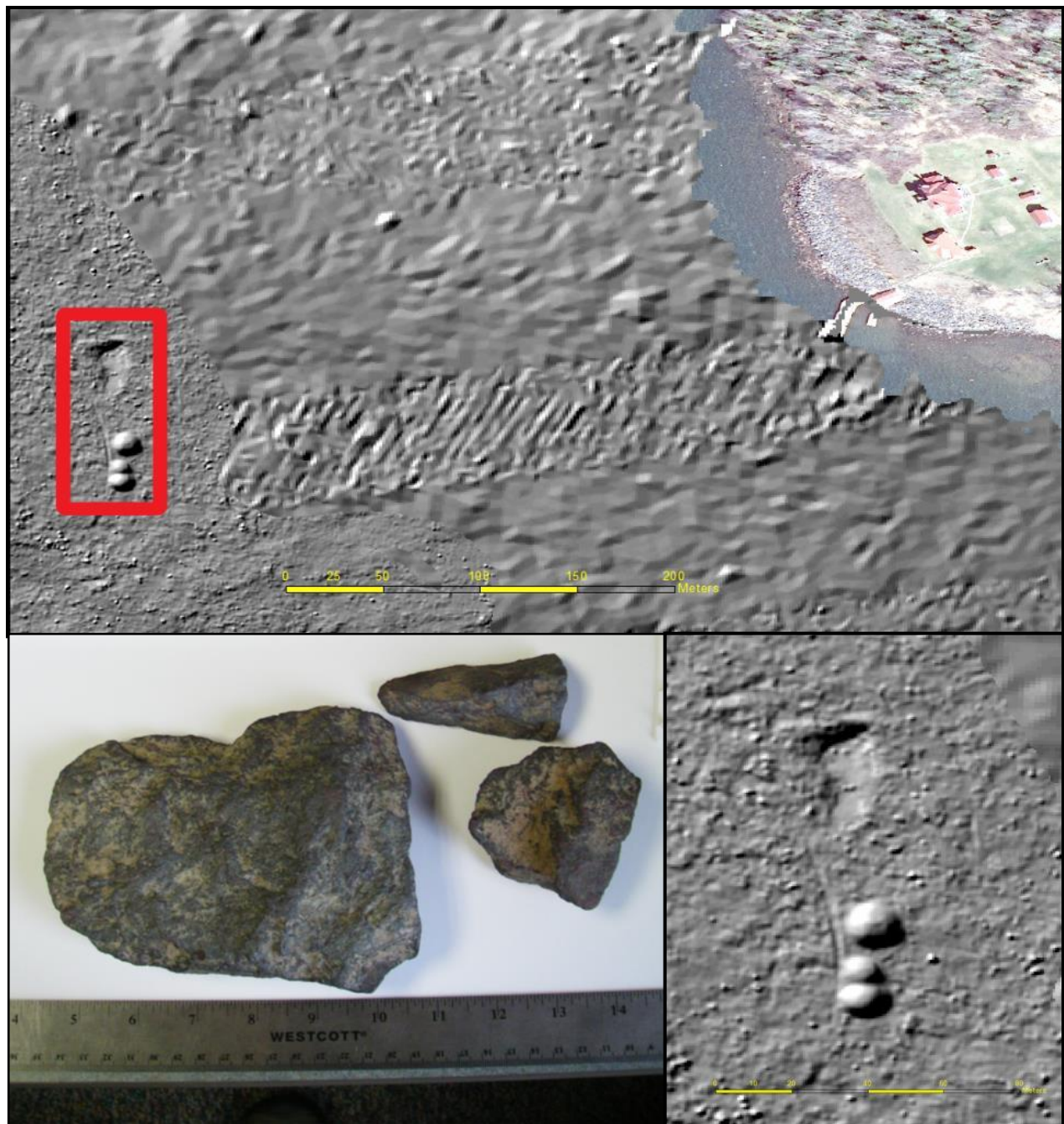




Coastal Bathymetry of Five Great Lakes National Parks

Natural Resource Report NPS/MWRO/NRR—2015/975



ON THE COVER

Bathymetric mapping at Apostle Islands National Lakeshore (Lake Superior) revealed a mystery pit and mounds just offshore from Raspberry Island Lighthouse. Park and Network staff dove on the site and retrieved iron ore from the mounds. Research by the cultural resource specialist at Apostle Islands revealed the site was where a steamship carrying iron ore ran aground in June 1898 and dumped its load in order to free itself from the reef.

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National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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Abstract

Land-based natural and cultural resources have been well-mapped in the Great Lakes national parks, but little is known about similar submerged resources. A project was undertaken in 2010 to combine existing and new data to create comprehensive bathymetric maps within the jurisdictional boundaries of five Great Lakes national park units. These maps will provide information on depths, bottom substrate-types, and the locations of cultural resources, as well as contribute to the creation of habitat maps, foster scientific research, and assist resource managers with decision-making.

Data have been collected at three locations on Lake Superior—Apostle Islands National Lakeshore, Isle Royale National Park, and Pictured Rocks National Lakeshore; and at two locations on Lake Michigan—Indiana Dunes National Lakeshore and Sleeping Bear Dunes National Lakeshore. Light detection and ranging (LiDAR) data were acquired from the U.S. Army Corps of Engineers through an agreement with the National Park Service. These data extend from the shoreline out to a maximum water depth of 25 m. Michigan Tech Research Institute used multi-source data, including high-resolution satellite imagery, to create bathymetric maps at Sleeping Bear Dunes. The National Park Service and Northwestern Michigan College used multibeam sonar to collect bathymetric data at depths greater than those accessible by LiDAR.

The results from these separate efforts are being combined into seamless bathymetric maps for the five park units. Sleeping Bear Dunes and Indiana Dunes are already completed. An additional benefit of this project has been the discovery of several cultural resources, including previously unknown shipwrecks.

Acknowledgments

A majority of this work was completed with funding from the Great Lakes Restoration Initiative (National Park Service Project 89) and we are grateful to the U.S. Environmental Protection Agency for making those funds available. Thanks also to Jerrilyn Thompson (National Park Service/Great Lakes–Northern Forest Cooperative Ecosystems Study Unit) who did a tremendous amount of work in keeping the project on track and the accounting balanced. This project has been a complicated mission with many moving parts since it began, and we’d like to thank all of the many collaborators who have helped move things forward. Sincere and deep thanks to those who put in time behind the wheel to pilot the *Echo* where she needed to go: Jason Charette, Dave Cooper, Ken Ekelund, Tommy Richardson, and Steve Witt at Apostle Islands; Katy Goodwin and Mark Romanski at Isle Royale; Josh Kuhn at Pictured Rocks; and Ted Gostomski and Rick Damstra at the Great Lakes Inventory and Monitoring Network. Thanks also to Dave Wilkins (Apostle Islands); Paul Brown (Isle Royale); Bill Smith (Pictured Rocks); and Bill Route, Joan Elias, and David VanderMeulen (Great Lakes Network), who made their staff’s time available to us. Steve Witt (Apostle Islands) and Thor Liimatta and Levi Brezee (Isle Royale) were integral in keeping the *Echo* seaworthy and operational. We are grateful to staff at Apostle Islands National Lakeshore, the U.S. Fish and Wildlife Service–Ashland Fish and Wildlife Conservation Office, and the NPS Great Lakes Exotic Plant Management Team who each loaned us a truck multiple times to tow the *Echo* across two or three states. Alan Holcombe was an assistant hydrographer during the 2014 field season and did an admirable job in learning the mapping system quickly enough to take on some of the data collection by himself.

Acronyms and Terms

APIS	Apostle Islands National Lakeshore (Lake Superior, Wisconsin)
GLRI	Great Lakes Restoration Initiative
INDU	Indiana Dunes National Lakeshore (Lake Michigan, Indiana)
ISRO	Isle Royale National Park (Lake Superior, Michigan)
LiDAR	Light Detection and Ranging
MTRI	Michigan Tech Research Institute (Michigan Technological University)
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
PIRO	Pictured Rocks National Lakeshore (Lake Superior, Michigan)
SLBE	Sleeping Bear Dunes National Lakeshore (Lake Michigan, Michigan)
USACE	U.S. Army Corps of Engineer

Introduction

The Great Lakes represent immense wealth in regard to natural resources and recreation. National parks located along the Great Lakes shorelines are renowned for their natural beauty, for the recreational opportunities they offer, and for the natural and cultural resources they protect. Many of these features are represented on detailed maps that show hiking trails, historic sites, topography, and vegetation communities. On all of these maps, the lakes themselves are represented as large expanses of uniform blue. How can we know so much about the terrestrial resources and know so little about what lies beneath those large blue portions of the map? Even in parks where scuba diving at shipwreck sites is a popular visitor activity, little is known about the context within which the wrecks are located (Lenihan 1994).

Lake charts help to fill in this blind spot by showing depths, obstructions to navigation, and in some cases, the type of benthic material. However, they lack the clarity of the contours on a topographic map or the habitat specificity of a terrestrial vegetation map. Further, many lake charts are out-of-date, and even the best charts are poorly-suited to informing resource management decisions as global climate change affects water levels on a long-term basis (Saunders et al. 2011).

Detailed bathymetric mapping has been used to document and inform management decisions regarding coral reefs (Walker et al. 2008), and more recently, highly detailed and technical submerged habitat maps were created for several national park units in Alaska, California, the Gulf of Mexico, and the Caribbean (Exelis VIS 2011, Curdts and Cross 2013). A very limited amount of similar work has been done on the Great Lakes even though there is much to know about fish spawning areas and similar habitat features; the location, context, and condition of cultural resources such as shipwrecks; and the nature and form of features such as erosional areas created by altered longshore currents and their associated sediment depositional zones. One of the more fascinating discoveries made on the Great Lakes using acoustic bathymetry technologies was the discovery of a series of stone features along the Alpena-Amberley ridge in Lake Huron that may have been used for caribou hunting in both prehistoric and ethnographic times when the lake level was below the ridge (O'Shea and Meadows 2009). Additionally, during sonar-based efforts to locate shipwrecks in Lake Huron's Thunder Bay Marine Sanctuary, researchers serendipitously discovered unique sinkhole ecosystems that are generating considerable microbial research interest (Biddanda et al. 2009).

Brock and Purkis (2009) noted that quantitative, high-resolution information on coastal elevations is needed for resource management and planning, establishing political and jurisdictional boundaries, navigation, commerce, scientific research, and ecosystem-based policies to guide decision making. Management of terrestrial resources requires park managers to (1) know what occurs within their jurisdictional boundaries (inventory), (2) have the ability to track changes in those resources (monitoring), and (3) have the ability to identify unique areas for protection or for development as visitor use areas. Curdts and Cross (2013) further noted that habitat maps provide "the foundation for ecosystem-based management and for detecting and monitoring human-caused change" and were as necessary for marine and coastal systems as for forests and grasslands. Thus, it seems logical that the

National Park Service would at least inventory benthic communities and morphology within its jurisdictional boundaries on the Great Lakes.

Recently, the National Park Service (NPS) recognized this information gap and set out to correct it (Davis 2004). A strategy to protect national park resources in and on the Great Lakes includes a goal to “inventory, map, and monitor natural and cultural resources within and near the submerged land boundaries of Great Lakes national parks” (NPS–MWR 2008). To that end, the strategy seeks to “ensure that adequate maps of Great Lakes coastal resources are available and accessible ... including lake bathymetry, nearshore benthic habitat, lake bed classification, sedimentology and geomorphology, water quality, and submerged cultural resources.”

By fortunate coincidence, around the time the NPS strategy was released, the U.S. Army Corps of Engineers (USACE) initiated a coastal LiDAR (light detection and ranging) acquisition project in the Great Lakes. Via this project, USACE collected LiDAR data for much of the mainland portions of Great Lakes shorelines including Indiana Dunes National Lakeshore (Lake Michigan). NPS entered into an agreement with USACE to purchase additional LiDAR coverage for Isle Royale National Park (Lake Superior) and for Apostle Islands National Lakeshore (Lake Superior) and the Manitou Islands at Sleeping Bear Dunes National Lakeshore (Lake Michigan).

Beginning in 2010, the NPS received funding through the Great Lakes Restoration Initiative (GLRI) to initiate a bathymetric mapping project using multi-beam sonar in the nearshore jurisdictional boundaries of four Great Lakes national parks: Apostle Islands National Lakeshore, Isle Royale National Park, and Pictured Rocks National Lakeshore in Lake Superior, and Sleeping Bear Dunes National Lakeshore in Lake Michigan. At Sleeping Bear Dunes, sonar mapping was coordinated with Northwestern Michigan College, and the NPS collaborated with the Michigan Tech Research Institute to secure satellite imagery for additional bathymetric information. Due to the minimal jurisdiction of NPS at Grand Portage National Monument (<1 mile of Lake Superior shoreline and no water area), Grand Portage was not included in the sonar-based mapping effort, and this section of shoreline was missed during the LiDAR flight. The monument and the surrounding bay would be ideal candidates for future satellite-based bathymetric work given the shallow depths in this area. Perry’s Victory and International Peace Memorial, in western Lake Erie, was also excluded from the current study due to its limited jurisdiction and historical park emphasis.

Overall, the project aims to provide seemingly basic but critically needed information on water depth, lake topographic features, and substrate types in NPS coastal waters, using this novel combination of boat-based multibeam sonar data, aerial LiDAR elevation data, and emerging satellite-based techniques. Specific objectives and technical approaches have been tailored to suit each park’s management interests.

Methods

Study Sites

There are seven national park units located on the five Great Lakes. On two of those lakes (Superior and Michigan), five park units have jurisdictional boundaries that encompass 183,906 hectares of Great Lakes waters: Apostle Islands National Lakeshore (APIS), Isle Royale National Park (ISRO), and Pictured Rocks National Lakeshore (PIRO) on Lake Superior; and Indiana Dunes (INDU), and Sleeping Bear Dunes National Lakeshores (SLBE) on Lake Michigan (Figure 1, Table 1). Two additional Great Lakes park units—Grand Portage National Monument on Lake Superior and Perry’s Victory and International Peace Memorial on Lake Erie—have limited jurisdiction in Great Lakes waters and were not included in the current mapping effort.

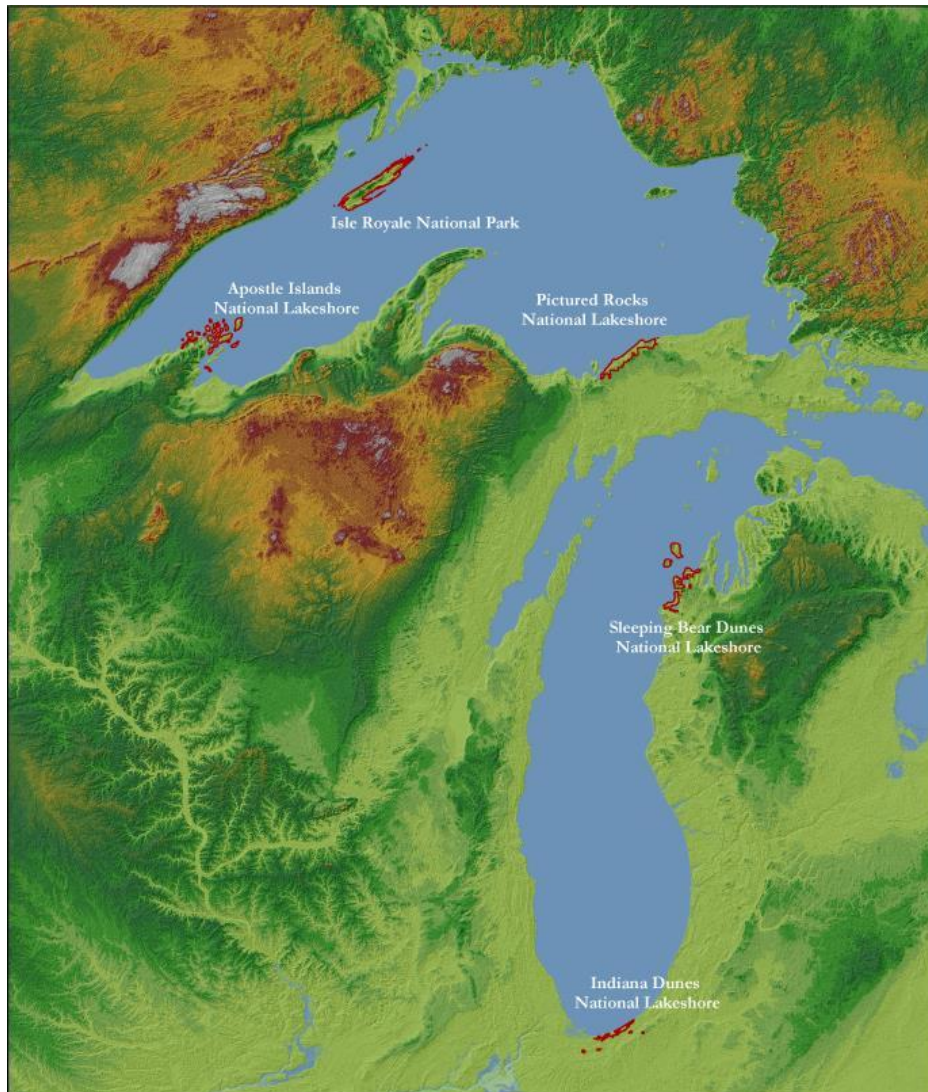


Figure 1. Locations of the five Great Lakes national park units where nearshore bathymetric data were collected: Apostle Islands National Lakeshore (Wisconsin), Isle Royale National Park (Michigan), and Pictured Rocks National Lakeshore (Michigan) on Lake Superior, and Sleeping Bear Dunes National Lakeshore (Michigan) and Indiana Dunes National Lakeshore (Indiana) on Lake Michigan.

Bathymetric maps are being constructed using a combination of existing LiDAR, high-resolution satellite imagery, and multi-beam sonar data collected by NPS staff and cooperating partners using specially-equipped vessels.

Table 1. Water area (in hectares) and length of coastline (in km) within the boundaries of five Great Lakes national park units (Curdts 2011).

Unit	Lake	Water Area (ha)	Coastline (km)
Apostle Islands National Lakeshore (APIS)	Superior	10,990	257
Indiana Dunes National Lakeshore (INDU)	Michigan	227	25
Isle Royale National Park (ISRO)	Superior	165,248	545
Pictured Rocks National Lakeshore (PIRO)	Superior	2,842	62
Sleeping Bear Dunes National Lakeshore (SLBE)	Michigan	4,596	104
TOTALS		183,903	993

Survey Approaches

LiDAR

The U.S. Army Corps of Engineers (USACE) National Coastal Mapping Program initiated a project to collect coastal LiDAR elevation data along Great Lakes shorelines in 2007. Data were collected from a zone extending 1,000 m lakeward (or to extinction due to depth) and 500 m landward of the shoreline. Details on this program and access to the datasets can be found at <http://coast.noaa.gov/digitalcoast/data/coastallidar>. The USACE program did not include complex shorelines and islands, so the NPS entered into an interagency agreement to fund the acquisition of LiDAR data for Isle Royale, Apostle Islands, and the Manitou Islands at Sleeping Bear Dunes. Complete LiDAR coverage for INDU and surrounding waters was obtained as part of the basic U.S. Army Corps of Engineers National Coastal Mapping Program for the Great Lakes. No additional LiDAR data were acquired by NPS, and no additional satellite-or sonar-based mapping was conducted at INDU.

LiDAR data from these projects have been delivered in 1-m and 5-m raster resolution, and bathymetric coverage extends up to 25 m in depth, depending on water clarity. Wave-wash zone also shows substantial “no-data” areas due to wave splash and/or turbidity in the very nearshore zone.

LiDAR elevation data is captured using rapid pulses of laser light generated on board an aircraft. Pulse rate for bathymetric laser is around 1000pulses/second, terrestrial LiDAR around 10,000 pulses/second. The time it takes for the light to hit the ground and bounce back to the on board sensor is recorded and converted to distance. This is similar to how RADAR (Radiowave Detection and Ranging) works, but LiDAR uses light instead of radio wave frequencies. Bathymetric LiDAR is a specific type of laser, and requires two different wavelengths, a red laser (1,064 nm) which captures the height of a water surface, and a green laser (532 nm), which penetrates the water column and

reflects back from the underwater substrate. More information can be found at: http://www.fugro-pelagos.com/lidar/tech/lidar_bathy.html and http://www.fugro-pelagos.com/lidar/lib/brochures/Marine_4pg.pdf.

Satellite imagery

Commercially-available, high-resolution satellite imagery for SLBE was acquired from the National Geospatial-Intelligence Agency's (NGA) Civil Applications Committee (CAC) and related sources. The team at MTRI (Michigan Tech Research Institute, a cooperating partner) applied a Great Lakes-specific depth mapping algorithm to these images using *in situ* collected sonar data and aerial LiDAR data from the United States Army Corps of Engineers to calibrate the model.

To further extend the bathymetric coverage at SLBE, MTRI's mapping algorithm was applied to Landsat 8 imagery (collected in May 2013) to derive depth information and fill in areas not covered by the higher resolution satellite imagery. This significantly increased the coverage and provides an updated bottom type/submerged aquatic vegetation map that was shared with the NPS as GIS-based data layers.

Sonar

With funding from the Great Lakes Restoration Initiative (GLRI), the NPS purchased a custom-built survey vessel equipped with a multibeam sonar system (Figure 2). This research vessel (R/V), named *Echo*, was used to survey park waters at Isle Royale, Apostle Islands, and Pictured Rocks. A research partner collected similar data at Sleeping Bear Dunes.



Figure 2. Left: The R/V Echo is a 28-foot vessel equipped with a multibeam sonar system. A generator (seen mounted under a cover on the transom) provides the necessary power to run the sonar system and associated computers. **Right:** the multibeam sonar head is lowered through a well in the stern deck.

A sonar system emits a sound pulse in short bursts that travel through the water to the lake floor, similar to the way in which bats perceive their terrestrial surroundings. The sound bounces off the lake bottom, and the sonar system records the echo. From this information, water depth is calculated using the speed of sound in water and the time it takes for the echo to return to the sonar. For this project, multibeam sonar was used. Multibeam systems send out many bursts of sound at once, creating a swath of coverage across the lake floor (Figure 3).

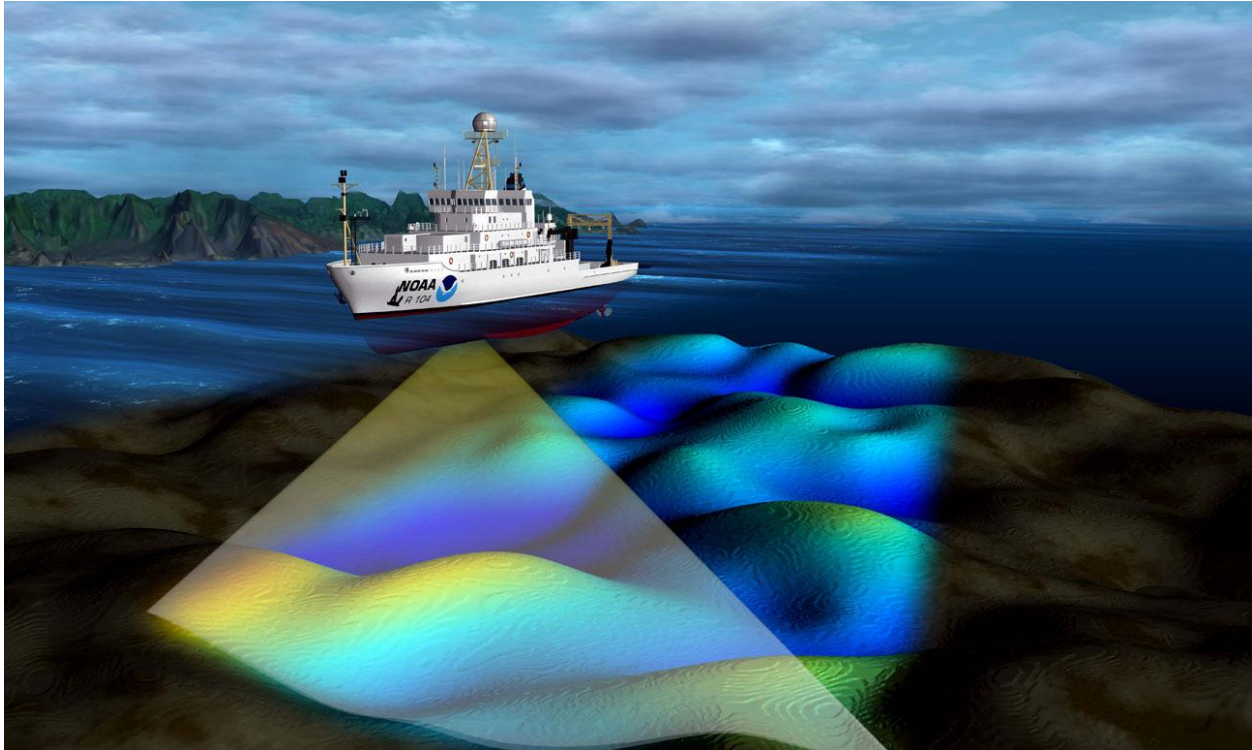


Figure 3. Multibeam sonar systems send out many bursts of sound at once, creating a swath of coverage across the lake floor. Image from U.S. National Oceanic and Atmospheric Administration (NOAA), available on Wikimedia Commons (http://commons.wikimedia.org/wiki/File:Collecting_Multibeam_Sonar_Data.jpg).

Sonar data can also be used to delineate characteristics of the lake bottom. The system uses the strength of the sound return to predict bottom type. For example, mud absorbs more of the sound pulse than rock, producing a weaker return signal.

Multibeam sonar provides bathymetric data for depths >25 m (the limit of LiDAR data), allowing us to extend the bathymetric map further out and into deeper waters from each park shoreline (Figure 4).

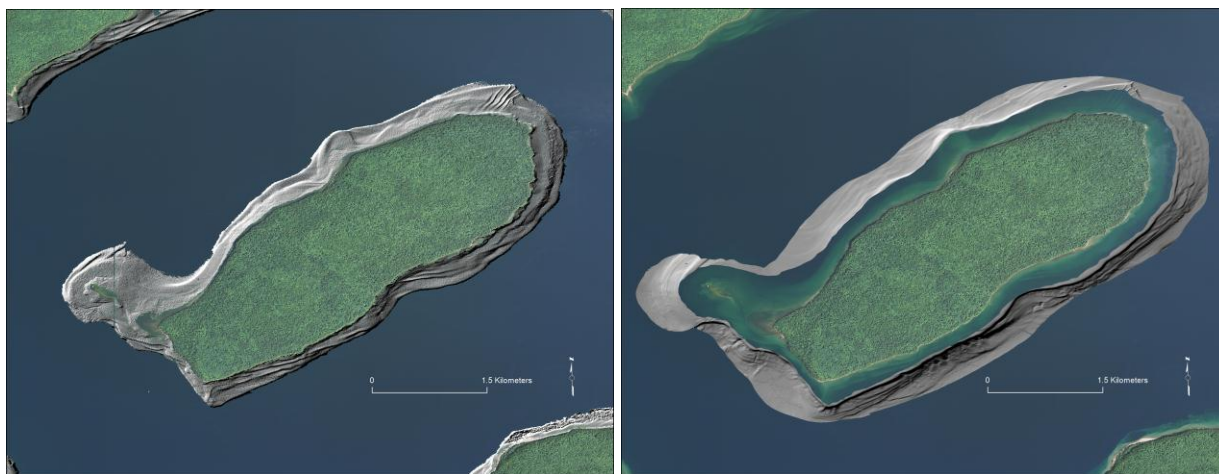


Figure 4. Example of the difference in coverage between LiDAR (*left*) and sonar (*right*). LiDAR data extend 1,000 m out from shore (or to extinction due to depth, which is typically 25 m). Data shown are from Manitou Island, Apostle Islands National Lakeshore (Wisconsin).

Surveying at APIS, ISRO, and PIRO

The R/V *Echo* is used to collect sonar data at the three Lake Superior parks—APIS, ISRO, and PIRO. Operating at speeds between 2- and 8-knots, the *Echo* can conduct bathymetric surveys in water depths between 2 m and 450 m, with a sound-swath width of four-times the water depth. The sonar is a Reson Seabat 7125 multibeam system with 200 kHz and 400 kHz projectors, up to 512 beams (maximum swath width is 140°), and up to 50 pings/second. The sonar head is mounted to a fixed pole that is deployed through a well on the aft deck. An onboard computing system operates the sonar and provides real-time visualization.

The sonar also requires the use of a high accuracy positioning system. This allows the sonar to know precisely where it is in space and which area of the lake bottom is being surveyed. The Applanix POS MV positioning system onboard the *Echo* is a GPS-aided inertial navigation system that includes an onboard computer, two GPS units, and an inertial measurement unit. The POS MV provides the sonar system with position, orientation (pitch, yaw, and roll), heave, and velocities of the vessel, and therefore the sonar head.

Surveying at SLBE

Multibeam sonar data was collected at Sleeping Bear Dunes by scientists from Northwestern Michigan College (NMC) using their boat, the R/V *Northwestern*. A Kongsberg EM3002 system was installed on the *Northwestern*. This Kongsberg system is a single-head, 254-beam sonar that uses a 300 kHz frequency, has 130° swath coverage (six times the depth), and has a maximum ping rate of 40 Hz.

Kongsberg's Seafloor Information System was used for sonar data acquisition, and a C&C Technology C-NAV positioning system or a Kongsberg Seapath 200 sensor were alternately used for positioning.

Data Processing and Compilation

In addition to the physical hardware of the sonar system, several software systems are used to collect and process the data. Reson's PDS 2000 software was used for acquisition and to apply calibrations. The Applanix POSPac MMS software was used to post-process the position data and provide an improved trajectory. The QPS Fledermaus suite was used to process the sonar data and provide three-dimensional visualization.

To ensure that the sonar data collected by MTRI for ground-truthing at SLBE were in agreement with the existing NMC sonar, the data were plotted against each other and produced a Root Mean Square Error (RMSE) of 0.20 m and an r^2 value of 0.999, which is near perfect agreement. The sonar data were then plotted against the LiDAR data to ensure that differing lake levels and datum were in agreement, and to provide a baseline for the assessment of the remote sensing results. This analysis found that the sonar and LiDAR produced an RMSE value of 0.27 m and an r^2 value of 0.992, which shows strong agreement between these two data sets.

To assess the accuracy of the satellite-derived bathymetry at SLBE, a ground-truth mission was conducted utilizing MTRI's bathymetric survey vessels. This effort at SLBE was primarily focused on Pyramid Point and Good Harbor Bay. These locations were chosen because of the distribution of submerged aquatic vegetation, the variety of satellite remote sensing sources, and coincident sonar data. The results from the field-truth mission verified the one-meter accuracy of the "all-source bathymetry" data (sonar, LiDAR, and satellite-derived imagery combined).

Elevation datasets from these three distinctly different sources have been combined to provide extensive coverage around the Great Lakes parks. The data are merged by overlaying the highest accuracy and highest resolution data on top of lower resolution and lower accuracy data. This process involved first merging the multibeam sonar over the LiDAR, (both 1 m resolution), then merging that layer over the high resolution satellite-derived data, (2 m resolution). The lowest resolution data, from Landsat, has a 30-m-pixel resolution. As such, it does not provide nearly the level of detail of bottom features and could be left as a separate layer. Nonetheless, this layer has been resampled in order to create 2 m resolution, comprehensive coverage from these multiple sources.

Results and Discussion

Since the inception of benthic mapping work in the Great Lakes national parks—via LiDAR data acquisition and later satellite- and sonar-based efforts—we have made considerable progress toward mapping and understanding Great Lakes coastal environments. More than 100,000 hectares of coastal waters have been mapped at Apostle Islands, Indiana Dunes, Isle Royale, Pictured Rocks, and Sleeping Bear Dunes (Table 2). At Indiana Dunes, LiDAR coverage is complete. At Sleeping Bear Dunes, three sources of data (LiDAR, sonar, and satellite-based) have been combined into a seamless bathymetric map. At the three remaining parks, LiDAR and sonar data will be combined when processing is complete. The mapping effort has revealed complex coastal environments within and among the Great Lakes parks and offered glimpses into previously undocumented natural and cultural features.

Table 2. Summary of the area surveyed (in hectares), by data type, in and around each of the five Great Lakes national park units, 2010–2013.

Park	LiDAR	Sonar	Satellite	Combined Area¹
Apostle Islands	27,000	4,020	0	31,020
Indiana Dunes	241	0	0	241
Isle Royale	13,000	5,957	0	18,957
Pictured Rocks	5,200	1,348	0	6,548
Sleeping Bear Dunes	13,800	7,164	23,500	44,464
Totals	59,000	18,489	23,500	100,989

¹Combined area totals do not distinguish areas of overlap between the data sources.

Status of Survey Effort by Park

Apostle Islands National Lakeshore

Apostle Islands is comprised of a mainland unit and 21 Lake Superior islands, and features significant natural resources (geological and biological) as well as a rich cultural and maritime history. As with all of the Great Lakes parks, our overarching goal was to develop a comprehensive hydrographic data baseline for APIS. Beyond this, we have conducted additional sonar-based mapping work in order to inform ongoing coastal restoration projects (associated with docks) and provide detailed coverage in areas of known cultural importance (including shipwreck sites).

To-date, a total of nearly 31,020 ha has been mapped at APIS, including 27,000 ha via LiDAR (Figure 5) and 4,020 ha via NPS sonar (see Table 2). This combined dataset includes locations well beyond the NPS boundary in many areas. The status of the sonar-based data processing at APIS varies by location; currently, processing has been completed for Basswood, Cat (Figure 6), Ironwood, Manitou, North Twin, and Raspberry Islands. The APIS mapping effort has revealed several potential undocumented wrecks as well as unique sand features (Figures 7, 8, and 9).

Future sonar-based mapping efforts at APIS will target remaining gaps in coverage (i.e., islands without complete LiDAR data), additional cultural sites such as known shipwrecks and areas around light stations, and important natural features such as the mainland sea caves and the Outer Island

sand spit. Additionally, we will seek opportunities to map areas between closely situated islands (such as Sand and York, Rocky and South Twin, and Rocky and Otter), creating larger areas of continuous hydrographic coverage.

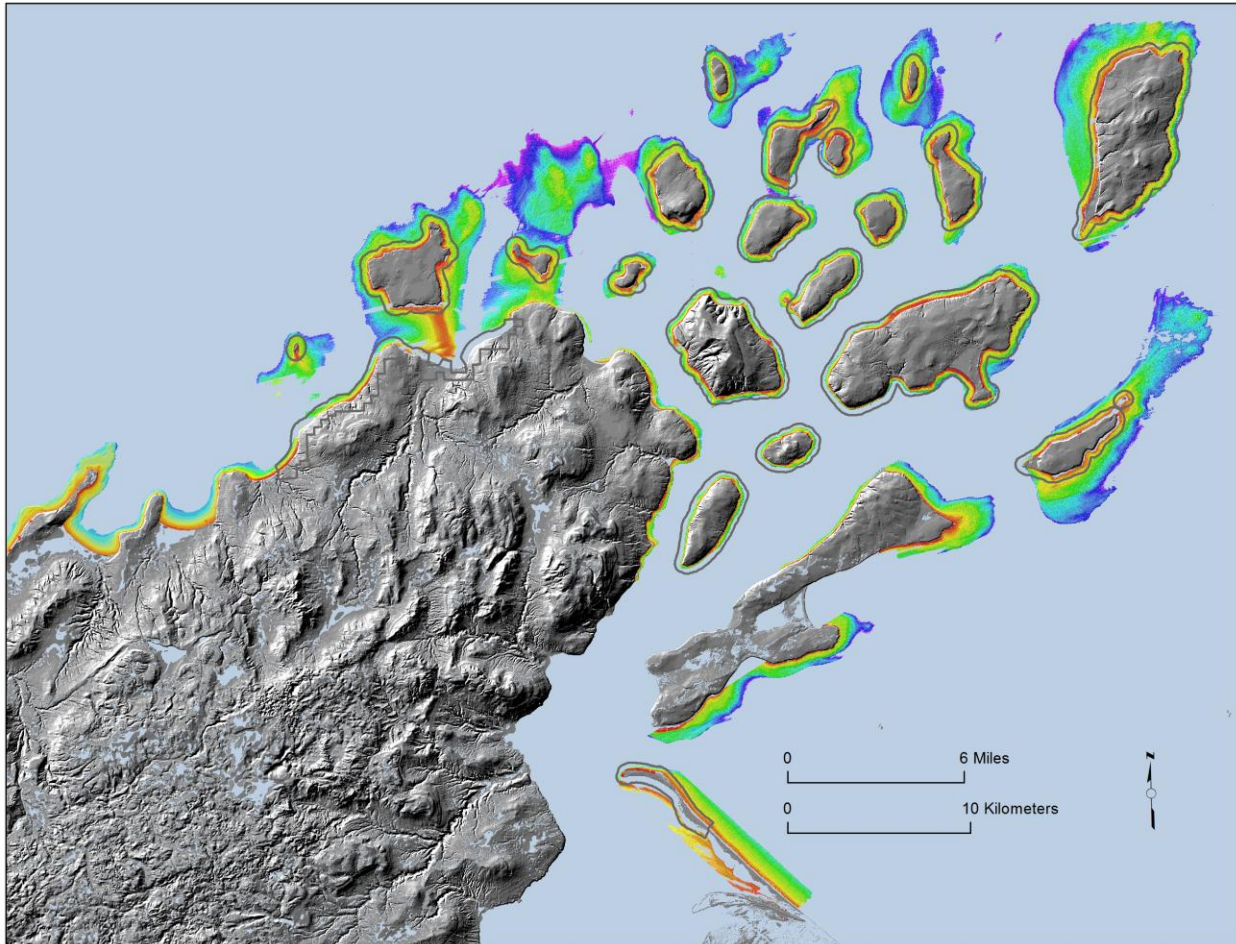


Figure 5. LiDAR data collected at Apostle Islands overlaid on a hill shade map.

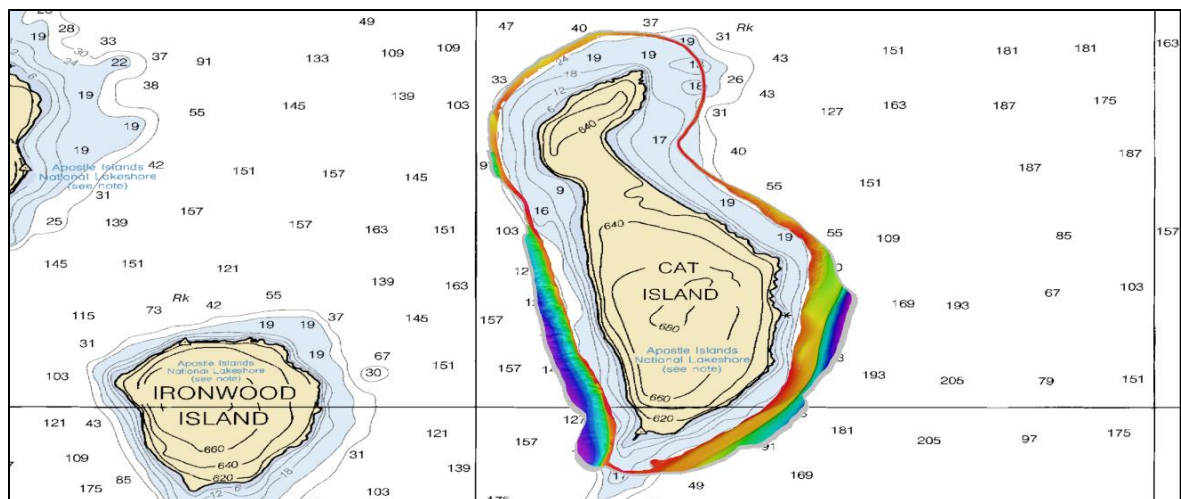


Figure 6. Sonar-derived bathymetry around Cat Island overlaid on a navigation chart for the Apostle Islands.

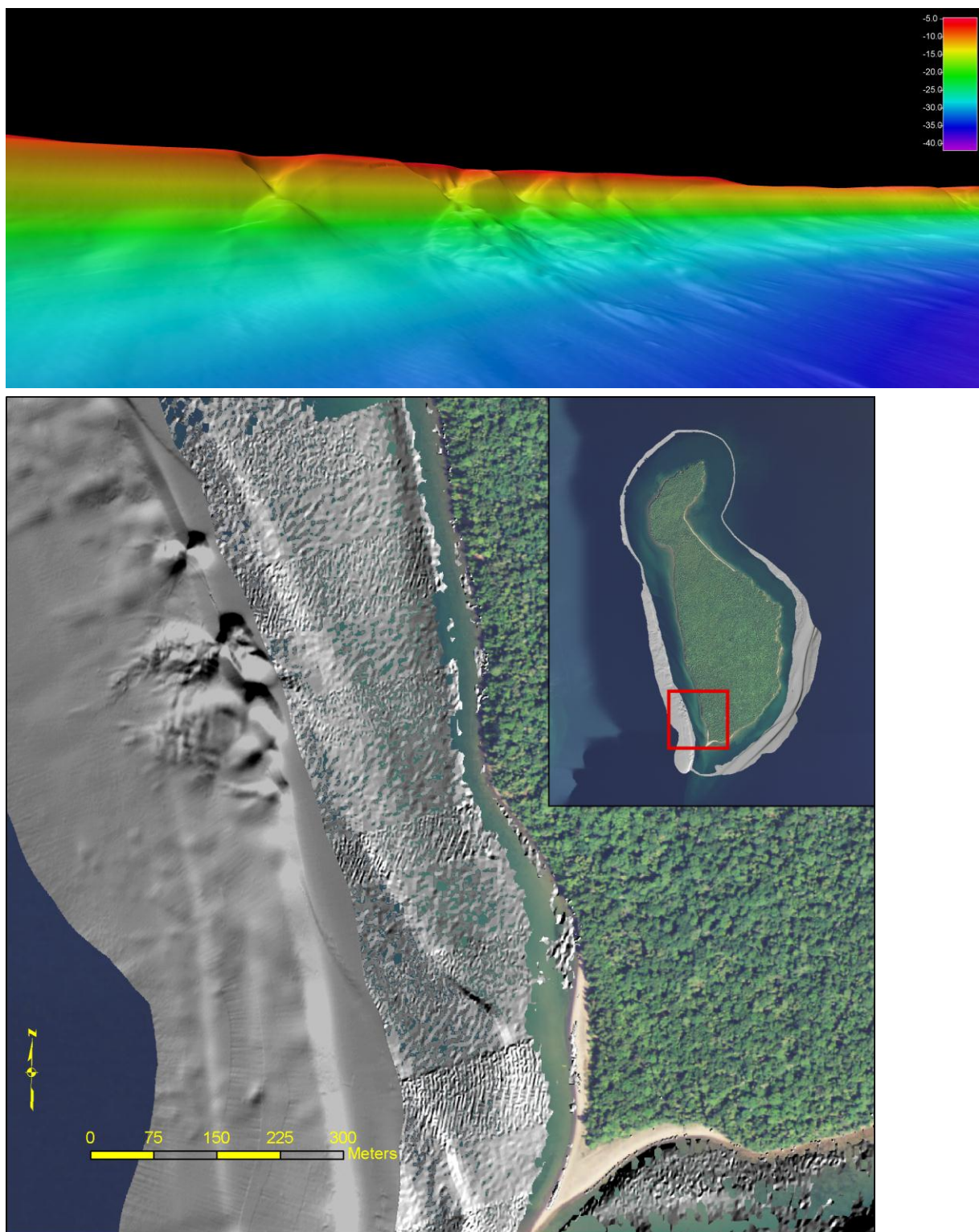


Figure 7. Two views of sand features on the west side of Cat Island. **Top:** Three-dimensional visualization (vertical exaggeration of three-color scale, in meters). **Bottom:** Plan view (vertical). Sand slump features are along southwest end of island (shown in inset).

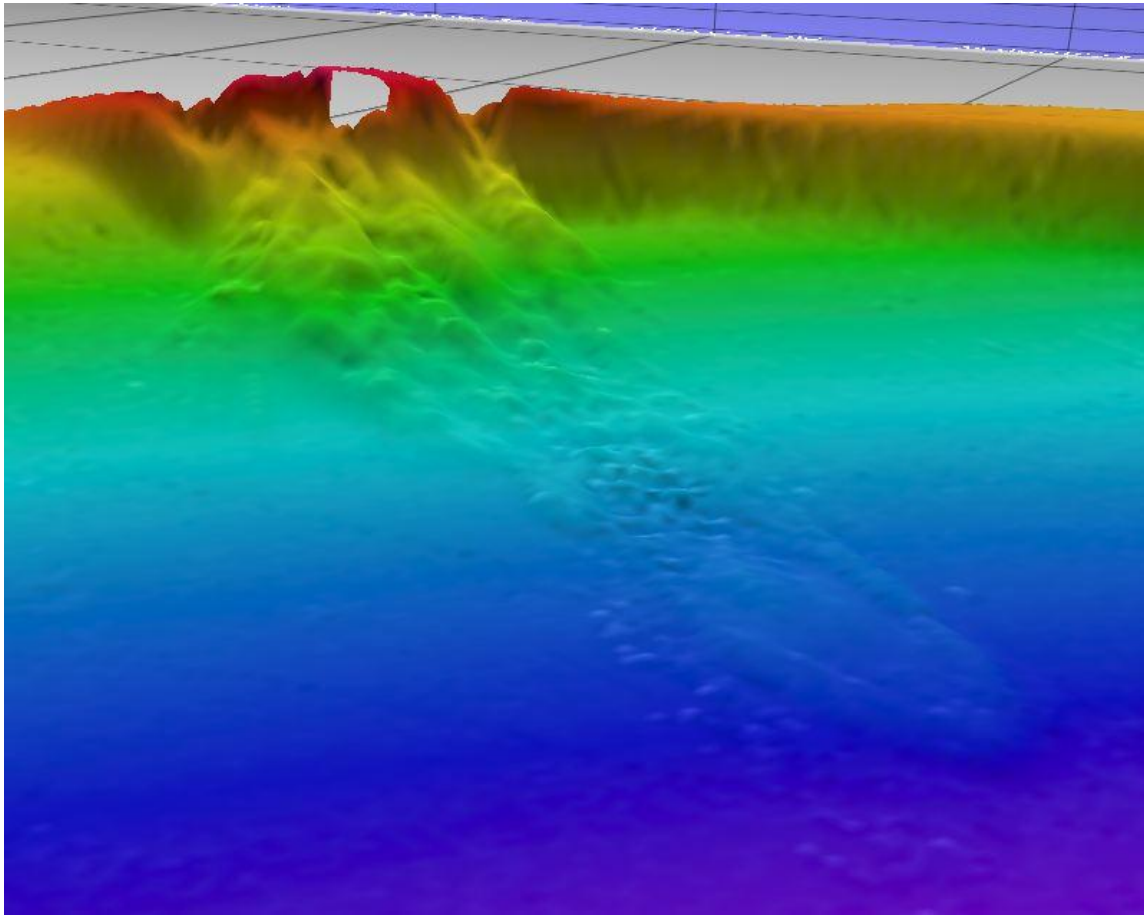


Figure 8. Three-dimensional visualization of sand features on the east side of Raspberry Island (vertical exaggeration of six). Depth varies from 3 m (red / orange) to approximately 25 m (blue / purple).

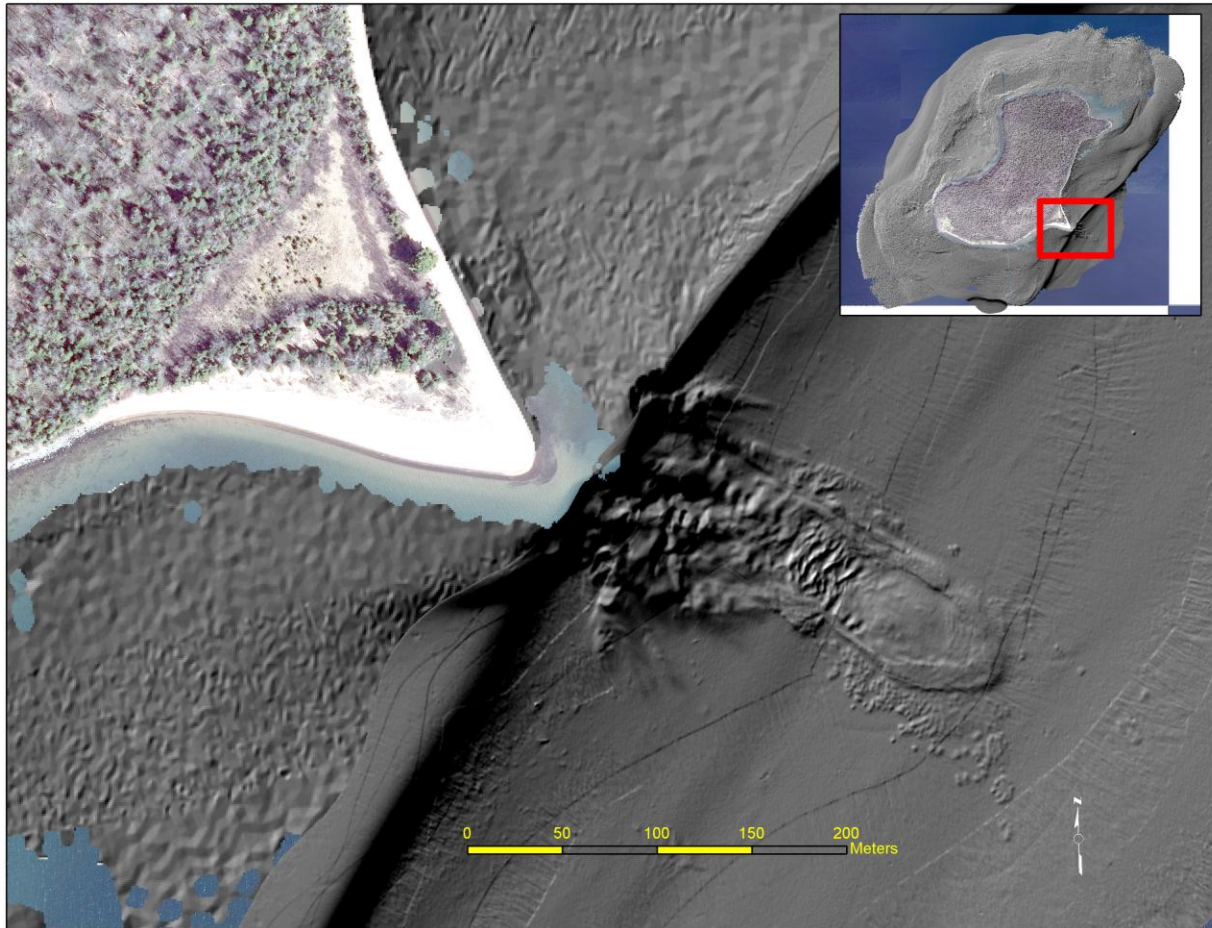


Figure 9. Plan view (vertical) of same feature at Raspberry Island shown in Figure 8. Sand slump feature is just off of the sand spit on the southeast corner of island (shown in inset).

Indiana Dunes National Lakeshore

Indiana Dunes is situated on the south shore of Lake Michigan and consists of several mainland units but no island features. The coastal LiDAR dataset effectively covers 100% of the coastal waters within INDU's jurisdiction, and provides additional coverage and context well beyond the NPS boundary, to depths approaching 18 m. The LiDAR coverage for INDU reveals an interesting coastal sandscape, as well as effects of artificial structures (e.g., docks, breakwalls, harbors) on sand movement and shoreline processes (Figure 10). Although NPS does not plan to conduct satellite- or sonar-based mapping at INDU, the existing LiDAR dataset will support ongoing shoreline restoration planning, inshore ecological studies, and fisheries management activities by NPS and partners.

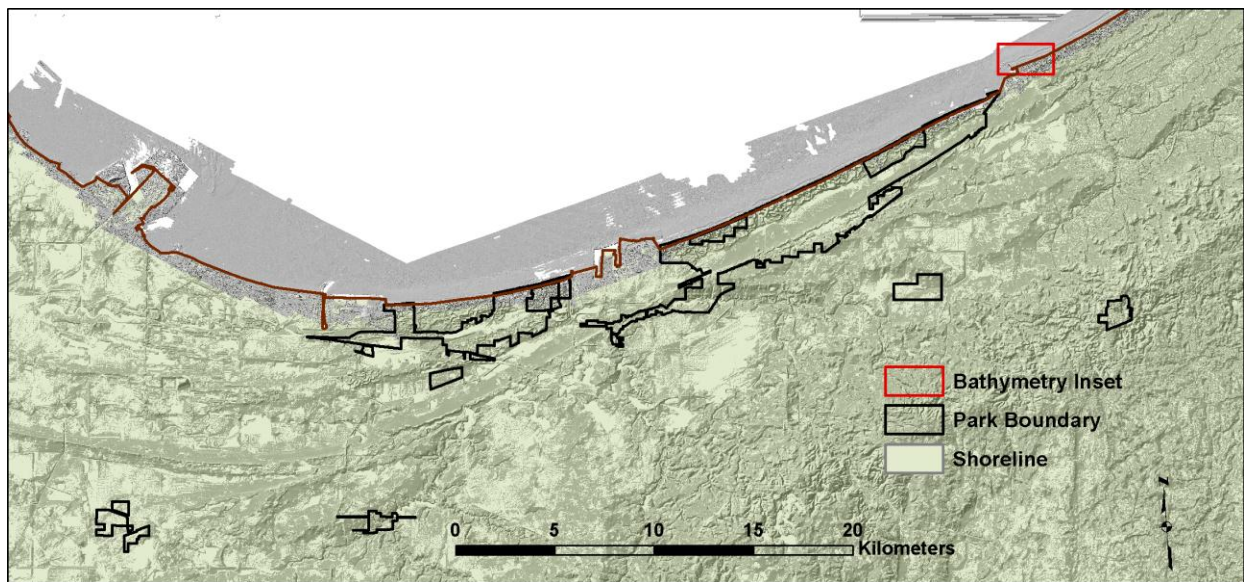


Figure 10. Top: Map showing extent of LiDAR bathymetry coverage for Lake Michigan around Indiana Dunes National Lakeshore. Red-boxed area (“bathymetry inset”) is shown in the bottom image. **Bottom:** Detailed view of “bathymetry inset” box. Arrow indicates the location of a jetty that is disrupting longshore current and sand movement. Rippling of the lake-bottom to the right (east) of the jetty is a subsequent effect of the disrupted current.

Isle Royale National Park

Isle Royale is a physically complex island archipelago, comprised of one main island and hundreds of smaller barrier islands. Isle Royale's boundaries extend four-and-a-half miles into Lake Superior, encompassing significant coastal resources across a range of depths and habitats. ISRO's extensive jurisdiction is unique among Great Lakes national parks and the NPS as a whole, as the park contains 16 percent of the total coastal water area represented within the national park system (derived from Curdts 2011). Within these Lake Superior waters lie important fishery resources, including naturally reproducing coaster brook trout populations and regionally unique lake trout morphotypes, as well as diverse marine cultural sites, including many notable shipwrecks. Underscoring the importance of these features, Kraft et al. (2010) included bathymetric assessments and benthic habitat mapping as one of ISRO's key natural resource needs.

Our sonar-based mapping efforts at ISRO have focused on filling gaps in existing LiDAR coverage, supporting lake trout research, extending coverage to known or suspected shipwreck sites, and supporting coastal restoration projects associated with shoreline structures and coastal processes.

To date, considerable portions of ISRO's shallow waters have been surveyed via LiDAR (13,000 ha) and NPS sonar (5,957 ha), for a combined total area of 18,957 ha (see Table 2 and Figure 11). Twenty-six reef habitat areas were surveyed in support of fisheries research (Figure 12). Each survey area was approximately one-nautical-mile long by a half-nautical-mile wide (Figure 13). Additional mapping has been conducted near the Siskiwit dock in support of a coastal restoration project. Data processing for all of these sonar survey locations is in progress. Mapping data for ISRO suggests complex bathymetric and substrate patterns consistent with those visible on land. We have also identified one previously undocumented shipwreck.

Given the large extent of ISRO's Lake Superior waters, it will take a sustained effort and considerable time and funding to develop complete bathymetric coverage for this park. Mapping priorities will be reassessed on an ongoing basis, but we will continue to include areas of cultural and natural resource interest, such as the *Algoma* shipwreck site, Siskiwit Bay, and potentially other coastal embayments.

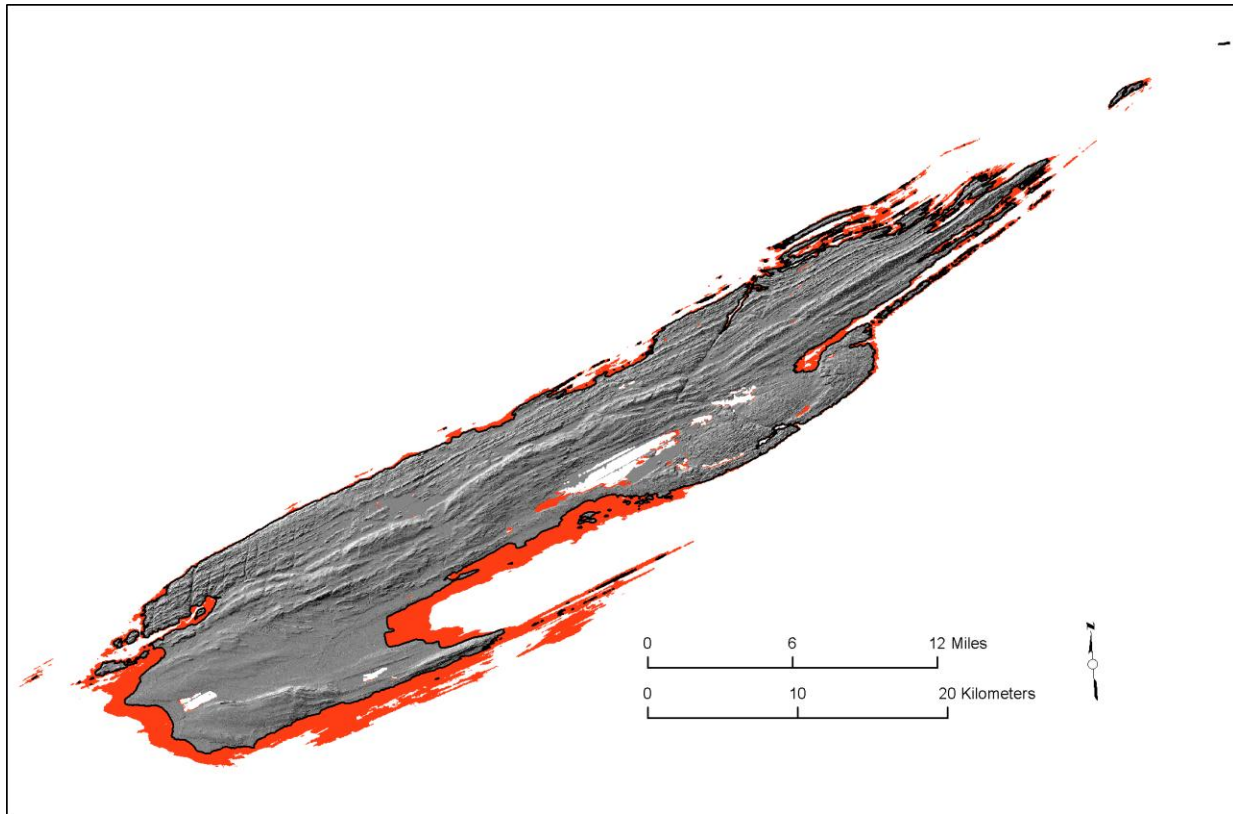


Figure 11. Extent of LiDAR data coverage for the Lake Superior coastline of Isle Royale.



Figure 12. Shoal locations around Isle Royale that were mapped using sonar onboard the R/V *Echo*.

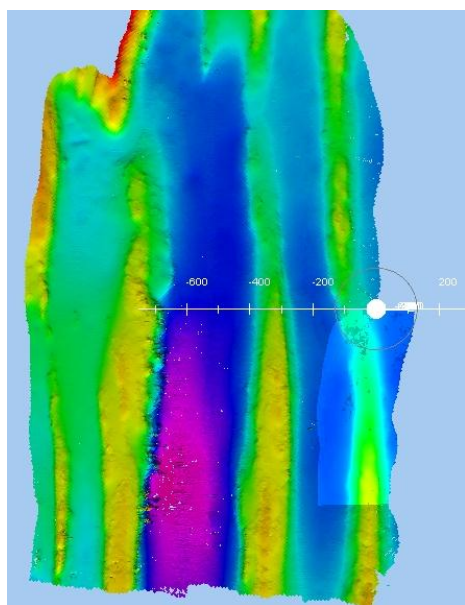


Figure 13. Example of multibeam sonar data collected near Fiver Finger Bay on Isle Royale. Increasing depths are indicated along the color spectrum of red (shallowest), orange, yellow, green, blue, and purple (deepest). The white dot indicates the position of the *Echo* while surveying, with the scale in meters.

Pictured Rocks National Lakeshore

PIRO's shoreline and Lake Superior jurisdiction are relatively simple and limited. However, park managers are interested in coastal issues ranging from coaster brook trout management to restoration of shoreline processes. Since PIRO is a linear park with no island features, the LiDAR data from the U.S. Army Corps of Engineers National Coastal Mapping Program for the Great Lakes provided good coverage of park waters in Lake Superior (Figure 14). Additional sonar-based mapping efforts have been conducted to fill gaps in the existing LiDAR coverage and support an analysis of sand movement, associated with a shoreline restoration project around PIRO's Sand Point (Figures 15 and 16). Used in conjunction with LiDAR data, this effort will inform natural resource and facility management decisions related to Sand Point.

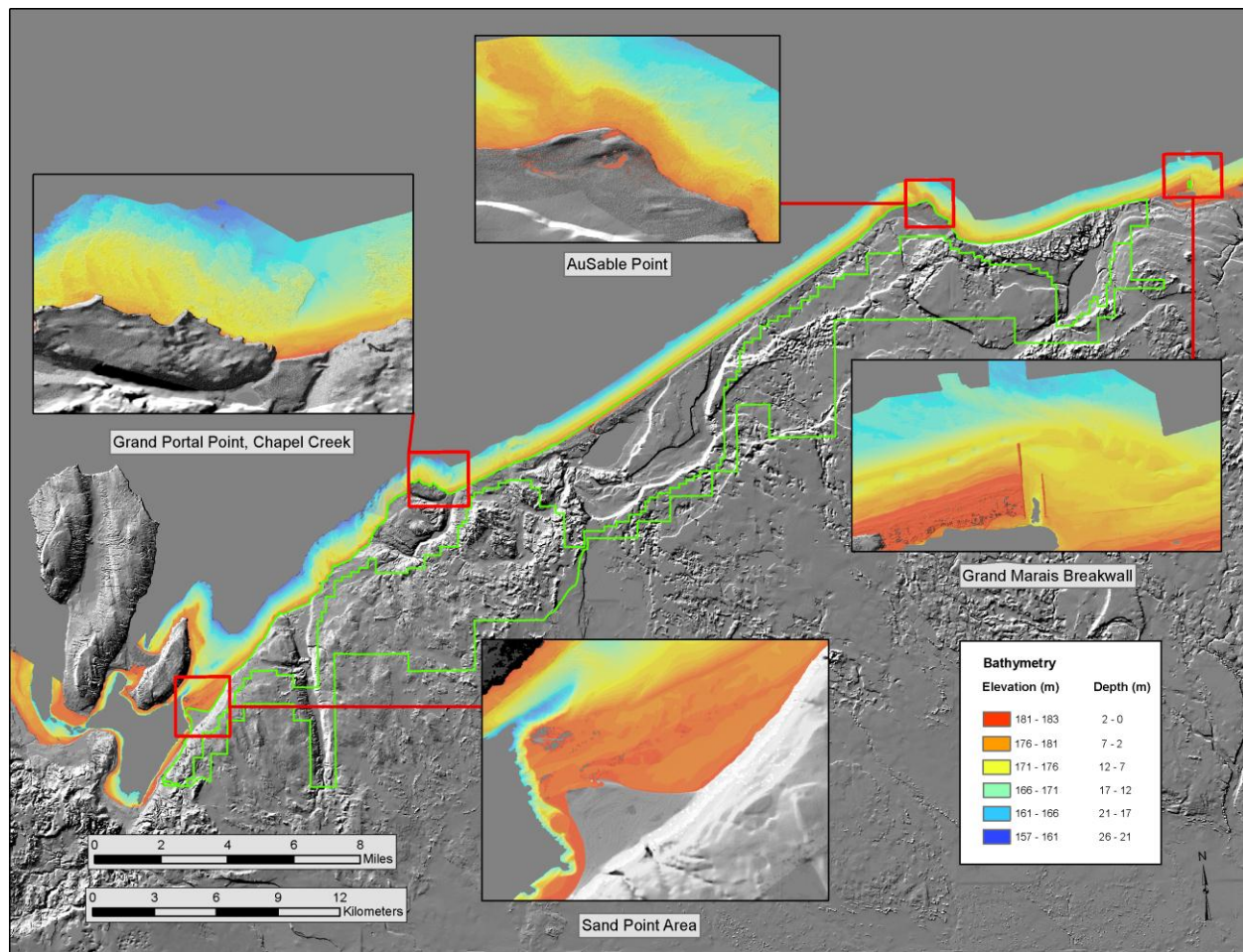


Figure 14. LiDAR bathymetry for the Lake Superior shoreline of Pictured Rocks National Lakeshore. The insets reveal the level of detail in the data.

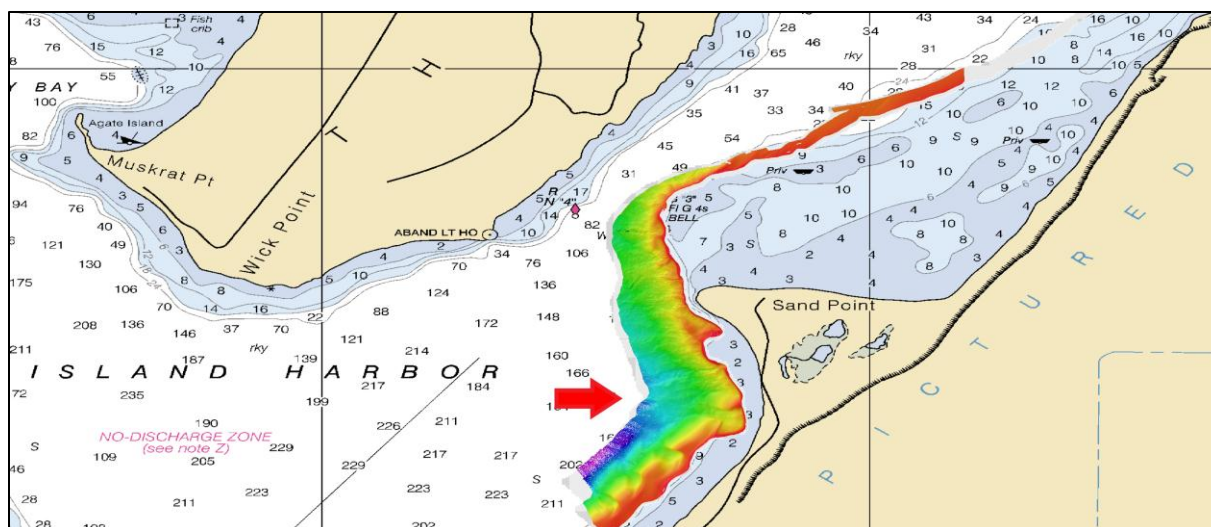


Figure 15. Sonar-derived bathymetry, overlaid on a navigational chart for Sand Point at Pictured Rocks National Lakeshore. Arrow indicates approximate perspective shown in Figure 16.

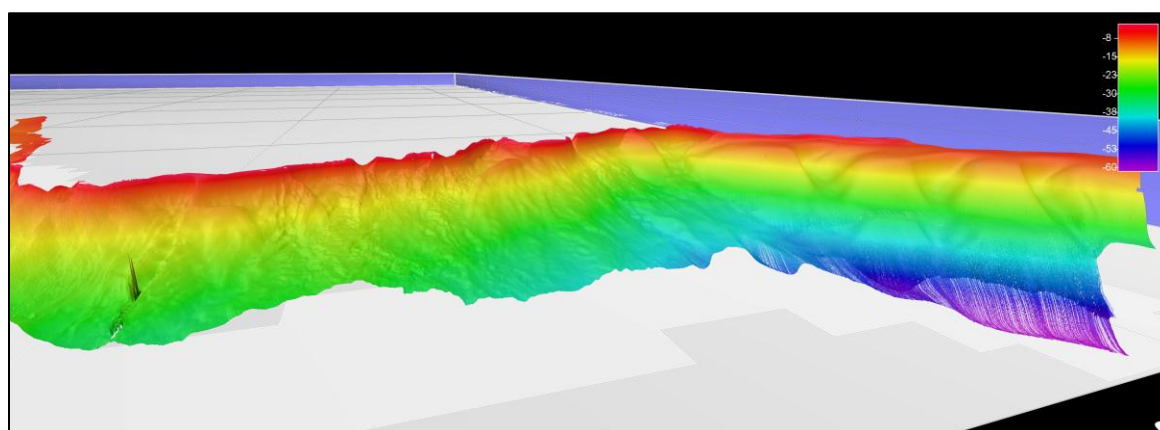


Figure 16. A three-dimensional view of Sand Point bathymetry. See arrow in Figure 15 for approximate location of this perspective.

Approximately 5,200 ha have been surveyed via LiDAR, with an additional 1,348 ha surveyed via sonar (see Table 2). The total water area surveyed at PIRO (6,548 ha) is effectively 100% of the waters within PIRO's jurisdiction. The sonar-based data are fully processed for the Sand Point to Chapel shoreline segment, with processing in progress for the remaining Chapel to Grand Marais segment. Lake Superior water depths within Pictured Rocks' jurisdiction are predominantly <15 m, with the exception of waters west of Sand Point, at the western most portion of the park. The bottom substrate is fairly level sand on the east side of the park, along Au Sable Dunes. Along the cliff walls further to the west, the substrate is mostly sandstone bedrock, with frequent drop-offs of 3–5 m. This area provides a more diverse habitat for numerous fish species.

Future hydrographic surveys at PIRO will likely be limited, since coverage is essentially complete. However, there may be a future need to revisit the Sand Point area to evaluate the effectiveness of

ongoing shoreline restoration work. Additionally, data processing and development of bottom habitat-related products for PIRO will continue.

Sleeping Bear Dunes National Lakeshore

Following the LiDAR data acquisition, which benefited all five parks, SLBE was the first park selected for additional benthic habitat mapping via sonar- and satellite-based efforts. Rapid ecological changes were taking place in SLBE's coastal environment at the time, including nuisance algal blooms, invasion by dreissenid mussels and round gobies, and large-scale avian botulism outbreaks. Accordingly, we tailored our mapping activities to support nearshore research addressing these issues. Early priorities included deeper coastal embayments (such as Good Harbor, Platte, Sleeping Bear, and South Manitou Bays) as well as isolated gaps in SLBE's LiDAR coverage (see Figure 17). As satellite-based mapping techniques became available, additional shallow areas were prioritized, including the large shallow shoal areas in Good Harbor and off the Manitou Islands and Sleeping Bear and Pyramid Points (Figure 17).

Bathymetric data collected at SLBE with each type of mapping technology have been combined and merged to create seamless hydrographic coverage for 44,464 hectares in extent—13,800 ha from LiDAR; 7,164 ha from sonar; and 23,500 ha from satellite. This constitutes 97% of the Lake Michigan waters within SLBE's jurisdiction and extends well beyond NPS jurisdiction in many areas. Together, these mapping data reveal a surprising degree of bathymetric and substrate complexity in the SLBE region, with many broad shoals apparently comprised of rock and sand, and diverse depositional areas ranging from small holes to large bays.

The mapping effort at SLBE is essentially complete. However, some additional work may be needed to fill data gaps associated with Pyramid Point and the Good Harbor Reef, since SLBE's nearshore monitoring efforts are focused in this area. Additional data collection may rely on MTRI's specialized sonar boat or the acquisition of additional high resolution commercial satellite imagery for this area.

A key concept in extending the reach of bathymetric data for SLBE was taking an “all sources” approach. Working with NPS staff, the MTRI team combined existing LiDAR data, NPS sonar data, satellite imagery, and its own sonar work with multi-beam echo soundings gathered from the Michigan Tech research vessel *Husky Traveler*. Great Lakes-focused satellite imagery analysis methods were developed from Lyzenga et al. (2006), enabling both 30-m resolution Landsat 8 satellite imagery and higher resolution GeoEye, WorldView-2, and Pleiades multispectral 2-m resolution data to be used. Bottom detection depth limits of satellite imagery were similar to LiDAR data, with typical ranges up to 20 m (Brooks et al. 2015) (Figure 18). Integrating all these sources enabled wider coverage, especially for larger, more complex offshore park areas where ship-based or airplane-based resources were not able to provide adequate coverage. Comparing these higher-resolution data sources to the traditionally available, historical NOAA bathymetry data, differences of greater than ± 10 m can be seen (Figure 19). Additionally, Landsat 8 data were used to create a new submerged aquatic vegetation map for SLBE using methods from Shuchman et al. (2013).

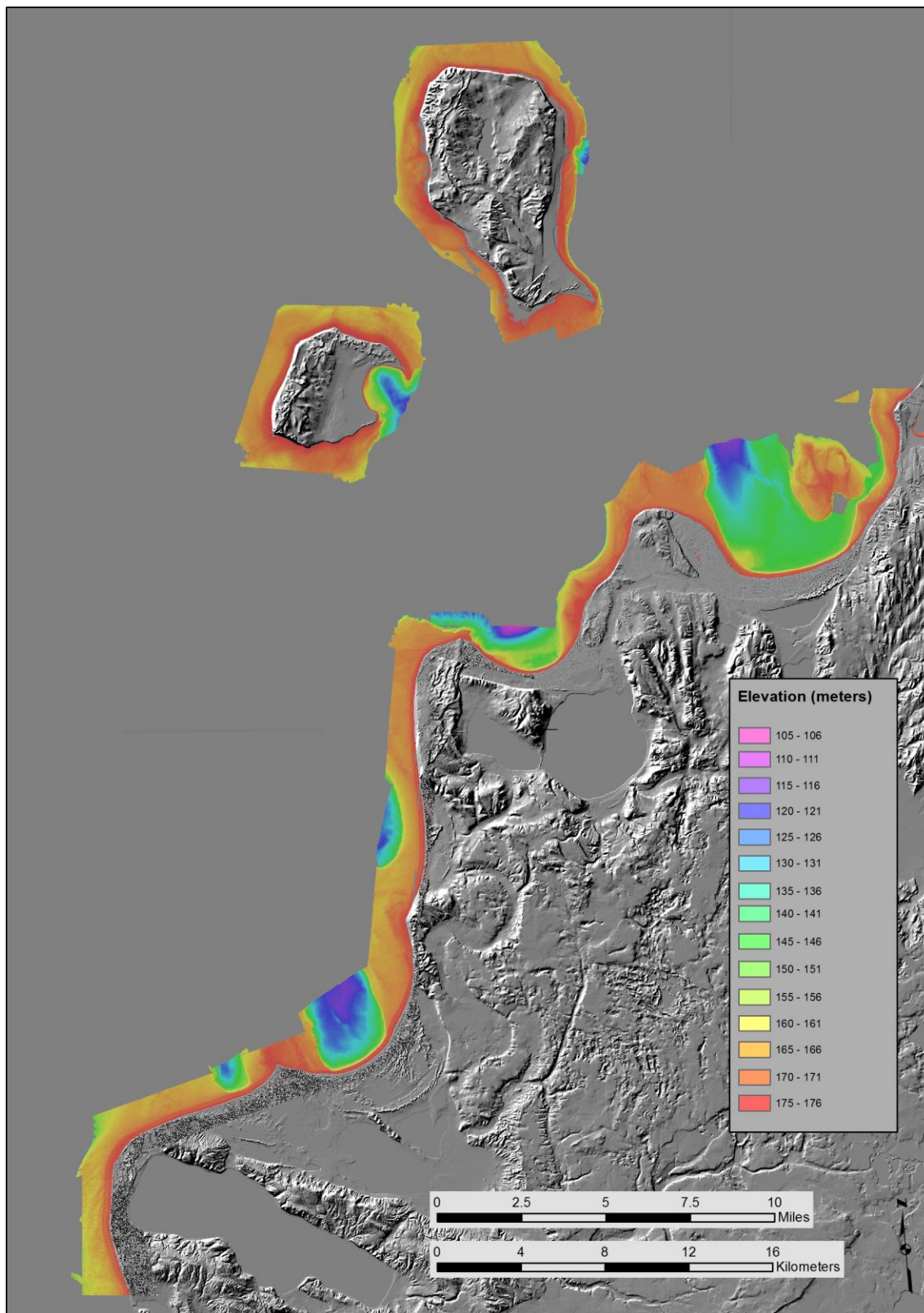


Figure 17. Extent of combined LiDAR and sonar bathymetry surrounding Sleeping Bear Dunes National Lakeshore, Michigan.

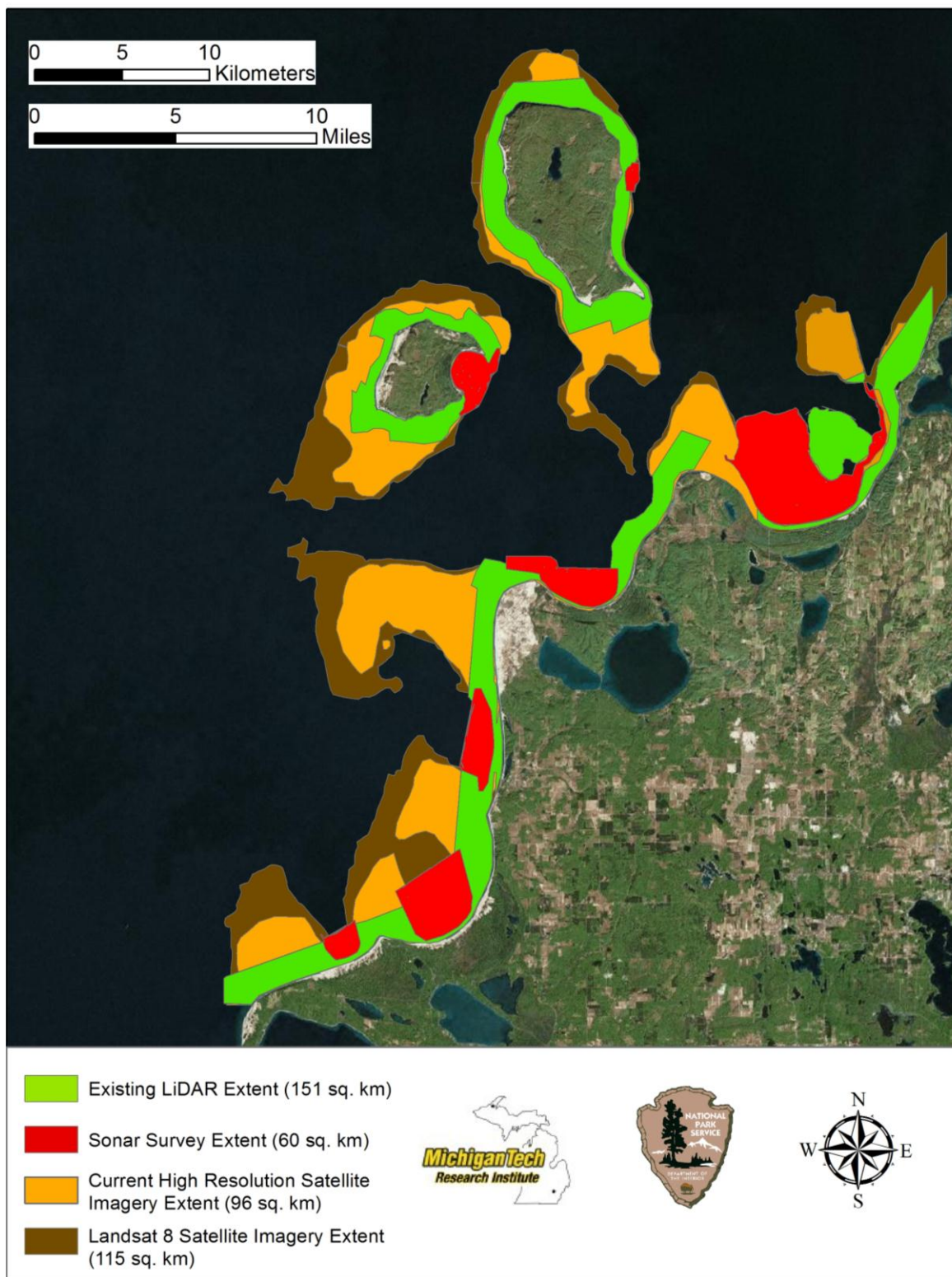


Figure 18. SLBE area showing the input data used for the “all source” approach to create an updated high-resolution bathymetry map for the offshore park areas.

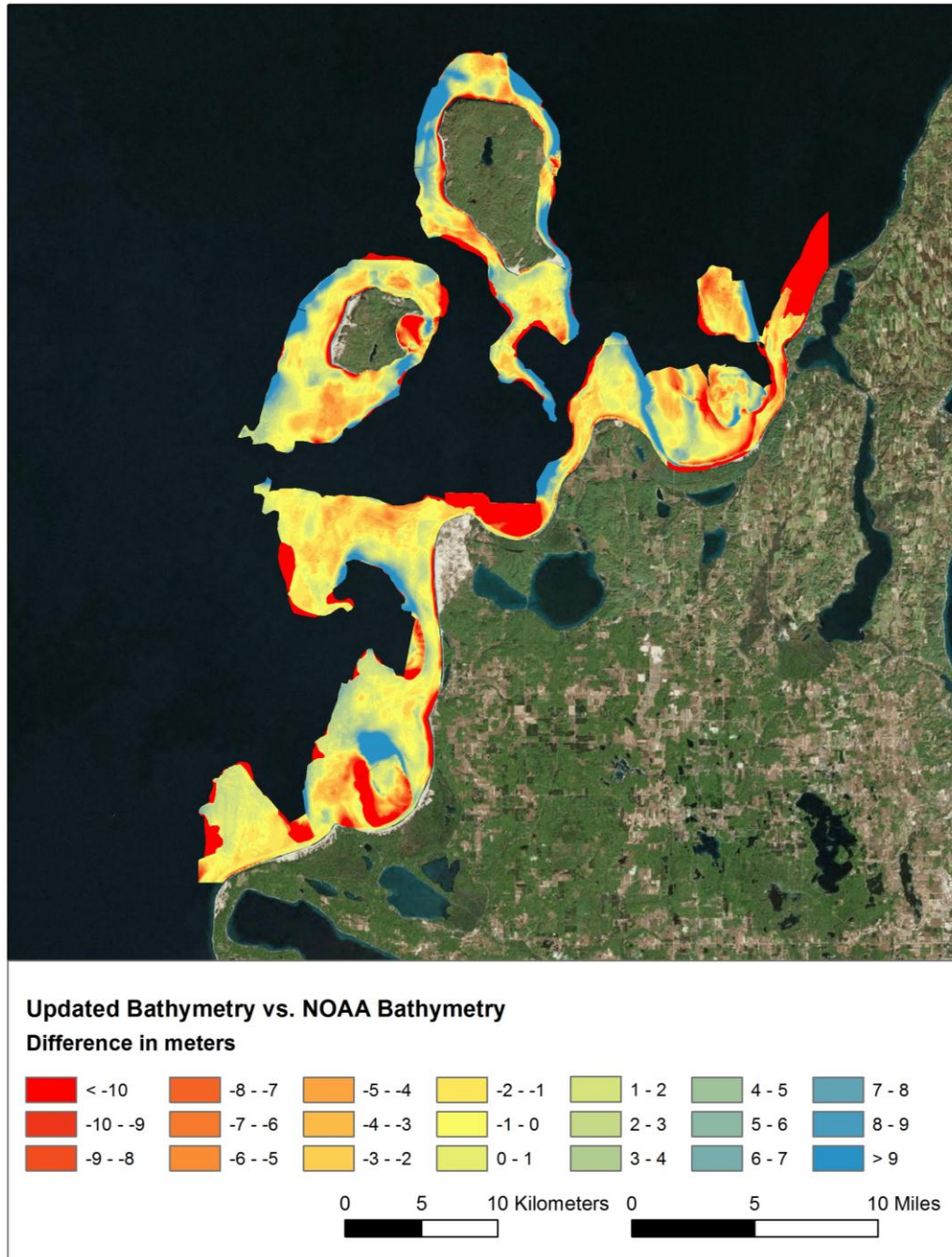


Figure 19. Comparison of new high-resolution bathymetric data with the existing, traditional NOAA bathymetric data. Notice that values highlighted in yellow and light shades of orange and green indicate similar values. However, in the red shades, the NOAA data set have values much deeper than the new bathymetric data, and NOAA values in the blue shades are shallower than values in the new bathymetric data. This highlights the increase in data accuracy by collecting with new, more advanced technologies.

Serendipitous discoveries

In the course of surveying coastal environments, the mapping project has uncovered several cultural and natural resource surprises (see cover photo, explanation provided on inside front cover). Perhaps the most remarkable are several potential wrecks identified within ISRO and APIS. Using sonar data

from the west end of ISRO, NPS staff detected a large rectangular object close to shore. Park divers and cultural resource staff investigated the find, identified it as a large, previously undocumented sunken barge (Figure 20), and have begun follow-up investigations. Potential wrecks have also been located at APIS and are awaiting field verification and further investigation.

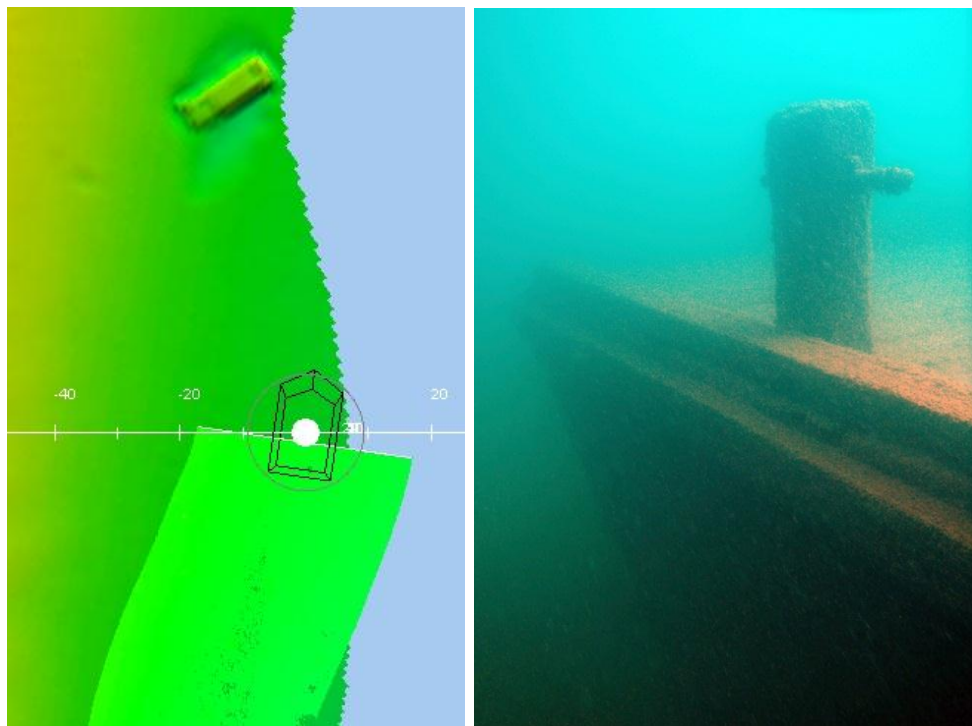


Figure 20. Sonar image on the left shows an object on the lake bottom (white dot indicates position of the *Echo* during data collection). This image was investigated by the Isle Royale dive team and found to be a previously uncharted sunken barge. The photo at right is a bollard on the bow of that barge.

Additionally, the mapping effort has identified sites of likely dredge spoils at SLBE and sand-dredging operations at APIS, revealing the impacts of historic extractive uses and ongoing management activities on coastal waters. Related to natural resources, sonar-based work at SLBE has identified a mysterious depression in Good Harbor Bay that is nearly 500 m long and uniformly 7 m deep. Based on depth, bedrock geology, and morphometry, we speculate that this depression could be a karst feature akin to the remarkable sinkholes in Lake Huron's Thunder Bay Marine Sanctuary (Biddanda et al. 2009). Follow-up investigations of this and other sites are planned.

Management Applications

Characterizing aquatic habitat

At ISRO, 26 fish habitat locations have been surveyed, including several historic but not well-described lake trout spawning reefs. Existing photos from other projects, combined with future ground-truthing efforts using video and photo images as part of this project will help validate substrate types and habitat classification at these and other locations. The substrate and habitat information at these locations will inform projects investigating ecological factors that affect diversity of the island's lake trout population. This information may be helpful to several agencies

investigating lake trout at Isle Royale, including NPS, the Michigan Department of Natural Resources (MDNR), U.S. Fish and Wildlife Service (USFWS), and National Oceanic and Atmospheric Administration (NOAA) Fisheries.

Although bathymetric and benthic habitat mapping is occurring elsewhere in the Great Lakes, this work has been conducted by multiple entities with minimal coordination between interested parties, and most of these data are not readily available for use by other organizations. The Great Lakes Aquatic Habitat Framework (GLAHF), a collaborative effort by the University of Michigan and the MDNR, aims to describe aquatic habitat in the Great Lakes. GLAHF currently uses a minimum mapping unit of 1.8 km² for nearshore and offshore areas, but will ultimately attempt to define specific habitat in 30-by-30-meter (0.0009 km²) units. One objective of this project is to collate the data and habitat information collected by multiple agencies and organizations, including the NPS, and to provide a location where it will be easily accessible.

Informing coastal restoration

At APIS, mapping efforts have provided support for analysis of shoreline sand movement. Sonar and LiDAR information has been used for coastal analysis at projects on Michigan and Sand Islands, and additional sonar mapping will be useful for monitoring projects on Stockton Island that will protect coastal and nearshore processes and habitat through coastal wetland protection.

In the southern end of PIRO, sonar and LiDAR are helping us understand hydrologic features that create constantly shifting sand bars. One prominent feature in this area is Sand Point, adjacent to park headquarters. In the early 1990s, a large rock revetment was constructed along the shoreline of Sand Point to protect park structures from historically high water levels on Lake Superior. This rock revetment had the unintended impact of changing the nearshore wave energy, hydrology, and sediment movement patterns that created and continued to maintain the large feature known as Sand Point (Young 2004). There is currently an analysis underway to determine the best method to restore this Sand Point, and data from our mapping efforts are being used to provide park managers and contractors with information needed to model sand movement and deposition features in this area.

In Siskiwit Bay at Isle Royale, a large dock and breakwall have impacted sediment routing in the southwest end of the bay, causing sediment deposition that effectively makes nearly half of the dock space unusable. Sonar and LiDAR data are being used for a coastal analysis to determine dock replacement or removal options. The park hopes to find a solution that will allow some dock accessibility as well as restoration of sediment movement and nearshore ecological processes.

Supporting nearshore research

At Sleeping Bear Dunes, management issues related to nuisance algae (*Cladophora*), invasive species, and avian botulism have led to intensive research and monitoring efforts in the area, particularly since GLRI was implemented in 2010. Benthic mapping data have aided this research effort in a growing variety of ways. Figure 21 shows an example of the updated extent of submerged aquatic vegetation (mostly *Cladophora*) created by the MTRI team and shared with the NPS.



Figure 21. Landsat 8-derived map of submerged aquatic vegetation (SAV) at SLBE; most SAV is *Cladophora*.

Initially, mapping data were used to delineate coarse benthic habitat types, make inferences about the distribution of zebra mussels, *Cladophora*, and round gobies (which have a preference for rocky habitats), and select sites for intensive food web studies. Since then, benthic mapping data have been used to contextualize research observations and generate hypotheses about where botulinum toxin is produced and how it is moved around in SLBE coastal environments. After NPS and partners discovered a small, algae-filled depositional near South Manitou Island, this area was prioritized for additional sonar-based mapping. Benthic mapping data revealed the extent of this depositional area and, importantly, the presence of many such areas in the SLBE vicinity. The role of depositional areas in botulinum toxin production continues to be a major research focus by NPS and partners. Additionally, the new bathymetric data layer has been used as a backdrop for plotting the distribution of *Clostridium botulinum* around SLBE, leading to new hypotheses about where toxin-production hot spots may lie. Finally, this new understanding of lake bottom structure has provided important insights into coastal processes and the movement of sand, sediment, and sloughed *Cladophora*. These insights led to a new hydrodynamic modeling project for the SLBE area, which will help NPS better understand local currents and upwelling and better position us to forecast future botulism outbreaks.

Investigating cultural resources

Submerged cultural resources are abundant in Great Lakes parks, popular with recreational divers, and at risk due to warming water temperatures, changing water levels, and invasive species such as dreissenid (zebra and quagga) mussels.

Several known shipwrecks within the parks have been surveyed, including the *Kamloops* at Isle Royale and the *Three Brothers* at Sleeping Bear Dunes. Other wrecks such as the *Lucerne* at Apostle Islands and the *Smith Moore* at Pictured Rocks have been mapped and lie in relatively shallow-to-moderately deep water. The *Smith Moore* lies off of Sand Point at Pictured Rocks in approximately 85–95 ft of water, adjacent to a very sandy area with somewhat active bed movement. As sand moves parallel to the shoreline of Pictured Rocks and off of Sand Point, the wreck may become more exposed or buried during different storm events. The *Lucerne* lies in approximately 25 ft of water off the north side of Long Island in the Apostle Islands. This wreck is also in a very sandy area and changes in the sand bed around that wreck may have an even greater impact on exposure or burial of the wreck. Sonar mapping at regular intervals, or after certain storm events, may be helpful for determining impacts from bedload movement related to changes in storm intensity or period.

Future Directions

Additional Surveying

Since mapping in the Lake Michigan parks is essentially complete, hydrographic surveys will focus on the Lake Superior parks. Surveys will continue at Apostle Islands and Isle Royale. In the future, project activities will include continued hydrographic survey work as well as intensified field verification, data processing, product development, and outreach. We plan to fill in remaining data gaps at APIS, map additional lake trout reefs at ISRO, and monitor changes in bathymetry and substrate related to a coastal restoration project at PIRO. Given that ISRO's boundaries extend well into Lake Superior waters, hydrographic surveys at this park may continue for some time into the future, whereas survey efforts for other parks may gradually diminish.

To validate substrate and begin investigating the serendipitous discoveries made to-date, detailed field verification efforts are planned for the coming years. Substrate images will be acquired from each of the parks using existing and new drop camera imagery. These photographic data will be related to the sonar and LiDAR data to better understand and map substrate types. Existing photographic footage is available from the U.S. Environmental Protection Agency's 2010 survey of coastal waters in five Great Lakes parks and from the U.S. Geological Survey Great Lakes Science Center's pilot mapping effort and ongoing botulism-related research at SLBE. Additionally, NPS scuba divers will investigate several possible shipwrecks and cultural finds within APIS. This work will be conducted in cooperation with cultural resources staff from APIS and potentially the State of Wisconsin. Finally, with partners from Northwestern Michigan College we plan to use a remotely operated vehicle to explore the possible sinkhole identified at SLBE.

Several years of hydrographic survey work across multiple parks have generated a substantial amount of raw hydrographic data. Processing these data is time consuming and labor intensive, and, as is often the case with large scale benthic mapping efforts, data processing lags behind data collection. In the future we hope to intensify the data processing work. We are increasingly proficient with the software and data processing techniques, and have worked through a variety of initial technical challenges. Further, we plan to hire an additional person (a student intern trained in hydrographic surveying or a second NPS position) to assist with the field surveys and preliminary data processing, freeing up other NPS staff to focus on final processing.

To date, most of our work has focused on bathymetric data; however, other types of data may be derived from the multibeam sonar. For example, we can derive measures of slope and rugosity, or use the sonar's backscatter data to interpret substrate conditions. We hope to begin exploring these other metrics and incorporating them into new mapping products.

A variety of data and mapping products are completed or in development. At the most basic level, this work has generated a wealth of processed bathymetric data. We have compiled these data from multiple sources (e.g., LiDAR, sonar, and satellite) into a seamless dataset for SLBE, and similar GIS products are in progress for the Lake Superior parks. Large maps, including high resolution insets for points of interest, have been developed for the parks, and will continue to be refined as additional data become available. In the longer term, we hope to formally classify benthic habitat types in NPS

waters using a framework consistent with the Coastal and Marine Ecological Classification Standard (CMECS). The CMECS framework addresses several components of the seascape (i.e., water column, geoform, substrate, and biota) and will incorporate many of the data types described above (i.e., bathymetric and backscatter data, photographic imagery from field verification efforts, and other data sources).

As our dataset and list of products has grown, we have begun reaching out to management and research partners within the Great Lakes community. We hope to increase these outreach efforts in the coming years. We presented posters at regional and national scientific meetings in 2014 and will pursue similar opportunities in 2015 (including the meeting of the American Fisheries Society). We have also begun discussions with staff from the University of Michigan's Institute for Fisheries Research, who are developing the Great Lakes Aquatic Habitat Framework, which is an aquatic habitat database and classification framework for the Great Lakes. We hope to integrate our hydrographic data into this framework, providing a Great Lakes-wide context for the NPS mapping data and elevating the profile of our work. Finally, we'll be sharing project outcomes with park visitors and Great Lakes residents more and more in the coming years. For example, a new NPS GLRI project ("New View of the Nearshore") slated to begin in 2015 aims to both generate nearshore monitoring data and share these data and insights with Great Lakes communities. We expect that benthic mapping data, hard-won and increasingly polished via this current project, will be incorporated into NPS interpretive efforts related to the new nearshore project.

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