Stamp Sand Threat to Buffalo Reef & Grand Traverse Bay: LiDAR/MSS Assessments Prior to "Trough" Dredging

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Executive Summary

A large metal-rich 'halo' exists in sediments around the Keweenaw Peninsula, a consequence of past copper mining. Waste rock from coastal tailings has migrated along extensive stretches of shoreline, threatening critical fish breeding grounds and coastal benthic invertebrate communities, damming stream and river outlets, intercepting wetlands and compromising recreational beaches. The Lake Superior LAMP considers migrating stamp sands one of the highest priority threats to the lake. In Grand (Big) Traverse Bay, Buffalo Reef is a productive spawning area for lake trout and whitefish, producing an estimated 80% of the catch taken by Wisconsin and Michigan commercial and recreational fishing in Keweenaw Bay. The reef is threatened by movement of tailings from a century-old pile off Gay, Michigan, where two stamp mills (Mohawk and Wolverine) discharged a total of 22.7 million metric tonnes (MMT) of stamp sands.

We proposed a 2016 CZMIL over-flight of the bay and reef, using a combination of Lidar and reflective imagery, to update stamp sand encroachment prior to dredging activities in the "trough" region. The "trough" is an ancient riverbed just up-drift of Buffalo Reef that had collected migrating stamp sands and protected the reef. The remote sensing studies would be conducted in conjunction with ground-truth Ponar and ROV studies. Four previous Lidar (2008, 2010, 2011, and 2013) over-flights addressed movement of stamp sands onto Buffalo Reef and across the bay. Combining Lidar with passive reflectance imagery (NAIP, CHARTS CASI) would allow updated, comprehensive estimates of area on Buffalo Reef covered by encroaching stamp sands. Prior multiple year Lidar over-flights combined with the 2016 effort also should allow difference calculations, estimates of erosion and deposition across the bay shoreline and underwater surfaces. Moreover, underwater stamp sand bar movement and deposition into the "trough" could be estimated in the vicinity of the proposed "trough" dredging region.

The Lidar images (2008-2016) showed that the upper and middle reaches of the "trough" are filled to the point that westward movement of stamp sand into the northern boulder fields of Buffalo Reef is occurring. From difference comparisons, underwater stamp sand bars migrating across bedrock of the coastal shelf can be seen to dump into the mid-section of the "trough", creating a mound and a westward migrating front. ROV and Ponar sampling confirmed the migrating front of stamp sands and the unusually high concentrations of copper in the sands. Benthic studies showed that high concentrations of stamp sands (>20%) have serious detrimental effects on species and diversity.

Spectral reflectance differences in 2009 suggested good shallow-depth resolution of three primary substrate types along the coastal margin: stamp sands, natural beach sands, and Jacobsville Sandstone bedrock (Kerfoot et al. 2012). The 2009 substrate classification used NAIP imagery to estimate 25% stamp sand cover over Buffalo Reef. The recent effort checked the original NAIP substrate map, calculating a similar value of 28.7% cover for the whole reef. However, both efforts had difficulties with "mixed stamp sand" classifications and differences in depth penetration of passive color reflectance, considerably less than the 22 m depth reached by Lidar. If mixed stamp sand regions were added to high stamp sand regions, area coverage could be as high as 33-35%. In the end, spatial substrate classification patterns for the 2009 NAIP, 2016 Sentinel-2, and CASI 2016 Multispectral were very similar. The detailed CASI analysis strips suggested 250 m more westward encroachment of stamp sands into the northern boulder fields since 2009. A third estimate of stamp sand cover came from 110 Ponar samples

(2013-2017), as sand grains could be classified as crushed basalt (stamp sand) or rounded quartz (eroded Jacobsville Sandstone). When percent stamp sand was contoured over Buffalo Reef, 35% of the area of the reef contained sand mixtures > 20% stamp sand. Higher concentrations of stamp sand (70-100%) were found largely along the shoreline (especially the stretch from the Gay Pile to the Coal Dock) and in the northern reaches of the "trough". A secondary high in stamp sand concentration (40-60%) was located near the Traverse River Seawall, which has recently confined migration of stamp sands. That is, the coverage estimates suggest Buffalo Reef still contains many areas where organisms are relatively undisturbed in boulder fields (mainly southern and southwestern rims), although the northern boulder fields are in peril.

Animation of historic aerial imagery showed that recruitment of wave-sorted material from migrating coastal stamp sand beach deposits has dispersed southward and westward along beaches down to the Traverse River Seawall, where it is overtopping into the Traverse River channel and starting to move underwater around the barrier. This area also deserves dredging attention, as the southern bay serves as an important lake whitefish rearing ground. Along the shoreline, the "Coal Dock" acted early as a "groin" during erosion of the main Gay tailings pile, initially capturing migrating stamp sands. Beach width measurements through time show that stamp sands have accumulated mainly immediately south of the Gay pile, and secondarily around the Coal Dock. Difference calculations from Lidar suggest that between 2008 to 2016, 18.5 cm deposition occurred within the proposed "trough" dredging area, i.e., around 24,196 m^3/yr, or about 32,660 metric tonnes. Given the estimated 75,700 metric tonnes eroding from the Gay pile in 2014-2015, revetment construction plus periodic dredging would seem important complementary mitigation tactics, previously proposed by Detroit USACE. If the amount of dredging in the "trough" is set at 100,000 tonnes, that may be sufficient for about 3-5 years. Using the 2016 Lidar data, we estimated that the ponds in stamp sands between the Gay pile and the Coal Dock have sufficient volume to receive 151,400 metric tonnes of dredged stamp sands. Because of their inherently high dissolved copper concentrations, filling in the ponds would eliminate these potential "death traps" to plants, invertebrates, and vertebrates (e.g. frogs, toads, fish) and level the region.

Saving the reef is critical. The structure is unusual as "lag" glacial boulders are strewn over a very large region of the coastal shelf associated with the bedrock (Jacobsville Sandstone) promontory of Buffalo Reef. Most other reefs in Keweenaw Bay stick up vertically or are ridges, both with little area. In the past, Buffalo Reef has been very productive, hence the 80% of commercial catch and the reason that Wisconsin tribes come over to fish in Keweenaw Bay under the 1842 and 1854 treaties. In 2016, Bill Mattes from the Great Lakes Indian Fish & Wildlife Commission (GLIFWC) estimated that the cost of Buffalo Reef failure would be around $1,679,400/yr. This total includes revenues lost from Bad River, Red Cliff, and Keweenaw Bay Tribes, recreational fishing, artificial restocking to compensate for missing fish, and displacement of tribal jobs.

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INTRODUCTION

A. Background Studies

1. Threat to Buffalo Reef and Grand Traverse Bay.

Lake Superior and northern Lake Huron watersheds contain many legacy mining sites (Kerfoot et al. 2009). A large metal-rich 'halo' exists in sediments around the Keweenaw Peninsula, a consequence of past copper mine discharges (Kemp et al. 1978; Kolak et al. 1999; Kerfoot et al. 2004). Waste rock from coastal tailings has migrated along extensive stretches of shoreline, threatening critical fish breeding grounds and coastal benthic invertebrate communities, damming stream outlets, intercepting wetlands and recreational beaches (Kraft 1979; Kerfoot et al. 2012). In Grand (Big) Traverse Bay (Figures. 1-2), Buffalo Reef is a productive spawning area for lake trout and whitefish essential for commercial enterprises, recreational fishing, and tribal activities. The reef is seriously threatened by movement of stamp sands from a century-old tailings pile off Gay (Chiriboga and Mattes 2008; Kerfoot et al. 2014).

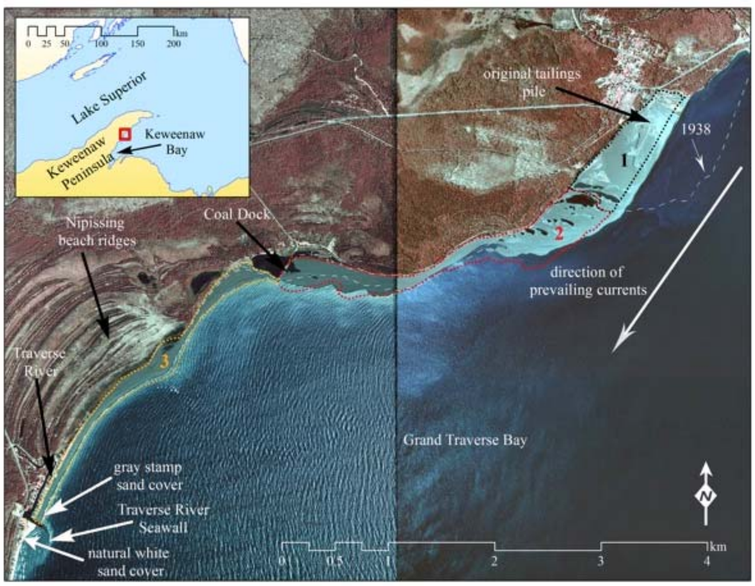


Figure 1. *Location of Grand (Big) Traverse Bay, Keweenaw Peninsula, MI. Labels indicate original tailings pile off Gay, the Coal Dock location, dark stamp sands and natural (white) sands along the beach, and the Traverse River Seawall. Numbers represent 2008 boundaries of tailings pile (#1), redeposited stamp sands down to the Coal Dock (#2), and stamp sands between the Coal Dock and Traverse River Seawall (#3). Dashed line indicates outer boundary of the tailings pile in 1938.*

Stamp sands are moving into northern boulder fields of Buffalo Reef, spilling over from filling of the northern “trough”, an ancient riverbed (Figure 2) cut into the Jacobsville Sandstone coastal shelf rock (Kerfoot et al. 2012, 2014; Yousef et al. 2013). Dredging of “trough” sediments is advocated as a practical solution to slow encroachment of stamp sands into the boulder fields of Buffalo Reef. Over-topping at the Traverse River Seawall also must be addressed. Completing environmental assessments prior to “trough” dredging, we examine stamp sand “encroachment” circumstances along the shoreline and into the northern boulder fields of Buffalo Reef and some environmental consequences of dispersing stamp sand.

2. Historical Calculations of Gay Tailings Pile Erosion & Shoreline Stamp Sand Deposition.

In Figure 2, a Light Detection And Ranging (Lidar)-derived Digital Elevation Model (DEM) highlights critical coastline features and indicates the central position of Buffalo Reef in Grand (Big) Traverse Bay. Of the 22.8 MMt (million metric tonnes) of stamp sands discharged by the Mohawk and Wolverine Mills at Gay, an estimated 15.8 MMt (69.3%) remained on the tailings pile in 1938 (earliest aerial photo). From subsequent aerial photographs, erosion was estimated from the Gay pile by calculating meters of shoreline lost each year, using four transect lines across the pile, each at right angles to the shoreline (Kerfoot et al. 2012). These measurements, derived from eight georegistered aerial photographs, showed that the loss in meters of shoreline each year at the pile has remained nearly constant through time ($y = -7.86x$, $R^2 = 0.990$), i.e., around 7.9 m yr^{-1} (8.6 yards, or ca. 26 feet). The four transect lines on the northern side of the pile indicated zero estimates (northern portion of pile gone) between 2021 and 2050.

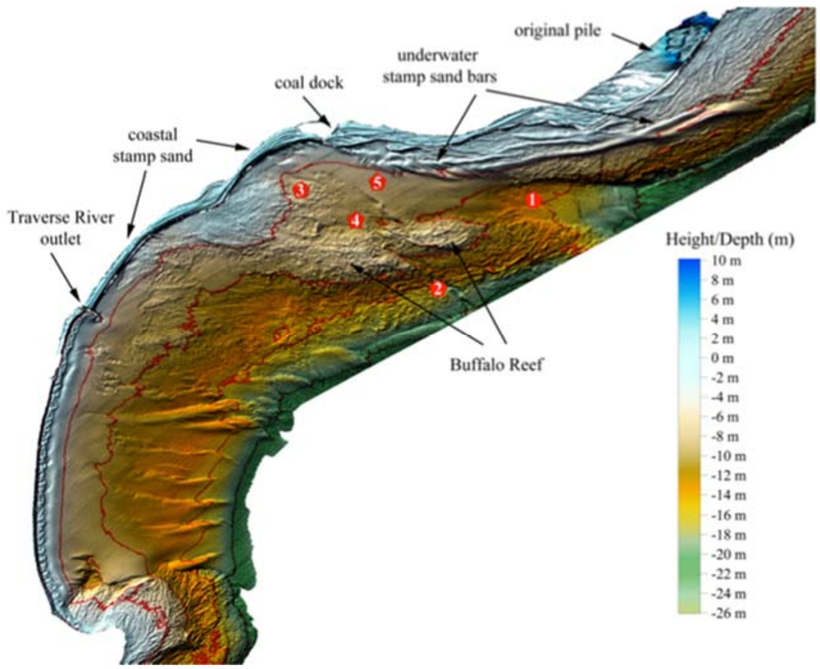


Figure 2. *2010 Lidar-derived bathymetry of Grand (Big) Traverse Bay, showing positions of the original Gay tailings pile, above-water stamp sands along the beach from the pile to the Coal Dock and southwestward to the Traverse River seawall, and the central Buffalo Reef area (Yousef et. al. 2013). The "trough" region is an old riverbed north of Buffalo Reef. To the northeast, note the underwater stamp sand bars moving across bedrock (Jacobsville Sandstone), and to the southwest, natural sands and silts moving out of the bay into Lake Superior. Horizontal contour lines are at 5m depth intervals.*

Estimating the volume of stamp sand eroding annually from the Gay pile required more complicated calculations, because the depth of stamp sands increased out into the bay. From a combination of the 2008 Lidar bathymetry profiles and several aerial photographs (Kerfoot et al. 2012), the mass of stamp sand in million metric tonnes (MMt) remaining on the pile was estimated for various dates (Figure 3). The time course for mass lost was clearly nonlinear. The best fit was with an exponential decay function [$y = (7.646 \times 10^{16}) e^{-x/53.82} - 1.42$], where x is in calendar years; $R^2 = 0.993$). With the exponential decay model, the zero intercept (indicating when the pile will be gone) was 2073, with a 95% confidence uncertainty envelope of 2041 to >2080. Logarithmic transformation of values allowed a linear regression fit (n = 8 points; $\ln y = -0.01978x + 41.1879$, $R^2 = 0.993$), and gave an estimated zero intercept of 2082, with 95% confidence intervals of 2077-2091. Thus the original source of stamp sands, the Gay pile, will be completely gone by 2073 to 2091, if mass erosion continues along historic patterns (Kerfoot et al. 2012). The two estimates (constant shoreline recession, negative exponential mass erosion) for the pile removal date (0 tonnes left) were similar, because the shoreline regression transects were laid across the northern portion of the pile, the first portion that will be removed by shoreline erosion.

Calculating yearly erosion loss using the exponential decay equation involved more uncertainty than using the log-transformed regression, where errors are normally distributed around the regression. Using the log-transformed regression and 2008-2009 values as an example, the Ln mass (2009) = - 0.01978x + 41.1879 = 1.351 or, converting Ln into arithmetic values, 3.861 MMt (million metric tonnes = Tg terragrams). Performing the same calculation for 2008, Ln mass (2008) = -0.01978x + 41.1879 = 1.4697, or converting again, 4.3479 MMt. The difference between 2008 and 2009, 4.3479-4.2627 = 0.0852 MMt, or 85,200 metric tonnes eroded annually from the main Gay pile. Converting this mass into volume, using 1.35 tonnes m^{-3}, yielded 63,111 m^3 or 82,546 yd^3. Using the other mass/volume conversion value, 1.65 tonnes m^{-3}, yielded 51,636 m^3 or 67,537 yd^3. Taking an average between the two mass-to-volume conversion values, gave 75,415 yd^3 eroded for 2008-2009.

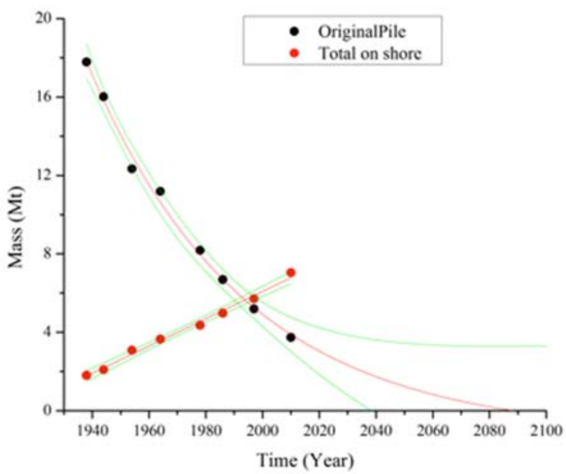


Figure 3. *Aerial photo and Lidar-derived estimates of erosion from the Gay tailings pile (black dots) and the corresponding accumulation of redeposited stamp sand on beaches southwest of the pile (red dots). Mass is in million metric tonnes (MMt). Green bands indicate 95% C.L. around regressions. Erosion of the tailings pile closely follows an exponential loss function, whereas accumulation on beaches closely fits a linear increase function.*

Another critical calculation was deposition along the beach margin southwest of the pile ("redeposited" stamp sands). Using aerial photographs, Lidar, and a 1906 bathymetry map, the equation seemed nearly linear (Y = 0.07x – 133.15), where "x" was the date. Finding the difference between 2009 and 2008 estimated of the amount deposited annually. Values for 2009 and 2008 were 7.48 and 7.41 MMt, yielding ca. 70,000 metric tonnes deposited annually along the beach.

A final critical estimate involved the amount moving underwater along the shoreline, calculated by differences between the first two estimates. For example, for 2008, taking the difference between the mass eroded from the Gay pile (85,200 metric tonnes) and the mass deposited along the beach (70,000 metric tonnes) yielded an estimate of the amount moving alongshore underwater that could be deposited annually in the "trough" (15,200 metric tonnes). Converting this mass into volume, using 1.35 tonnes per m^3, gave 11,515 m^3 or 15,061 yd^3 deposited each year into the trough. Repeating these calculations for 2014-2015 produced Gay pile erosion of 75,700 metric tonnes, annual deposition along the beach of 70,000 metric tonnes, and (using the 1.35 tonnes m^{-3} conversion) the amount moving underwater along the coast as 4444 m^3, or 5813 yds^3. These erosion and deposition values are critical to assessing impacts and recovery after revetment construction and dredging. We now have 5 Lidar over- flights (2008, 2010, 2011, 2013, 2016), allowing much more refined calculations. Moreover, newly discovered bathymetry maps (1920s, 1930s) provide additional, more refined, measurements of coastal depths for calculations of stamp sand volume deposited along beaches.

Although active discharges at the Gay site (Mohawk and Wolverine Mills) ended in 1932, the original boundaries of the Gay tailings pile were determined from a georegistered 1938 aerial photograph. In 1938, the tailings cone covered 0.9 km^2. In 2008, redeposited stamp sands covered 1.3 km^2 along the southern beach to Traverse River, whereas the underwater portion covered an estimated 5.1 km^2 of bay bottom. That is, over the past 110 years, unrestrained coastal erosion of the Gay pile has resulted in stamp sand aerial impacts increasing about 711%.

Although pre–mining- and mining-era bathymetry maps are rare for Grand Traverse Bay, depths and contours were originally obtained from a 1906 Army Corps bathymetric map, allowing estimates of stamp sand mass underneath the above-water volume measured by Lidar. Thus the total volume of stamp sand redeposited along the shoreline could be estimated, Pixel calculations estimated the mean depth for the entire shoreline (pile + southern redeposited portion) as 2.94 m (SD = 1.07). For the entire shoreline (pile + southern portion), the above-water total mass was estimated from the 2008 Lidar as 4.5 MMt, whereas the mass under water level was estimated as 7.2 MMt. Including the pile mass gives a total shoreline mass of 11.7 MMt. The historic accumulation of redeposited stamp sands along the shoreline from the original pile to the Traverse River seawall (7.41 MMt in 2008, 7.83 by 2014) has been nearly constant through time (Figure 3). At present, the region southwest of the pile to the Coal Dock contains more stamp sands than the stretch from the Coal Dock to the Traverse River Seawall (Kerfoot et al. 2012). Both the stretch from the original pile to the Coal Dock Pond and the remaining stretch from the Coal Dock Pond to the Traverse River Seawall show constant accumulation of stamp sands. The slopes of the two regressions are nearly identical (Original Tailings Pile to Coal Dock, 4.5 MMt, slope = 0.034, S.E. = 0.003; $R^2 = 0.93$; Coal Dock to Traverse River, 2.6 MMt, slope = 0.033X, S.E. = 0.001; R^2=0.99; Yousef et al. 2013). In retrospect, the Coal Dock was constructed in one of the deepest shoreline regions, 3-6 m deep, at the head of the “trough”.

Final estimates from the 2008 Lidar involved indirectly estimating the amount of stamp sands that ended up underwater in the Bay. Starting in the 1950s, a certain amount of stamp sand was removed by the Keweenaw Road Commission from the inland side of the Gay pile, for application on roads during winter. However, given the high resolution of Lidar and the clear gouges left on the pile by the Road Commission, we estimated the road application loss as around 1.0 MMt of the Gay pile total (4.4%). So of the 22.7 MMt originally discharged onto the pile, 3.1 MMt remain (13.7%), 8.6-7.1 MMt (37.9-31.3%) were redeposited along the southwestern shoreline, and 1.0 MMt (4.4%) were removed for road application. By difference, the remaining 10.0-11.5 MMt (44.1-50.7%) moved into Grand Traverse Bay, spreading underwater along the beach and coastal margin (Kerfoot et al. 2012).

Underwater regions (Figure 2) southwest of the original tailings pile show stamp sand bars migrating towards the “trough’ (Yousef et al. 2013). These bars contain substantial mass (original estimate 0.6-0.7 MMt) and reach the "trough" at mid-level below the Coal Dock. The "trough" appears to be an ancient riverbed, 2 km long, scoured to a depth of 2-5 m into surrounding bedrock (Jacobsville Sandstone). The U.S. Army Corps of Engineer's Environmental Lab at the Engineering Research and Development Center (ERDC-EL) in Vicksburg in 2009 initially estimated that the "trough" has a surface area of ca. 1,275,400 m^2 (1.3 km^2) and a volume of 4,205,200 m^3. The deeper reaches of the "trough" appear to show bedrock, i.e. bedding planes of Jacobsville Sandstone cutting across the channel, whereas the upper and middle reaches are filled with stamp sands and natural sands/silts derived from eroding shelf rock (Jacobsville Sandstone). Given the gradient of the "trough", eventually sediments will funnel down the channel and off the coastal shelf into deeper waters. Since the "trough" has served as a sink, capturing migrating sediments, estimates of amounts to be dredged are also critical calculations.

3. Original NAIP Estimates of Stamp Sand Cover Across Buffalo Reef (25% cover).

At present, enlargements of Figure 2 show that the upper and middle reaches of the "trough" are filled to the point that westward encroachment of stamp sand has begun. The deep migrating stamp sand bars can be seen to dump into the mid-section of the "trough", creating a mound and a westward migrating front. Moreover, MSS imagery (Figure 4) shows that recruitment of wave-sorted material from migrating coastal stamp sand beach deposits has already dispersed southward and westward into and through the northern cobble field. On Buffalo Reef, the broad cobble and natural sand fields are used by breeding lake trout and whitefish that migrate in from deeper waters. Along the shoreline, the "Coal Dock" acted as a "groin" during early erosion of the main pile, capturing shoreline migrating stamp sands and deflecting portions into the upper reaches of the northern cobble field around Buffalo Reef. A major closed depression to the west of Buffalo Reef is also filled with stamp sands (Figures 2 and 4). MSS substrate classification showed that stamp sands had either broken through a bathymetric low NW of Buffalo Reef, and spread westward across the bottom, to now surround two-thirds of the reef (Figure 4; Kerfoot et al. 2012), or stamp sands from the amounts accumulating along the shoreline had moved south into deeper waters. A 3-band 2009 USDA NAIP image was used to construct the substrate map. Based on the MSS substrate classification, we estimated that 25% of Buffalo Reef was covered by stamp sands. If the sands encroach into gravel and cobble beds around the reef, then high Cu concentrations in interstitial pore waters may be toxic to eggs or fry. Additional concerns expressed by the Great Lakes Indian Fish & Wildlife Commission (GLIFWC) were that large amounts of fine stamp sands could fill interstitial spaces and small openings that provide shelter for eggs and young fish, further reducing suitable habitat. Impairment of reef habitat could lead to a decline in important fish species, infringement upon federally guaranteed treaty reserved rights, and a health impact on the tribal and local Keweenaw population that consumes these resources.

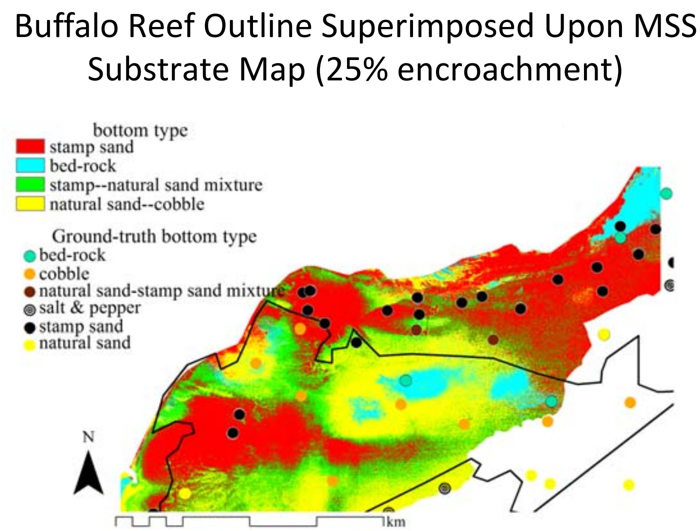


Figure 4. *NAIP Grand (Big) Traverse Bay substrate classification map, based on bottom spectral reflectance, showing stamp sand surrounding Buffalo Reef. Colored dots represent Ponar samples and underwater camera substrate ground-truth (Kerfoot et al. 2012).*

4. Airborne Survey (Lidar) Data.

Our four recent Lidar (2008, 2010, 2011, 2013, 2016) over-flights address encroachment of stamp sands onto Buffalo Reef. Four of the airborne surveys (2008, 2011, 2013, 2016) were conducted by the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX), using the predecessor sensor suite (CHARTS) with concurrent ground truth measurements. The detailed Lidar substrate mapping (Figure 2) and upwelling reflectance color data (Figure 4) produced preliminary maps of stamp sand encroachment across natural bottom substrates around Buffalo Reef cobble fields. The fourth airborne survey (2010) came from NOAA (National Oceanic and Atmospheric Administration) through the Great Lakes Restoration Initiative (GLRI) authorized bathymetric Lidar data. The data were collected and made available in CHARTS format by the Fugro LADS Mk II system. Combining Lidar images and additional reflectance data allow updated, comprehensive estimates of area for trough stamp sands and for adjacent Buffalo Reef regions covered by encroaching stamp sands.

Most of the airborne coastal mapping and charting data assembled by JALBTCX to date was collected using the CHARTS system (Rief et al. 2013). CHARTS is a NAVOCEANO-owned asset shared with the USACE (Wozencraft, 2002), which includes an Optech SHOALS-3000T20 with a 3-kHz bathymetric full waveform Lidar (green laser in the 532 nanometer wavelength) and a 20-kHz topographic discrete return Lidar (near infrared laser in the 1064 nanometer wavelength), measuring land elevations with high resolution and accuracy (1 meter spot spacing, ±15 centimeter elevation accuracy; Wozencraft and Lillycrop, 2006), as well as water depths in areas of relatively clear water, or two to three times the Secchi depth (5 meter spot spacing, ±30 centimeter elevation accuracy; LaRocque et al., 2004). The system also includes an Itres Compact Airborne Spectrographic Imager (CASI)-1500 for hyperspectral imaging, in which many narrow, contiguous spectral bands are measured across the electromagnetic spectrum (Lillesand et al., 2008). We also use the NOAA (National Oceanic and Atmospheric Administration) 2010 Great Lakes Restoration Initiative (GLRI) bathymetric Lidar data in our analysis, where the data were collected and made available in CHARTS format by the Fugro

LADS Mk II system.

Initial ERDC-EL CHARTS surveys were coordinated with Kerfoot and Green's (MTU) concurrent ship-based measurements using MTU's 34' R/V Agassiz and 22' R/V Polar. The surveys were accomplished with the second-generation CHARTS system operated from a fixed-wing King Air Beechcraft 200 aircraft. The surveys included bathymetric and topographic Lidar, collected simultaneously with aerial and hyperspectral imagery. The 2008, 2011, and 2013 Lidar scenes have not yet been fully analyzed, especially for difference calculations, but were recently used for checking stamp sand movement in the Vicksburg bathymetric modeling exercise and for estimating movement and volume of underwater bars (Yousef et al. 2013).

The preprocessed CHARTS Lidar and 8/16-band multispectral data for 2008, 2011, 2013, and 2016 were forwarded to MTU and MTRI for further study. Using the GIS-referenced high-resolution Lidar DEM portion of the data set, we can construct finished 2 m^2 resolution Lidar bathymetry maps for the region around Buffalo Reef. The use of five over-flights in the same region enhances substrate resolution, by filling in lost data tracks, and provides an updated, detailed bottom assessment. Moreover, multiple year over-flights allow estimates of underwater stamp sand bar volume, mass and movement (difference calculations; Yousef et al. 2013). For a check on the accuracy of bathymetric measurements, the Lidar -derived depths will be cross-compared with each other and with georegistered NWRI (National Water Resources Institute) SONAR-derived depths (Bieberhofer and Prokopec 2008). The SONAR and Lidar data sets are independently derived and very useful for cross-calibration and change detection. Statistical software packages (SYSTAT, OriginPro) will be used for determining spatial cross- correlations.

ENVI 4.7 is used for the entire image processing procedure. The strips are mosaicked and re-projected. The original coordinate system is unprojected Geographical Latitude/Longitude (decimal degrees, WGS84), yet for further distance, aerial, and volume calculations the data is re-projected to the appropriate local, Universal Transverse Mercator (UTM; projection= WGS84, zone=16) coordinate system.

PROJECT RESULTS

B. Shoreline Calculations

1. Analysis of Aerial Extent, Volume, and Mass of the Gay Stamp Sands Calculated Using 2008 and 2016 Lidar Elevation Data

Introduction. This study addresses the erosion of stamp sands from the original Gay tailings pile and deposition alongshore and into Keweenaw Bay. Lidar data from 2008 and 2016 were used to calculate the extent, volume, and mass of terrestrial stamp sands in the northern region where the original pile was deposited by the stamp mills and in the region south of the original pile where the sediment was transported alongshore. Since the shoreline has been highly dynamic in previous years, quantifying shoreline erosion from 2008 to 2016 indicates additional net erosion of stamp sand from the shoreline component into Keweenaw Bay, which has the potential to negatively impact biology in Buffalo Reef. Whereas the tailings pile was originally emphasized as the primary source of stamp sands into the bay, with underwater migrating stamp sand bars dumping into the "trough", mounding up and moving into boulder fields, stamp sands along the shoreline are beginning to become an important secondary source for stamp sands moving into the bay.

Methods. Terrestrial stamp sand volume estimates were computed for years 2008 and 2016 using the 2008 USACE Lidar downloaded from NOAA Digital Coast. The 2008 Lidar was converted from NAVD88 to height by subtracting the water level on June 23, 2008 at local noon, 183.345 m, and the 2016 NCMP Lidar from the U.S. Army Corp was converted from IGLD85 to height by subtracting 183.794 m, the water level at local noon on September 20, 2016. Whereas the height of stamp sands only indicated the onshore thickness of stamp sand above water level, a value of 2 m was added to the height to account for the stamp sand deposition from bedrock to the water to create a raster representing terrestrial stamp sand thickness, based on a comparison to historical bathymetric values (as was done in Yousef et al. 2013). Pond areas where there were empty (missing) values in the Lidar data were filled in with a value of 2 m. Note this assumes that in addition to the depth scoured by the ponds, there was also an additional 2 m of stamp sands below the pond, which is likely a relatively small overestimation of stamp sands. To convert stamp sand thickness to volume, the 2008 and 2016 thickness layers were multiplied by the area of an individual pixel (2 m x 2 m for 2008 and 0.838 m x 0.838 m for 2016).

The zonal statistics tool was used to sum the volume of onshore stamp sands. The 2008 and 2016 terrestrial stamp sand shoreline extent polygons were separated into three regions: the northern original Gay stamp sands tailings pile, the area south of the Gay pile to the Coal Dock, and the southern shoreline extent south of the coal dock to the Traverse River Seawall.

Results. Shoreline erosion is apparent, as both the area of the Gay pile and the area of stamp sands deposited along the shoreline decreased from 2008 to 2016, thus increasing the amount of stamp sands moved into Keewenaw Bay. Figure 5 shows the dynamic nature of the shoreline from 2008 to 2016. The greatest area of erosion is off the original Gay pile, totaling 6 Ha or 21% shoreline extent loss (Table 1). The area extent decline of terrestrial stamp sands south of the Gay pile was much less than the erosion that occurred in the Gay pile area. The area between the

Gay pile and the Coal Dock lost 3% of its extent from 2008 to 2016 and the shoreline stretch south of the coal dock lost 2% of its total area (Table 1). Care must be taken not to directly transform area into mass, because the thickness of deposits varies from the tailings pile (with its high cliffs) versus the thinner deposits along the shoreline. The decreased aerial extent of onshore stamp sands corresponded to a decrease in mass of terrestrial stamp sands over time, whereas the Gay pile mass decreased from 14% of the original pile in 2008 to 11% in 2016, the mass from the Gay pile to the Coal Dock declined from 20% to 17%, and the southern shoreline stretch mass from 11% in 2008 to 10% in 2016 (Table 2; Figure 6). Erosion from 2008 to 2016 resulted in an additional 1.6 Tg (million metric tonnes) of stamp sands entering Keewenaw Bay during that time period.

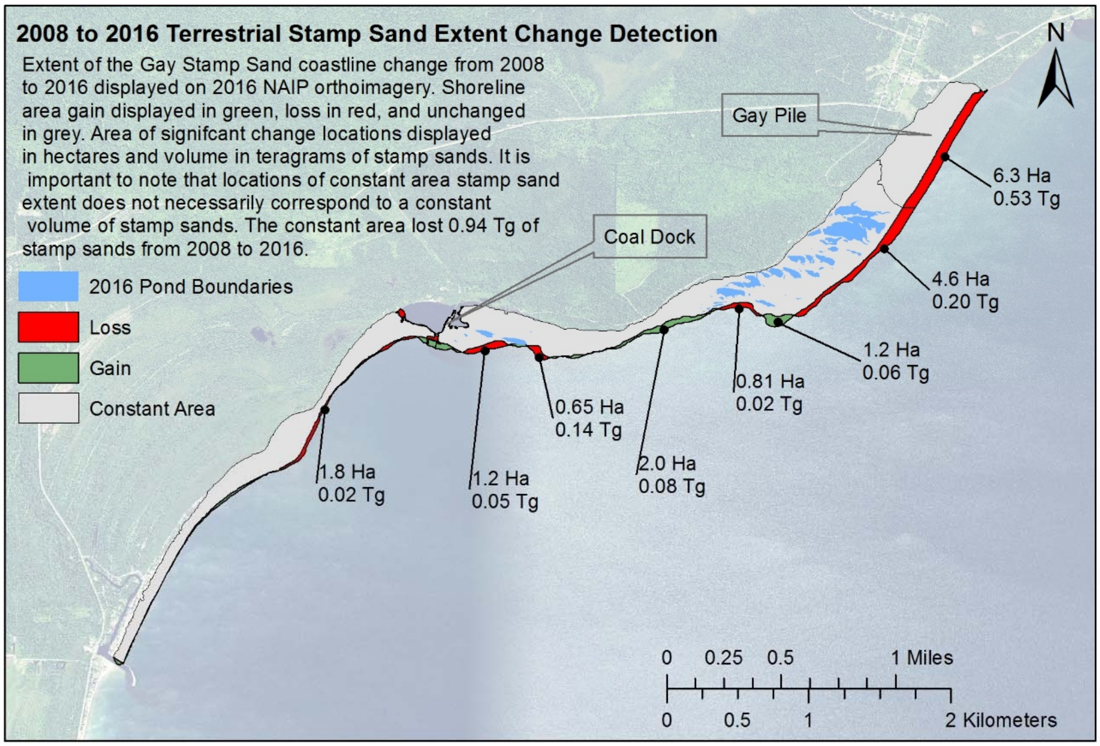


Figure 5. *Changes in terrestrial stamp sand extent (cover) and mass using 2008 and 2016 aerial imagery and Lidar data*

Table 1*. Preliminary onshore, Gay tailings pile and shoreline, and eroded offshore stamp sand aerial extent from 2008 and 2016 Lidar.*

Location	Year	Area (ha)	Percent Loss from 2008 to 2016 (%)
Gay Pile	2008	31	21%
	2016	25	
Shoreline: South of Coal Dock	2008	41	2%
	2016	40	
Shoreline: Between Gay Pile and Coal Dock	2008	95	3%
	2016	92	

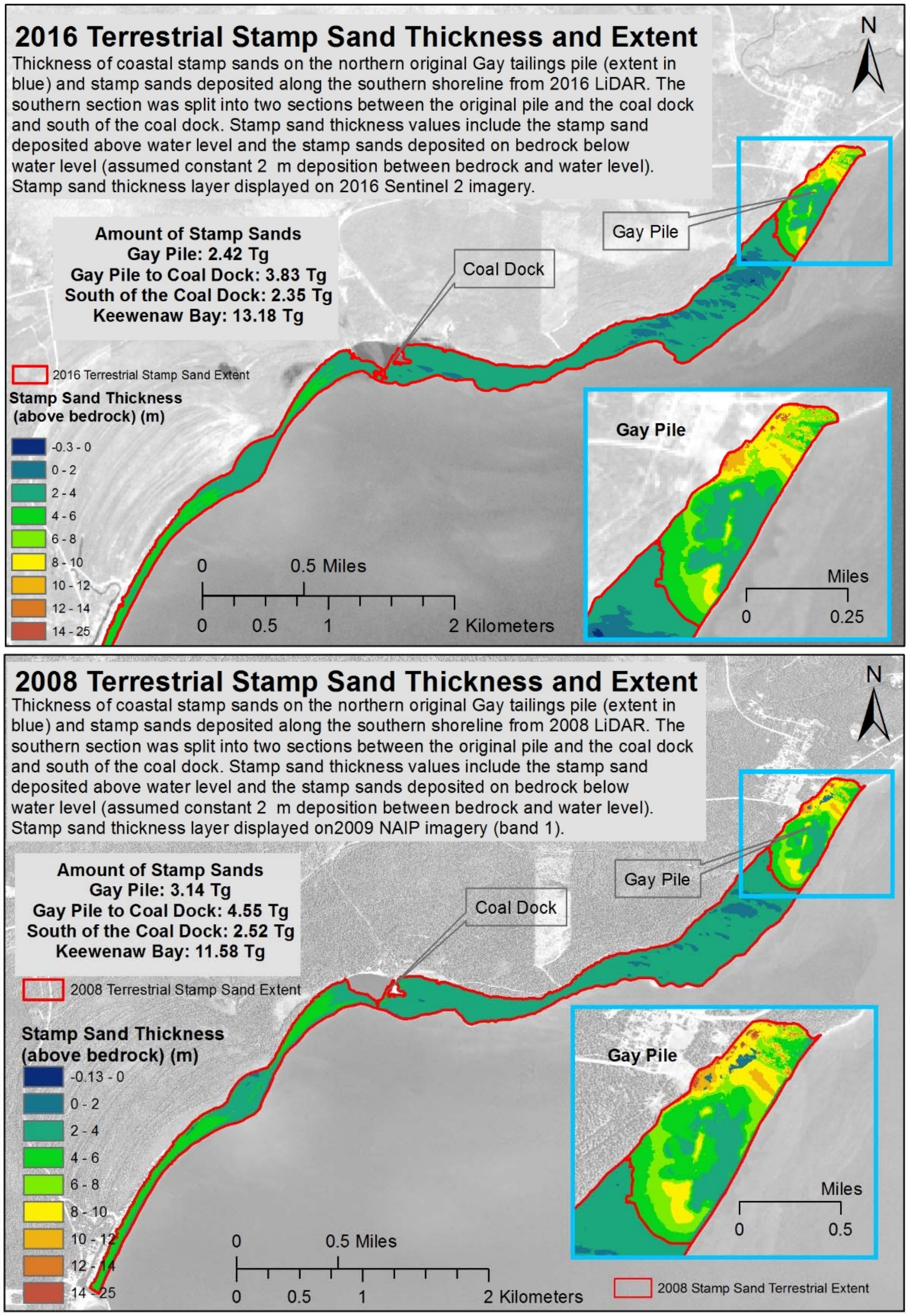


Figure 6. *Detailed data on 2008 and 2016 terrestrial stamp sand thickness and extent.*

Table 2. *Preliminary onshore, Gay pile and redeposited shoreline mass, plus eroded offshore stamp sand mass estimates from 2008 and 2016 Lidar. 1 Tg equals 1 million metric tonnes.*

<table>
<tr><th>Location</th><th>Year</th><th>Stamp Sand Mass (Tg)</th><th>Percent of Original Pile (%)</th><th>Percent Change 2008 to 2016 (%)*</th></tr>
<tr><td rowspan="3">Gay Pile</td><td>1901-1932</td><td>22.79</td><td>100.0</td><td>NA</td></tr>
<tr><td>2008</td><td>3.14</td><td>13.76</td><td rowspan="2">-22.95</td></tr>
<tr><td>2016</td><td>2.42</td><td>10.60</td></tr>
<tr><td rowspan="2">Shoreline: South of Coal Dock</td><td>2008</td><td>2.52</td><td>11.04</td><td rowspan="2">-6.50</td></tr>
<tr><td>2016</td><td>2.35</td><td>10.32</td></tr>
<tr><td rowspan="2">Shoreline: Between Gay Pile and Coal Dock</td><td>2008</td><td>4.55</td><td>19.95</td><td rowspan="2">-15.78</td></tr>
<tr><td>2016</td><td>3.83</td><td>16.80</td></tr>
<tr><td>Roads (sand used by local road commissions)</td><td>NA</td><td>1.01</td><td>4.4</td><td>NA</td></tr>
<tr><td rowspan="2">Keweenaw Bay</td><td>2008</td><td>11.58</td><td>50.82</td><td rowspan="2">13.82</td></tr>
<tr><td>2016</td><td>13.18</td><td>57.84</td></tr>
</table>

* Negative value indicates percent loss and positive indicates percent increase. Stamp sand volume increased from 2008 to 2016 in Keweenaw Bay as the amount of terrestrial stamp sands decreased over time.

2. Animation: Shoreline Deposition Through Time 1932-2016 (See Appendix A).

Periodic Aerial and Lidar images where used to construct progressive deposition of stamp sands along the shoreline from the eroding Gay tailings pile. The animation compresses a series of power point slides.

3. Stamp Sand Beach Width Quantified Through Time.

Increase in stamp sand beach width was measured along a series of transects perpendicular to the shoreline from the main Gay tailings pile southwestward towards the Traverse River Seawall. The measurements complement calculations of total mass accumulating along the stretch from the Gay pile to the Traverse River Seawall. Original calculations from the 1906 bathymetry map, aerial photographs, and the 2008-2010 Lidar overflights suggested constant accumulation of stamp sand mass along the shoreline from the Gay Pile to the Seawall through time (see Figure 2; Yousef et al. 2013, Kerfoot et al. 2014). Amounts accumulating in the sub-stretches (Pile to Coal Dock, Coal Dock to Seawall) were also nearly constant through time, i.e. same slopes for regressions, although the absolute amounts were greatest in the Gay Pile-Coal Dock stretch and less in the Coal Dock-Seawall stretch. More detailed measurements here on just beach width show stamp sands accumulating most in three regions, immediately down-drift of the Gay Pile, around the Coal Dock, and where Buffalo Reef intersects the shoreline. The transects are shown in Figure 7, whereas widths measured by date are shown in Figure 8.

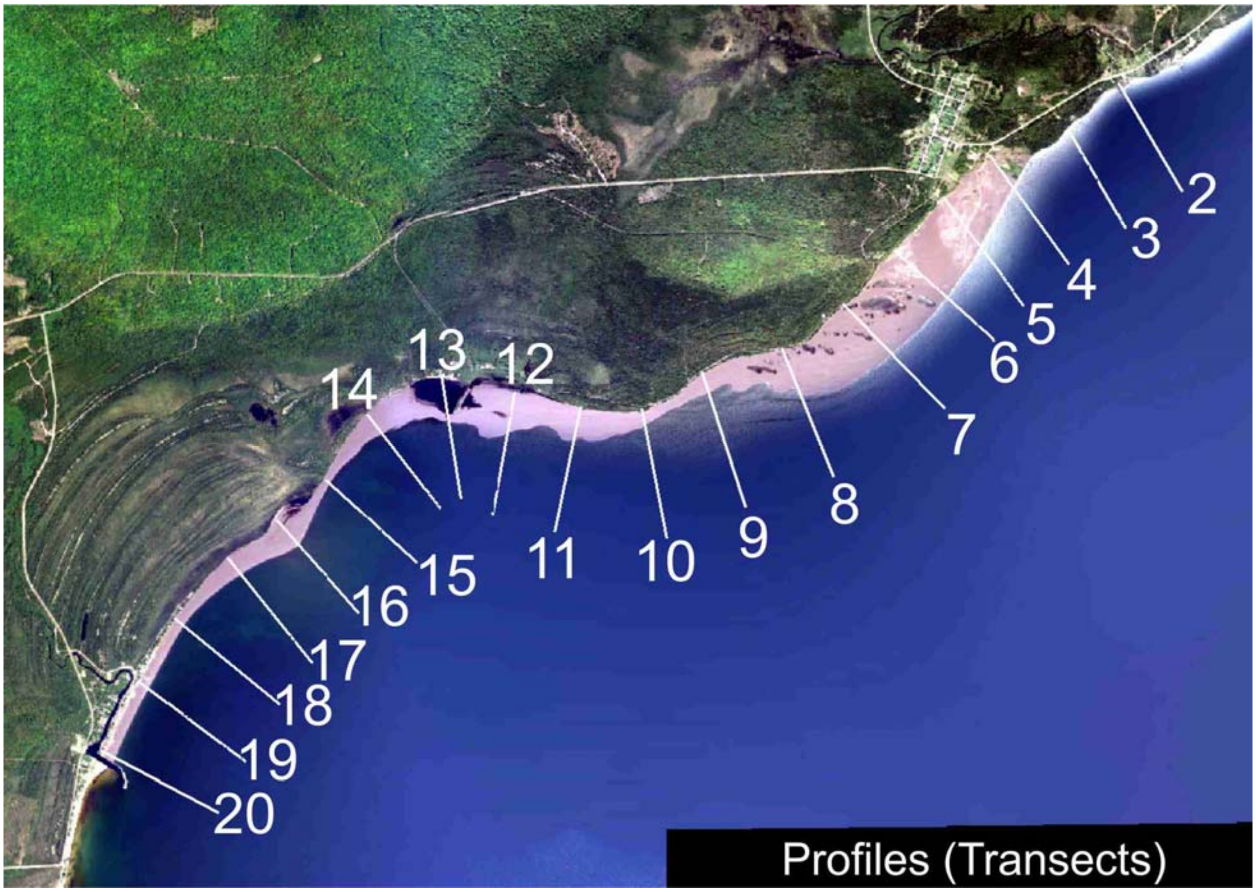
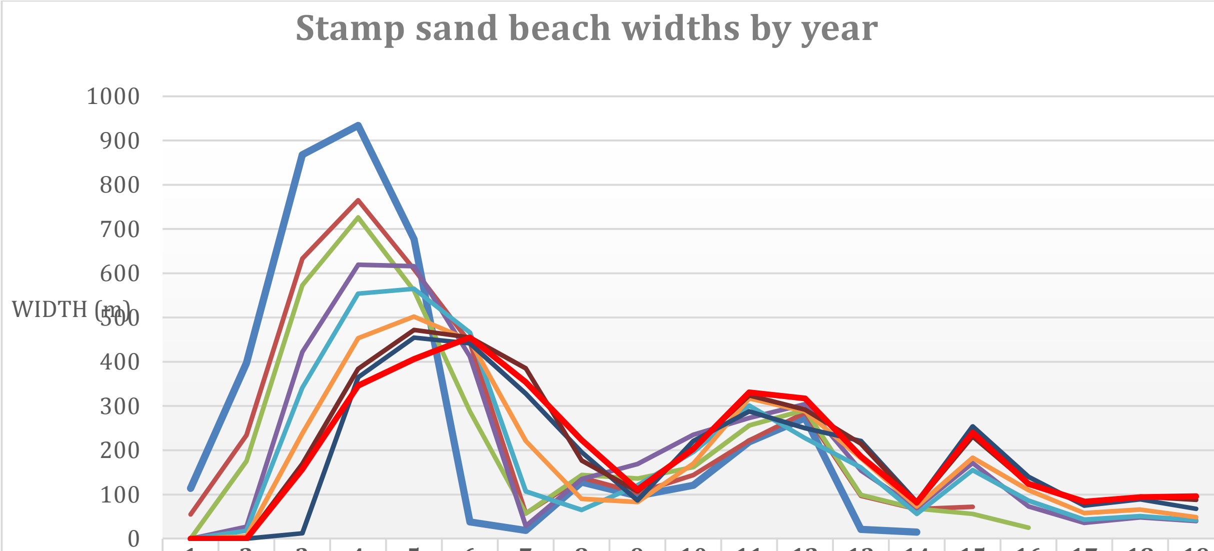


Figure 7. *Transects for measuring beach width through time (see Figure 8).*



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1938	114	397	868	934	677	38	19	128	97	121	219	273	21	15					
1954	55	234	633	765	609	443	57	138	104	144	222	285	97	67	72				
1964	0	175	573	726	561	288	57	144	136	162	256	291	99	68	56	25			
1978	0	27	422	619	616	412	29	135	169	235	273	304	154	69	171	73	36	48	40
1986	0	18	341	554	565	466	107	65	121	196	301	227	161	56	155	86	43	51	42
1997	0	5	238	453	502	448	221	90	83	170	317	288	182	73	183	110	58	66	49
2008	0	0	12.5	365	455	442	328	196	87	221	288	250	221	83	254	140	75	89	67.5
2010	0	0	169	384	472	455	385	177	107	205	324	292	215	80	231	124	81	95	88
2013	0	0	157	346	406	455	354	223	111	203	331	317	186	82	240	124	84	94	96

Figure 8. *Stamp sand beach width through time (see Figure 7 for transect locations). Years are color-coded, widths are in meters.*

4. Gay Stamp Sands 2016 pond volume estimates using 2016 U.S. Army Corps of Engineers Lidar elevation data

We were asked to determine the volume of ponds directly southwest of the Gay tailings pile. The ponds were created when stamp sands were periodically deposited in storm events, adding to the shoreline stamp sand beach. The accumulated stamp sands were added as ridges, with enclosed low spots. The high concentrations of dissolved copper in these ponds (ranging between 80-400 ppb; Joeng et al. 1999; Lytle 1999; Kerfoot et al. 1999) make them death traps for many aquatic vertebrates (frogs, toads, fish), invertebrates (*Daphnia*, amphipods), and macrophytes. Filling in the ponds with dredged stamp sands would eliminate this problem. Here we summarize estimates of pond volumes in stamp sands in the Gay Pile-Coal Dock stretch and the potential stamp sand fill capacity of these ponds.

Rasterized topobathy Lidar elevations were obtained from the Army Corps of Engineers and collected by the Coastal Zone Mapping and Imaging Lidar (CZMIL) System in the International Great Lakes Datum of 1985 (IGLD-85). The individual tiles were mosaicked together in ArcMap using the Mosaic to New Raster tool. The mosaicked image was reprojected into NAD1983_UTM_Zone_16N with the Project Raster (Data Management) tool and the resampling technique was set to bilinear. The Raster Calculator was used to adjust the elevation data to height and depth by subtracting the average mean water level, 183.735 m, on September 20, 2016 obtained from the National Oceanic and Atmospheric Administration (NOAA) tide gauge in Marquette, MI (https://tidesandcurrents.noaa.gov/).

Pond boundaries were digitized manually in ArcMap using the National Agriculture Imagery Program (NAIP) 2016 near-infrared band 4 and true color images as boundary guidelines. Since there were some gaps in the Lidar data within pond boundaries, data gaps were filled with an estimated depth of 1.5 m using the raster calculator (based on the typical bottom depth of other stamp sand ponds). The length of each cell was 0.8381 m, so 0.7023 m^2 was multiplied by the depth raster to obtain a raster layer where each pixel represented the volume.

The Zonal Statistics as Table tool was used to compute the sum of the volume within each pond. The input raster was the layer of volume and the zone field was the pond boundaries. It is important to note that any pixels above mean water level were positive and below were negative. Thus the volume of the pond is representative of the volume below mean water level. The zonal statistics tool was also used to compute the mean depth and the area of ponds using the depth layer as the input in place of the volume layer.

The total volume was 91,773 m^3 and could hold 151,426 metric tonnes of stamp sands (with a density of 1.65 metric tonnes per m^3). Out of 50 ponds total, 11 had an area greater than 1000 m^3. The volume sum of the 11 ponds contributed to 97.6% of the total pond volume, and thus, further analysis focused on this subset of ponds (Table 3; Figure 9). Two ponds were located in the section close to the old Coal Dock (ponds F and J). Pond F has been largely dynamic in the past few years. A portion of the pond that existed in 2014 is now in the lake as the coastline has migrated inland. Ponds B, E, and G, which are located in the northeastern area of ponds, are farther inland. However, Lidar data were not available for the majority of these ponds (with the assumed depth of 1.5 m). Ponds A, C, D, H, I, and K were relatively stable over the past two years and the majority of data were available from the Lidar. Pond A was the largest pond, 55,014 m^3, which was 58.5% of the total volume.

Table 3. *Summary of ponds with an area greater than 1000 m^3*

Pond	Mean Depth (m)	Area (m^2)	Volume (m^3)	Percent total Volume (%)	Potential Stamp Sand Capacity (metric tonnes)
A	0.9	78329	55014	58.5	90774
B	0.8	13043	9161	9.7	15115
C	0.7	9368	6580	7.0	10857
D	0.9	6448	4529	4.8	7472
E	0.6	5947	4177	4.4	6891
F	0.8	5422	3808	4.1	6284
G	1.0	3763	2643	2.8	4361
H	0.5	3258	2288	2.4	3776
I	0.2	2738	1923	2.0	3173
J	0.3	1339	940	1.0	1551
K	0.4	1011	710	0.8	1172
Sum	--	130667	91773	--	151426

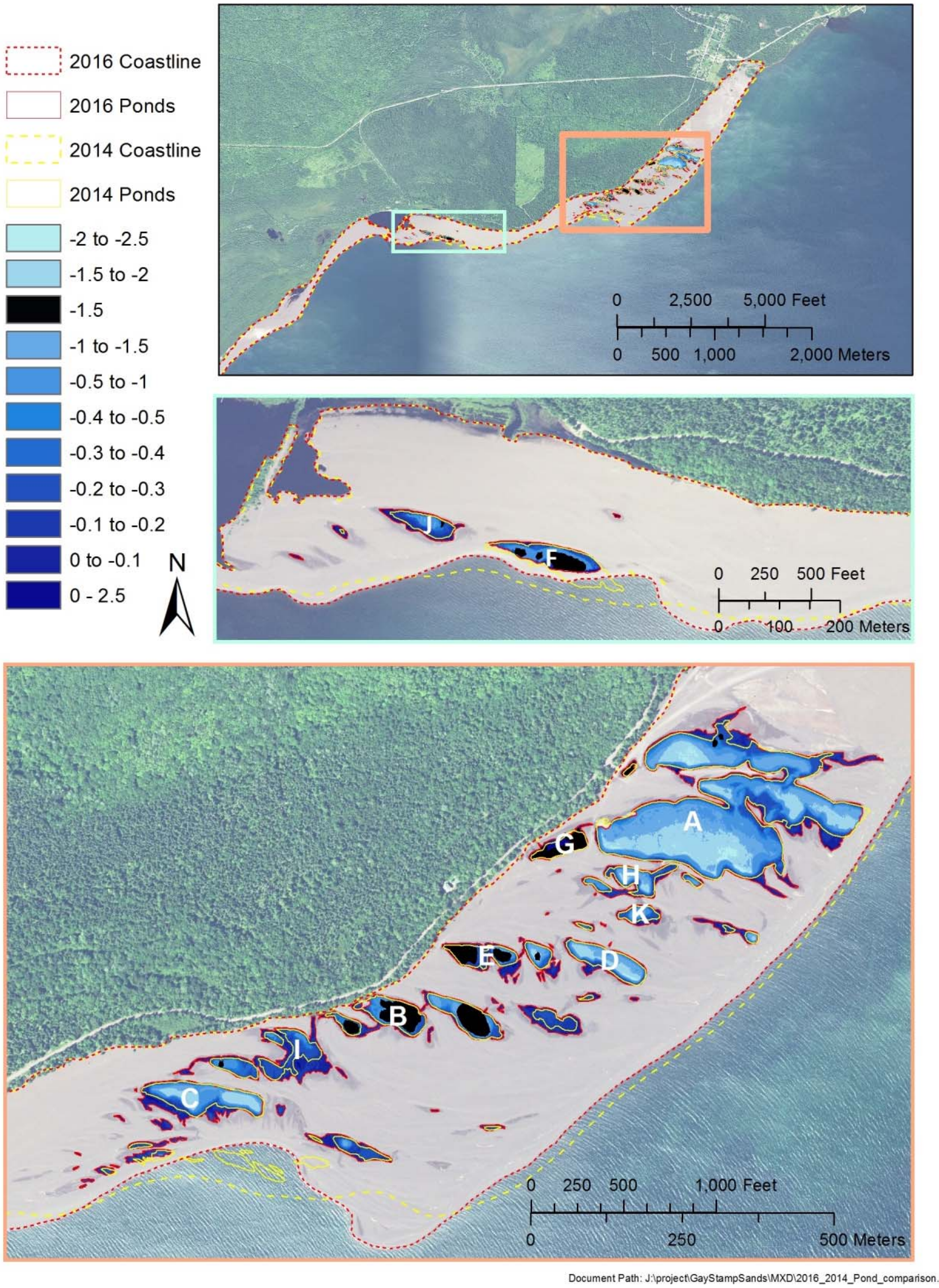


Figure 9. *Digitized pond boundaries shown for 2014 (yellow) and 2016 (red) along respective coastlines. The images underscore the dynamicity of ponds by stamp sands through time and season along the Gay Pile-Coal Dock coastal stretch. Ponds are contoured by depth values in meters relative to mean water level. Areas where Lidar data were not available are shown in black and values were assumed 1.5 m below mean water level. The 2016 NAIP compressed ortho-image is displayed in the background.*

C. Calculating Percentage Stamp Sand Cover On Buffalo Reef

1. Buffalo Reef: Comparison of 2009 Substrate Map with 2016 Substrate Map (2009 27.8%stamp sand cover; 2016 28.8%, with mixtures 35.5%).

To quantify percentage change of stamp sand extent in the Buffalo Reef region of Grand Traverse Bay 2009 NAIP color photography and 2016 Sentinel-2 ocean color satellite data were used to map the bottom type substrate. Depth correction procedures were applied to both data sets to identify stamp sand deposits. Due to varying water clarity during 2009 and 2016 the observable area of the lake bottom varied between the two dates. To allow for inter-comparison between the 2009 and 2016 bottom type maps the analysis was constrained to the bottom area visible on both images. The total area of Buffalo Reef is 9.2 km^2 while the area visible on both images is 4.83 km^2 or approximately 52% of the Buffalo Reef area.

Figure 10 summarizes the analysis of the 2009 NAIP and 2016 satellite data. The left two panels represent the 2009 analysis reported in Kerfoot et al. 2012, while the bottom center and right panels are the classification of the 2016 satellite data. Note from the lower panels on the figure that the stamp sands (red) appear to be more uniformly distributed in 2016 throughout the area successfully resolved by the remote sensing systems. The percent of stamp sands successfully identified in Buffalo Reef in 2009 is approximately 33%, while the 2016 analysis indicates approximately 35% dense stamp sand and a 20% stamp sand/native sand mixture for an approximate total of 55%. Note, the portion of Buffalo Reef shown in brown is where the bottom was not detectable to the sensors. Due to uncertainties in the remote sensing analysis (water clarity changes, sensor resolution, sensor fidelity) caution should be taken in respect to utilizing specific the percentages presented. The table summarizes the comparisons present in the figure.

Table 4. *Buffalo Reef area, percent stamp sands in northern region, where brown region (no data) removed. This is not the percentage over entire reef (see paragraph above).*

The Total Area of Buffalo Reef (polygon) is 9.2 km^2	Imagery Date	
	2009	2016
Area of Buffalo Reef Identified (km^2)	4.83	4.83
Dense Stamp Sand Area Identified in Buffalo Reef (km^2)	1.6	1.72
Mixed Stamp Sand Area Identified in Buffalo Reef (km^2)		0.94
Percent of Dense Stamp Sands in Identified Buffalo Reef	33%	35%
Percent of Total Stamp Sands Identified in Buffalo Reef	33%	55%

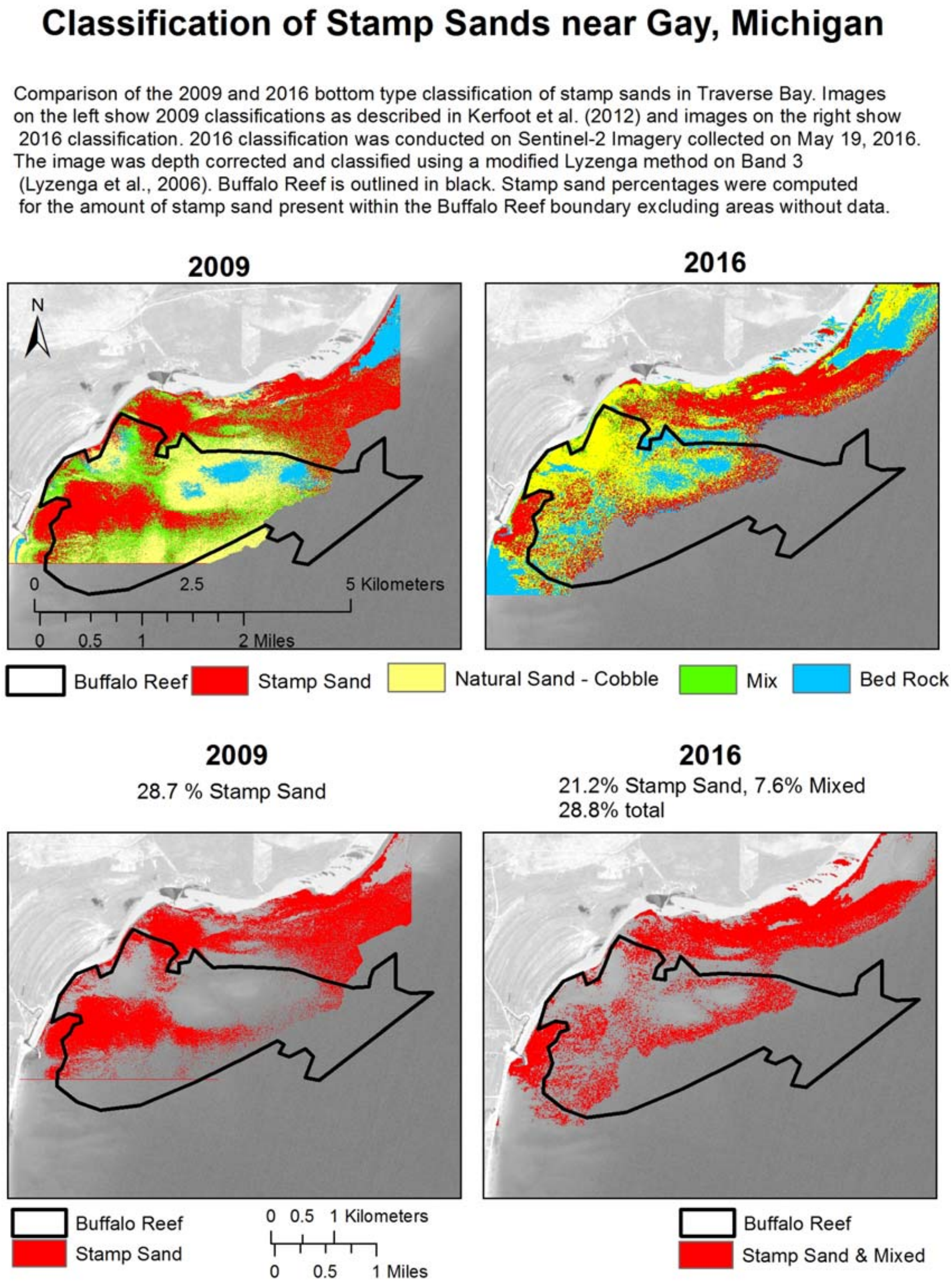


Figure 10. *Comparison of the 2009 and 2016 bottom type classification of stamp sands near Traverse Bay.*

Percentage stamp sand cover was calculated within the Buffalo Reef boundary assuming deep-water regions had low percentages of stamp sands, consistent with Ponar sampling. Our calculations for stamp sand cover in the 2009 image was 27.8% total area covered, close to the 25% calculated earlier by Yousef and Kerfoot (Kerfoot et al. 2014). The 2016 substrate classification from the Sentinel-2 imagery suggested 28.8% cover, but the total area of Buffalo

Reef covered by reflectance data was less than in 2009. To try to compensate for less than complete cover of Buffalo Reef, we shaded deep regions in brown (Figure 11), then calculated the stamp sand cover for shallow regions where substrate classification was possible. Using this perspective, northern shallow-water regions in 2009 had 33% stamp sand cover, whereas 2016 had 35% stamp sand cover. If the mixed stamp sand percentage from the 2016 image was added to the strong signal, the percentage stamp sand cover increased to 55% on the northern shallow-water region. However, remember that this calculation is only for half the reef area, the northern half where stamp sands are the most abundant (see Ponar sampling data in Figure 12). If stamp sands are scarce in the brown region, half of 55% will give you only 27% stamp sand cover for the entire reef.

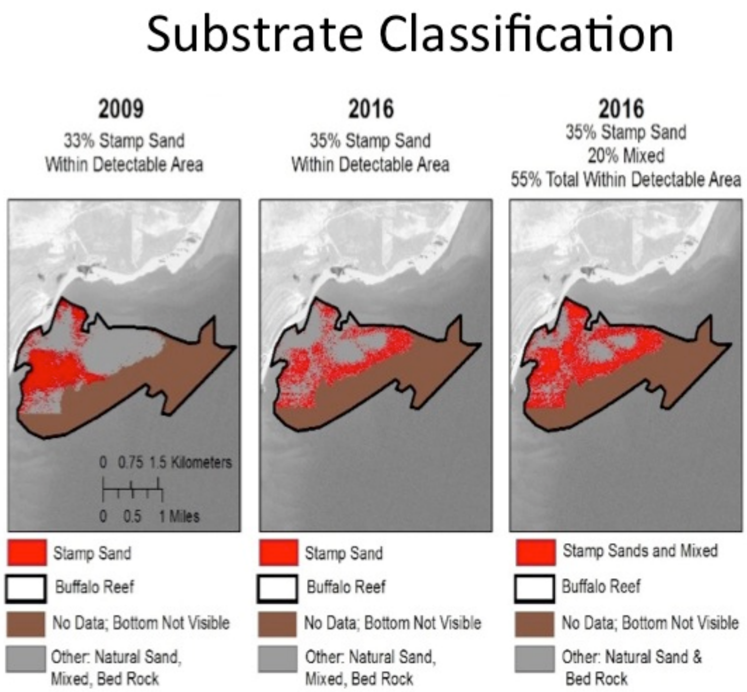


Figure 11. *Final substrate classification results summarized by common mapping area.*

Ponar Stamp Sand Data Comparison to 2016 Classification

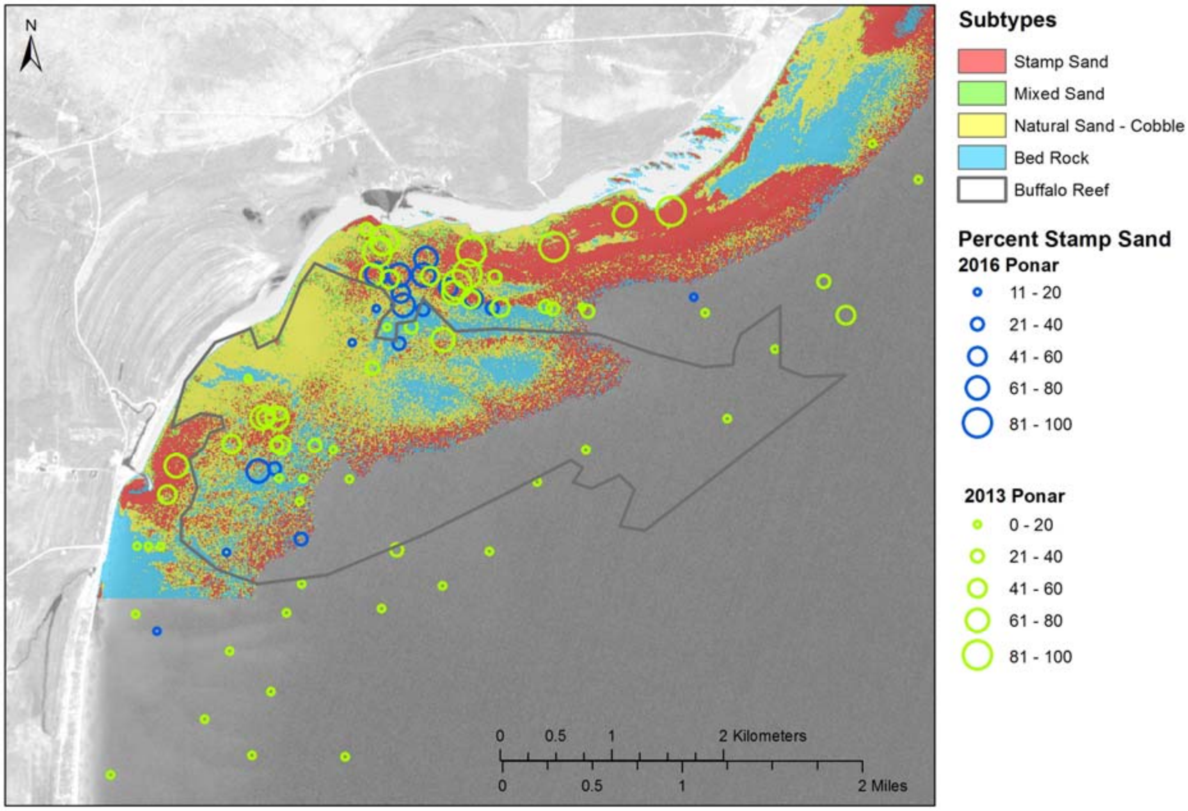


Figure 12. Comparison of observed stamp sand percentage from ponar collections in 2013 and 2016 bottom type classification of stamp sands in traverse bay from corrected and classified Sentinel-2 Imagery collected on May 19, 2016. The image was depth corrected and classified using a modified Lyzenga method on Band 3 (Lyzenga et al., 2006).

2. Using % Stamp Sand Determinations from Ponar Samples to Calculate % Stamp Sand Cover On Buffalo Reef (ca. 35% area covered by >20% stamp sand mixtures).

Going through Ponar samples, we discovered that grains from the basalt stamp sand pile (dark, fragmented) could be easily distinguished from natural sands eroding out of the Jacobsville Sandstone (transparent quartz, rounded). The stamp sands are crushed basalt from the Portage Lake Series, a deposit that runs down the center of the Peninsula, far removed from the Gay location. From 80 stations in the 2013 Ponar survey, we determined the percentage of stamp sand grains in a count of 200-400 grains, then plotted values across the bay. We then contoured the Buffalo Reef region (Figure 13). The pattern that emerges is different from previous depictions in that in sand grain mixtures clearly show highest concentrations near the shoreline stamp sand beaches, especially south of the pile and off the pile to Coal Dock stretch. Concentrations of stamp sand grains in sand mixtures diminish as sites move progressively out into the bay and across Buffalo Reef. Clearly loss of stamp sand percentage is occurring as stamp sands mix with natural sands collecting across Buffalo Reef. Percentages also drop westward along the Coal Dock to Seawall stretch, reaching only 50% in mixtures off the beach. One important calculation from the contour diagram was to determine over Buffalo Reef how much area was covered by regions containing >20% stamp sand. By superimposing the Buffalo Reef boundary over the region, then determining contour areas, we calculated that ca. 35% of Buffalo Reef was covered by regions >20% stamp sand.

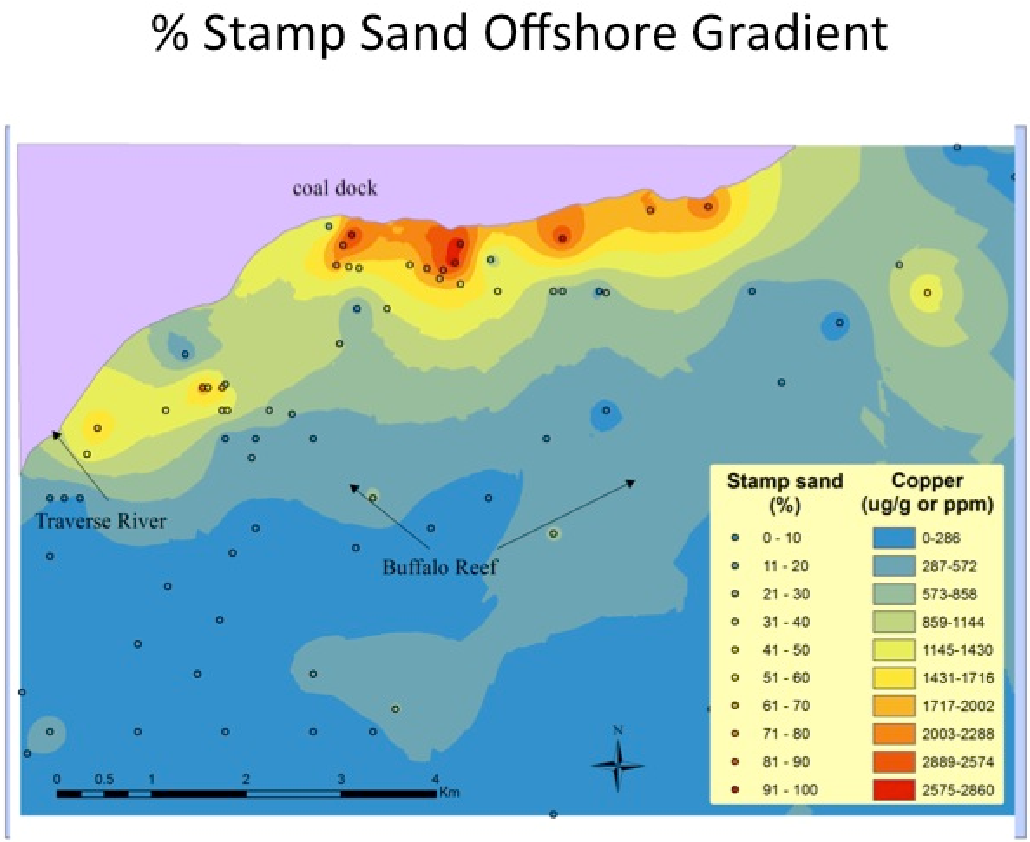


Figure 13. *Contour map of Ponar Stamp Sand percentages. Dots indicate sampling locations (2013 Ponar survey). Grains classified in sand mixtures. Corresponding copper concentrations can be found in insert.*

3. Gay Stamp Sands 2016 Hyperspectral Bottom Feature Mapping

Introduction. The main objective of this study is to assess the utility of airborne hyperspectral imagery to map stamp sand extent and percent cover in Traverse Bay. Expansive deposits of stamp sands are located throughout Traverse Bay, particularly in and around Buffalo Reef. These deposits have varying stamp sand percentages depending on the abundance of natural sands. Multi-spectral airborne and satellite imagery has proven effective in mapping stamp sands extent (Kerfoot et al. 2012); however, there limitations in the ability to map percent stamp sand cover due to the limited number of high bandwidth spectral channels. Hyperspectral imagery has the potential to identify small spectral differences in reflectance between varying stamp sand percent cover mixtures. Hyperspectral imagery collected from the 2016 USACE flights over Traverse Bay was processed and examined to map stand sand extents.

Methods. The 2016 USACE hyperspectral imagery was geo-rectified using processing codes provided by the USACE. Image strips within several flight lines from optically deep water locations were glint corrected using an approach suggested by Hedley et al. 2005. Images that were not close to deep-water locations were not glint corrected.

Examination of the geo-rectified images revealed apparent differences in radiance values for multiple areas overlapped by two image strips, which indicate significantly varying illumination conditions. The varying illumination is a function of solar zenith angle geometry and atmospheric variability. Corrections were applied to normalize multiple overlapping images to each other thus providing comparable radiance values between image strips. Variations in radiance values between overlapping images are also a function of terrain, both in and out of water, as sun angle changes. In order to correct for these variations a “normal” map was generated from the Lidar elevation data. A “normal” map captures the slope and aspect information of a given pixel relative to the light source illuminating the pixel. This map can be used to estimate the reflected radiance of a given surface depending on sun angle, which can be calculated from each image track location and time. Application of these methods produce “normalized” hyperspectral image strips with the time of day effects on the radiance distribution minimized. Figure 14 is an example of the “normal” map generated from the Lidar elevation data set. The figure shows Ponar sample locations with the circles sized by increasing percent cover of stamp sand.

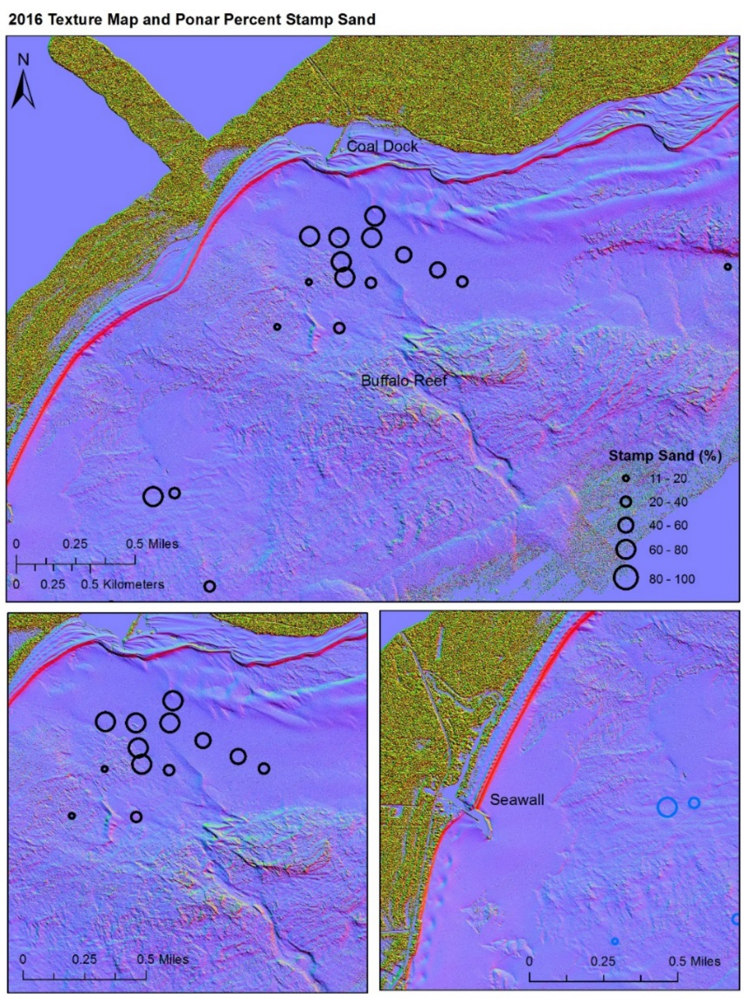


Figure14. *Lidar generated "normal" texture map showing the slope and direction of the bottom terrain. The map is used to correct multispectral images for sun angle differences.*

Two image mosaics are shown in Figure 15 both before (left) and after (right) time of day radiance correction. These corrections allow for better comparison between image strips for visual inspection and analysis. As evident in Figure 15, there is still substantial differences in radiance values of adjacent image strips in the water areas, which are likely due to differing sea surface states between passes.

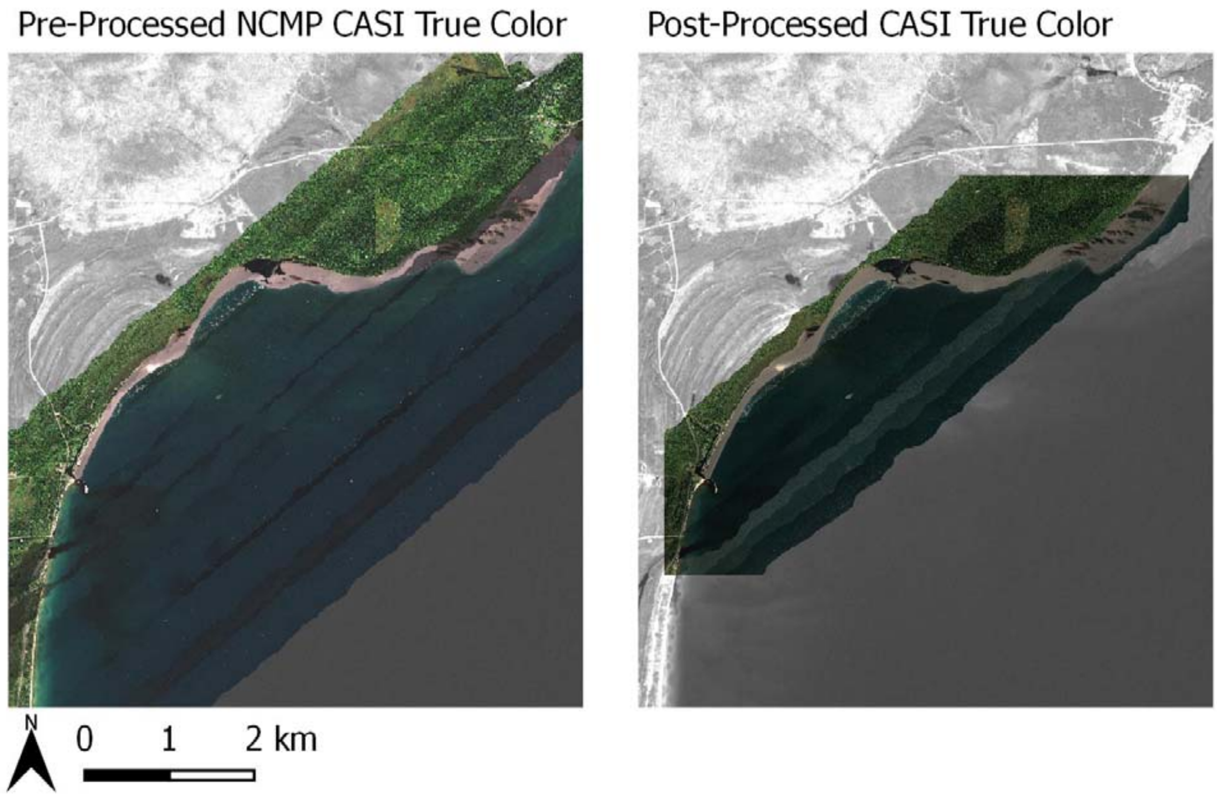


Figure 15*. True color maps before image strip normalization (left panel) and after (right panel). Note the improved continuity in radiance values along the stamp sand pile.*

Results. After the radiances were normalized between strips, spectra of different bottom types that included variable stamp sand percent coverage were compared to assess the mapping feasibility. Figure 16 is a spectral plot of the different bottom cover types. The spectra shown on the figure show clear difference between 0 percent stamp sand and bottoms with some percent stamp sands in the blue/green region (~490 nm), but very little differences between all other stamp sand bottom covers. This indicates the inability of the aircraft imagery to differentiate stamp sand percent coverage.

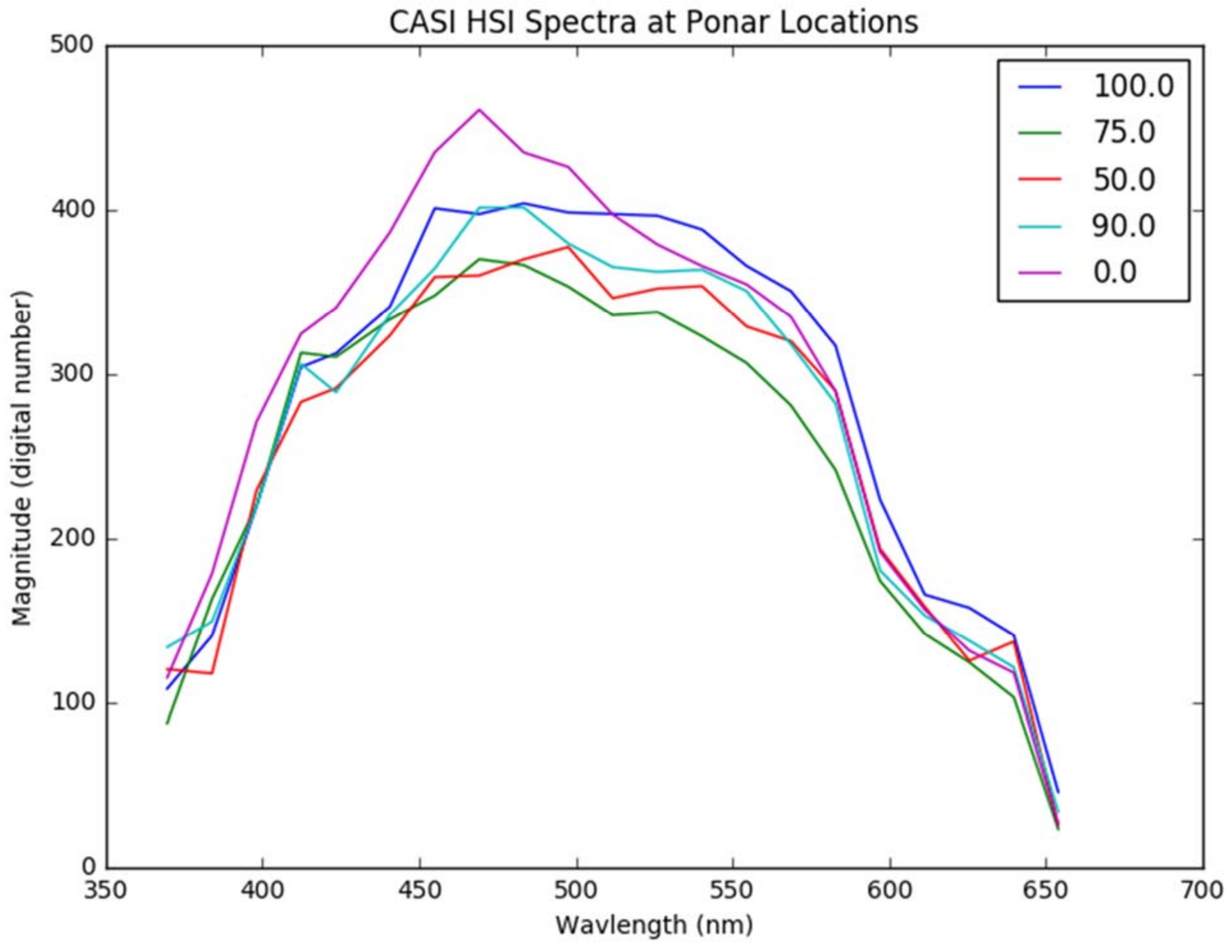


***Figure 16**. Spectral radiance plots from the CASI aircraft imagery for different stamp sand concentrations. Spectra were identified using Ponar stamp sand field data.*

Even with this limitation, it is possible to map areas with some stamp sands cover. Several of the image strips exhibiting the best quality with respect to minimal glint, good lighting conditions, etc… were processed using the depth invariant approach of Lyzenga et al. (1981, 2006) to produce a bottom feature map comparable with those reported in Kerfoot et al. 2012. Figure 17 is a bottom classification map using the aircraft imagery processed using the depth correction technique. Also shown on the figure are the 2009 NAIP and 2016 Sentienl-2 bottom type maps for comparison. Figure 18 is a map showing stamp sand change by comparing the 2009 NAIP and 2016 hyperspectral bottom classifications. Areas shown in red were classified as stamp sands in both 2009 and 2016. Areas in green are stamp sands identified in 2016. Areas in orange are stamp sands present only in 2009. The blue areas represent areas where stamp sands were not identified in 2009 or 2016. The figure highlights areas of good agreement (red) between the 2009 and 2016 images, however, there does appear to be more stamp sand extent toward the northern edge of buffalo reef in 2016. There is also an increasing area of stamp sands near the southern end of the image strip. The table shown on the figure displays the relative percentages of stamp sands extents between 2009 and 2016. Given the difference between stamp sand percent cover in 2009 only and 2016 only (25.45% – 13.25% = 12.2%) it would appear an approximate 12% gain of stamp sand cover occurred in the area represented in this image strip.

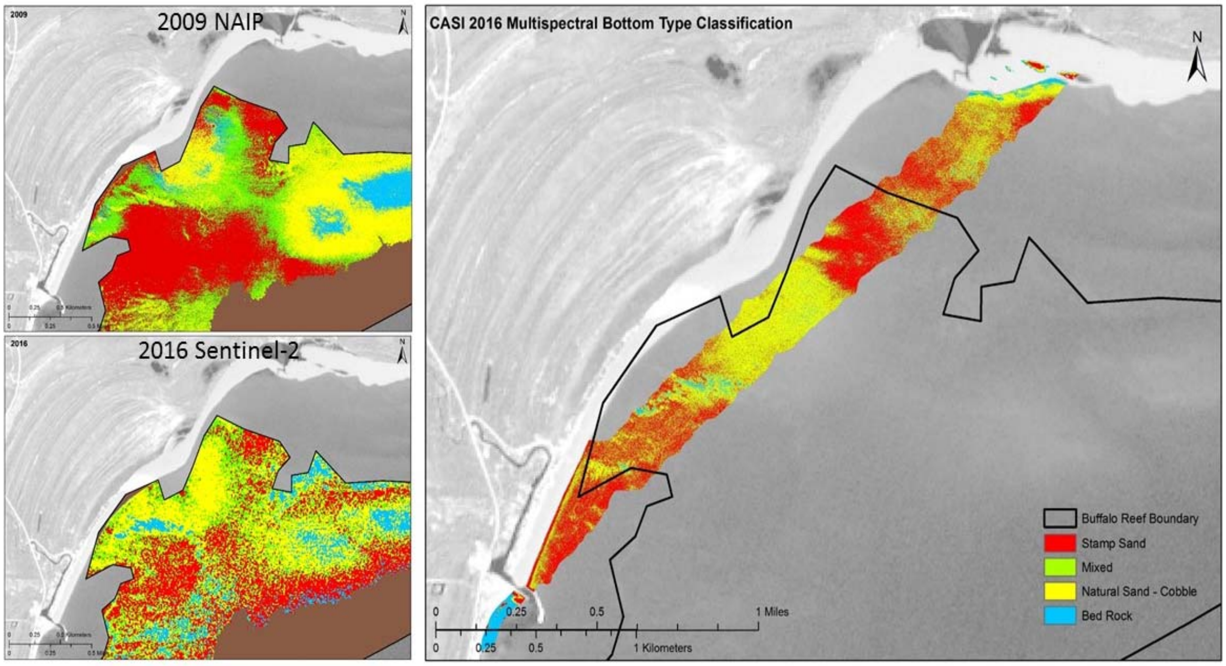


Figure 17. *Airborne CASI bottom type classification (right panel) for a single image strip. The left two panels are the bottom type classifications from the 2009 NAIP (top left) and Sentinel-2 (bottom right). Relatively good agreement exists between the three classifications.*

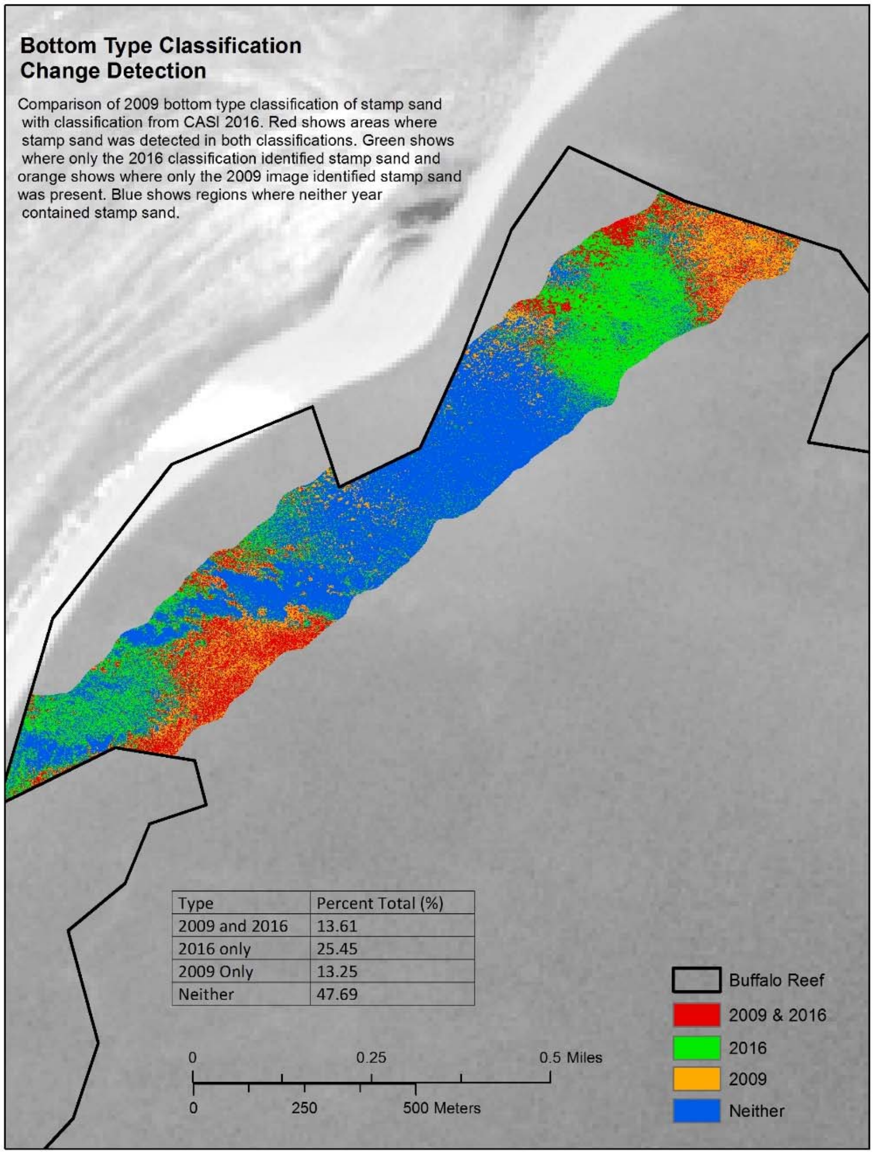


Figure 18. *Stamp sand change map created by comparing the bottom classifications from the 2009 NAIP image and the 2016 USACE hyperspectral classified image. Increasing stamp sand cover is noted (green) in both the northern and southern ends of the image strip.*

Using the aircraft classified bottom type map, a closer examination of the stamp sand migration near the Traverse River Harbor is possible. Figure 19 shows the classified bottom map (right panel) zoomed in to show the Traverse River mouth. Also shown on the figure are photographs labeled by year showing the dramatic increase in stamp sand overtopping of the seawall. The high resolution of the aircraft image confirms the almost 100% stamp sand cover just offshore of the Traverse River indicating the continued likelihood of overtopping to continue at a very high rate in the foreseeable future.

Figure 19. *Airborne CASI image strip classification zoomed in the Traverse River mouth (right panel). The photos on the left of the figure show the overtopping progression from 2009 to 2017. The bottom type classification indicates the presence of significant stamp sands just offshore.*

D. Underwater Erosion & Deposition Estimates

1. Entire Grand (Big) Traverse Bay substrate calculations (2008 to 2016 Lidar difference comparisons).

Introduction & Methods. To determine regional underwater erosion and deposition patterns over the bay, the 2016 Lidar DEM bathymetric surfaces were subtracted from the 2008 Lidar DEM surfaces, giving losses (erosion) and gains (deposition). The 2016 and 2008 grids were recalculated to make pixel calculations comparable. Lidar data from the U.S. Army Corps were reprojected into NAD 1983 UTM Zone 16N in ArcGIS. The 2016 layer was resampled to the resolution of the 2008 layer (from 0.838 x 0.838 m to 0.54 x 0.54 m). The raster calculator was used to compute the difference between the 2008 and 2016 layers. The difference raster was multiplied by the area of a pixel to obtain a volume layer and the zonal statistics tool was used to compute the volume total within the area. The absolute amount of loss or gain was calibrated on a scale of -3 to +2 meters and color-coded from red (erosion) to blue (deposition). The movement of underwater bars, originating from the Gay tailings pile source and moving off stamp sand beach redeposition dominate the erosion and deposition dynamics. Changes are pronounced where the bars move over the escarpment into the ancient river bed ("trough") and where they migrate over Jacobsville Sandstone bedrock south of the pile and pile to Coal Dock region. In Figure 20, the boundaries of Buffalo Reef (black outline) are superimposed over the coastal underwater shelf region and the shoreline stamp sand beach region is outlined in purple. With this large-scale and other more restricted difference calculations, there must be consideration of Lidar resolution in the vertical dimension, an accuracy of 0.185 m for the 2016 Lidar and 0.25 m for the 2008 Lidar propagates to a total error of 0.31 m in difference calculations. Thus caution should be used in interpreting differences between +0.31 and -0.31 m. An insert enlarges the western region off the edge of the "trough". Underwater migrating bars in this region are dumping into the "trough", shown by sonar images elsewhere in Kerfoot et al. (2014). The migrating underwater stamp sand bars to the east seem to be moving southward across the Jacobsville Sandstone bedrock to eventually intersect the lower reaches of the "trough" or to move over the edge of the coastal shelf into deeper waters.

The newly proposed dredging area, outlined in green, is 9 hectares (Ha= 10,000 m^2, 9 Ha = 90,000 m^2). Given an estimated 0.35 m/yr deposition (see below) in the trough x 90,000 m^2 area, gives 31,500 m^3 deposition. Converting volume into mass (1.65 tonnes/m^3) yields a net deposition of 0.05 Tg (51,973 tonnes) of stamp sands between 2008 and 2016. If a stamp sand depth of 1m deeper than current surface levels is assumed, then there are approximately an additional 0.15 Tg of stamp sands, for a 0.20 Tg total in the proposed dredging area.

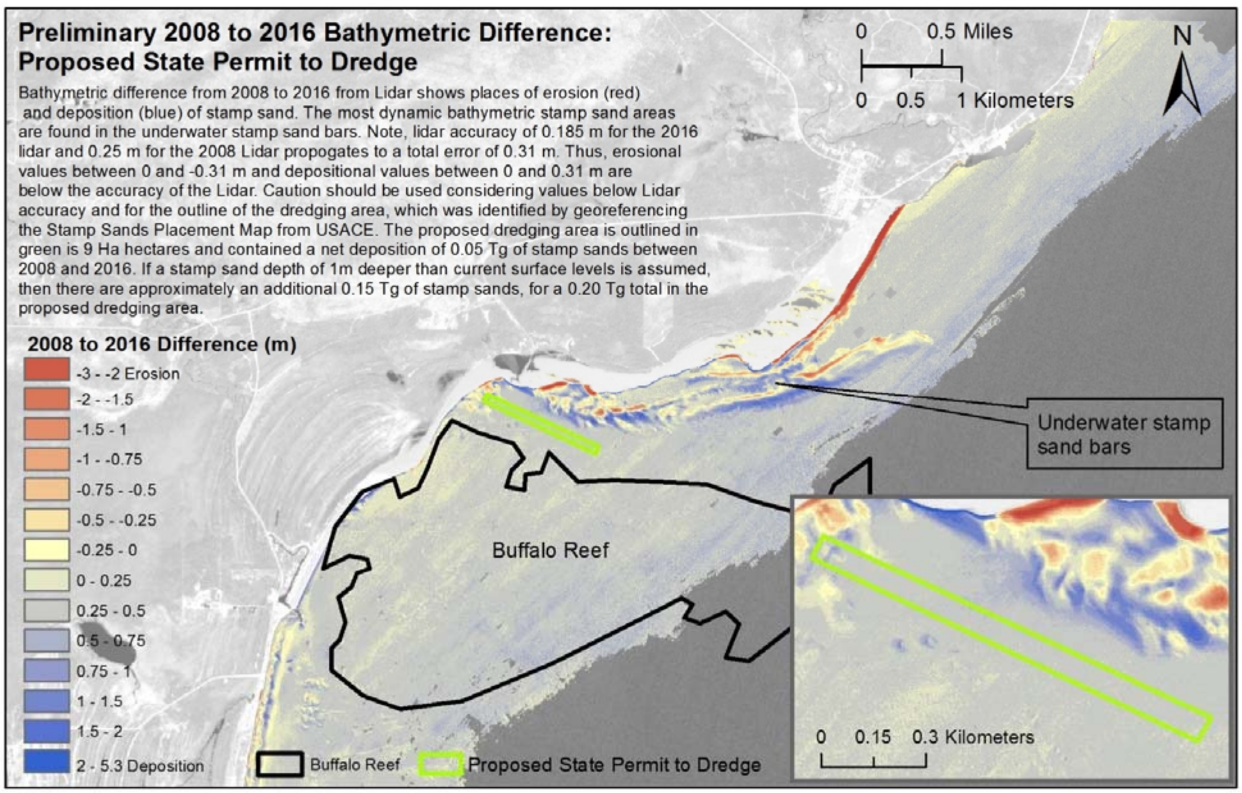


***Figure 20**. Bathymetric difference from 2008 to 2016 from Lidar shows places of erosion (red) and deposition (blue) of stamp sand.*

2. Trough Deposition Volume Estimates from Lidar Elevation Data: Proposed Dredging Polygon.

This study addresses the encroachment of stamp sands towards Buffalo Reef in recent years. Lidar data from 2008, 2013, and 2016 were used to trace the migration of stamp sands as well as to quantify the amount of stamp sands deposited and the annual rate of deposition in a potential dredging area north of the reef, further referred to as the "dredging area" (Figure 21).

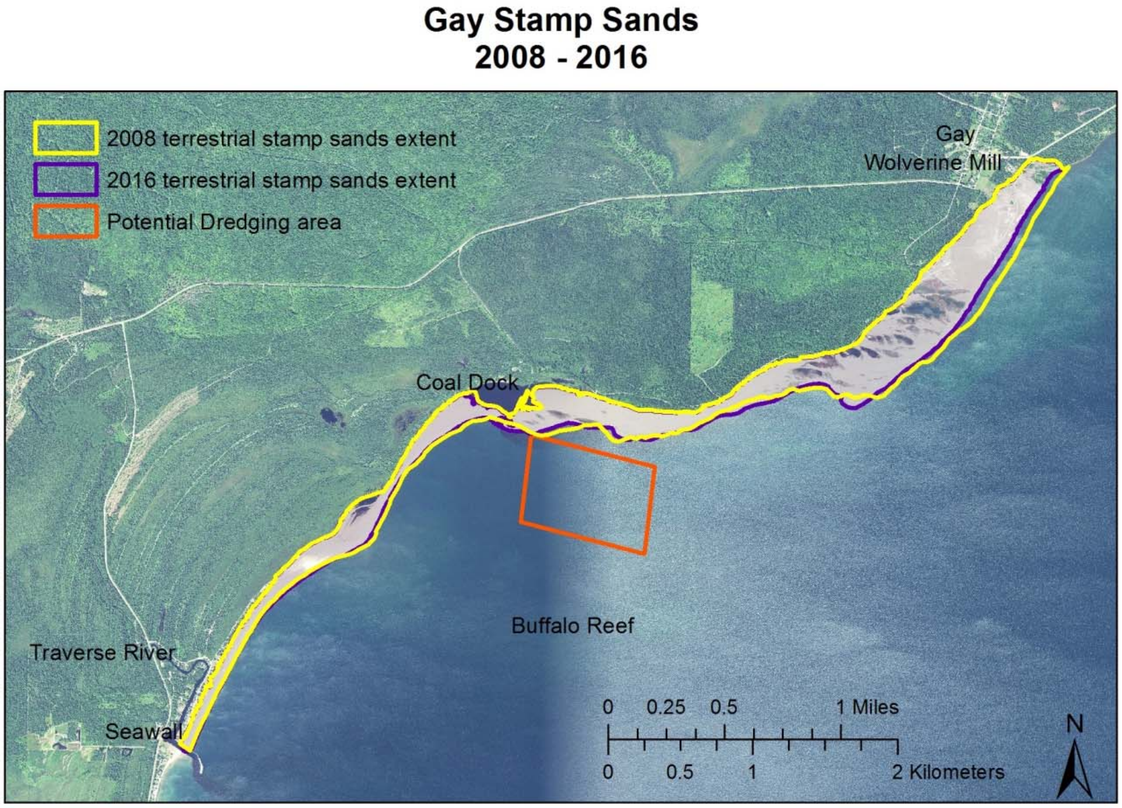


Figure 21. *Shoreline stamp sand extend from 2008 to 2016 overlayed on 2016 NAIP imagery.*

Methods. To assess the migration of stamp sands in recent years, the volume of stamp sand deposition was computed from 2013 to 2016, 2008 to 2013, and 2008 to 2016. For the 2013 to 2016 change detection, Lidar data from the U.S. Army Corp were reprojected into NAD 1983 UTM Zone 16N in ArcGIS. The 2016 layer was resampled to the resolution of the 2013 layer (from 0.838x0.838 m to 0.54x0.54 m). The raster calculator was used to compute the difference between the 2013 and 2016 layers. The difference raster was multiplied by the area of a pixel to obtain a volume layer and the zonal statistics tool was used to compute the volume total within the dredging area. The polygon used to define the dredging area was 529,541 m^2. To separate the highly dynamic region within the previously defined dredging area polygon from the more stable trough area, the dredging area polygon was divided into two regions defined as the “trough” and the dynamic “bars” regions. The separation was determined qualitatively based on the 2016 Lidar to separate areas of smooth from fluctuating bathymetry. The area of the trough is approximately 2/3 of the pre-defined dredging area, 361,319 m^2. Net deposition of stamp sands was also calculated for areas in the trough and dynamic bars area.

The same methods outlined above were followed for change detection from 2008 to 2016 and 2008 to 2013. For 2008 to 2016, the 2008 layer was resampled to the grid size of the 2016 Lidar (from 2x2 m to 0.838x0.838 m) and for 2008 to 2013, the 2008 layer was resampled to the 2013 layer grid size (from 2x2 m to 0.54x0.54 m). While the 2013 and 2016 layers were both collected with the same sensor and contained the same vertical datum, the 2008 Lidar was downloaded from NOAA Digital Coast in NAVD88 instead of IGLD85. The difference in vertical datum s was small relative to the 18.5 cm accuracy of the Lidar because accuracy in datum conversion is typically within 10 cm[1]. A summary of Lidar accuracy is provided in Table 5.

__Table 5__. Lidar collection years available and respective accuracy.

Lidar Year	Vertical Accuracy (m)	X-Y Accuracy (m)	Sensor
2016	0.185	3.5 *	CZMIL[2]
2013	0.185	3.5*	CZMIL[2]
2008	0.25	0.75	Hawk Eye Mark II Lidar

*2013 and 2016 Lidar X-Y accuracy is reported by Optech as a function of depth, d, where accuracy = 3.5 + 0.05 x d

Since the Lidar vertical bathymetric measurement accuracy was nominally 18.5 cm, an additional analysis was conducted to remove any deposition or erosion values below or equal to 18.5 cm. NOAA tide gauges measure water level to 0.1 ft resolution, however water depth is factored into the vertical datum.

Results. Change detection analysis from 2013 to 2016, 2008 to 2016 and 2008 to 2013 showed net deposition of stamp sands within the proposed dredging area (Table 6). From 2013 to 2016, the annual deposition rate, 12,905 m^3/yr, was approximately half of the rate for 2008 to 2016 (24,196 m^3/yr) for the entire dredging area (Figures 22 and 23). During the recent period of change from 2013 to 2016 the dynamic migrating underwater bars had a greater percentage of total deposition than the trough section, unlike for the longer time-series from 2008 to 2016 (Figure 23). However, the annual deposition rate of stamp sands is lower for more recent years from 2013 to 2016 than for 2008 to 2013 (Figure 24). The declining rate of stamp sand deposition in recent years may indicate deposition as a function of severity of ice cover. Higher ice coverage in 2014 and 2015 suppresses wave action, which may result in less transport of stamp sands from bars into the trough region.

Removal of the deposition and erosion below the Lidar reported accuracy shows that the majority of the trough area for the 2013 to 2016 analysis is less than 18.5 cm and the longer time-series contains greater transport of stamp sands beyond the inherent uncertainties in vertical accuracy of the Lidar. For the 2013 to 2016 analysis, the net deposition calculation changed from 63,879 to 29,164 metric tonnes of stamp sands when excluding values lower than 18.5 cm in calculations (Table 7; Figure 25). Since 2013 to 2016 only spans three years, the lack of deposition greater than 18.5 cm is consistent with what we would expect, especially during a period of high ice coverage. For the 2008 to 2016 change detection, much of the deposition of stamp sands in the trough area was greater than 18.5 cm deposition and thus included in the analysis giving a total of 317,154 metric tonnes of stamp sands deposited within the total proposed dredging area.

Table 6. *Preliminary summary of change in stamp sand deposition.*

Years	Value	Trough	Dynamic Bars	Total Dredging Polygon
2013 to 2016	Net Deposition Volume (m^3)	13,158	25,557	38,714
	Net Deposition Volume (metric tonnes)	21,710	42,169	63,879
	Percent Total (%)	34	66	--
	Annual Deposition Rate (m^3/yr)	4,386	8,519	12,905
	Average Deposition depth (cm)	4	15	7
2008 to 2016	Net Deposition Volume (m^3)	127,176	66,391	193,566
	Net Deposition Volume (metric tonnes)	209,840	109,545	319,385
	Percent Total (%)	66	34	--
	Annual Deposition Rate (m^3/yr)	15,897	8,299	24,196
	Average Deposition depth (cm)	35	39	37
2008 to 2013	Net Deposition Volume (m^3)	112,714	40,004	152,718
	Net Deposition Volume (metric tonnes)	185,979	66,006	251,985
	Percent Total (%)	74	26	--
	Annual Deposition Rate (m^3/yr)	22,543	8,001	30,544
	Average Deposition depth (cm)	31	24	29

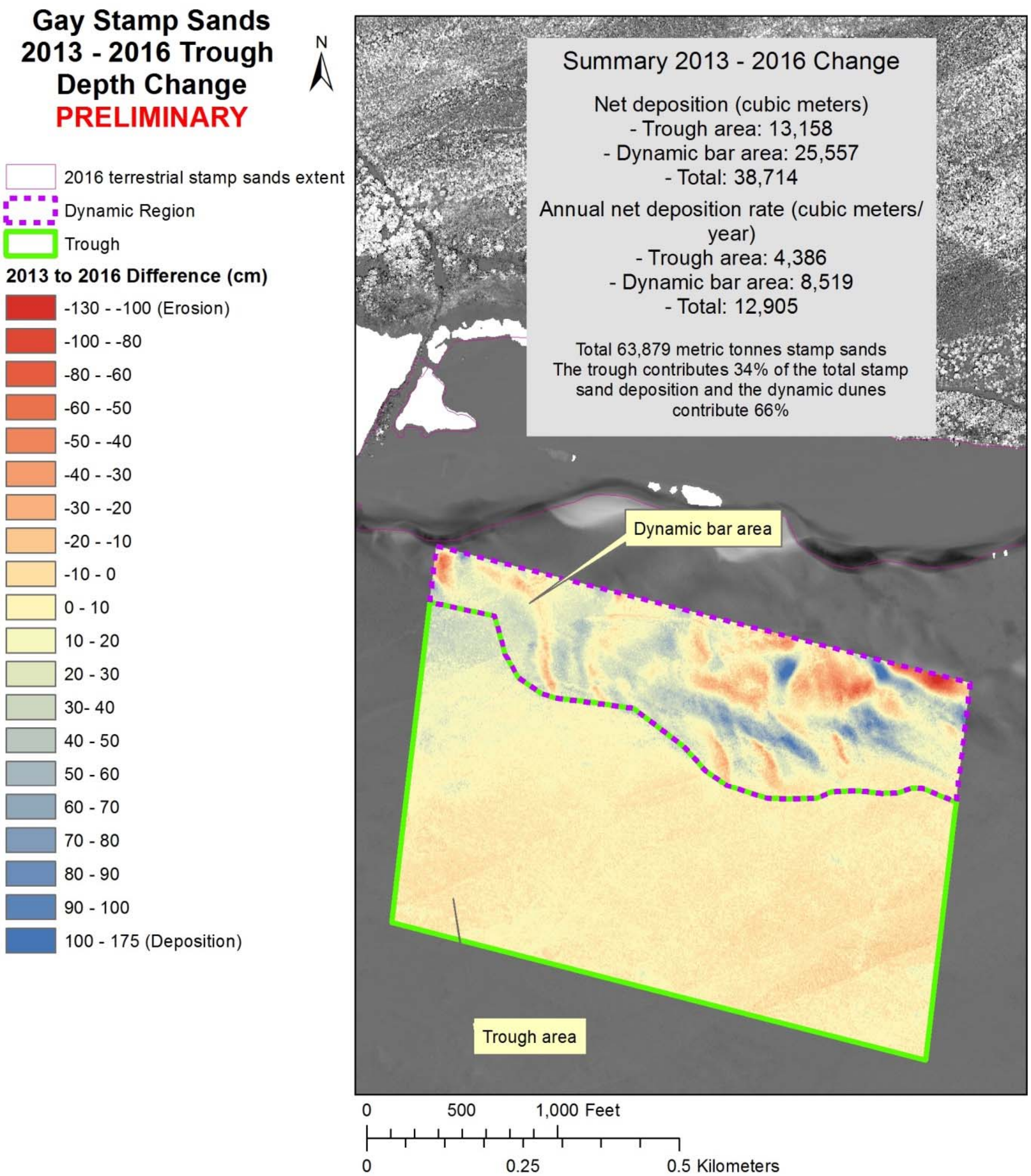


Figure 22*. Difference in bathymetry between 2013 and 2016. Negative values indicate erosion of stamp sands and positive represent depositional areas.*

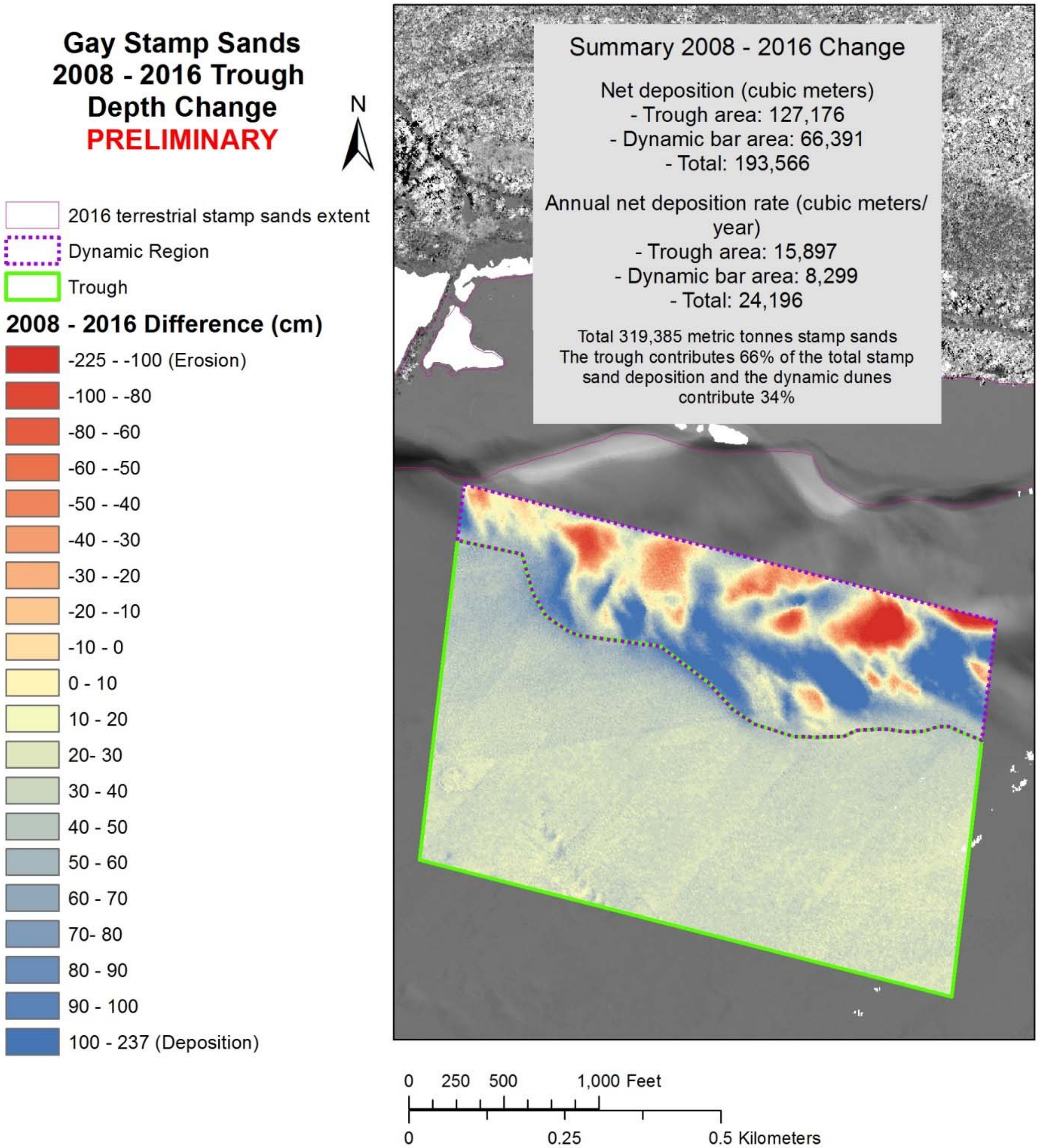


Figure 23. *Difference in bathymetry between 2008 and 2016. Negative values indicate erosion of stamp sands and positive represent depositional areas.*

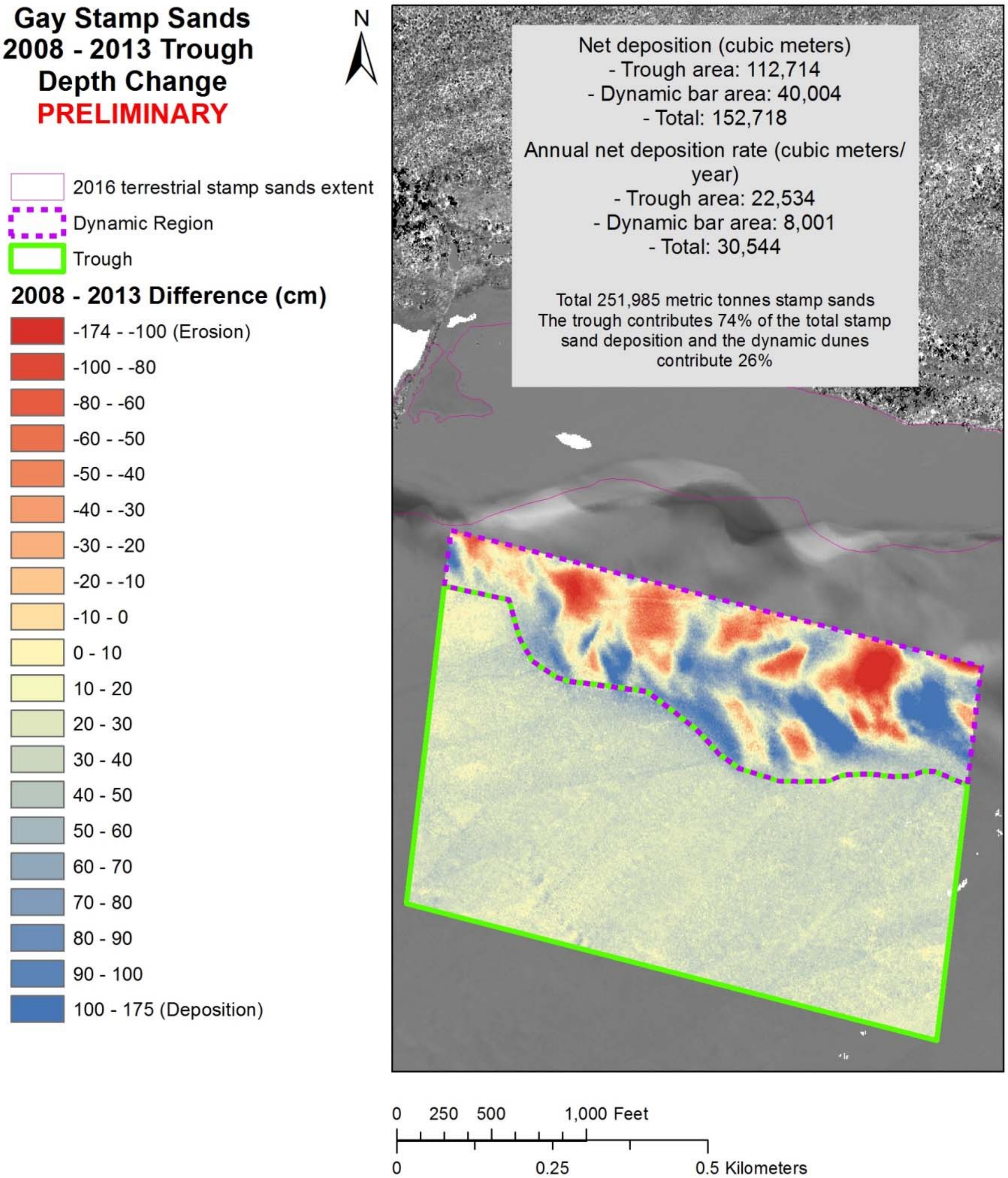


Figure 24. *Difference in bathymetry between 2008 and 2013. Negative values indicate erosion of stamp sands and positive represent depositional areas.*

Table 7. *Preliminary summary of uncertainty due to 18.5 cm Lidar accuracy in change detection of stamp sand deposition for total dredging area.*

Years	Value	Total Dredging Area	
		All Data	Exclusion *
2013 to 2016	Net Deposition Volume (m^3)	38,714	27,972
	Net Deposition Volume (metric tonnes)	63,879	46,155
	Annual Deposition Rate (m^3/yr)	12,905	9,324
	Average Deposition depth (cm)	7	5
2008 to 2016	Net Deposition Volume (m^3)	193,566	192,215
	Net Deposition Volume (metric tonnes)	319,385	317,154
	Annual Deposition Rate (m^3/yr)	24,196	24,027
	Average Deposition depth (cm)	37	36
2008 to 2013	Net Deposition Volume (m^3)	152,718	149,416
	Net Deposition Volume (metric tonnes)	251,985	246,537
	Annual Deposition Rate (m^3/yr)	30,544	29,883
	Average Deposition depth (cm)	29	28

* Uncertainties were values of erosion and deposition within 0 and 18.5 cm, thus values between -18.5 and 18.5 cm.

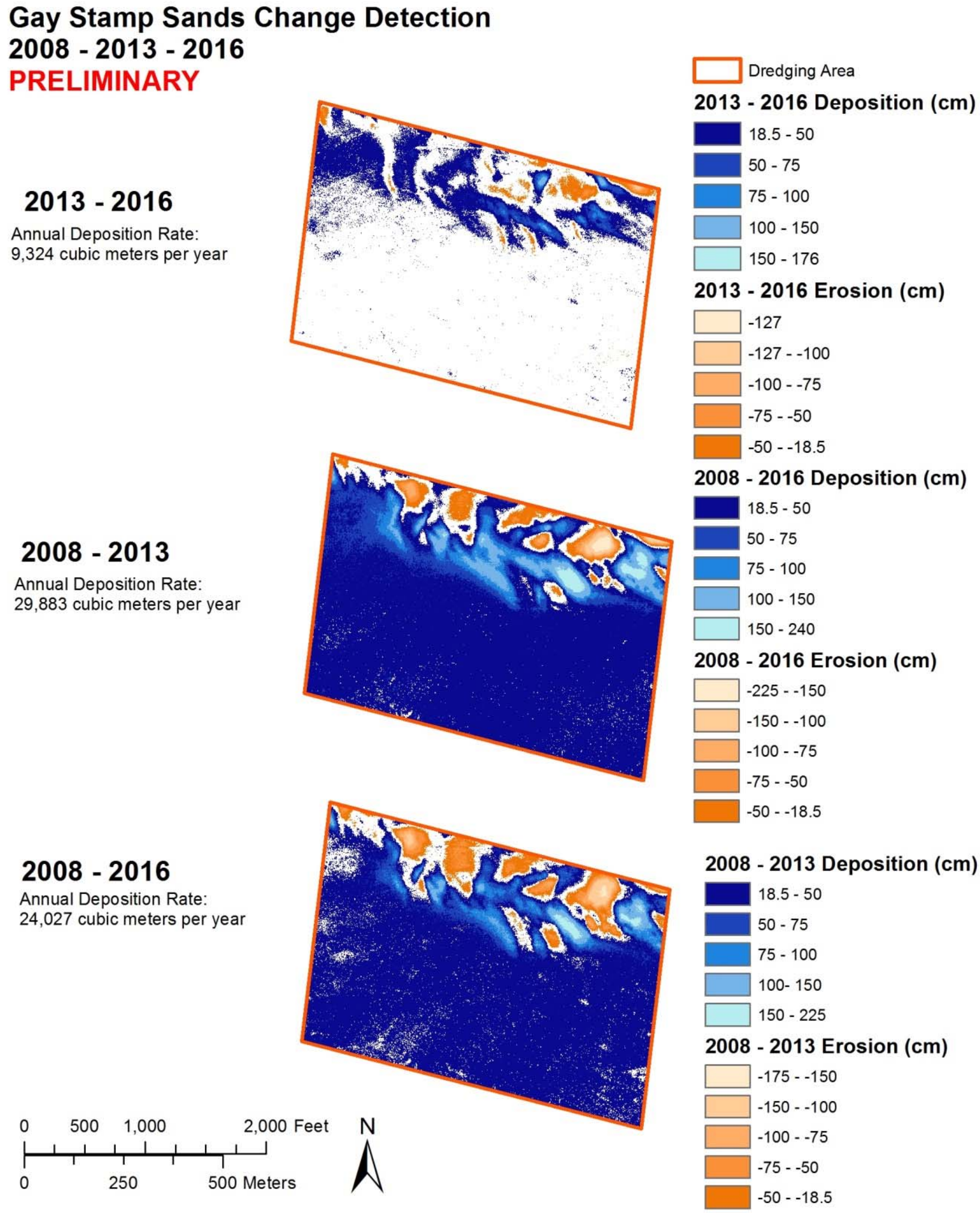


Figure 25. *Change detection of stamp sand erosion and deposition within the potential dredging from 2013 to 2016, 2008 to 2013, and 2008 to 2016 filtered based on the accuracy of the Lidar. Blue shows deposition and orange shows erosion of stamp sands. The white areas are values within the accuracy of the Lidar, -0.185 to 0.185m, and thus exclude from calculations of net deposition and annual deposition rates.*

E. Benthic Invertebrate Diversity Influenced by % Stamp Sand.

In additional, although very impressive on a large scale, the Lidar/MSS/Iver images do not capture what is happening during encroachment, i.e. biotic impacts on diatoms (rock surfaces, sediments), benthic invertebrates, and juvenile fish. Additional information on those components, vital to calculating primary and secondary production impacts, is key to understanding the nature of environmental perturbations from stamp sands. To gain some preliminary insight into these environmental impacts, in 2013 ERDC and MTU jointly sampled sediments across Grand (Big) Traverse Bay (Figures 13 and 26) to aid transport modeling, determine stamp sand percentages, and to look at associated impacts on benthic invertebrate communities. Eighty of the Ponar samples were examined for benthic invertebrates and corresponding determinations of stamp sand percentages.

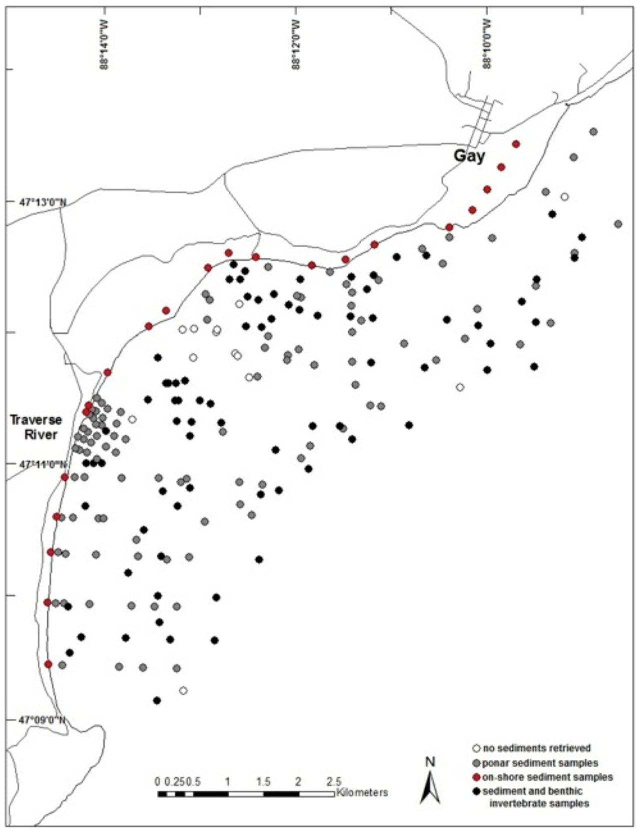


Figure 26. *Ponar sediment sampling stations in Big Traverse Bay 2013. Black circles mark 80 with benthic community characterization.*

Potential environmental impacts of stamp sands in Grand Traverse Bay are expected to be high. Previous knowledge is available on the elemental composition and toxicity of stamp sands. In stamp sands, copper (Cu) occurs at toxic levels for aquatic systems and there is a secondary suite of metals (Ag, As, Cd, Co, Cr, Hg, Mn, Ni, Pb, Zn) that often flag aquatic protection levels (Malueg et al. 1984; U.S. EPA Baseline Study Report 2001; MDEQ 2006; Kerfoot et al. 2009). Stamp sand concentrations of Cu are high and slime clay fractions (<1 μm) tend to be enriched in metals (Cu 2.8X, Zn 3.4X, As 1.3X) above coarse fractions, due to higher surface:volume ratios plus an absorbing rime of Fe and Mg (Kerfoot and Robbins 1999).

Stamp sands from Gay have been characterized by several methods (Neutron Activation and ICP Mass Spectrometry, Kerfoot and Robbins 1999, Kerfoot et al. 2009; AA Jeong et al. 1999; ICP

Mass Spectrometry, MDEQ 2006). Early studies of Cu concentrations in Gay coarse stamp sand found values ranging between 1620-5486 µg g^{-1} (mean 2697µg g^{-1}, *n*=7; Kerfoot et al. 2002, 2009), whereas more recent sampling studies by MDEQ on the Gay tailings pile found Cu

concentrations 1500-13000 µg g^{-1} (mean 2863 µg g^{-1}; *n*=274) and only slightly lower, 710-5300 µg g^{-1} (mean=1443 µg g^{-1}; *n*=24) for the southern redeposited beach sands (MDEQ 2006). Metals in the secondary suite at the main Gay pile averaged concentrations of: Ag 0.4-7.7 µg g^{-1} (mean 1.8), As 1.0- 15.5 µg g^{-1} (mean 1.5), Cr 18-52 µg g^{-1} (mean 28.8), Co 16-36 µg g^{-1} (mean 22.9), Hg 0.06-0.11 µg g^{-1} (mean 0.027), Ni 20-48 µg g^{-1} (mean 31), Pb 5.1-6.1 µg g^{-1} (mean 2.6), and Zn 48-120 µg g^{-1} (mean 74.7; MDEQ 2006). Of the metals, copper is the primary toxic compound in tailings, greatly exceeding the consensus-based Great Lakes sediment PEC of 149 ppm (MacDonald et al., 2000; Malueg et al. 1984; West et al. 1993).

Based on % stamp sand composition from the eighty 2013 Ponar samples, expected sediment Cu concentrations in the vicinity of the Gay pile to the Coal Dock Pond region are very high (Figure 27). Copper concentrations diminish into the deeper shelf regions. Recall that Michigan Probable Effects Levels are 149 ug g^{-1} (MacDonald et al. 2000). The calculated concentrations suggest severe effects on benthic organisms (periphyton, invertebrates, larval fish) along the shoreline region when % stamp sand exceeds 20%. Beyond 26% stamp sand, the data below underscore the peril to Buffalo Reef if the high concentration sediments around the Coal Dock Region transgress into boulder fields. However, these indirect calculations need to be verified with direct analyses of copper concentrations.

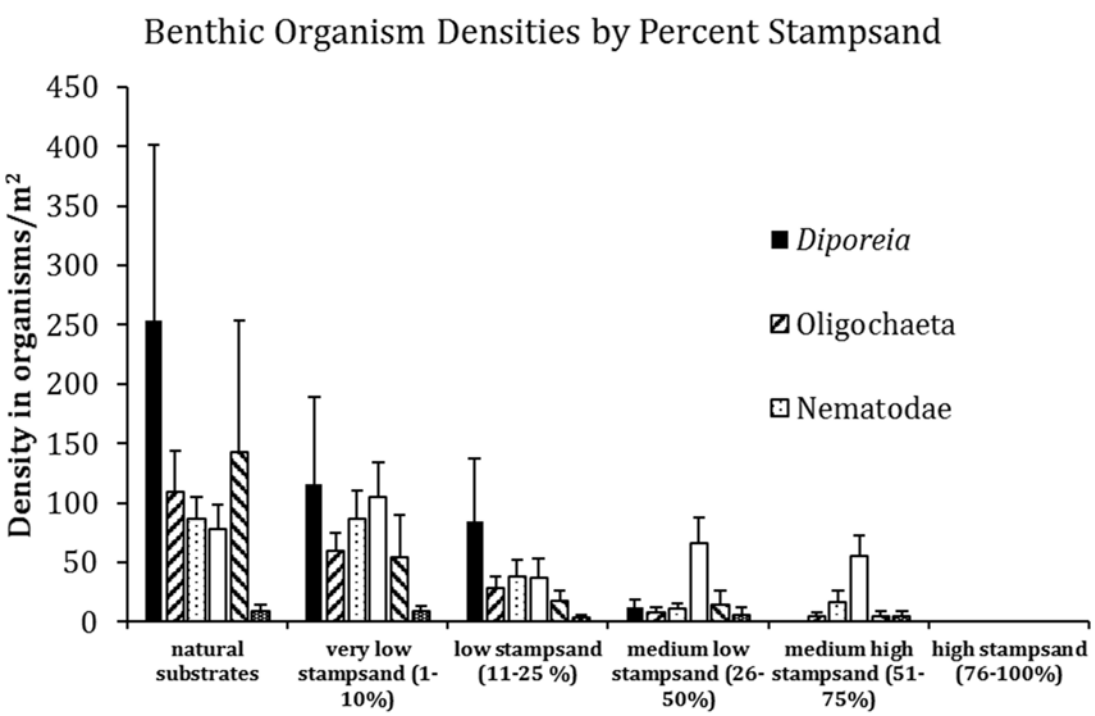


Figure 27. *Ponar samples document major decrease in benthic organism density associated with an increase in stamp sand percentage. The bars give a mean density with 95% C.L.; individual taxa are listed above. B) Percent stamp sand in bottom sediments versus taxonomic richness of the benthic community. Polynomial regression fit (2nd order) with R^2 value. Site locations in Figure 26.*

In Figs. 26-27, benthic sediment samples were collected with a PONAR grab sampler (area= 0.052 m^2) deployed from the Michigan Tech *R/V Agassiz* and the USGS *R/V Sturgeon* in the summer of 2013. The samples were collected in duplicate for each station: one grab sample was bagged in labeled zip lock bags and retained for sediment characterization, whereas the other was used for benthic invertebrate sampling by washing it in a sediment elutriator and filtering it through a 350 µm mesh. Benthic organisms were preserved in 10% formalin sucrose and kept in cold storage until analyzed. Taxa were identified and enumerated under a dissecting microscope using identification keys by Pennak (1989), and Thorpe and Covich (2001). Sediment samples were analyzed for material composition (stamp sands vs. natural sands component) by visually separating the dark basalt fragments (stamp sands) from the translucent yellow- white quartz sand grains (natural sands) under a dissecting microscope, and counting the number of each in at least 3 subsamples per sediment sample. The ratio of the two categories was used to estimate the percentage of the substrate consisting of stamp sand, at each station (see Fig. 13).

2012-2013 ROV images verified concerns about two separate processes: 1) wave and current-driven drift and deposition of stamp sands into cobble fields, filling up crevices and "drowning" the boulder field in a sea of stamp sand, and 2) toxic effects of copper upon benthic organisms, including periphyton (diatoms and bacteria), invertebrates and fishes (Kerfoot et al. 2014). Counts of invertebrates in Ponar samples showed severe effects at higher concentrations of stamp sands (Figure 27).

Direct effects would include copper impacts on benthic algae, benthic invertebrates and fish. Indirect effects are physical, e.g. stamp sands filling in crevices in boulder fields, reducing breeding options and reducing breeding area. Using beach seine techniques, Bill Mattes (GLIFWC) has documented abundant lake whitefish fry along the southern white sandy beach stretch, but none along the comparable stamp sand beaches. We suggest that whitefish (and most other species) are absent along black stamp sand beaches because copper kills benthic organisms (algae and invertebrates) directly, eliminating the food for invertebrates and the invertebrate forage for fishes. Fish would avoid large stamp sand regions because there is no food. Alternatively, fish may sense elevated copper concentrations directly and avoid regions with high toxic values. Initially living periphyton coated boulders and cobbles on the reef, and sloughed off onto sediments between rocks, enhancing food for invertebrate fauna. In addition to Buffalo Reef, the western portions of Grand (Big) Traverse Bay off the white beach seem an important "rearing ground" for lake whitefish. A 23% decline in lake whitefish catch in Keweenaw Bay, recently reported by GLIFWC, could be an early indicator of effects, since this species spawns in the shallow boulder fields now being affected by stamp sands.

F. Coal Dock Images and Maps.

As part of the project, we obtained photos of the Coal Dock from MTU Archives in addition to finding a 1920 bathymetry map. The early photo of the "Gay Dock" shows where the rails ran onto the dock, plus a lot of fishing boats. The 1920 bathymetry map shows a clear image of the Coal Dock, decommissioned at this time because of accumulating stamp sand. The water depths in the 1920 map are in feet. The length of the primary Coal Dock as marked on the 1920 map is around 374m long. The crib-work captured on the additional image appears added onto the extreme end of the regular dock. Kerfoot recalls seeing the crib-work extending out into the bay from the shoreline in 1989 (Kerfoot, personal communication). This shoreline is extremely active with erosion and deposition (see last section). Today (Figure 30) there is an appreciable amount of stamp sands deposited over the end of the Coal Dock. A small unnamed stream with humic-stained water discharges into the Coal Dock Pond and overflows in spring, cutting a narrow channel. In summer the channel dries up, and should permit truck traffic around the Coal Dock.

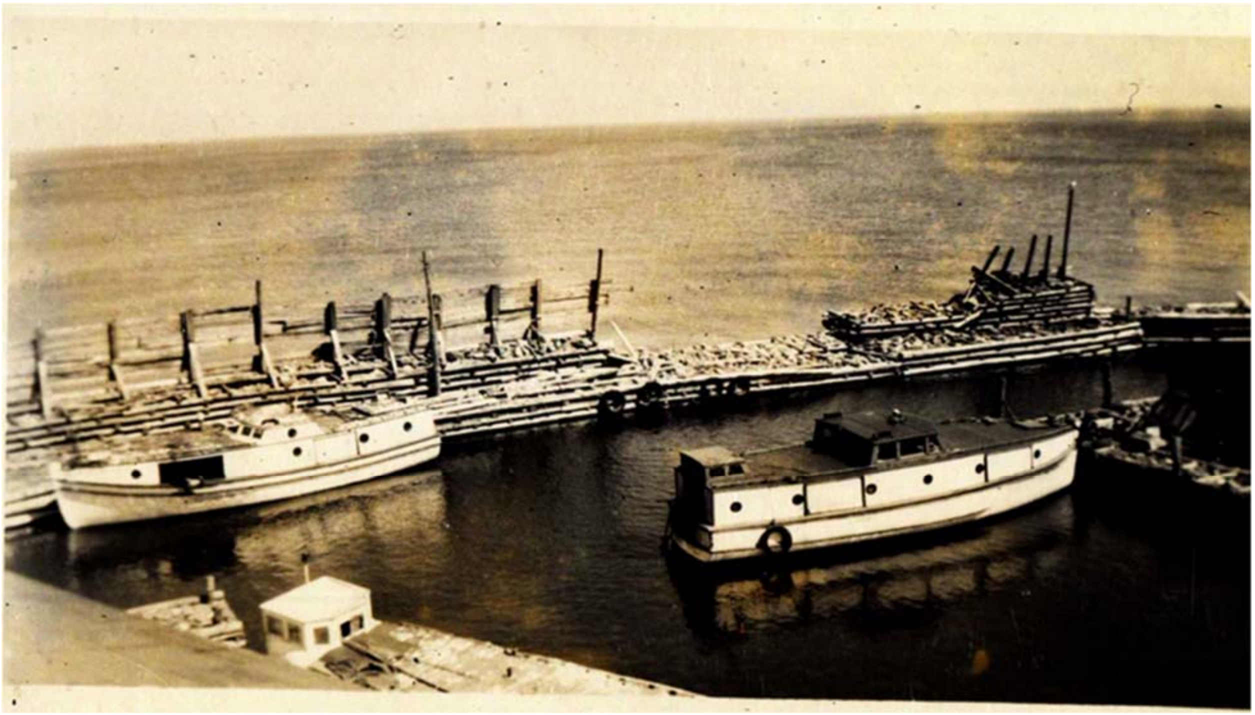


***Figure 28**: Photograph of "Gay Coal Dock" from MTU archives (date not given). Notice rail lines running onto the dock from the shore end.*

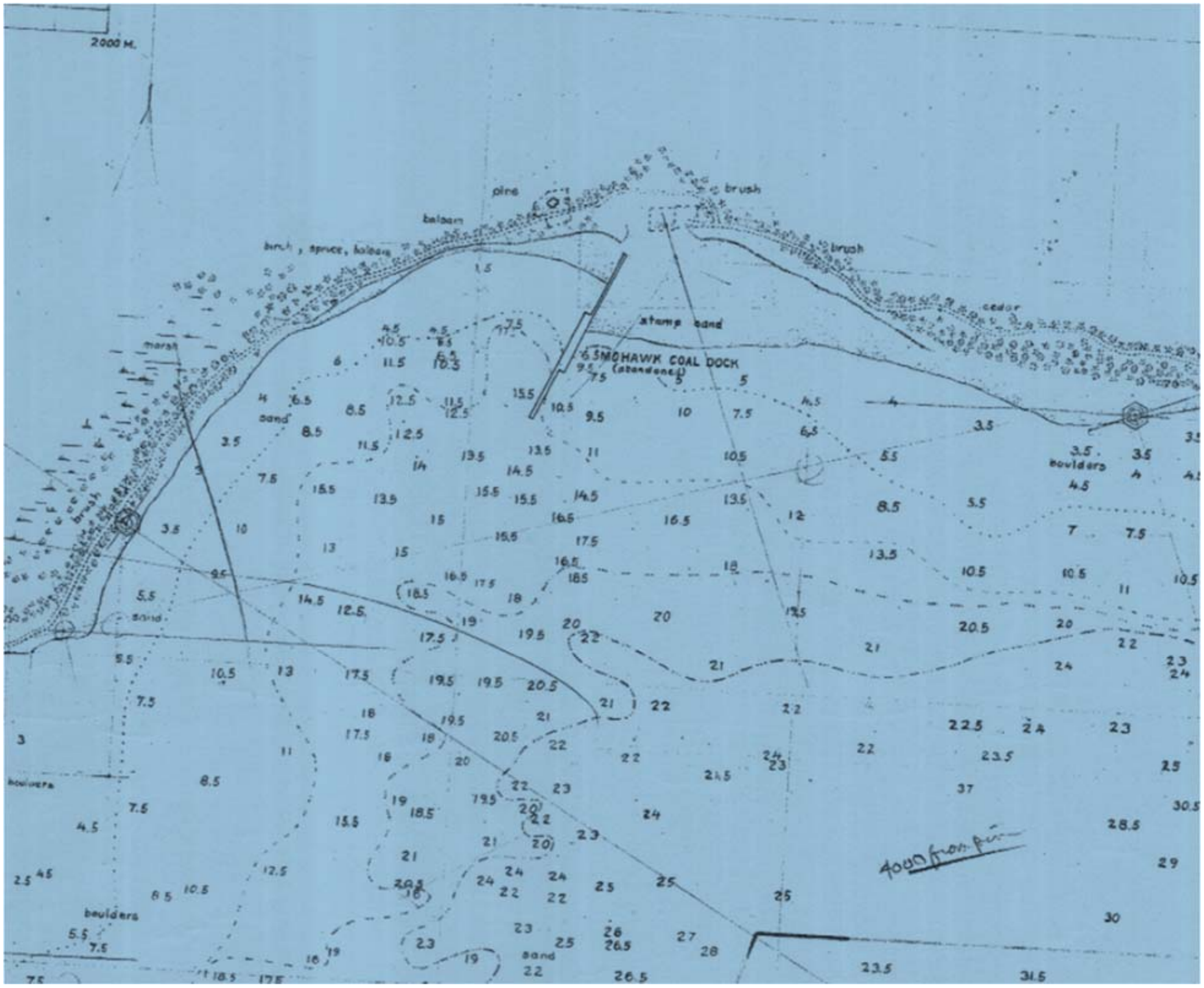


Figure 29: *Bathymetric map (1920) of Grand (Big) Traverse Bay, showing Coal Dock region. Depth in feet.*

Figure 30: *2016 NAIP Image of Coal Dock Pond. Note humic waters discharging into the bay.*

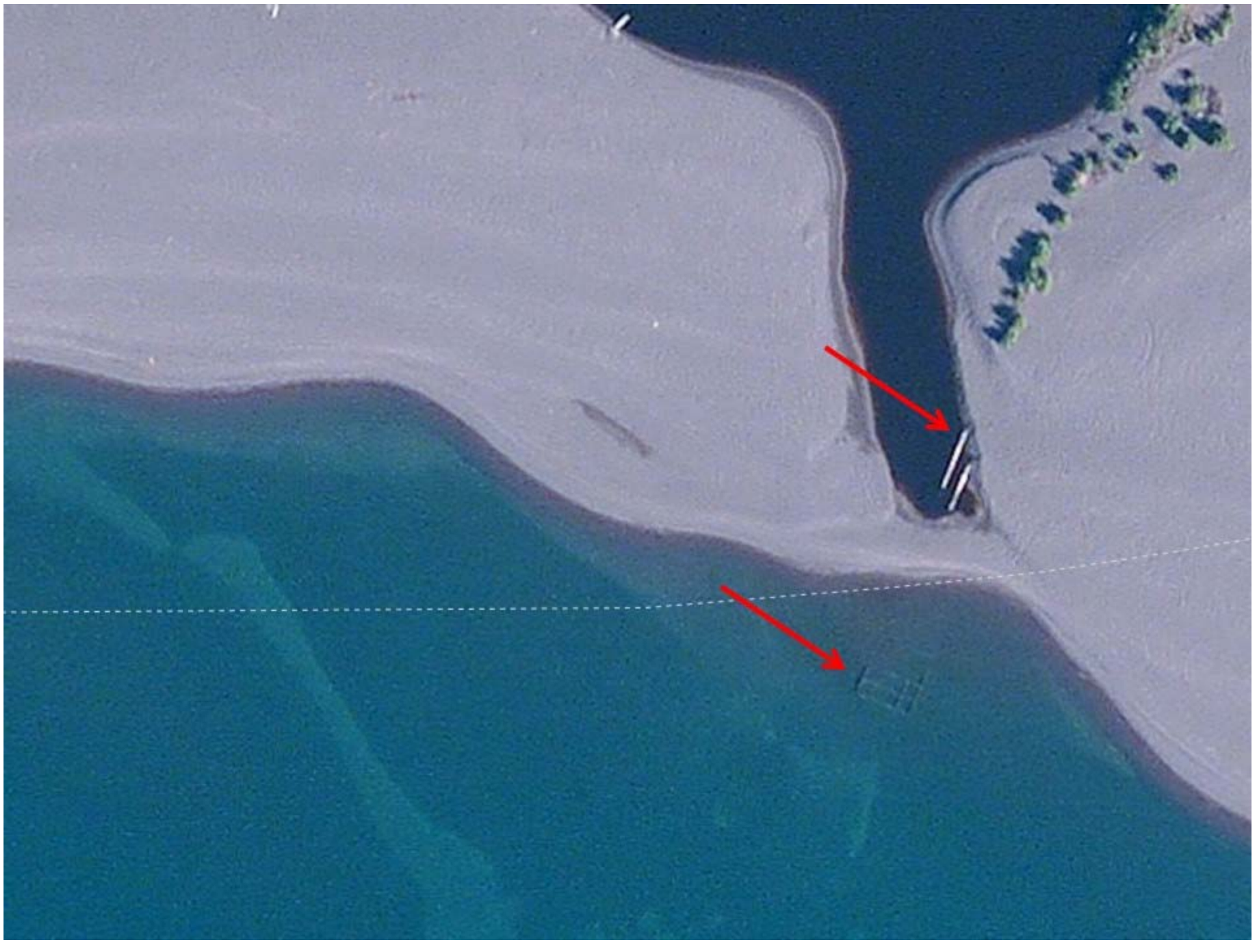


Figure 31: *High resolution image showing remnants of Coal Dock and cribs (circa 2012 image).*

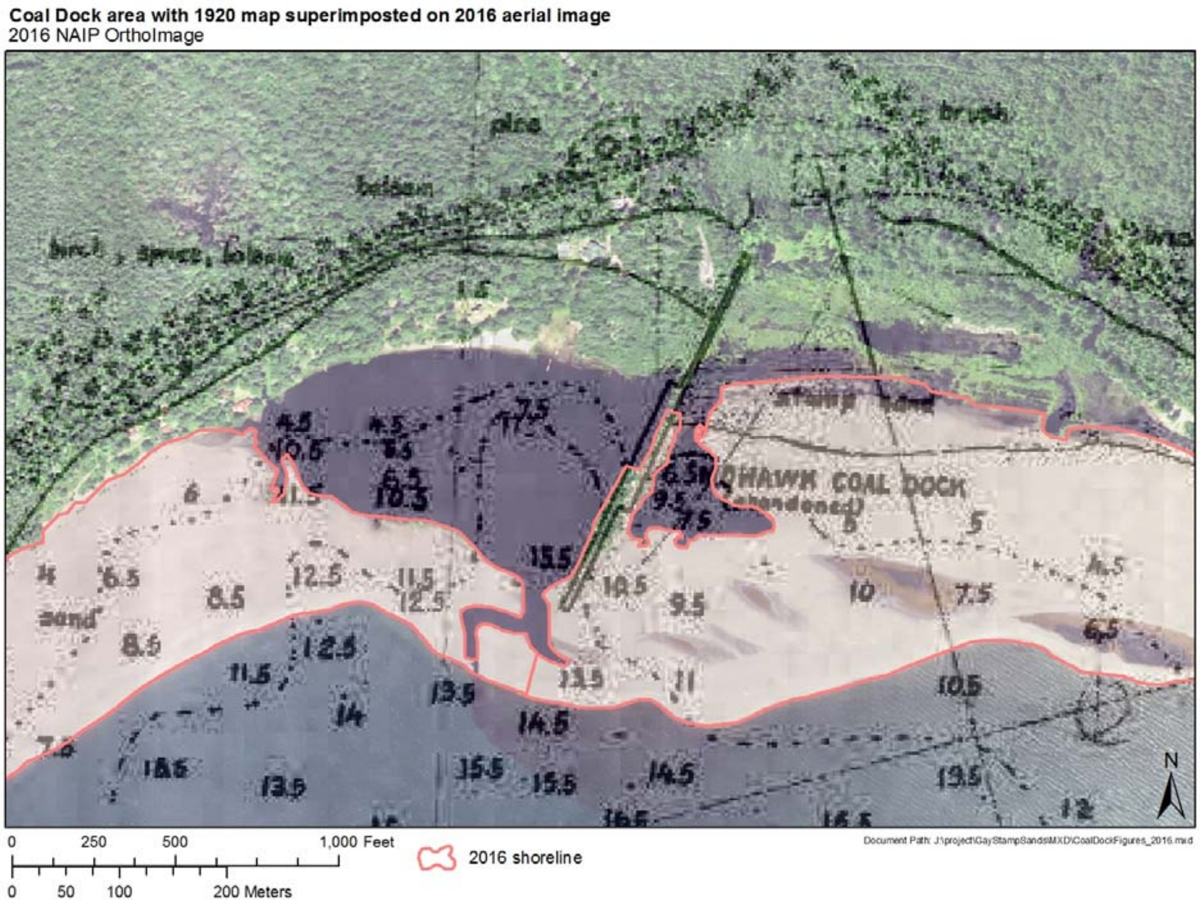


__Figure 32__: Coal Dock with 1920 map superimposed on 2016 aerial map.

G. User-friendly informational mapping site

To help communicate analysis results, a user-friendly informational mapping site was created, which is available at http://spatial.mtri.org/stampsands/ and hosted by the Michigan Tech Research Institute. Figure 33 shows a representative view of the mapping site, with multiple layers turned on, such as 1938 aerial photography, 2016 substrate classification results, multiple terrestrial stamp sand boundaries, locations of ponar sampling in 2013, extent of ponds within the stamp sands in 2014, 2016 bathymetric Lidar results, and important labeled features. Readers of this report are encouraged to use the site to view geospatial project results. The five analysis reports used to create this final report are also available. A webpage version with the same report content is available at the main MTRI web page at http://www.mtri.org/stampsands.html (which also links to the interactive mapping page).

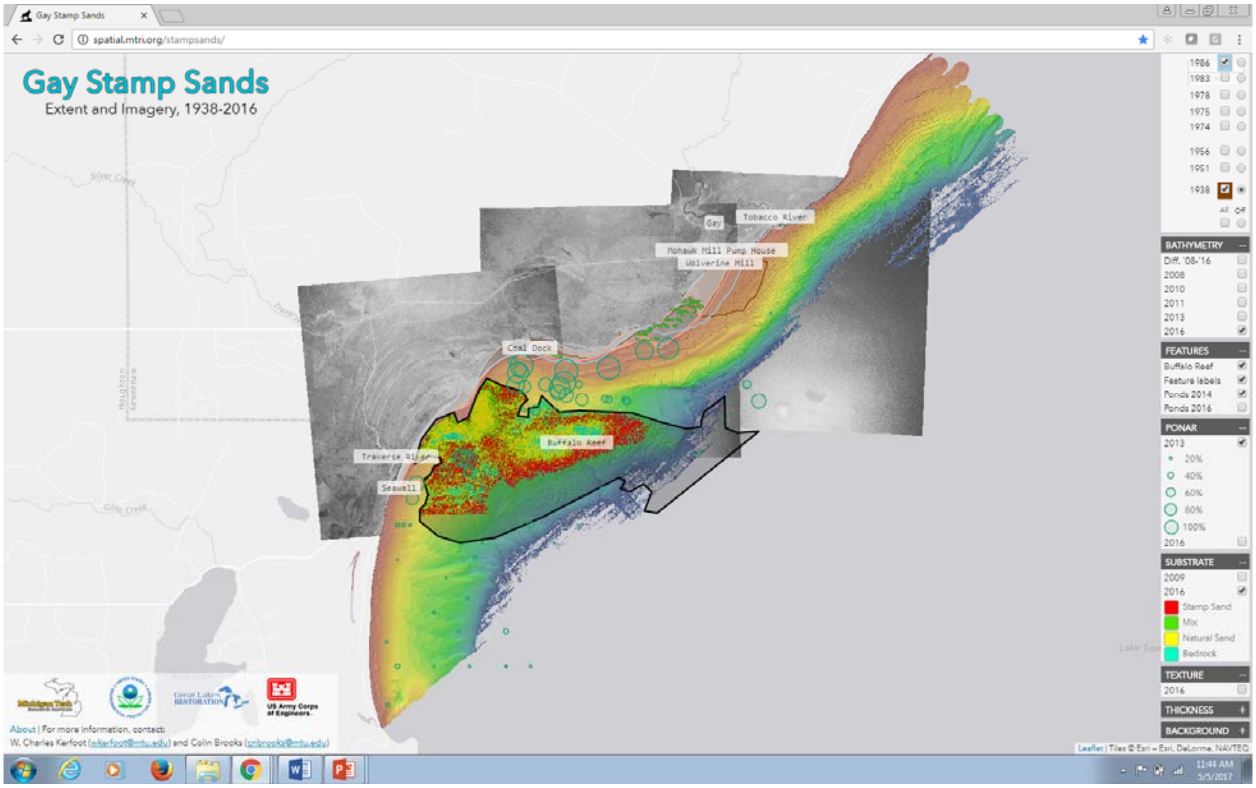


__Figure 33:__ A view of the interactive Gay Stamp Sands mapping page showing how multiple data layers can be turned on and visualized, available at http://spatial.mtri.org/stampsands/.

H. Conclusions

Stamp sands are moving into the northern boulder fields of Buffalo Reef. Migrating bars of stamp sands are moving across bedrock, spilling into and filling the northern "trough" region, an ancient riverbed cut across the Jacobsville Sandstone coastal shelf. As stamp sands mound up in the northern "trough", they begin to move westward into Buffalo Reef boulder fields. Dredging of "trough" sediments is recommended as a practical solution to slow encroachment of stamp sands into the northern boulder fields of Buffalo Reef, and dredging of the Traverse River is recommended as a means of temporarily alleviating Seawall overtopping and navigation impediments.

Lidar data sets (dates 2008 from 2016) were used to update estimates of Gay pile erosion, showing that erosion is continuing at a nearly constant rate, reducing the pile mass 21% over 8 years to around 2.4 MMT (million metric tonnes). From 2008 to 2016, the shoreline areas south of the original Gay pile appeared to lose mass for the first time, ca. 0.9 MMT. The total accumulative amount moved into Grand (Big) Traverse Bay is now 13.2 million metric tonnes. The practical consequence of our recent calculations is that we are entering a transition where the Gay pile is no longer the sole source of tailings input into the bay. Now both the Gay tailings pile and coastal stamp sand beaches are exporting stamp sands into the bay. Quantification of stamp sand moving down the shoreline shows progressive movement and thickening of stamp sand beaches, leading to overtopping at the Seawall at the Traverse River mouth. Stamp sand has accumulated predominately in three regions (immediately south of the Gay Pile, in the pond region; Coal Dock region, and where the Buffalo Reef promontory intersects the shoreline).

Direct estimates of stamp sand cover on Buffalo Reef came from three sources: NAIP/ Sentinel-2 images, Ponar grid sediment samples, and MSS/hyperspectral studies. The original estimates from 2009 NAIP studies were around 25% cover (Kerfoot et al. 2014). Updating these estimates for the entire reef resulted in estimates of 28.7% stamp sand cover for 2009 and 28.8% cover for 2016. For the areas in common between the 2009 and 2016 imagery, 33% of the detectable reef area was covered in stamp sand in 2009 and 35-55% in 2016. However, only 50% of the area of Buffalo Reef was covered by reflectance spectra, so again 20-30% of the entire reef was judged covered by stamp sand. Grain counts from Ponar sediment samples gave direct measurements of percent stamp sand. Based on contouring of the Ponar samples, we estimated 35% of Buffalo Reef was covered by >20% stamp sand mixtures. The MSS/hyperspectral studies allowed resolution of substrate from a few transects, enough to show correlations with NAIP/Sentinel-2 images and increased westward encroachment by stamp sands.. Detailed hyperspectral images emphasized the high cover of stamp sand around the Coal Dock and Traverse River locations.

ROV transects clearly revealed regions where stamp sands are encroaching into northern boulder fields. Transects around the western portions of the northern boulder field, the southwestern rim and the southern rim of Buffalo Reef show areas with low percentage stamp sand and hence minimal intrusion.

The 2016 Lidar data sets could be used with other overflights (2008, 2010, 2011, 2013) to calculate deposition and erosion across the entire bay and near the proposed dredging region. Calculations comparing differences between 2008 and 2016 clearly showed the most active regions of deposition and erosion were movement of migrating underwater stamp sand bars, especially where bars migrate across the bedrock shelf and where they dump into the "trough". In 2008 to 2016 comparisons, vertical bathymetric differences spanned a range of -3 to +2 meters. Net deposition was greater than the approximate Lidar error rate of 18.5 cm in the original proposed dredging area, amounting to 317,154 metric tonnes in the 529,541 m^2 area. Between 2008 to 2016, there are indications that deposition has varied with ice cover.

We checked the volume of ponds in the Gay Pile-Coal Dock region, to see how much tailings could be used to fill the ponds, which act as death traps to most organisms because of elevated copper concentrations. Total volume of the ponds was estimated at 91,773 m^3, i.e., pond volume could hold 151,426 metric tonnes of stamp sands. Studies of stamp sand impacts on benthic biota in the bay show that abundance and diversity are significantly lowered by increased concentrations of stamp sands.

Although many pre-dredging questions have been answered, additional issues remain to be addressed. Key questions and next steps are listed below. These concerns originated from the MTU and USACE team during the project, plus queries from the National Park Service, and input from concerned parties. For example, the Keweenaw Bay Indian Community (KBIC) raised several issues October 18-20, 2016, at the Keweenaw Stamp Sands Meeting organized by the US EPA Great Lakes National Program Office. These suggestions seem more appropriate for future environmental assessment activities, rather than being impediments for proposed dredging actions.

Key questions and recommendations for next steps:

1. **Mass Balance**

- A complete mass balance model of stamp sand fate and transport is needed to understand where stamp sands are underwater now and eventually where they will end up in Grand (Big) Traverse Bay and Keweenaw Bay.

- Where is the fine fraction going and how toxic are effects? (if fine fraction is ~10% of the Gay pile, ca. ~2.3 Mt of fine material has moved into the bay). MODIS & MERIS imagery can help quantify movement & estimate amounts, refine hydrodynamic models.

- How much stamp sand is mixed with natural underwater sands, both above and below the Traverse River Seawall? Is stamp sand disappearing by progressive mixing? Broader Ponar, Iver & video sampling is needed to resolve missing amounts.

- How much stamp sand is in the migrating underwater "bars" that dump into the "trough"; how much is in the "trough"?

- What is the likely fate of stamp sands over the next 5, 10, and 20 years with no remediation (dredging, revetment) actions?

2. **Dredging Consequences**

- Will the dredging slow or accelerate migration of stamp sands onto Buffalo Reef? Our previously proposed before-after high resolution side-scan sonar work or Iver transects could directly address this issue by documenting not only how much stamp sand is removed from the trough, but also how much down-drift might happen.

- Will dredging increase beach sand transport onto the reef, influence movement (over-topping) past the Traverse River Seawall? Will it change wave intensity?

- Could additional dredging remove encroached stamp sand from Buffalo Reef boulder fields, from migrating bars that feed into the "trough"? These would be ideal candidates for demonstration projects.

- Apply satellite and unmanned aerial vehicle (UAV) remote sensing to monitor plume extent and movement during the dredging period.

3. **Toxicity Questions**

- Tribal members were concerned that dredging of "trough" sediments could enhance mercury contamination of fish in the bay. Previous studies of mercury contamination in Keweenaw Bay suggest only low-level effects (Kerfoot et al. 2009) from stamp sand, as there are no smelters.

- Much of the bay is contaminated with stamp sand mixed into the natural sand. How toxic are mixtures to benthos, fish eggs, and larvae? What is a "safe" level of stamp sand in Grand (Big) Traverse Bay sediments? Do humic-rich river discharges complex copper?

- Is the stamp sand that is migrating into river mouths and along wetlands having impacts on water quality and organisms? What is the possibility of flooding along the Traverse River if the channel is filled with over-topping stamp sands?

4. **Public Outreach**

- Public Website Project- Show the public project Lidar, MSS maps, calculations.

- Construct Exhibit at the Gay Museum (Old Elementary School in Gay). Show pictures of Lidar plane, shoreline and underwater DEM maps, document changes in the Bay through time. Include artifacts (pieces of sluices, boats) eroding out of shoreline piles.
  Include a narrative of events (computer display).

- Conduct Informative Tours of pile shoreline erosion, deposition, over-topping, remedial action.

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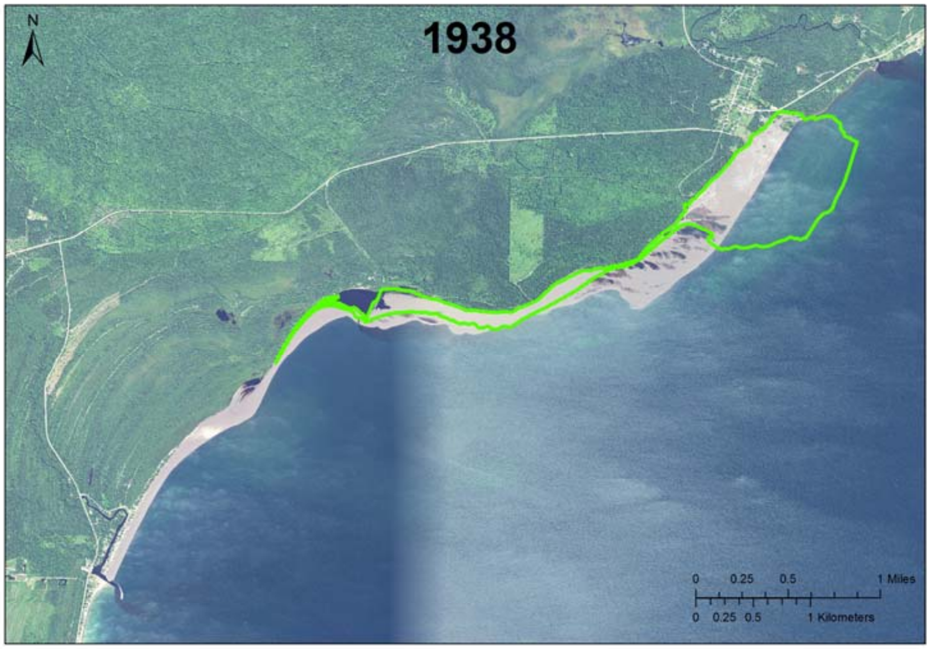
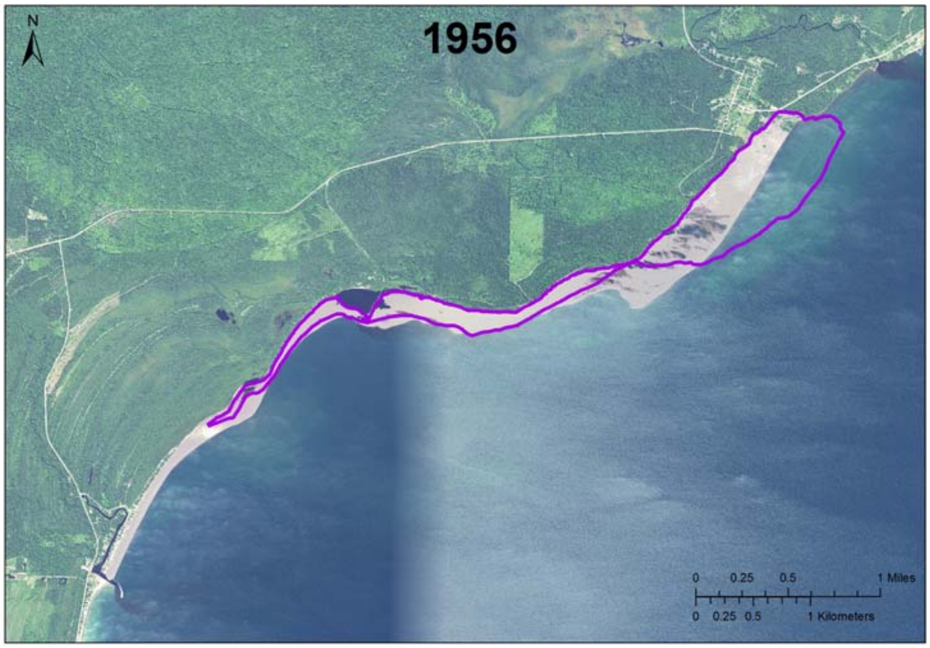
APPENDIX 1: STAMP SAND MOVEMENT ANIMATION

The following graphics show the changing extent of stamp sands from 1938-2016, drawn on top of a 2016 NAIP composite aerial image. The sources of the boundaries are historical imagery and recent Lidar.

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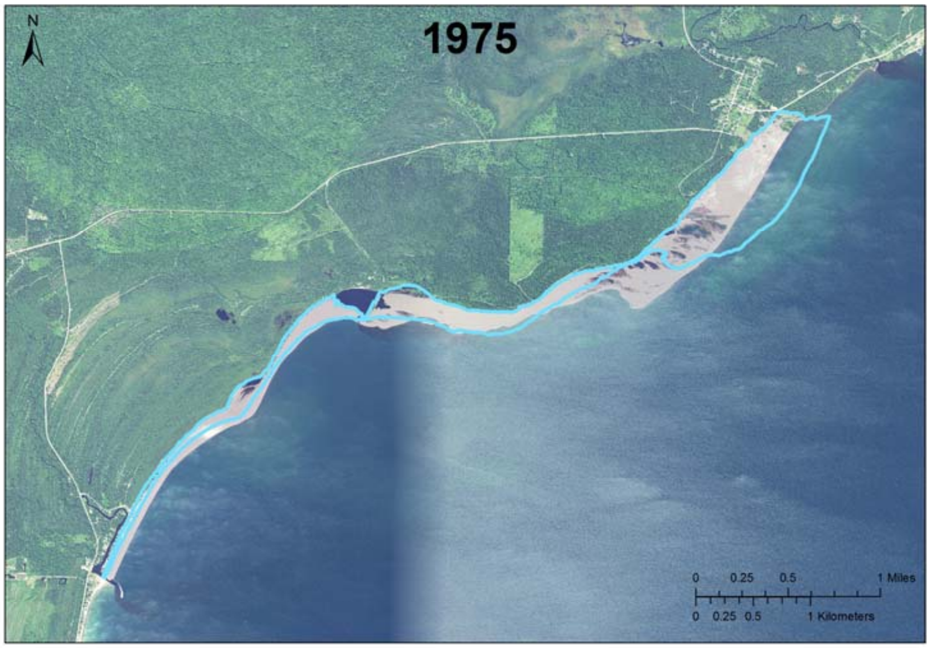
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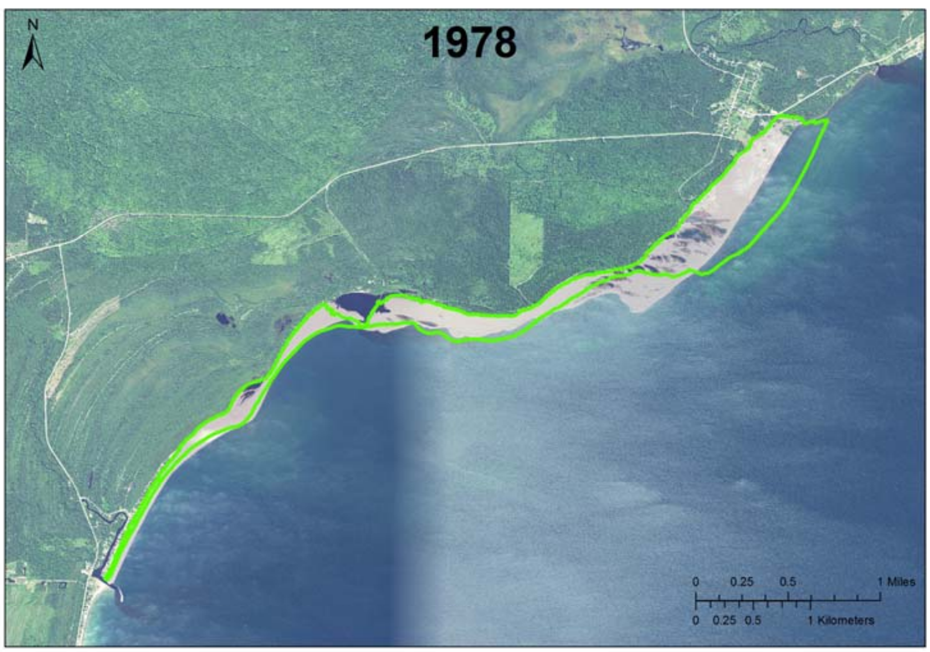
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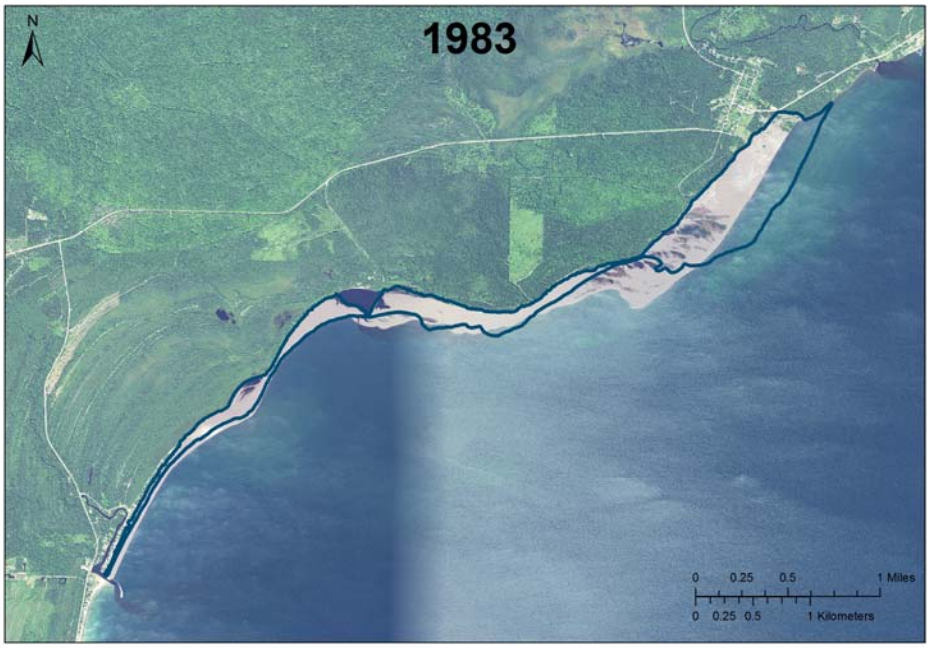
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1986
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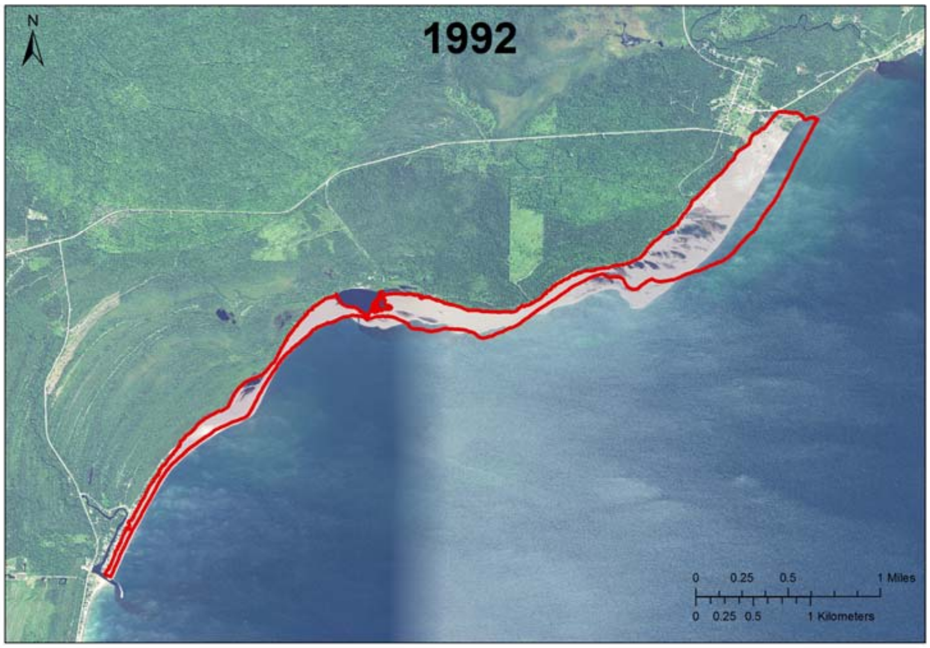
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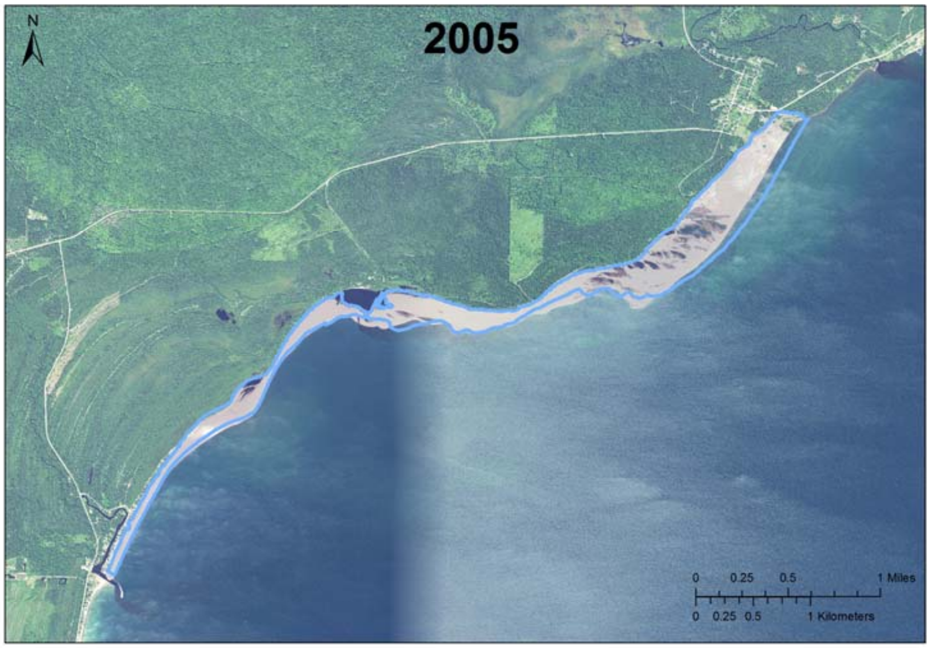
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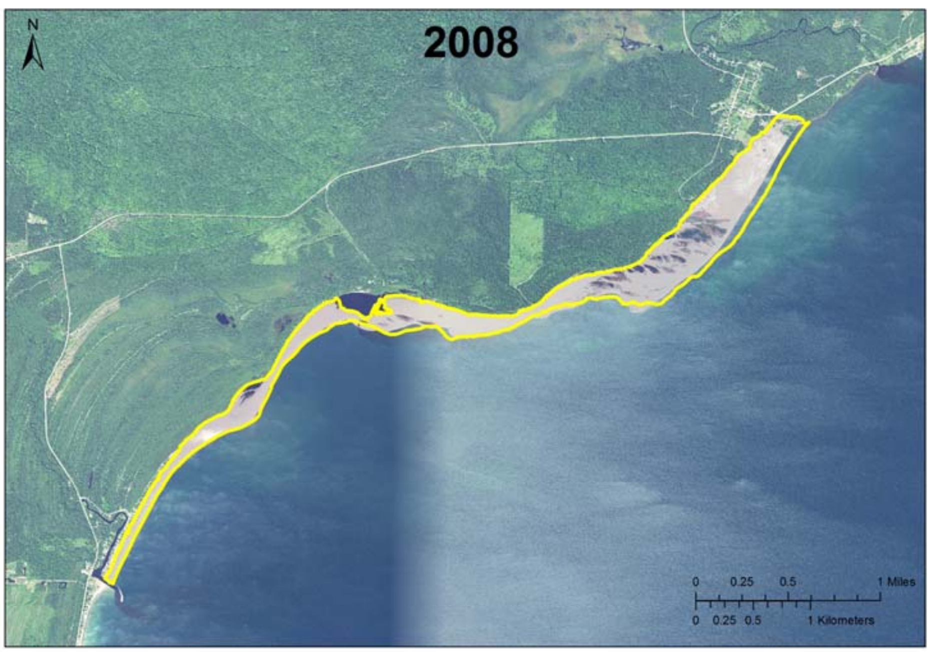
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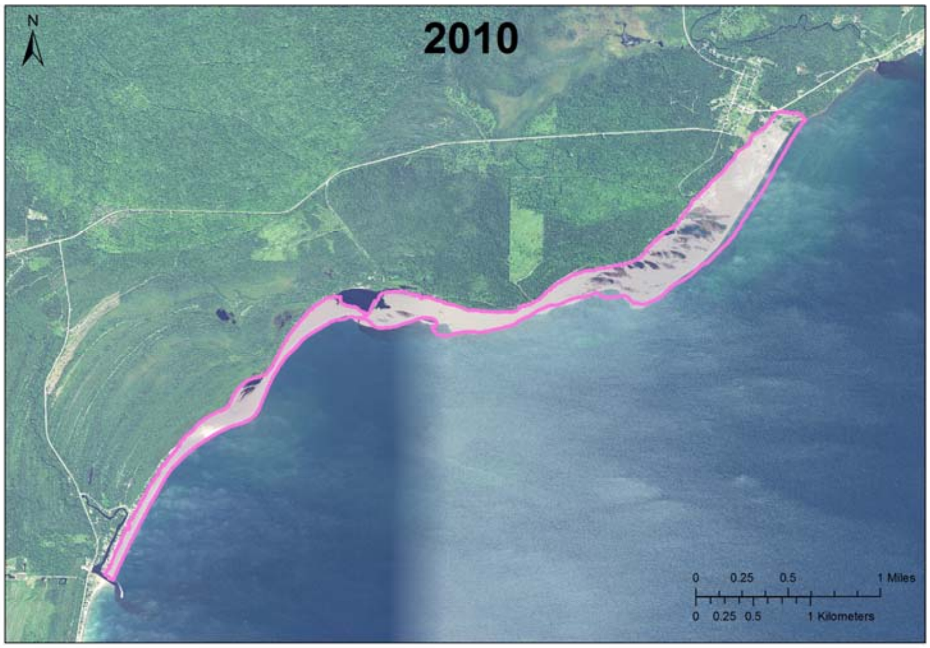

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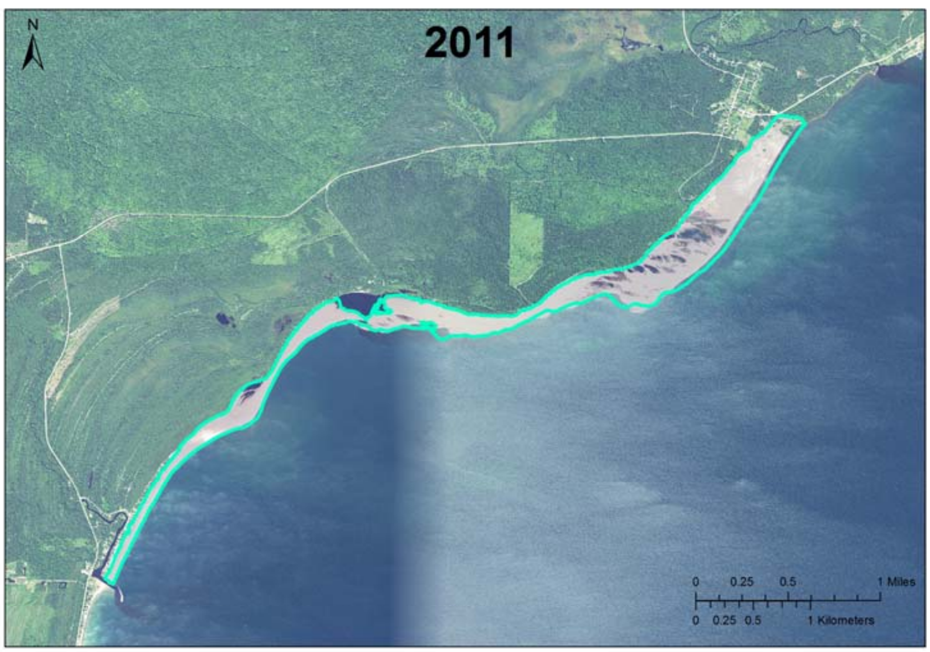

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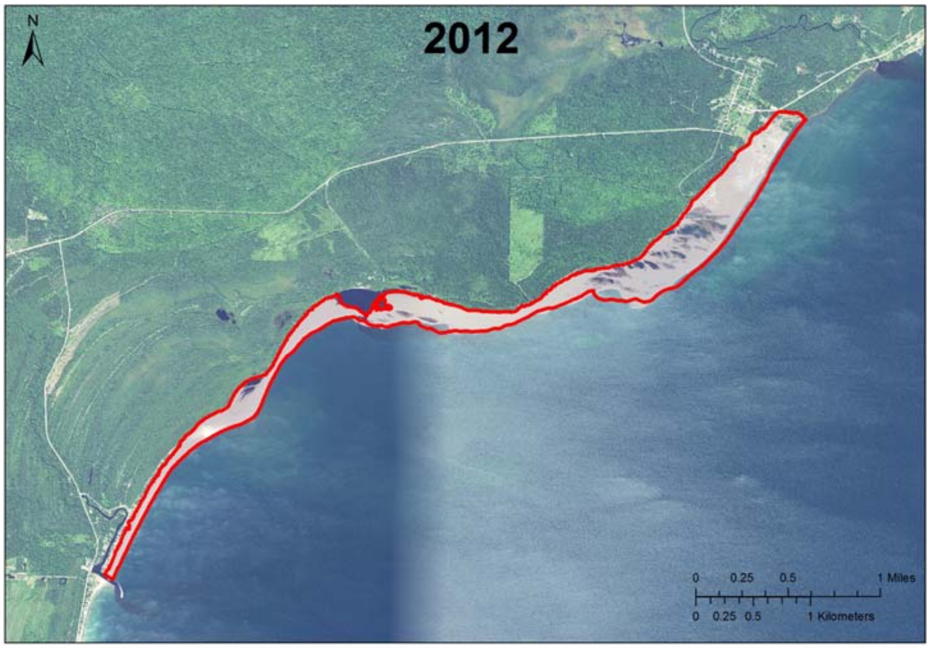
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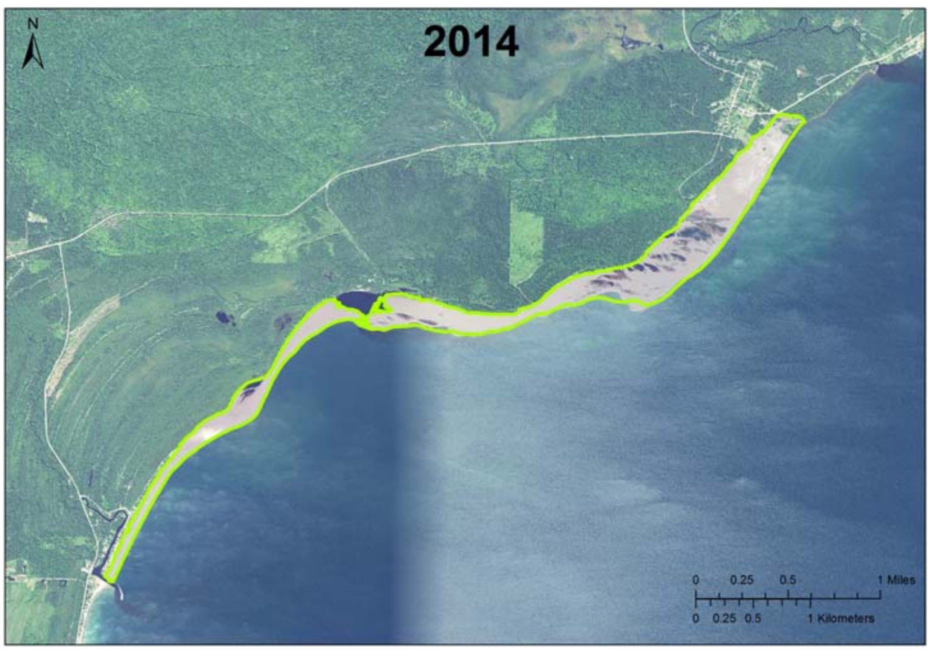
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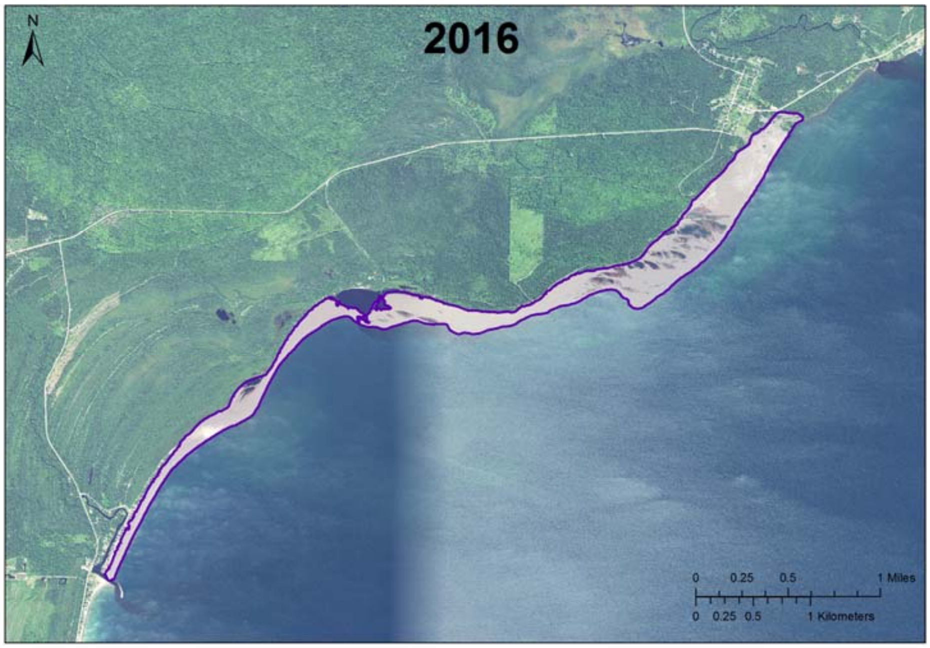
2016
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0 0.25 0.5 1 Kilometers

APPENDIX 2: ROV TRANSECTS

Included in this appendix is an overview of the ROV images taken at specific sites shown in the map figure. Images clearly show that stamp sand encroachment on Buffalo Reef is primarily in the northern region of the reef.

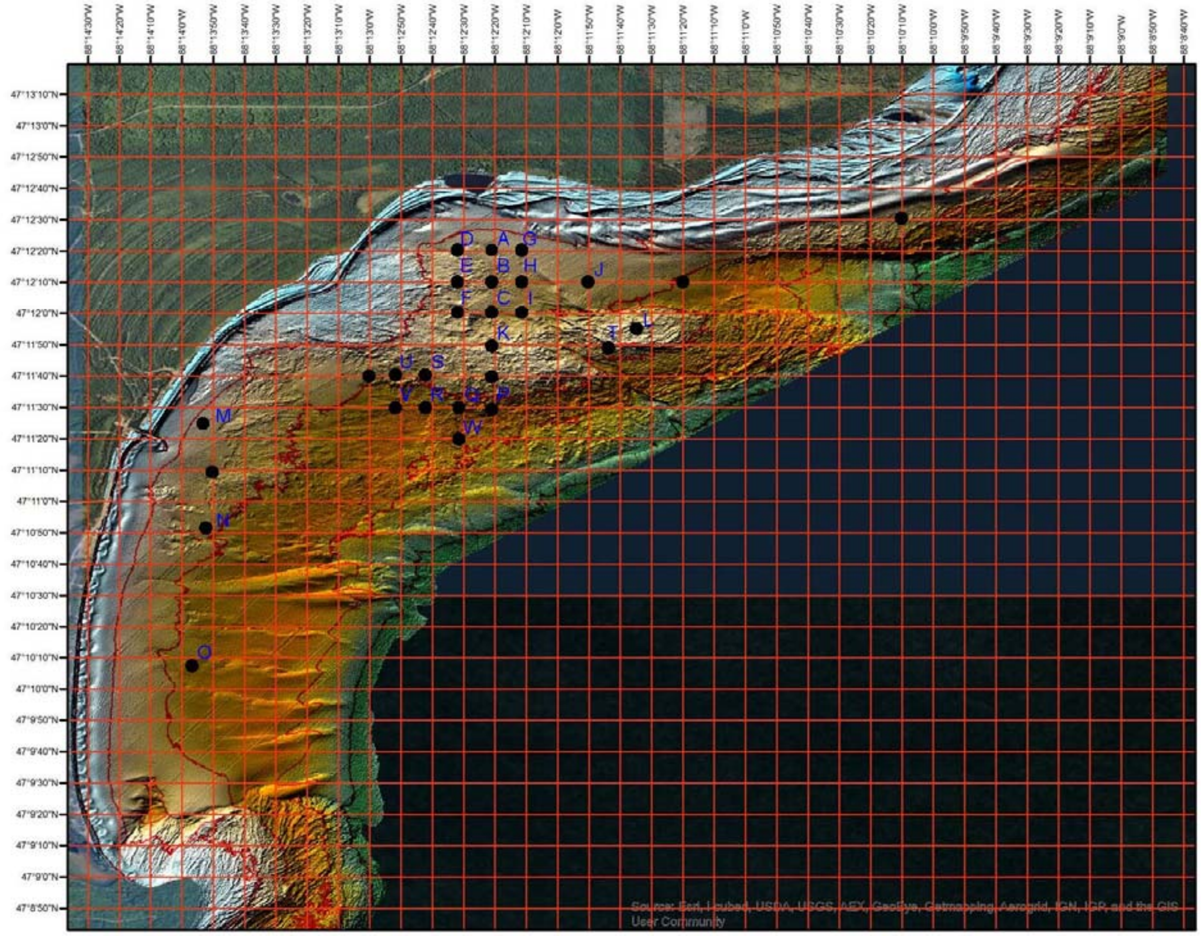


Figure App 2-1: Overview map of ROV sampling stations.

Each of these photos corresponds to a sampling station shown in the figure above. Waypoint numbers refer to images taken around a particular lettered site (for example, location E has three images shown below taken nearby at waypoints 13, 14, & 15).

Figure App-2-2: *ROV survey location A (waypoint 2) – within trough*

Figure App-2-3: *ROV survey location B (waypoint 5) – cobble area*

Figure App-2-4*: ROV survey location C (waypoint 8) – stamp sand / Buffalo Reef edge*

Figure App-2-5: *ROV survey location D (waypoint 11) – trough area*

Figure App-2-6: *ROV survey location E (waypoint 13) – trough / Buffalo Reef edge*

Figure App-2-7: *ROV survey location E (waypoint 14) – stamp sand encroached on Buffalo Reef*

Figure App-2-8: *ROV survey location E (waypoint 15) – stamp sand encroached on Buffalo Reef*

Figure App-2-9: *ROV survey location F (waypoint 16) – Stamp sand encroached on Buffalo Reef*

Figure App-2-10*: ROV survey location F (waypoint 17) – transition from stamp sand to Buffalo Reef cobble*

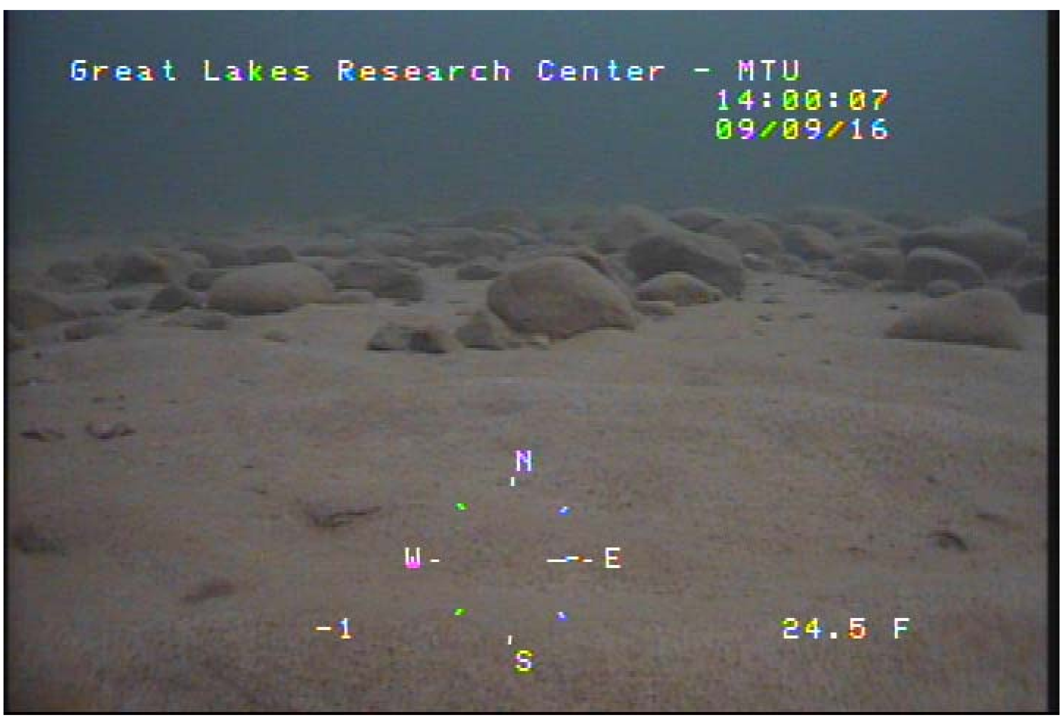


Figure App-2-11*: ROV survey location F (waypoint 18) – transition from stamp sand to Buffalo Reef cobble*

__Figure App-2-12__: ROV survey location G (waypoint 20) – trough area

__Figure App-2-13__: ROV survey location G (waypoint 21) – trough area

__Figure App-2-14__: ROV survey location H (waypoint 23) – edge of trough

***Figure App-2-15:** ROV survey location H (waypoint 24) – edge of trough*

APPENDIX 3: FINAL POWERPOINT BRIEFING

This briefing was given to the US Army Corps of Engineers via GoToMeeting on Tuesday, May 9th, 2017 to review accomplishments of the project. Extra page numbers are from a printed two-slide-per-page version. An original Powerpoint version is available upon request or via anonymous ftp at ftp://ftp.mtri.org/pub/USACE_StampSands/.

Michigan Tech

Review of Gay Stamp Sands

Charlie Kerfoot, Mike Sayers, Colin Brooks

Michigan Tech Research Institute

Great Lakes Research Center
Michigan Technological University

Mining Legacy: Tailings Impacts Of "Gay Pile" And How Legacy Tailings Contribute To The Copper "Halo" Around The Keweenaw Peninsula

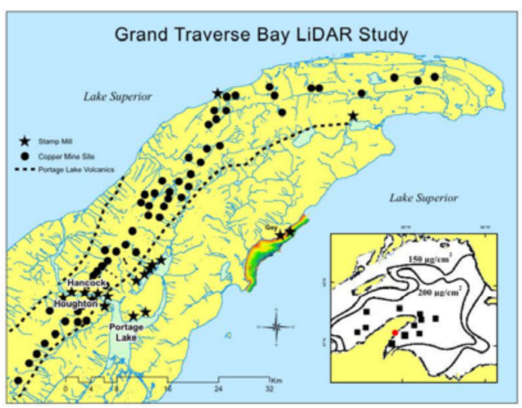


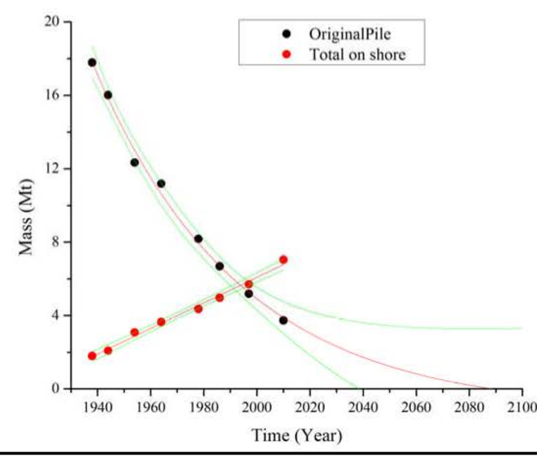
Figure 5a. Wave erosion of the Gay tailings pile. The near-vertical 7 m bluffs contain well-preserved remnants of wooden troughs that sluiced stamp sands across the pile.

SS Overtopping: Traverse River

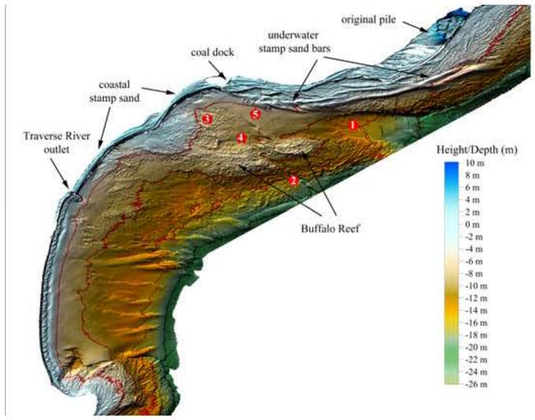
Migrating Tailings:

- 1) have progressively moved along coastline,
- 2) dammed stream/river outlets & overtopping seawalls (Traverse River)
- 3) transgressed into coastal wetlands and threaten recreational beaches (southern white beach region)
- 4) suppressed coastal pond & benthic communities
- 5) threaten critical fish breeding grounds (Buffalo Reef) & whitefish rearing site (southern bay)

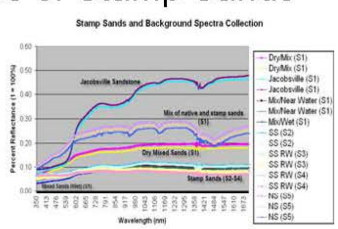
Mass Eroded From Pile & Deposited On Beach

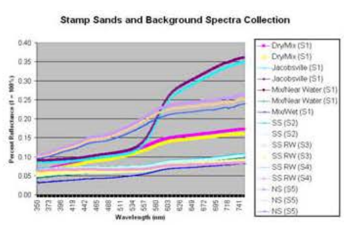


Features Revealed By LiDAR: Underwater Stamp Sand Bars Move Across Coastal Bedrock & Dump Into "Trough" (#1, #5), Transgress Into Boulder Fields (#3, #4))



Spectral Signatures of Stamp Sands





4

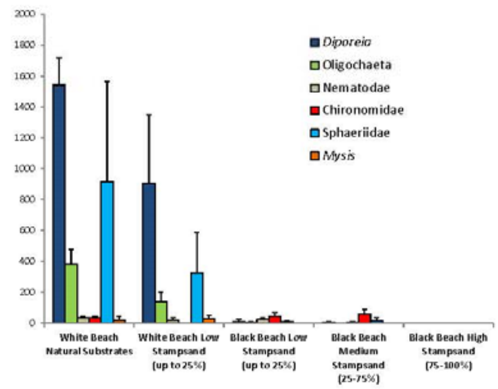
Migrating Stamp Sand Field

Stamp Sand Encroachment

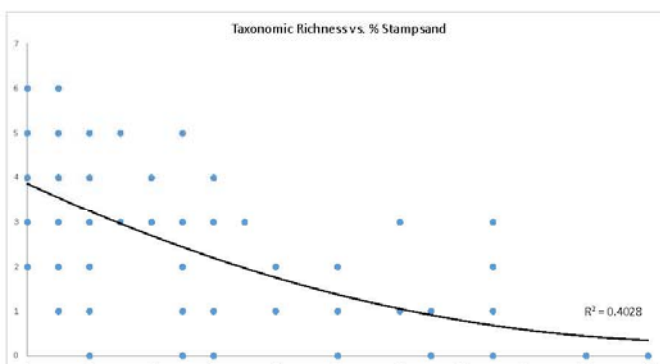
Buffalo Reef Cobble/Boulder Field

Hi-Res Side-scan Sonar (R/V Storm): Stamp Sands Moving Into Boulder Field

Stamp Sand Effect On Benthic Organisms



Benthic Species Richness Versus Stamp Sand %



7

Summary

- In Grand (Big) Traverse Bay, the magnitude of Gay mine waste discharges into the coastal zone initiated a perturbation that has played out for over a century.
- Stamp sands contain relatively high concentrations of copper and a secondary suite of elements that can have detrimental environmental effects. We applied LiDAR/MSS techniques and aerial photo images to estimate the expanding influence of migrating sands.
- Tailings pile shows exponential decay (erosion) through time, down to ca. 3 Mt; waves and currents have spread ca. 7 Mt of SS along beaches (covering 1.6-2.3 km^2), and ca. 10 Mt into bay (5.1 km^2). We identified underwater movement of stamp sand bars along the coastal shelf. An ancient riverbed ("trough") has been intercepting migrating stamp sands; yet the upper reaches now appear full.
- Images disclosed a serious threat to Buffalo Reef; sampling suggested severe SS impacts on benthos and fish along shoreline. Underwater cameras and high-resolution side-scan sonar verified encroachment of stamp sands into boulder fields.

Economic Impacts – Loss of Buffalo Reef

- Native Fisheries
  - Bad River, Red Cliff and Keweenaw Bay Tribes (1842 and 1854 treaties)
  - Current 23% losses:
    - Dockside Whitefish and Trout $191,023/yr
    - Recreational fishing $68,360/yr
    - Artificial re-stocking $380,00/yr
    - Displacement of 10.4 tribal jobs $1,040,000/yr
  - Total : $1,679,383/yr
  - Eleven year total: $18,473,213

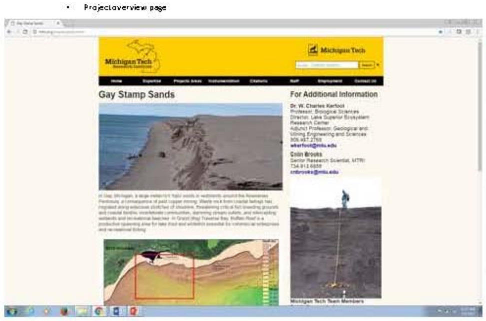
Source: Bill Mattes (Great Lakes Indian Fish and Wildlife Commission), 2016

Review of Work Completed Under New Project

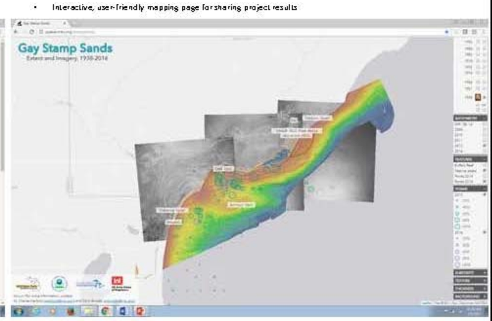
- Two main tasks
  - Estimating Stamp Sand Cover Across Buffalo Reef (Validation of USACE-ERDC hydrodynamic model predictions).
  - Update Passive Color (CZMIL Hyperspectral) Substrate Classification Around Buffalo Reef.
- Show Project website to demonstrate completed analysis results
- Review five reports in context of the two main tasks and related deliverables
  - Analysis of Aerial Extent, Volume, and Mass of the Gay Stamp Sands Calculated Using 2008 and 2016 LiDAR Elevation Data Five reports
  - Gay Stamp Sands 2016 pond volume estimates using 2016 U.S. Army Corps of Engineers Lidar elevation data
  - Stamp Sands Mapped from 2009 and 2016 Using Remote Sensing Data
  - Gay Stamp Sands 2016 Trough Volume Estimates from LiDAR Elevation Data
  - Hyperspectral Bottom Feature Mapping

Website Review

- http://mtri.org/stampsands.html
- Project overview page



- http://spatial.mtri.org/stampsands/
- Interactive, user-friendly mapping page for sharing project results



Project Accomplishments – Results Summarized in Five Reports

- Analysis of Aerial Extent, Volume, and Mass of the Gay Stamp Sands Calculated Using 2008 and 2016 LiDAR Elevation Data
- Gay Stamp Sands 2016 pond volume estimates using 2016 U.S. Army Corps of Engineers Lidar elevation data
- Stamp Sands Mapped from 2009 and 2016 Using Remote Sensing Data
- Gay Stamp Sands 2016 Trough Volume Estimates from LiDAR Elevation Data
- Hyperspectral Bottom Feature Mapping

Report 1: Analysis of Aerial Extent, Volume, and Mass of the Gay Stamp Sands Calculated Using 2008 and 2016 LiDAR Elevation Data

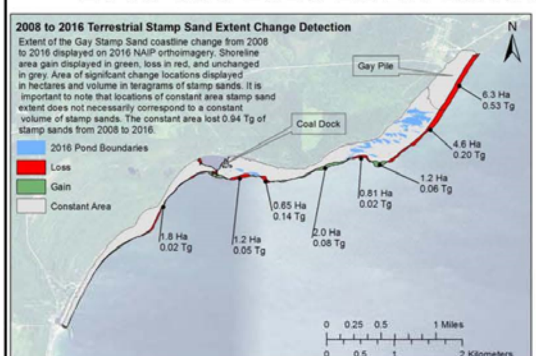


Table 1. Preliminary onshore, Gay pile and shoreline, and eroded offshore stamp sand aerial extent from 2008 and 2016 Lidar.

Location	Year	Area (ha)	Percent Loss from 2008 to 2016 (%)
Gay Pile	2008	31	21%
	2016	25	
Shoreline: South of Coal Dock	2008	41	2%
	2016	40	
Shoreline: Between Gay Pile and Coal Dock	2008	95	3%
	2016	92	

Report 1: Analysis of Aerial Extent, Volume, and Mass of the Gay Stamp Sands Calculated Using 2008 and 2016 LiDAR Elevation Data

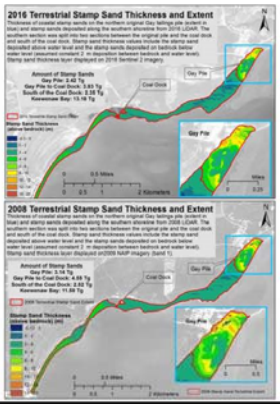


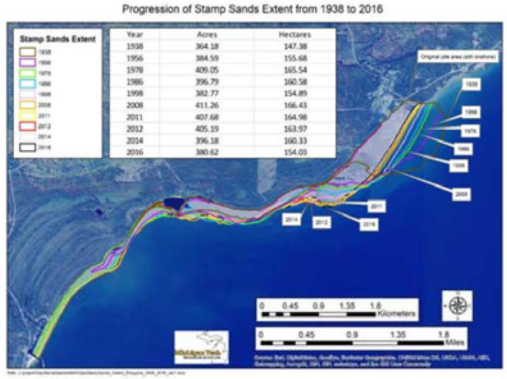
Table 2. Preliminary onshore, Gay pile and shoreline, and eroded offshore stamp sand volume estimates from 2008 and 2016 Lidar.

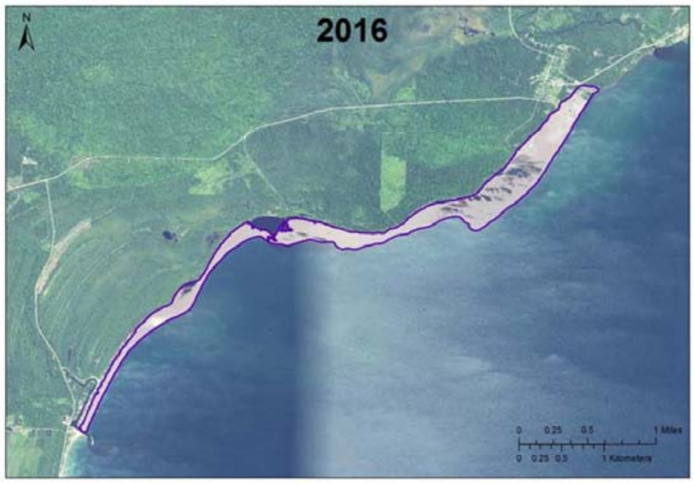
Location	Year	Stamp Sand Mass (Tg)	Percent of Original Pile (%)	Percent Change 2008 to 2016 (%)[A]
Gay Pile	1901-1932	22.79	100.0	NA
	2008	3.14	13.76	-22.95
	2016	2.42	10.60	
Shoreline: South of Coal Dock	2008	2.52	11.04	-6.50
	2016	2.35	10.32	
Shoreline: Between Gay Pile and Coal Dock	2008	4.55	19.95	-15.78
	2016	3.83	16.80	
Roads (sand used by local road commissions)	NA	1.01	4.4	NA
Keweenaw Bay	**2008**	**11.58**	50.82	13.82
	2016	**13.18**	57.84	

A. Negative value indicates percent loss and positive indicates percent increase. Stamp sand volume increased from 2008 to 2016 in Keewenaw Bay as the amount of terrestrial stamp sands decreased over time.

Inputs to Terrestrial Stamp Sands Extent Analysis

Progression of Stamp Sands Extent from 1938 to 2016





Report 2: Gay Stamp Sands 2016 pond volume estimates using 2016 U.S. Army Corps of Engineers Lidar elevation data

Table 1. Summary of ponds with an area greater than 1000 m^3

Pond	Mean Depth (m)	Area (m^2)	Volume (m^3)	Percent total Volume (%)	Potential Stamp Sand Capacity (metric tonnes)
A	0.9	78329	55014	58.5	90774
B	0.8	13043	9161	9.7	15115
C	0.7	9368	6580	7.0	10857
D	0.9	6448	4529	4.8	7472
E	0.6	5947	4177	4.4	6891
F	0.8	5422	3808	4.1	6284
G	1.0	3763	2643	2.8	4361
H	0.5	3258	2288	2.4	3776
I	0.2	2738	1923	2.0	3173
J	0.3	1339	940	1.0	1551
K	0.4	1011	710	0.8	1172
Sum	--	130667	91773	--	151426

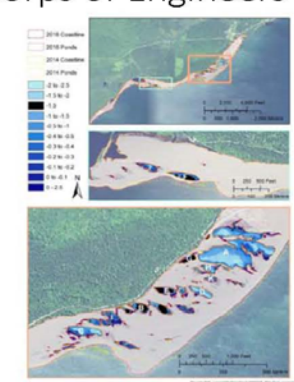
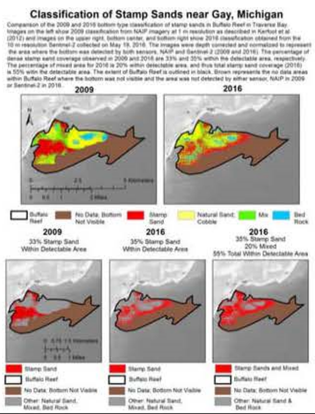
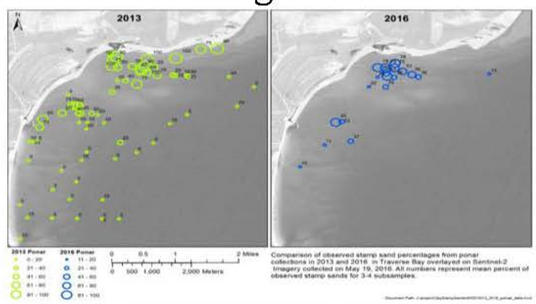


Figure 1. Digitized pond boundaries shown for 2014 (yellow) and 2016 (red) with the respective coastlines show the dynamicity of ponds by stamp sands near Gay, Michigan. Ponds are filled by depth values in meters relative to mean water level. Areas where lidar data were not available are shown in black and values were assumed 1.5 m below mean water level. The 2016 NAIP compressed orthoimage is displayed in the background.

Report 3: Stamp Sands Mapped from 2009 and 2016 Using Remote Sensing Data





The Total Area of Buffalo Reef (polygon) is 9.2 km2	Imagery Date	
	2009	2016
Area of Buffalo Reef Identified (km2)	4.83	4.83
Dense Stamp Sand Area Identified in Buffalo Reef (km2)	1.6	1.72
Mixed Stamp Sand Area Identified in Buffalo Reef (km2)		0.94
Percent of Dense Stamp Sands in Identified Buffalo Reef	33%	35%
Percent of Total Stamp Sands Identified in Buffalo Reef	33%	55%

2013 Ponar (% Stamp Sand in Sand Mixtures). 35% Buffalo Reef Cover >20% SS

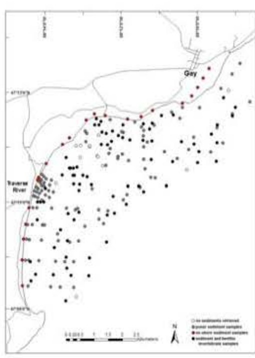


Fig. 1. Ponar sediment sampling stations in Grand (Big) Traverse Bay 2013. Black circles mark 80 sites with benthic community characterization and % stamp sand determinations.

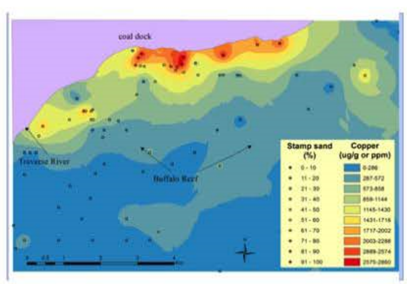


Fig. 2. Stampsand percentages and calculated Cu concentrations for eighty Ponar sites. 100% stamp sand is set at 2863 μg g⁻¹ (tailings pile). Highest concentrations are found off beach front, diminishing with distance offshore as sands are mixed with other sediments.

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Report 4: Gay Stamp Sands 2016 Trough Volume Estimates from LiDAR Elevation Data

Table 2. Preliminary summary of change in stamp sand deposition with 2008, 2013 and 2016 Lidar[A]

Years	Value	Trough	Dynamic Bars	Total Dredging Polygon
2013-2016	Net Deposition Volume (m^3)	13,158	25,557	38,714
	Net Deposition Volume (metric tonnes)	21,710	42,169	63,879
	Percent Total (%)	34	66	--
	Annual Deposition Rate (m^3/yr)	4,386	8,519	12,905
	Average Deposition depth (cm)	4	15	7
2008-2016	Net Deposition Volume (m^3)	127,176	66,391	193,566
	Net Deposition Volume (metric tonnes)	209,840	109,545	319,385
	Percent Total (%)	66	34	--
	Annual Deposition Rate (m^3/yr)	15,897	8,299	24,196
	Average Deposition depth (cm)	35	39	37
2008-2013	Net Deposition Volume (m^3)	112,714	40,004	152,718
	Net Deposition Volume (metric tonnes)	185,979	66,006	251,985
	Percent Total (%)	74	26	--
	Annual Deposition Rate (m^3/yr)	22,543	8,001	30,544
	Average Deposition depth (cm)	31	24	29

A. Changes in net deposition volume from 2008 to 2013 plus 2013 to 2016 do not sum to the 2008 to 2016 analysis due to Lidar accuracy. Each change detection was computed separately with the Lidar from the respective years.

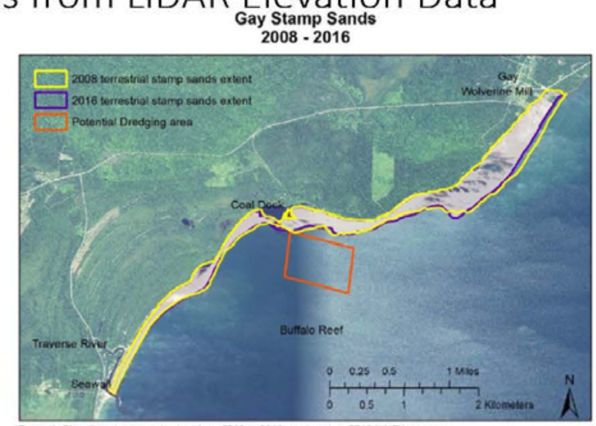
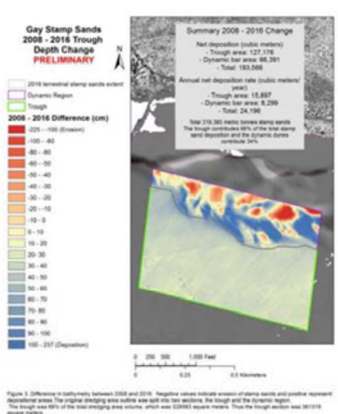


Figure 1. Shoreline stamp sand extent from 2008 to 2016 overlayed on 2016 NAIP Imagery.

Report 4: Gay Stamp Sands 2016 Trough Volume Estimates from LiDAR Elevation Data



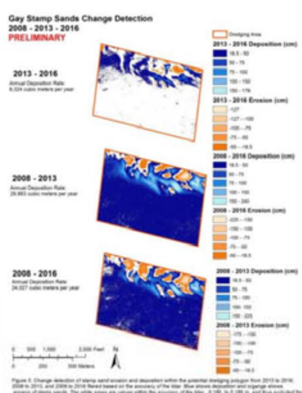


Table 3. Preliminary summary of uncertainty due to 18.5 cm Lidar accuracy in change detection of stamp sand deposition for total dredging area.[A]

Years	Value	Total Dredging Area	
		All Data	Exclusion[B]
2013-2016	Net Deposition Volume (m^3)	38,714	27,972
	Net Deposition Volume (metric tonnes)	63,879	46,155
	Annual Deposition Rate (m^3/yr)	12,905	9,324
	Average Deposition depth (cm)	7	5
2008-2016	Net Deposition Volume (m^3)	193,566	192,215
	Net Deposition Volume (metric tonnes)	319,385	317,154
	Annual Deposition Rate (m^3/yr)	24,196	24,027
	Average Deposition depth (cm)	37	36
2008-2013	Net Deposition Volume (m^3)	152,718	149,416
	Net Deposition Volume (metric tonnes)	251,985	246,537
	Annual Deposition Rate (m^3/yr)	30,544	29,883
	Average Deposition depth (cm)	29	28

A. Changes in net deposition volume from 2008 to 2013 plus 2013 to 2016 do not sum to the 2008 to 2016 analysis due to Lidar accuracy. Each change detection was computed separately with the Lidar from the respective years.
B. Uncertainties were values of erosion and deposition within 0 and 18.5 cm, thus values between -18.5 and 18.5 cm.

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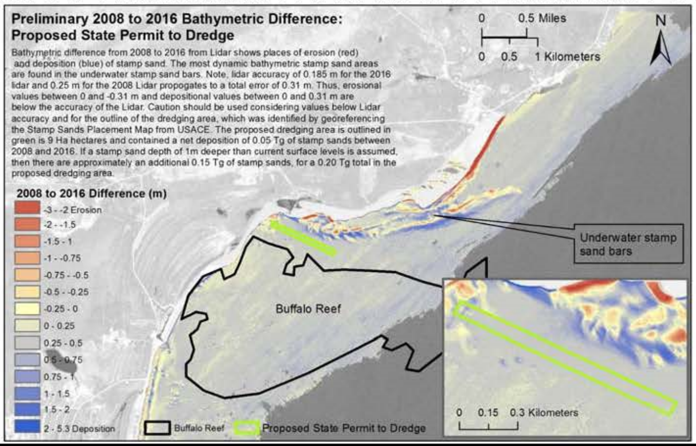
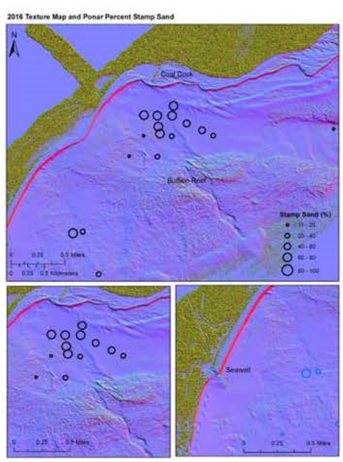
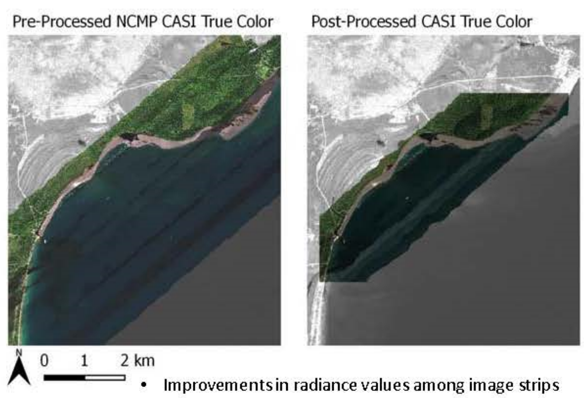
Report 4: Gay Stamp Sands 2016 Trough Volume Estimates from LiDAR Elevation Data



Report 5: Hyperspectral Bottom Feature Mapping





- Improvements in radiance values among image strips with processing. Most notable near stamp sand pile.

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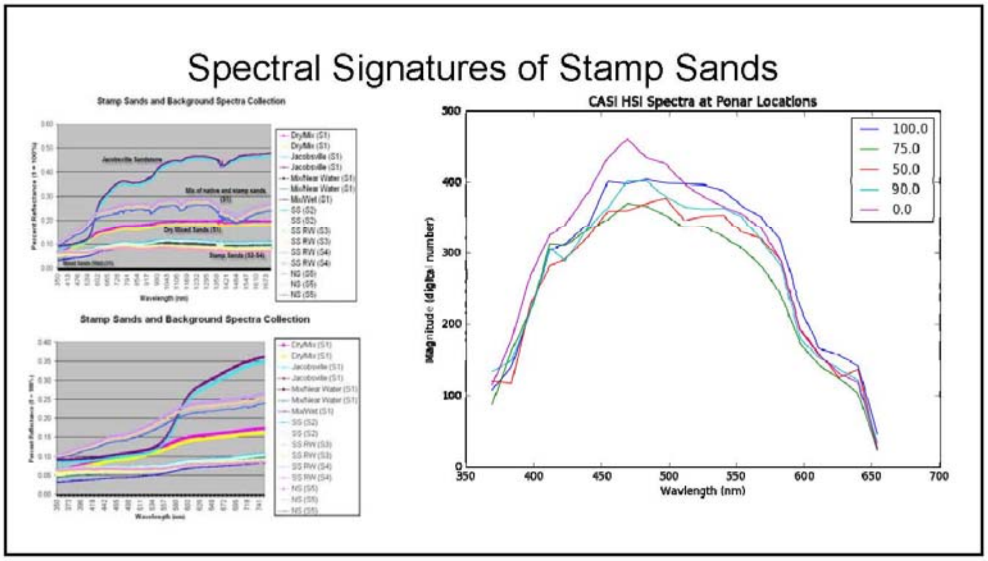
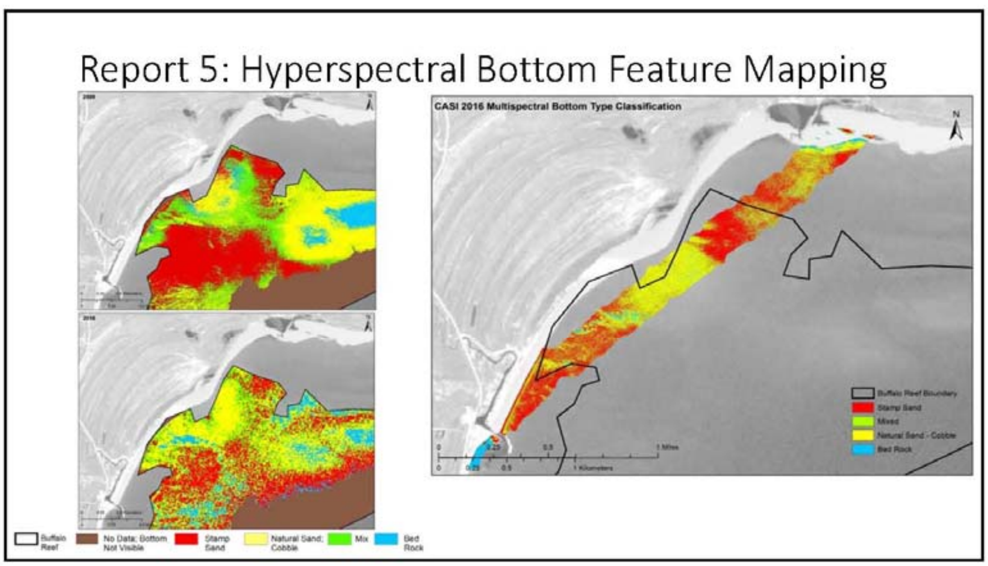
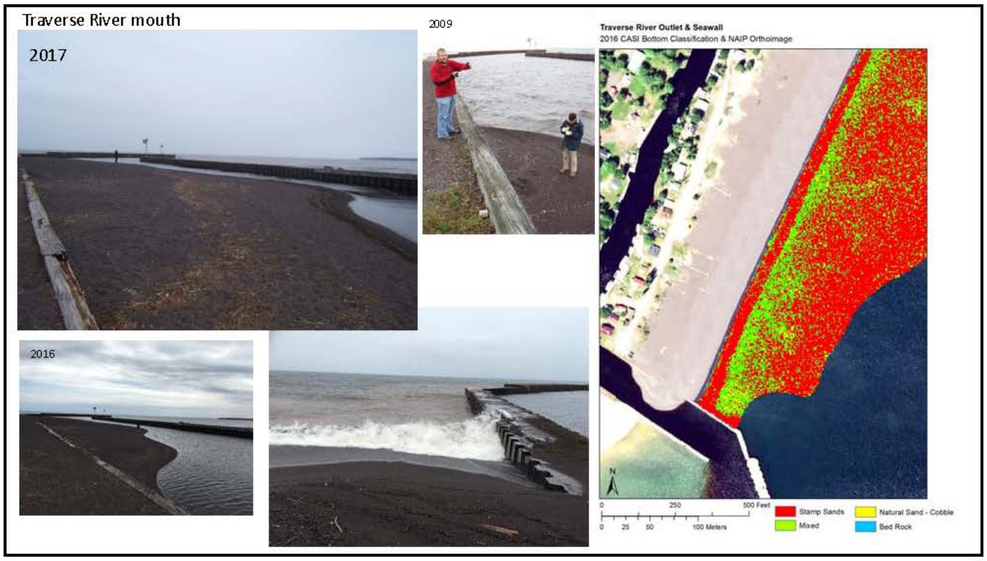


Spectral Signatures of Stamp Sands
Stamp Sands and Background Spectra Collection
CASI HSI Spectra at Ponar Locations
Magnitude (digital number)
Wavlength (nm)
100.0
75.0
50.0
90.0
0.0



Report 5: Hyperspectral Bottom Feature Mapping
CASI 2016 Multispectral Bottom Type Classification
Buffalo Reef
No Data; Bottom Not Visible
Stamp Sand
Natural Sand; Cobble
Mix
Bed Rock



NEXT STEPS – issues

1. **Mass Balance**
- A complete mass balance model of stamp sand fate and transport is needed to understand where stamp sands are now and eventually where they will end up in Grand (Big) Traverse Bay and Keweenaw Bay.
- Where is the fine fraction going and how toxic are effects? (the fine fraction is ~10% of the Gay pile, so ~2.3 Mt of fine material has moved into the bay.) MODIS & MERIS imagery can quantify movement & estimate amounts.
- How much stamp sand is mixed with natural underwater sands, both above and below the Traverse River Seawall? Broader Ponar & video sampling is needed.
- How much stamp sand is in the migrating underwater "bars" that dump into the "trough"; how much is in the "trough"?
- What is the likely fate of stamp sands over the next 5, 10, and 20 years with no remediation (dredging, revetment) actions?

2. **Dredging Consequences**
- Will the dredging slow or accelerate migration of stamp sands onto Buffalo Reef? Our previously proposed before-after high resolution sidescan sonar work would directly address this issue by documenting not only how much stamp sand is removed from the trough, but also how much down-drift might happen.
- Will dredging increase beach sand transport onto the reef, influence movement (over-topping) past the Traverse River Seawall? Will it change wave intensity?
- Could additional dredging remove encroached stamp sand from Buffalo Reef boulder fields, from migrating bars that feed into the "trough"? These would be ideal candidates for demonstration projects.
- Apply satellite and unmanned aerial vehicle (UAV) remote sensing to monitor plume extent and movement during the dredging period.

3. **Toxicity Questions**
- Tribal members were concerned that dredging of "trough" sediments could enhance mercury contamination of fish in the bay.
- Much of the bay is contaminated with stamp sand mixed into the natural sand. How toxic are mixtures to benthos, fish eggs, and larvae? What is a "safe" level of stamp sand in sediments?
- Is the stamp sand that is migrating into river mouths and along wetlands having impacts on water quality and organisms?

4. **Public Outreach**
- Website Project - Show public LiDAR, MSS maps, calculations.
- Construct Exhibit at Gay Museum (Old Elementary School). Show pictures of LiDAR plane, shoreline and underwater DEM maps, document changes in the Bay through time. Include artifacts (pieces of sluices, boats) eroding out of shoreline piles. Include a narrative of events (computer display).
- Conduct Informative Tours.

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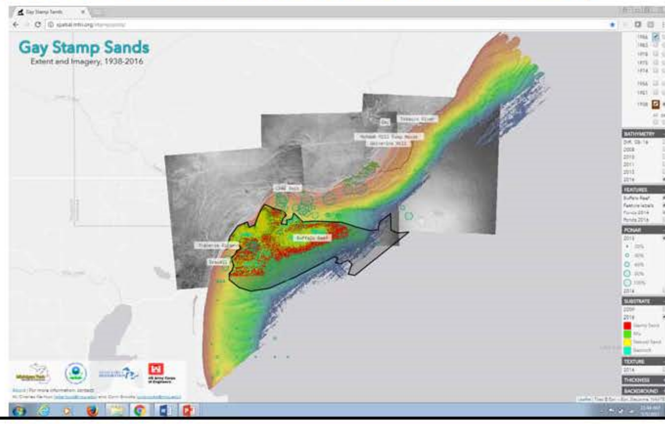
Interactive Website Tour - http://spatial.mtri.org/stampsands/



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