlas Hydrosweep	Transit
EW9605	1996	MGDS	Ewing	Atlas Hydrosweep	Transit
EW0102	2001	MGDS	Ewing	Atlas Hydrosweep	Transit
EW0103	2001	MGDS	Ewing	Atlas Hydrosweep	Transit
EW0106	2001	MGDS	Ewing	Atlas Hydrosweep	Transit
EW0302	2003	NGDC	Ewing	Atlas Hydrosweep	Transit
EW0309	2003	MGDS	Ewing	Atlas Hydrosweep	Transit
EW0403	2004	NGDC	Ewing	Atlas Hydrosweep	Transit
EW0404	2004	MGDS	Ewing	Atlas Hydrosweep	Transit
EW0405	2004	NGDC	Ewing	Atlas Hydrosweep	Transit
HLY-05-TH	2005	MGDS	Healy	SeaBeam 2112	Transit
KN151L4	1997	NGDC	Knorr	SeaBeam 2100	Transit
KN161L07	2000	MGDS	Knorr	SeaBeam 2100	Transit
KN173L02	2003	NGDC	Knorr	SeaBeam 2100	Transit
RB0208	2002	NGDC	Ron Brown	SeaBeam 2112	Puerto Rico Trench survey
RB0303	2003	NGDC	Ron Brown	SeaBeam 2112	Puerto Rico Trench survey

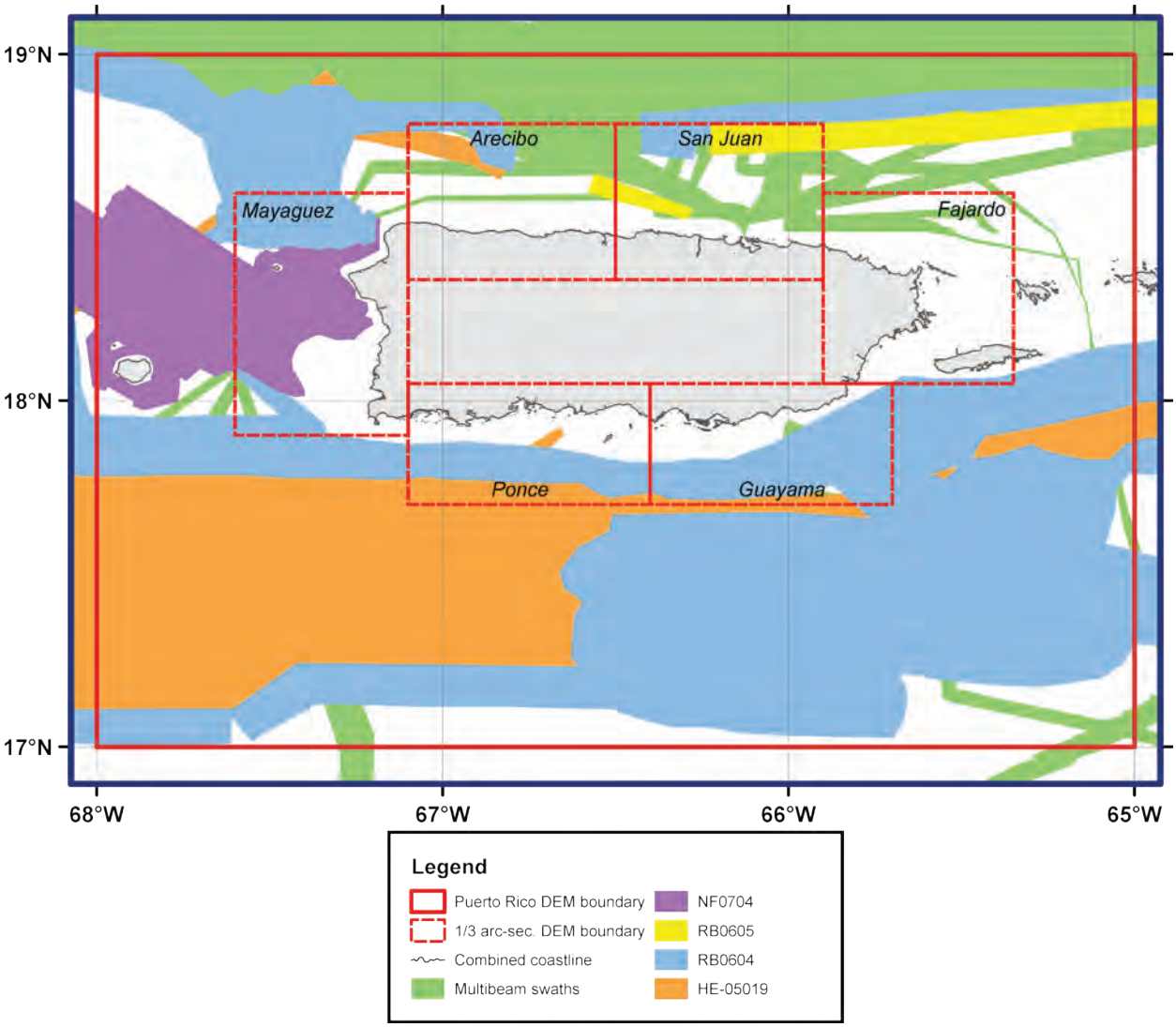


Figure 8. *Source and coverage of multibeam sonar datasets used in compiling the Puerto Rico DEMs.*

7) 9 arc-second DEM

No detailed bathymetric datasets were available for the southeast corner of the Puerto Rico region (see Fig. 2). Thus, depth values were extracted from an intermediate 9 arc-second DEM that NGDC built in 2005—compiled from the 'Measured and Estimated Seafloor Topography' 2-minute DEM (Smith and Sandwell, 1997; http://topex.ucsd.edu/WWW_html/mar_topo.html) and GEBCO bathymetric contours (http://www.ngdc.noaa.gov/mgg/gebco/).

3.1.3 Topography

Two topographic datasets of Puerto Rico (Table 9; Fig. 9) were obtained from the Puerto Rico Office of Management and Budget and the U.S. Geological Survey, and were used in building the Puerto Rico DEMs.

Table 9. Topographic datasets used in compiling the Puerto Rico DEMs.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum*	*Original Vertical Datum*	*URL for more info*
Puerto Rico Office of Management and Budget	1996–1998	Photometrically derived elevations	10 meters	NAD83 HARN US Virgin Islands, Puerto Rico State Plane	NAVD88 (MSL)	http://www.crimpr.net/
USGS	2007	National Elevation Dataset (NED)	1/3 arc-second	WGS84 geographic	GEOID99?	http://seamless.usgs.gov/

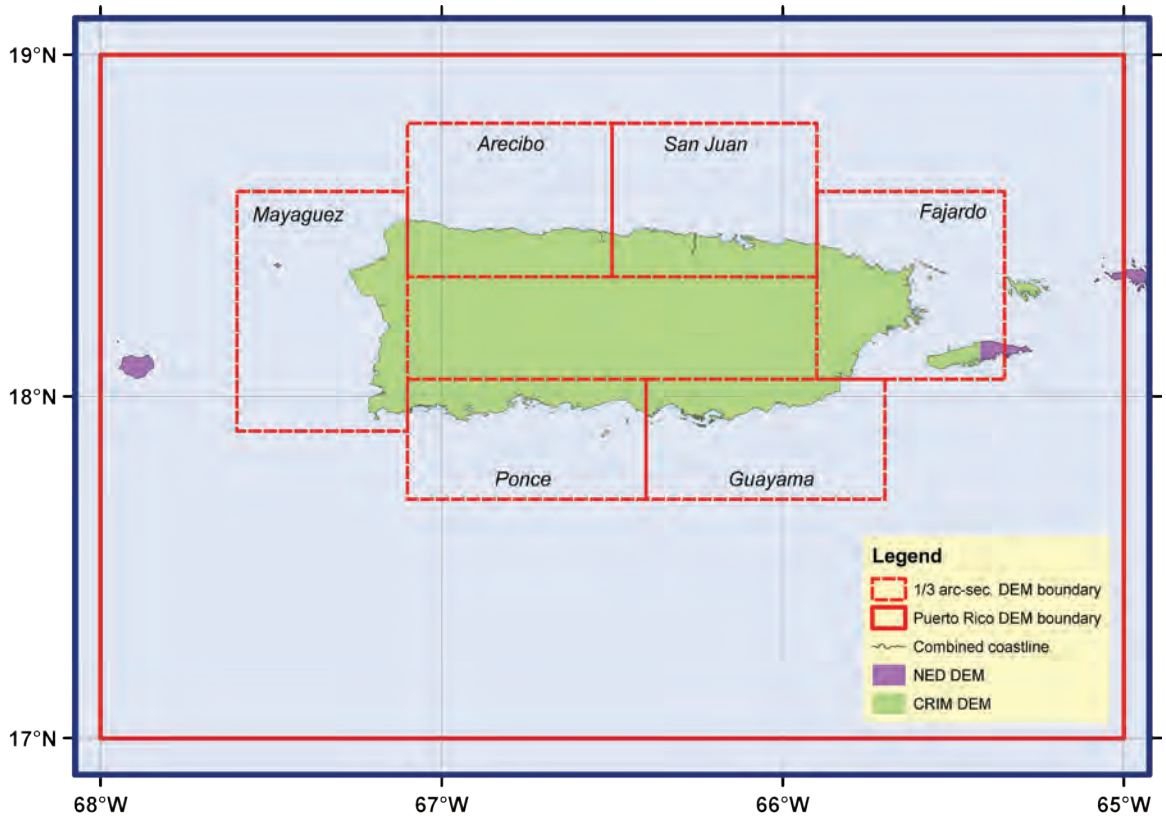


Figure 9. *Source and coverage of topographic datasets used in compiling the Puerto Rico DEMs.*

1) Puerto Rico Office of Management and Budget photometrically derived elevations

DEMs of photometrically derived elevations over USGS Quadrangles in Puerto Rico, with fixed spatial cell size of 10 meters, was obtained from the Puerto Rico Office of Management and Budget (PROMB). The Centro de Recaudación de Ingresos Municipales (CRIM) Basemap Project provided the original linework, elevation points and breaklines to PROMB. PROMB derived the DEMs from TINs previously generated from elevation mass points and 3-D features such as hydrography, and breaklines at a scale of 1:2,000. Elevation values are referenced to mean sea level. This dataset covers Puerto Rico and Culebra islands and the western half of Vieques (Fig. 9).

2) USGS NED 1/3 arc-second DEM

A newly created National Elevation Dataset (NED)[3] 1/3 arc-second DEM of Puerto Rico was provided to NGDC by Louis Driber and Charles Nelson with the USGS. This topographic DEM was derived principally from LiDAR data collected by 3001, Inc. for the USACE in 2004 as part of an effort to develop digital orthophoto imagery for administration of the U.S. Department of Agriculture GIS Orthophotography update program. The DEM also included supplemental LiDAR data collected by the USGS. The NED DEM was built by gridding the LiDAR data in USGS quadrangle quarters using TINs (triangular irregular networks), then mosaicing the grids together. No data buffers were utilized along the edges of quadrangle quarters, which resulted in the gridding process connecting the corners of some quadrangle quarters with triangles of anomalous elevations. These anomalous triangles occur where LiDAR data gaps fall in regions of steep of topography (mostly interior of the Island of Puerto Rico at high elevations) and along quadrangle quarter boundaries (e.g., Fig. 10). NGDC could not remove these "seams", which remain in the Puerto Rico DEMs.

The NED DEM appears to be referenced to GEOID99 over the islands of Puerto Rico, Vieques and Culebra as substantial parts of the coastal zone are below MHW; the metadata documents the DEM as being referenced to "NAVD88", which is not a valid vertical datum for Puerto Rico. GEOID99 is on average 2.29 meters below MSL along the north side of the Island of Puerto Rico (Dave Doyle, NGS, pers. communication), likely contributing to the anomalous "underwater" land areas in the DEM. Also apparent in the NED DEM are shifts in the coastline north of Fajardo, and artificial flat regions along the southern coast. The islands of Mona and Desecheo are consistent with a mean sea level datum. NGDC used this dataset only where the PROMB DEMs were unavailable.

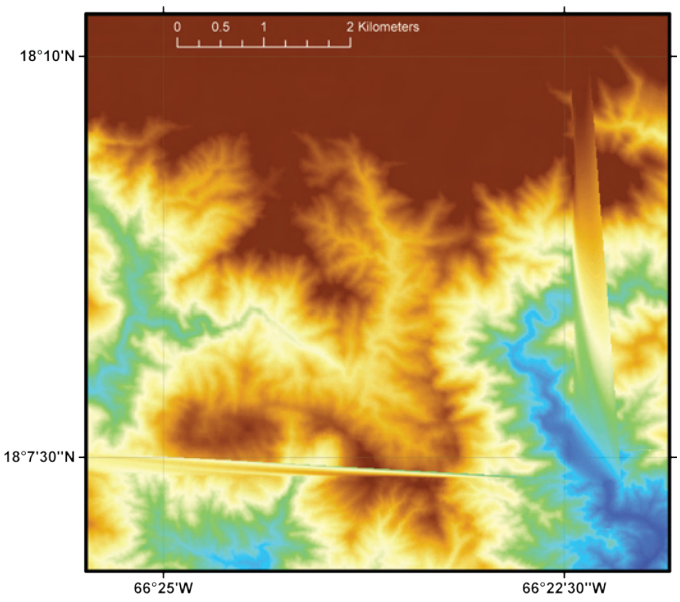


Figure 10. *Detail of NED 1/3 arc-second DEM showing processing errors generated by USGS gridding algorithm.*

3. The USGS National Elevation Dataset (NED) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000-scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360-scale DEM data for Georgia. The dataset provides seamless coverage of the United States, HI, AK, and the island territories. NED has a consistent projection (Geographic), resolution (1 arc second), and elevation units (meters). The horizontal datum is NAD83, except for AK, which is NAD27. The vertical datum is NAVD88, except for AK, which is NGVD29. NED is a living dataset that is updated bimonthly to incorporate the "best available" DEM data. As more 1/3 arc second (10 m) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED website]

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Puerto Rico DEMs were originally referenced to a number of vertical datums including Mean Lower Low Water (MLLW), Mean Low Water (MLW), Mean Sea Level (MSL), and North American Vertical Datum of 1988 (NAVD88). All datasets were transformed to MHW, to provide the worst-case scenario for inundation modeling, by averaging tidal values measured at the NOAA tidal stations at San Juan (#9755371) and Magueyes Island (#9759110).

1) Bathymetric data

The NOS hydrographic soundings, and SHOALS and NOS LiDAR surveys were transformed from MLW and MLLW to MHW, using FME software, by adding constant offsets of -0.270 and -0.300 m, respectively (Table 10). The USGS multibeam sonar DEMs and multibeam swath sonar data are referenced to MSL and were shifted by adding a constant offset of -0.132 m.

2) Topographic data

The PROMB DEMs were referenced to MSL. USGS NED 1/3 arc-second DEM was referenced to NAVD88 in its metadata, which is not defined for Puerto Rico: this dataset was inferred to be referenced to MSL. Conversion to MHW, using FME software, was accomplished by adding tide-station derived constant offset of -0.132 (Table 10).

Table 10. Relationship between Mean High Water and other vertical datums in the Puerto Rico region.*

Vertical datum	*Difference to MHW*
MSL+	-0.132
MLW	-0.270
MLLW	-0.300

* Datum relationships averaged from values at tide stations #9755371, San Juan and #9759110, Magueyes Island.
+ NAVD88 is inferred to be equivalent to MSL.

3.2.2 Horizontal datum transformations

Datasets used to compile the grids were originally horizontally referenced to Puerto Rico and Virgin Islands State Plane, Early Puerto Rico Island Datum, Puerto Rico Datum, NAD83 UTM Zone 19, and NAD27, NAD83 and WGS84 geographic; the relationships and transformational equations between these horizontal datums are well established. NOS hydrographic survey data was converted to WGS84 using GEODAS (NADCON). All other data were converted to a horizontal datum of WGS84 using FME software (http://www.safe.com). FME is an integrated collection of spatial extract, transform, and load tools for data transformation and data translation.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets.

After horizontal and vertical transformations were applied, ESRI shape files were generated for each data file, and value consistency between datasets was checked in ESRI ArcMap. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shape files were then converted to xyz files in preparation for gridding. Problems included:

- The USGS NED 1/3 arc-second DEM for Puerto Rico includes “seams” along the edges of quadrangle quarters in regions of steep topography (island interior at high elevations). NGDC could not remove these gridding artifacts.
- Vertical units for the NCCOS bathymetric DEM was determined to be feet instead of meters, as indicated in the accompanying metadata. The DEM was converted to meters before gridding.
- A few bad soundings were discovered in the NOS hydrographic surveys (positive values rather than negative ones) and were corrected. Several NOS surveys had mixed units of feet and fathoms, which also had to be corrected.

- The SHOALS bathymetric LiDAR data included positive elevations that were deleted. They also included occasional anomalously deep values along the coast, which were deleted.
- Numerous bad sonar pings and beams were identified in the raw multibeam swath sonar data. These pings and beams were excised from the data prior to gridding, using the MB-System tool 'mbedit'. Some transits were exceptionally noisy on their outer beams, which were removed using the automated MB-System tool 'mbclean'.
- The USGS multibeam sonar bathymetric DEMs contained some cells with anomalous values. These were deleted once the DEMs had been converted to ESRI point shapefiles.
- The USGS NED 1/3 arc-second topographic DEM was found to be low by a meter or two along most coasts in the Puerto Rico region. This is inferred to result from the GEOID99 model for Puerto Rico, which is low by ~2.29 meters along the northern coast of the Island of Puerto Rico.
- The PROMB topographic DEMs contained "zero" values over the open ocean, and anomalous values along the edges of DEMs. These values were deleted.

3.3.2 Gridding of multibeam swath sonar data with MB-System

The raw multibeam sonar files from transits in the Puerto Rico region (Table 8) were gridded using the MB-System tool 'mbgrid' at 3 arc-second resolution covering a region 0.1 degrees larger than the Puerto Rico DEM; deep-water sonars generally provide between 30 and 150-meter beam footprints depending upon water depth. A short interpolation spacing of 2 grid cells was used to infill small gaps between beams while limiting interpolation into regions without sonar coverage. Sonar data that was exceptionally noisy or diverged significantly from other bathymetric datasets was either edited or discarded. The resulting 3 arc-second grid was brought into ArcGIS for evaluation, then converted to ESRI point shapefile for editing. Points were deleted where coverage of the "transit" multibeam sonar grid overlapped the USGS multibeam sonar grids (dedicated seafloor surveys; Table 7). The multibeam swath sonar files from the two Puerto Rico Trench surveys (RB0208 and RB0303; Table 8) were gridded separately at 1 arc-second as they were deemed to be of high quality.

3.3.3 Surfacing of bathymetric data

The NOS hydrographic surveys are generally sparse at the resolution of the Puerto Rico DEMs: in deep water, the NOS survey data have point spacings up to 3 km apart. In order to reduce the effect of artifacts in the form of lines of "pimples" in the DEMs due to this low resolution dataset, and to provide effective interpolation into the coastal zone, a 3 arc-second-spacing 'pre-surface' or grid was generated using GMT, an NSF-funded share-ware software application designed to manipulate data for mapping purposes (http://gmt.soest.hawaii.edu/). NOS soundings that overlapped the multibeam sonar grids were deleted as the resolution of the NOS surveys was significantly less than that of the multibeam sonar data.

The remaining NOS hydrographic point data, in xyz format, were combined with xyz data from the multibeam sonar and NCCOS grids, and bathymetric LiDAR surveys into a single file, along with points extracted from the combined coastline—to provide a "zero" buffer along the entire coastline. These point data were then median-averaged using the GMT tool 'blockmedian' to create a 3 arc-second grid 0.1 degrees (~10%) larger than the Puerto Rico DEM gridding region. The GMT tool 'surface' then applied a spline tension to interpolate cells without data values. The GMT grid created by 'surface' was converted into an ESRI Arc ASCII grid file, and clipped to the coastline to eliminate data interpolation into land areas. The resulting surface was compared with original soundings to ensure grid accuracy (e.g., Fig. 11), converted to a shape file, and then exported as an xyz file for use in the final gridding process (see Table 11).

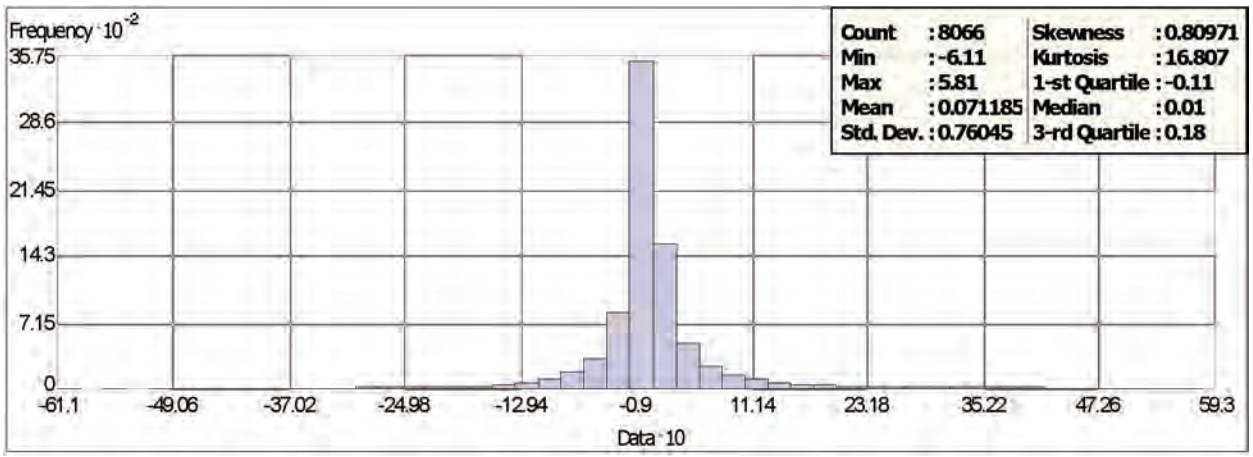


Figure 11. *Histogram of the differences between NOS hydrographic survey H09491 (Bahia de Jobos, south coast) and the 3 arc-second pre-surfaced bathymetric grid. Large discrepancies between survey soundings and the pre-surface bathymetric grid occur where multiple, closely spaced points, in regions with significant relief, contribute to one cell value.*

3.3.4 Gridding the 1 arc-second Puerto Rico DEM

All processed xyz data files were gridded at 1 arc-second using MB-System (http://www.ldeo.columbia.edu/res/pi/MB-System/). The MB-System tool 'mbgrid' was used to create each DEM—a modeled surface draping the point data—comprised of weighted elevation point data. The data hierarchy used in the 'mbgrid' gridding algorithm as relative gridding weights is listed in Table 11. Greatest weight was given to the NOS and SHOALS coastal bathymetric LiDAR data. Least weight was given to values extracted from the 3 arc-second bathymetric grid.

Table 11. Data hierarchy used to assign gridding weight in MB-System.

Dataset	Relative Gridding Weight
NOS bathymetric LiDAR surveys	1000
SHOALS bathymetric LiDAR	100
1 arc-second multibeam sonar bathymetric grids	100
PROMB topographic DEMs	100
USGS NED topographic DEM	10
NOS hydrographic surveys	1
NCCOS bathymetric DEM	1
3 arc-second pre-surfaced bathymetric grid*	0.1
1 arc-second Puerto Rico DEM+	0.1

* Used only for building the 1 arc-second Puerto Rico DEM.
\+ Used only for building the 1/3 arc-second DEMs.

3.3.5 Building the 1/3 arc-second DEMs

The 1/3 arc-second DEMs were built using all of the processed xyz files and points extracted from the 1 arc-second Puerto Rico DEM, using MB-System. The MB-System tool 'mbgrid' was used to create each DEM, comprised of weighted elevation point data. The data hierarchy used in the 'mbgrid' gridding algorithm as relative gridding weights is listed in Table 11. Greatest weight was given to the NOS and SHOALS coastal bathymetric LiDAR data. Least weight was given to values extracted from the 1 arc-second Puerto Rico DEM.

3.4 Quality Assessment of the DEMs

3.4.1. Horizontal accuracy

The Puerto Rico DEMs have an estimated horizontal accuracy of 10 meters for topographic features. Bathymetric features are resolved only to within a few hundred meters in most deep-water areas; shallow, near-coastal regions have an accuracy approaching that of subaerial topographic features. Positional accuracy of deep-water bathymetric features is limited by large interpolation between scattered soundings, and by potentially large positional accuracy of pre-satellite navigated (GPS) hydrographic surveys.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the Puerto Rico DEMs is dependent upon the source datasets contributing to DEM cell values. Topographic areas have an estimated vertical accuracy between 0.5 meters (for PROMB DEMs) and up to 7 meters (for NED topographic DEM). Bathymetric areas have an estimated accuracy of between 0.1 meters (coastal SHOALS and NOS LiDAR data) and ~2% of water depth (~100 meters in the deepest areas of the 1 arc-second Puerto Rico DEM). Those values were derived from the wide range of input data sounding measurements from the early 20th century to recent, GPS-navigated multibeam sonar surveys. Gridding interpolation to determine values between sparse, poorly-located NOS soundings degrades the vertical accuracy of elevations in deep water.

3.4.3 Slope maps and 3-D perspectives

ESRI ArcCatalog was used to generate slope grids from the Puerto Rico DEMs to allow for visual inspection and identification of artificial slopes along boundaries between datasets (e.g., Fig. 12). The DEMs were transformed to UTM Zone 19 coordinates (horizontal units in meters) in ArcCatalog for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Three-dimensional viewing of the UTM-transformed DEMs (e.g., Fig. 13) was accomplished using ESRI ArcScene. Analysis of preliminary DEMs revealed suspect data points, which were corrected before recompiling the DEMs. Figure 14 shows color images of the Puerto Rico DEMs in their final version.

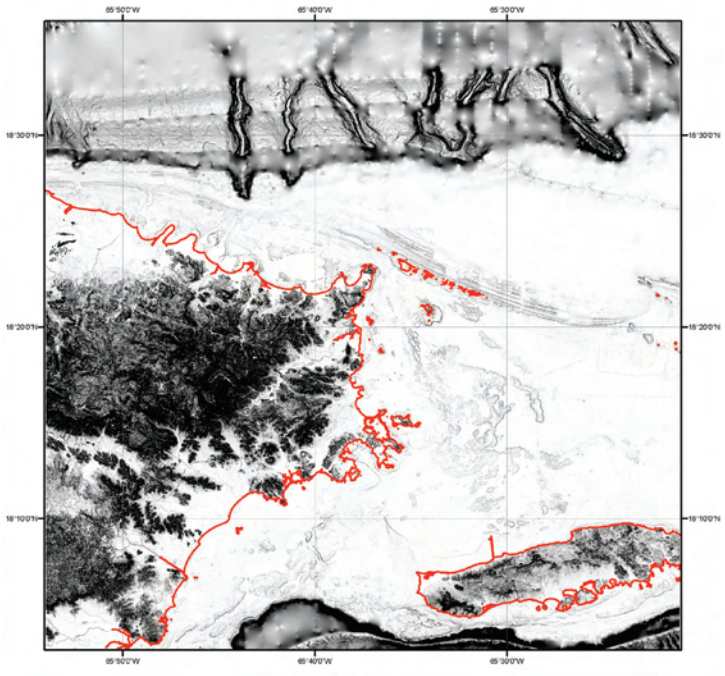


***Figure 12**. Slope map of the 1/3 arc-second Fajardo DEM. Flat-lying slopes are white; dark shading denotes steep slopes; combined coastline in red.*

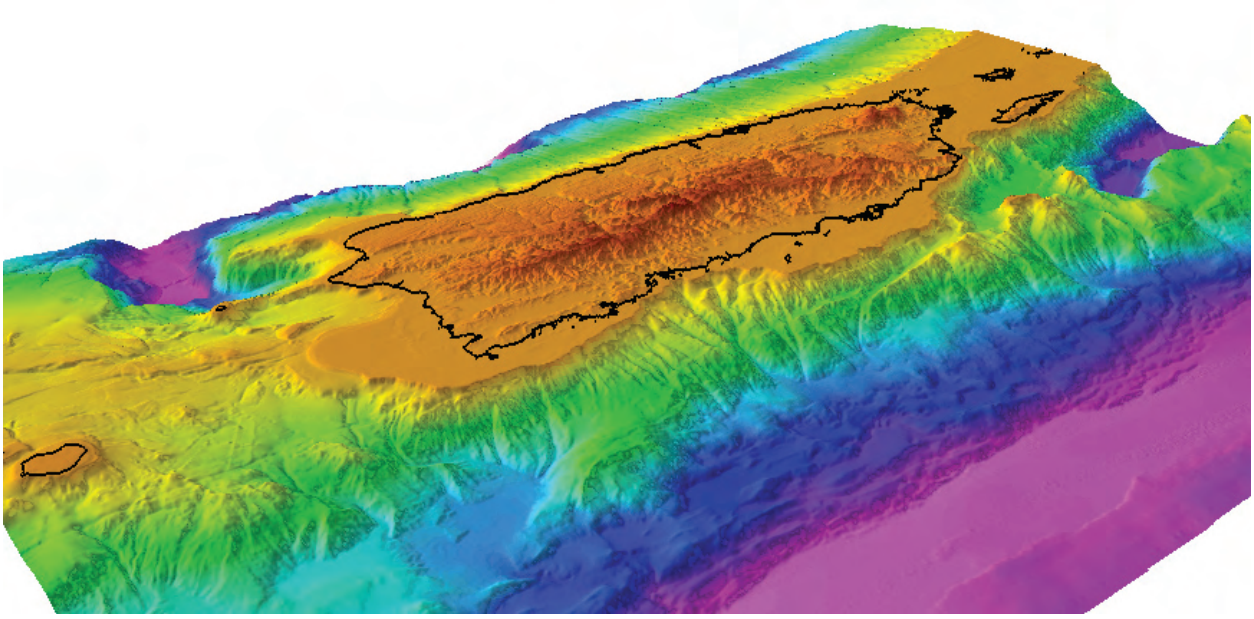


***Figure 13**. Perspective view of the 1 arc-second Puerto Rico DEM. Vertical exaggeration times 3; combined coastline in black.*

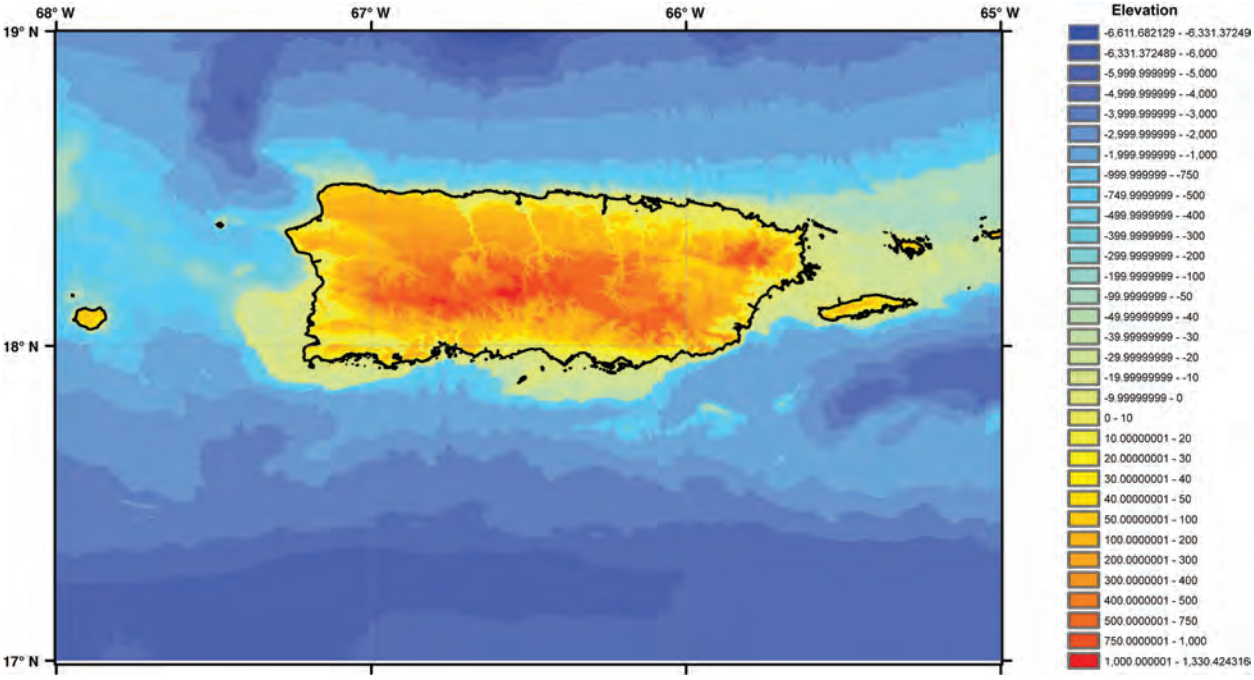


***Figure 14a**. Color image of the 1 arc-second Puerto Rico DEM. Combined coastline in black.*

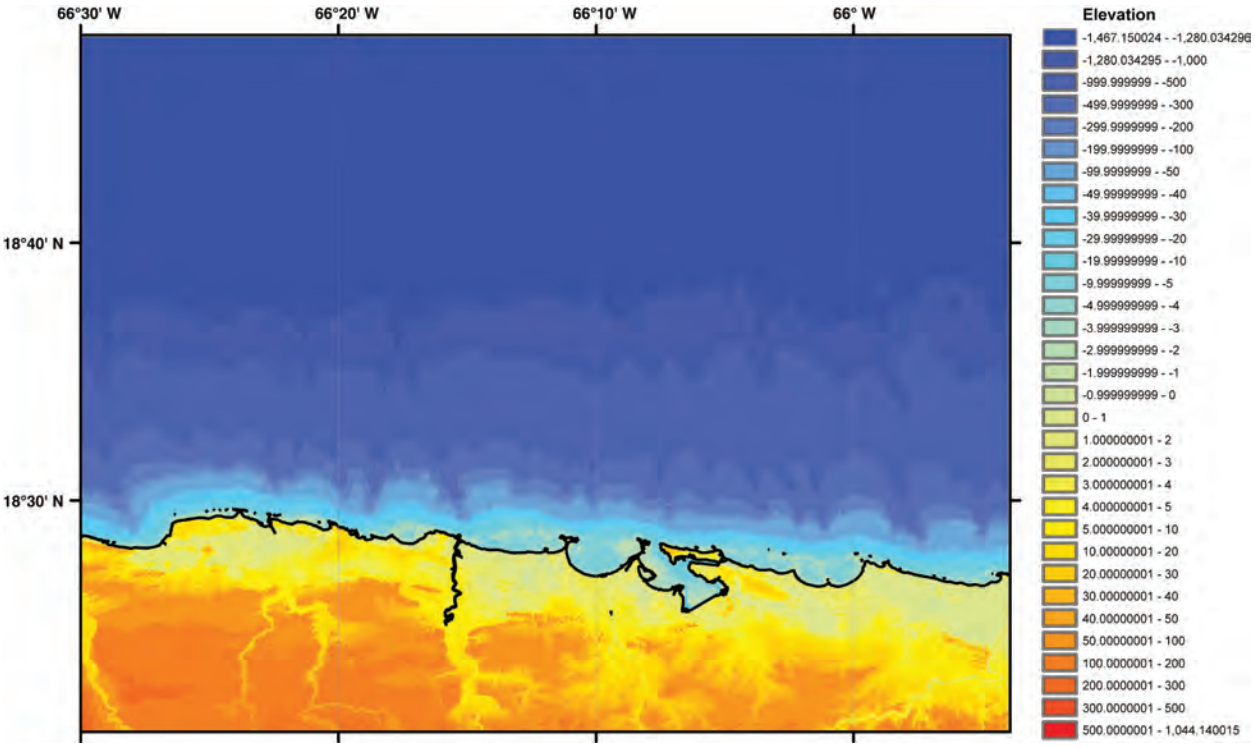


***Figure 14b**. Color image of the 1/3 arc-second San Juan DEM. Combined coastline in black.*

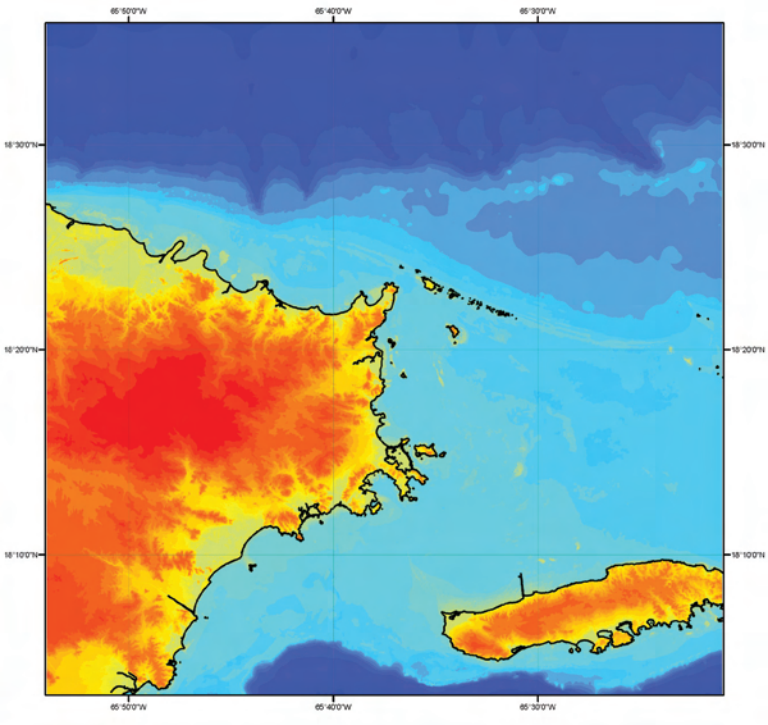


***Figure 14c**. Color image of the 1/3 arc-second Fajardo DEM. Elevations colored as in Figure 14b; combined coastline in black.*

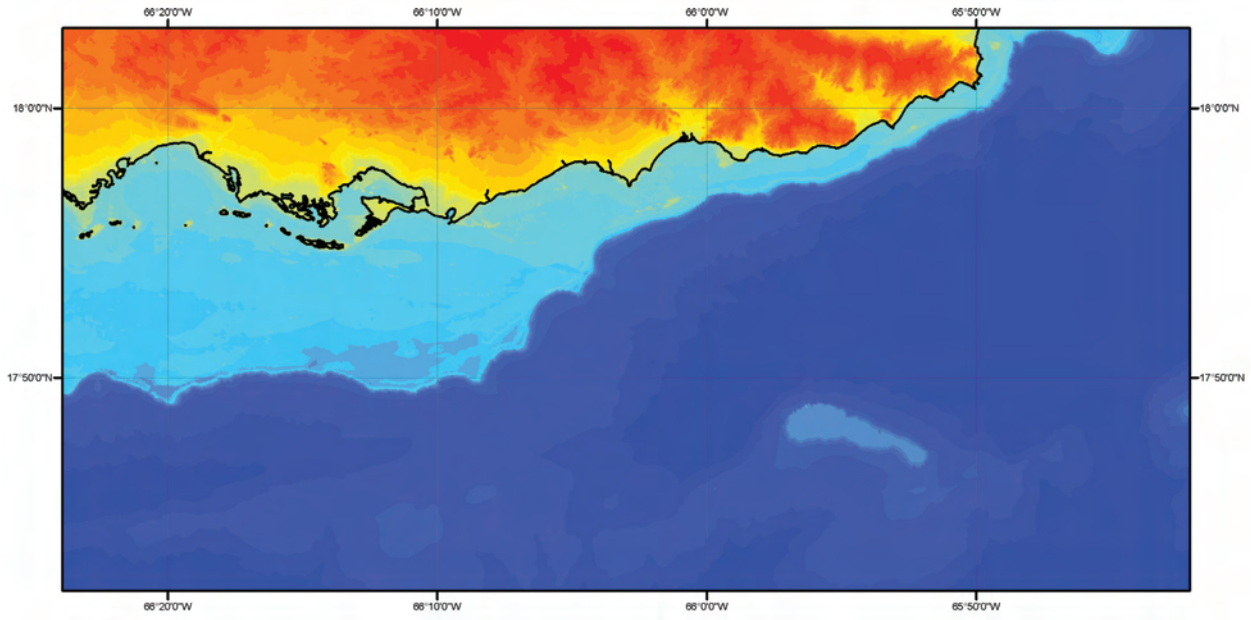


***Figure 14d**. Color image of the 1/3 arc-second Guayama DEM. Elevations colored as in Figure 14b; combined coastline in black.*

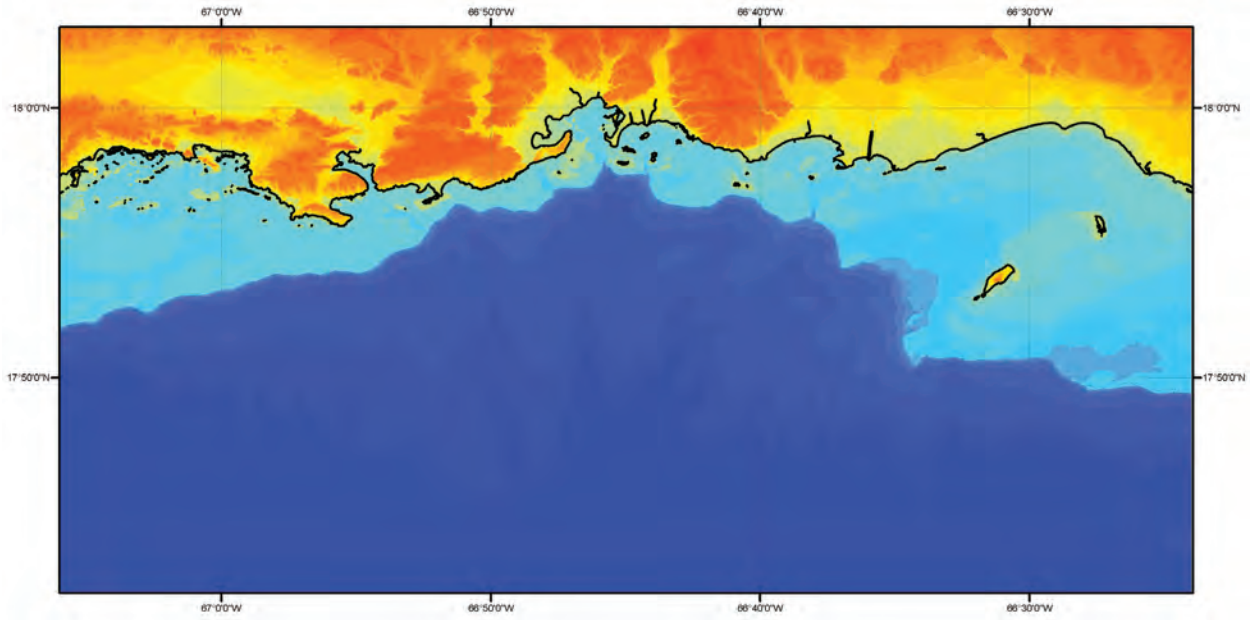


***Figure 14e**. Color image of the 1/3 arc-second Ponce DEM. Elevations colored as in Figure 14b; combined coastline in black.*

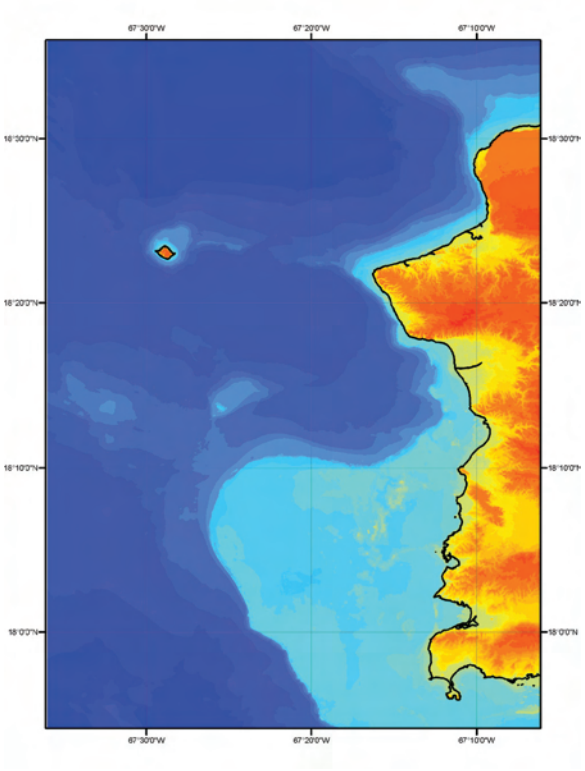


***Figure 14f**. Color image of the 1/3 arc-second Mayagüez DEM. Elevations colored as in Figure 14b; combined coastline in black.*

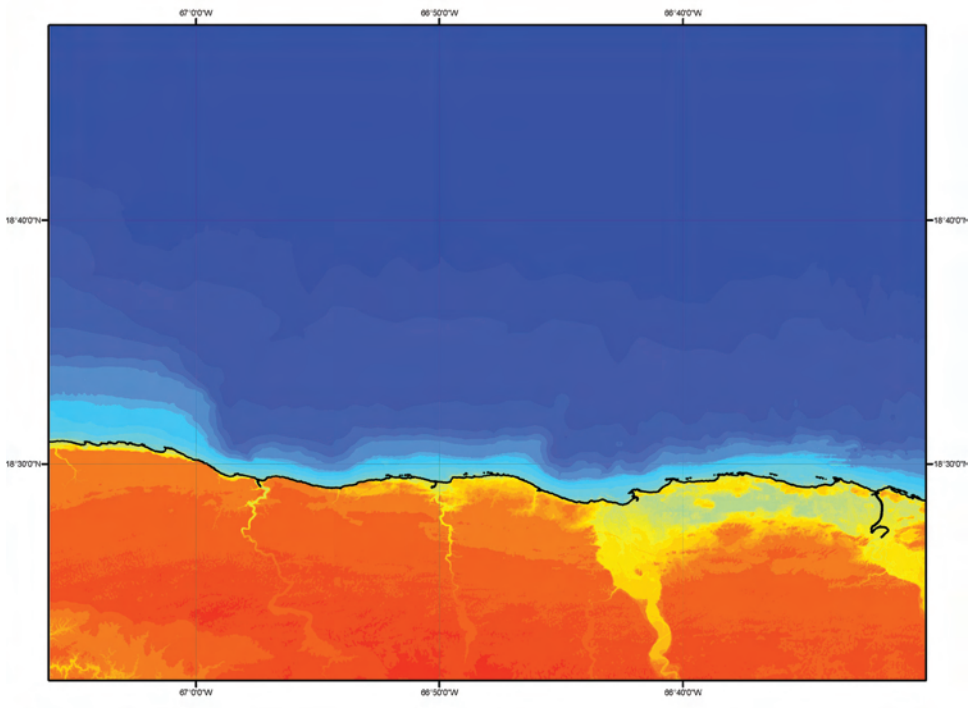


***Figure 14g**. Color image of the 1/3 arc-second Arecibo DEM. Elevations colored as in Figure 14b; combined coastline in black.*

3.4.4 Comparison with source data files

To ensure grid accuracy, the Puerto Rico DEMs were compared to select source data files. Files were chosen on the basis of their contribution to the grid-cell values in their coverage areas (i.e., had the greatest weight and did not significantly overlap other data files with comparable weight). A histogram of the differences between a SHOALS bathymetric LiDAR survey file and the 1/3 arc-second Arecibo DEM is shown in Figure 15. Differences cluster around zero, with only a handful of soundings—overlapping PROMB topographic elevations—exceeding 0.5 meter from the DEM. These are interpreted as anomalous soundings returned from the land surface rather than sea bottom.

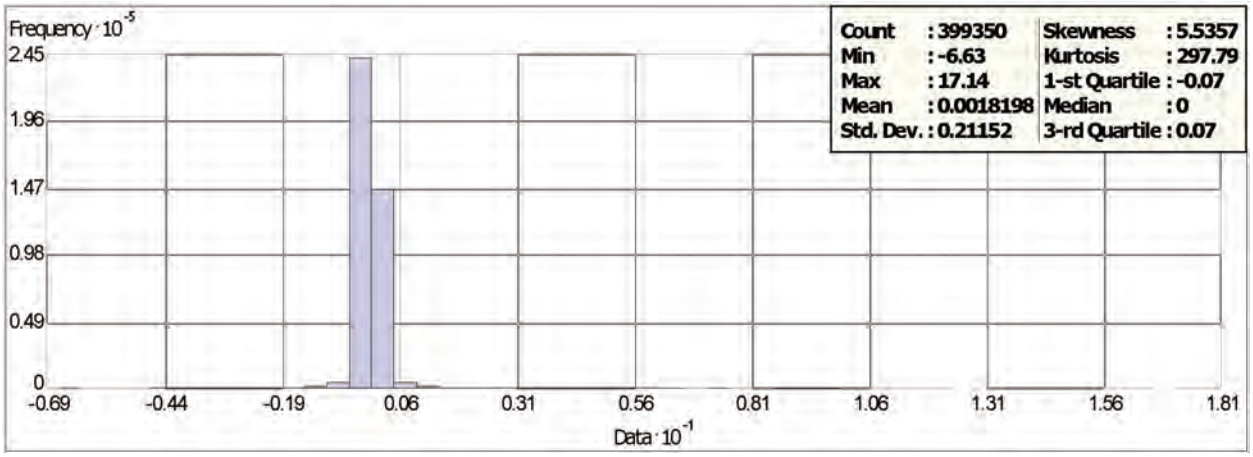


Figure 15. *Histogram of the differences between one SHOALS bathymetric LiDAR survey and the Arecibo DEM.*

3.4.5 Comparison with NGS geodetic monuments

The elevations of 906 NOAA NGS geodetic monuments were extracted from online shape files of monument datasheets (http://www.ngs.noaa.gov/cgi-bin/datasheet.prl), which give monument positions in NAD83 (sub-mm accuracy) and elevations in NAVD88 (in meters). Elevations were shifted to MHW vertical datum (see Table 10) for comparison with the Puerto Rico DEMs (see Fig. 16 for monument locations). Figure 17 shows the differences between the Ponce DEM and the NGS geodetic monuments, which range from -30 to 5 meters, with a negative value indicating that the DEM is less than the monument elevation. The monument with the largest offset from the DEM (TV0350, -30.13 meters) is located on the Muertos Island Lighthouse.

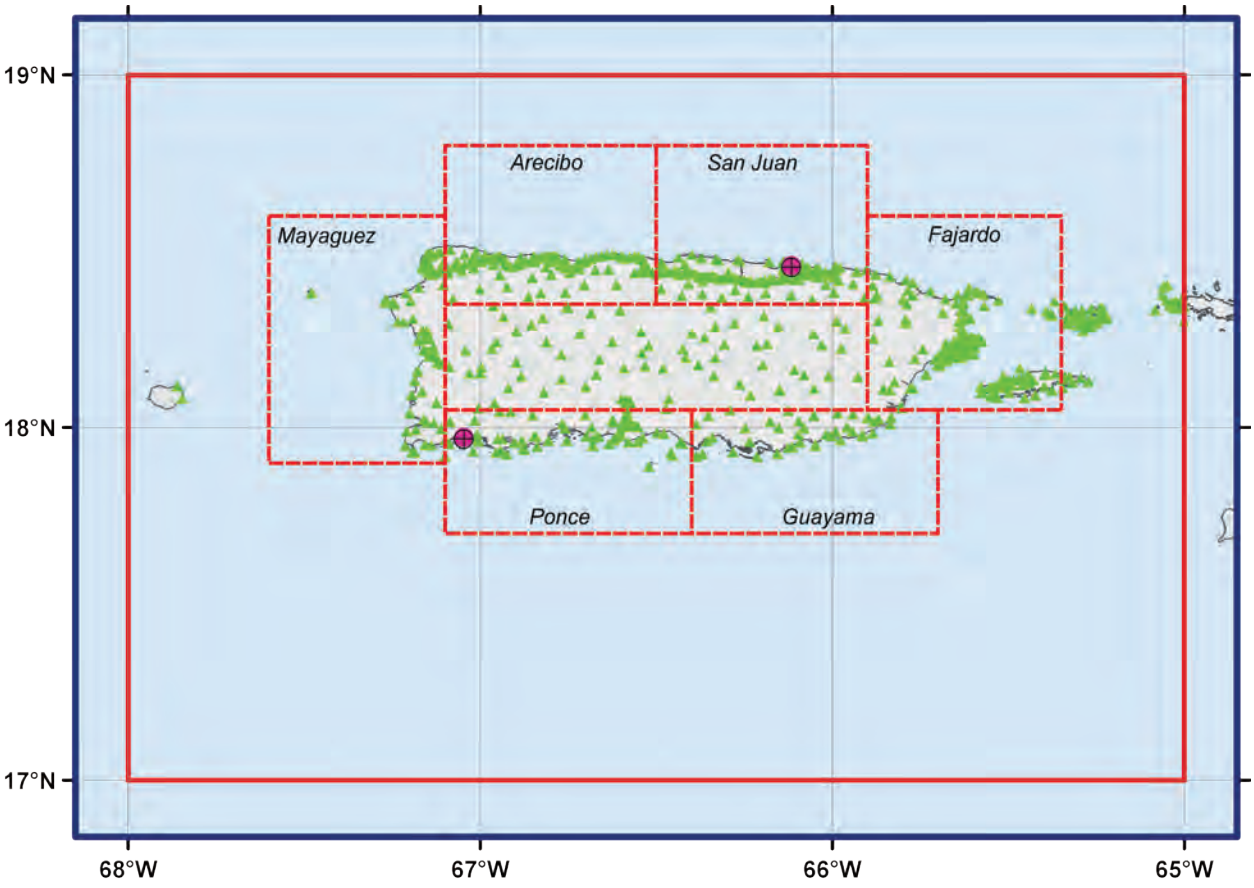


Figure 16. *Location of NGS monuments and NOAA tide stations in the Puerto Rico region. NGS monument elevations were used to evaluate the Puerto Rico DEMs.*

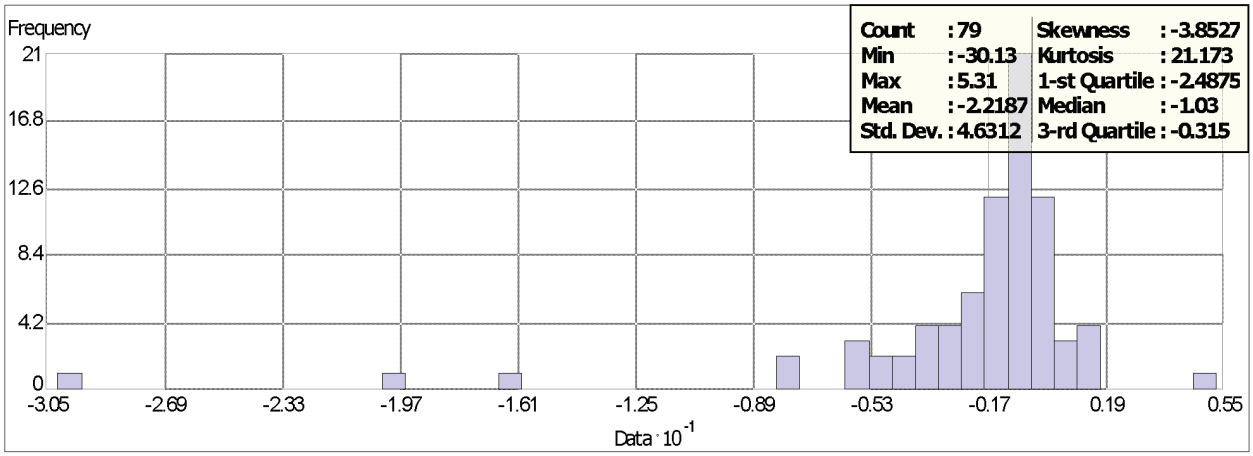


Figure 17. *Histogram of the differences between NGS monuments and the Ponce DEM.*

4. Summary and Conclusions

Combined topographic–bathymetric digital elevation models of Puerto Rico were built for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research. A 1 arc-second DEM was built that spans the entire island of Puerto Rico and offshore areas, as well as six 1/3 arc-second DEMs—centered on Arecibo, Fajardo, Guayama, Mayagüez, Ponce and San Juan—that completely encircle the island. The best available digital data from U.S. federal, state and local agencies, and academic institutions were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI ArcGIS, FME, CARIS, GMT, MB-System, QT Modeler, and GEODAS software.

Recommendations to improve the DEM based on NGDC's research and analysis include:

- Correct artifacts in NED DEM introduced by USGS gridding algorithm and resolve vertical datum issues with this dataset.
- Conduct SHOALS bathymetric LiDAR surveys along southern coast of the Island of Puerto Rico, and around Mona and Desecheo islands.
- Include remaining NOS bathymetric LiDAR surveys around southwest portion of Puerto Rico once those surveys have been processed.

5. Acknowledgments

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7. DATA PROCESSING SOFTWARE

ArcGIS v. 9.2, developed and licensed by ESRI, Redlands, California, http://www.esri.com/

CARIS Bathy DataBASE v. 2, developed and licensed by CARIS, Fredricton, NB, Canada, http://www.caris.com/

Electronic Navigational Chart Data Handler for ArcView, developed by NOAA Coastal Services Center, http://www.csc.noaa.gov/products/enc/

FME 2006 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/

GEODAS v. 5 – Geophysical Data System, shareware developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas/

GMT v. 4.1.4 – Generic Mapping Tools, shareware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/

MB-System v. 5.1.0, shareware developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System/

Quick Terrain Modeler v. 6.0.1, LiDAR processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/