Mapping Stamp Sand Dynamics: Gay, Michigan

Thomas Rasmussen¹*, Rolland Fraser¹, David S. Lemberg¹, and Robert Regis²

¹Department of Geography
Western Michigan University
Kalamazoo, Michigan 49008

²Department of Geography
Northern Michigan University
Marquette, Michigan 49855

ABSTRACT. Monitoring coastal change is vital because a high percentage of the world’s population lives in close proximity to coastal areas. This paper examines a portion of Lake Superior’s shoreline where coastal landscape has been shaped by the introduction of 25 billion kg of stamp sand from the copper industry and subsequent dynamics associated with longshore currents. Shoreline areal change from this movement is documented through comparison of archival and current air photos. A series of historical air photo mosaics were processed with a Geographic Information System (GIS). Sets of spatially registered, temporal map polygons were developed to illustrate and allow measurement of the areas of erosion and deposition, relevant to shoreline planning and measurement. Measurements indicate that the length of shoreline affected by the stamp sand increased by 2.4 km during a 59-year period. Measurements of area indicate a decrease of 8 ha in the same amount of time. Breadth of the stamp sand shows discernable decline of 630 m width at the original deposit area at the north near Gay, Michigan, and increase of 410 m width 1,500 m southward along the coast. The methodology and results are relevant to a diversity of linear and areal landscape considerations along shorelines (property rights, planning, conservation, etc.).

INDEX WORDS: Remote sensing, GIS, sediment, stamp, sands, mill tailings, coastal geomorphology, Keweenaw, Lake Superior.

INTRODUCTION

Michigan’s Keweenaw Peninsula extends into Lake Superior some 80 km from the mainland (Fig. 1). Alternating strata of sedimentary and igneous rock found along the northwest side of the peninsula contain copper (metallic or “native” copper, and copper sulfide or chalcocite). Native Americans first exploited native copper deposits some 5,000 years ago. French explorers made reports of copper in the area as early as 1636 in the “Relactions” of Lagarde. Douglass Houghton, Michigan’s first state geologist, urged development in 1841 when he reported copper bearing rock in the Upper Peninsula (Dorr and Eschman 1970).

Mining began at Copper Harbor in 1844 and continued in the Keweenaw until 1968 when deep shaft copper mining became unprofitable (Dorr and Eschman 1970). An estimated 4.989 billion kilograms (kg) of refined native copper were extracted from Keweenaw mines (Bornhorst et al. 1983) during that Copper Mining Era. Ore processing placed approximately 500 billion kg of associated waste material in the Keweenaw’s waterways and Lake Superior during the 123 years (Babcock and Spiroff 1970, Kerfoot et al. 1999).

Mining of the Kearsarge Amygdaloid, the district’s second most productive deposit, began in 1887 and ended in 1967 with the production of 1.04 billion kg of refined copper. Two mine operations, the Wolverine and Mohawk, worked the Kearsarge Amygdaloid, with the process including transfer of ore to stamp mills at Gay, Michigan. Milling operations began in 1902 and reached a capacity of 4.166 × 10⁶ kg per day by 1907. With the closing of the Wolverine mill in 1925, production was consolidated at the Mohawk mill at a reduced capacity of
The milling process at Gay consisted of stamping (crushing) the ore by steam-powered hammers to yield particles 4.76 mm in diameter to facilitate separation of copper from rock. The ore was then mixed with water and chemicals to extract the copper from the bulk of the material. Coarse material and water were separated and the coarse material known as stamp sand was deposited onto the lakeshore (Benedict 1955). Water, fine sediment, and chemicals were piped to the end of the conveyor where they were used to flush the stamp sand away from the end of the conveyor (Lankton and Hyde 1982).

This disposal method discharged approximately 25 billion kg of stamp sand (Babcock and Spiroff 1970), plus associated sediment-laden water into the Lake Superior shore at Gay, Michigan. Wind powered currents in Lake Superior have moved the stamp sand along the shoreline during the intervening years (Lankton and Hyde 1982).

Problem and Objectives

Winds, particularly those in storms, drive waves that in turn power shoreline currents (National Research Council 1989) and continuously reshape the coastline of Lake Superior. In order to provide information about the areal dynamics of the stamp sand, the first objective of this research was to create a temporal series of air photo mosaics to illustrate trends in the 8.6 km section of the Keweenaw Bay shoreline over a 59-year period. The second objective was to use these mosaics as the basis for measurements of the location, area, and breadth of the shoreline occupied by stamp sand.

Komar (1976) suggests that describing and mapping historical development of shoreline features enhances understanding of the currents and sediment flows that shape sections of coastline. Viles and Spencer (1995) further support the study of historical maps and remotely sensed data, noting the value of this approach “for detection and measurement of coastal change.” Kerfoot and Nriagu (1999) express several environmental interests in this type of data because of concerns including possible “threat to fish rearing areas” and “nearshore benthic habitats,” contribution to “the contaminant load of nearshore coastal waters” by the fine fraction and the potential that the material “is progressively contaminating the beaches of the Keweenaw Peninsula coastline as particles are transported and redeposited along the shoreline.” The scope of this approach does not directly address coastal geophysical processes so much as provide geographic record in context of the local human and environmental history. Although remnants of the original billions of kilograms of stamp sand are still visually discernable from native quartzite sands through casual observation, the impact and dynamics of the stamp sand on the coastal geomorphology of Keweenaw Bay have not been documented either cartographically or quantitatively.

Location of Study Area

The study area was defined by an examination of the United States Geologic Survey (USGS) Gay, Michigan Topographic Quadrangle. The stamp sand is shown and labeled (tailings) as a reach of unvegetated shoreline (uncharacteristic for the area) between the Tobacco and Traverse rivers in Keweenaw and Houghton counties. Extent was confirmed on-site by visual discernment of shoreline sand deposits. As of summer, 2000, both counties have zoned the area as some form of “Residential,” which both consider as the “best possible use” for the area.

COASTLINE MAPPING

Literature regarding mapping of historical changes in the geomorphology of Lake Superior’s 4,385 km of shoreline is limited. Sources that de-
scribe coastal geomorphology in the Great Lakes are primarily engineering studies concentrating on sediment transport processes rather than geographic and temporal trends.

The dynamics of beach and shoreline environments on Lake Michigan’s eastern shoreline were studied by Davis and Fox (1971), Davis (1994), and Davis et al. (1975). Their research was oriented toward developing relationships between weather, wind, and waves to determine which were potential indicators of dynamic processes. Beach profile changes occurred during “periods of high wave energy” (Fox and Davis 1972). Davis (1994) summarized the work on beach profile changes by stating that the determining factors are the amount of sediment available, strength and shape of waves, slope of the near shore area, and subtle site-specific factors. Flow rates (to 1 m/s) and sediment dispersion pattern of the Keweenaw Current have been documented along the northeast and southeast shorelines, in relation to the circulation of Lake Superior (Green and Terrell 1978, Van Luven et al. 1999, Viekman and Wimbush 1993). A current of this magnitude is considered capable of eroding stamp sands and transporting the fine and coarse fractions into the offshore waters of Lake Superior (Kolak et al. 1999). While the referenced sources have contributed to the body of knowledge about sediment erosion, transport, and deposition, none address the particular circumstances of historical changes in shoreline geomorphology caused by stamp sand on an active shoreline.

Beach erosion was surveyed in North Carolina by Stafford (1971), who collected air photos, spaced several years apart, and used them to map the shoreline’s temporal development. Noted advantages of air photo mosaics are that they represent a permanent record of the time and location, are more detailed than standard maps, and provide more frequent data sets. Limitations of air photo mosaics include system factors (errors of scale within the photo caused by lens distortion, platform tilt, and relief) and environmental factors such as storm events that may skew shoreline data and in air photos; only areas of change are detectable not the volume of the material removed or deposited.

Guo and Pusty (1997) reported the use of air photos, maps, and a geographic information system (GIS) to study the “Sequential Spatial Evolution” of deltaic wetlands. They mapped temporal changes by manually digitizing hardcopy photos and maps. Once digitized, the maps were referenced to a coordinate system and projection. The last step was to input the maps into the GIS for analysis. The GIS was then used for making linear measurement and spatial analysis of the wetlands. The techniques of Guo and Pusty were combined with those of Stafford as guidelines for this project.

DATA PROCESSING

Primary Data Sources

Primary source materials were sets of air survey photos of the stamp sand site. Photos used were of a relatively large scale, between 1:15,840 or 1:20,000. Black and white infrared (IR) photos from 1986 and 1997 and 1978 color infrared (CIR) photos were acquired from the Michigan Department of Natural Resources (MDNR) Real Estate Division, Lansing, MI. Black and white panchromatic photos (PAN) from 1938 and 1954 IR photos were acquired from the National Archives, Washington, D.C. A set of 1964 IR photos was acquired from the United States Geologic Survey (USGS), Sioux City, IA. The total period covered is thus approximately 59 years. Ancillary locational data were from USGS 7.5-minute Topographic Quadrangle (hard-copy and digital raster graphics, DRGs) and a set of 1866 plat-maps copied from microfilm at the State of Michigan Archives.

Methodology

The methodology was to construct a series of temporally sequenced mosaics based on historical sets of air photos. The photos required correction to compensate for distortion as per Stafford (1971). Distortion was minimized by geo-referencing the photos, which registered the reference system of the photos to the coordinate system, NAD 1927, of the topographic quadrangles. After these corrections, the digital photoproducts were used within a GIS to create mosaics of the shoreline study area, illustrating the stamp sand movement and serving as spatial reference for measurements.

Photo Processing

Preparation for referencing and transforming required locating Ground Control Points (GCPs) in the study area. The position data of the GCPs served to “anchor” the images to fixed points on the ground. Criteria for GCP sites were that the sites had to be identifiable in each of the six photo
sets (Fig. 2). Latitude-longitude data for the GCPs were obtained in the field by accessing the Global Positioning System (GPS) satellite network and averaging multiple readings over a period of time as suggested by Kardoulas et al. (1996). The GPS unit used was a Garmin GPS II PLUS® fitted with an adapter for reception of differential GPS correction data. Readings were collected once a second over a period of 5 minutes. The real-time error in the X-Y axis was in the range of 0.46–0.61 m at all points. Additional GCPs were acquired from the DRGs.

The predominance of lake surface and forestland limited the number of total GCPs and created a spatial sampling bias of on-shore points for use in transformation. The shoreline is not perfectly linear, however, so resulting GCPs were distributed on either side of a mean transect through the study area. The lack of visual landmarks due to the terrain and forest cover created concentrations of GCPs in the north and south that were located in and around the village of Gay and the settlement at the mouth of the Traverse River leaving the middle area with a scarcity of field collected GCPs (Fig. 2).

The air photos were digitized on a flatbed scanner at 300 dpi before the digital files were assembled into mosaics. Raw scanned files were geo-reference with a second order polynomial to the 7.5-minute quadrangle projection (NAD 27). Image files were then mosaiced and resampled to yield an average ground resolution of 1.34 m per pixel among the photo sets.

Two forms of correction, geo-referencing and orthorectification, were considered. Orthorectification would have removed most of the distortion from the images. This level of accuracy would have been superior but with the minimum number of GCPs available, and the on-shore GCP bias, the feasibility of successful orthorectification was limited. Therefore it was decided that because of the particular characteristics of the study area, (essentially a linear feature lying along a single plane of the surface of Lake Superior), geo-referencing would produce mosaics with acceptable precision.
The mosaics were transformed and imported to a vector GIS to construct temporal maps. The purpose of these maps was: (1) to illustrate the sand’s movement over time; (2) to make linear measurements of the width of the stamp sand at selected sites; and (3) to calculate the area of stamp sand coverage on each of the photo dates.

The finished maps of the stamp sand (Fig. 3) were simple polygons overlaid on the 1938 mosaic. Each polygon was derived by screen-digitizing from the associated mosaic of each year represented. This required manual delineation between the water line, the stamp sand boundaries, and the older vegetated shoreline with native quartzite sand. Vegetation, native sand, and the stamp sand were distinct in all mosaics, regardless of the film types.

**Measurement Calculations**

The extent of the stamp sand coverage changes over the period was calculated from the digitized polygons. Linear measurements of the width of stamp sand beach were made on transects defined as “perpendicular” to the 1938 vegetation/beach line at each of a number of reference locations. The starting point for measuring sites was north of Gay on the south bank of the Tobacco River. Nineteen measurement sites were located every 500 m with the final site positioned at the north bank of the Traverse River (Fig. 3). Based on historical lake level records (Army Corps of Engineers 2002; Fig. 4) in each of the photo years (183.1 to 183.8 m), it was calculated that 0.6 m difference in water levels on a 10% slope would yield potential error of 3.5 m, or less than three pixels. Because the images were geo-referenced, a point and azimuth on one mosaic would be equivalent on each of the other mosaics allowing a comparison of measurements. Measurement points were located along the line where the beach and sand dunes met in 1938 to provide a consistent initial measuring point.

Three steps were used to determine the bearing from each point for each transect. First, the slope of the baseline connecting the two sites on either side of each measurement point was calculated. This equation required adding two points outside of the main sample shoreline reach: one north of the Tobacco River and the other south of the Traverse River. Second, the reciprocal of the slope calculated above was determined, yielding the slope of a measurement line perpendicular to the base. Finally, the point-slope equation was used to project the measurement line through the measurement point with a slope perpendicular to the base in two-dimensional space. Linear measurements were made along this transect on each of the mosaics (using GIS on-screen tools) so changes in width of the stamp sand would be comparable. Area measurements were made directly from the polygon attributes.

**RESULTS**

**Description by Map / Polygon Analysis**

Study of the stamp sand movement was simplified by separating the shoreline reach into three sections. These sections are the areas between measurement lines 2 and 8, 9 and 13, and lines 14 through 20.

The shoreline of the first section (transects 2 through 8) shows the area where the stamp sand was deposited by the mill on to the Lake Superior shore (Fig. 3). From the 1938 image of this area, it is apparent that as new material was deposited the stamp sand moved to both the northeast and southwest from the end of the conveyor system, which was located between transects 4 and 5.

The first section also reveals that the stamp sand area has experienced significant erosion associated with the generally southwesterly flow of the KeWEENAW CURRENT (Sloss and Saylor 1976). Polygons from successive years show that the stamp sand has retreated from the 1938 shoreline to the pre-mill shoreline at the north end. However, the stamp sand is seen to be increasing in width during later decades to the southwest.

In the middle section (transects 9 through 13), the 1986 shoreline begins to show southwesterly movement of the stamp sand evidenced by increasing width (Fig. 3). This increase continued through the 1980s and 1990s as shown in the 1997 shoreline.

The third section (transects 14 through 20) shows the beginning of small but relatively consistent advance and deposition throughout the period, 1938 to 1997 (Fig. 3). By 1978, the boundary of the advancing stamp sand has reached the north Traverse River breakwater. From 1978 through 1997, the width of the stamp sand shoreline continued to make small increases from transects 18 through 20.

In summary, the stamp sand polygon maps show the dynamics of the human-created shoreline. This includes a decrease in the areas of the original deposition at the northeast portion of the reach and increases in width southwestward along the coast as the stamp sand boundary advances. As all polygons are shown in context of the base photo mosaic of...
FIG. 3. Measured widths of above-water stamp sand polygons, derived from aerial photographs from different years (inset shown against 1938 photo mosaic).
1938, the southwestern advancement will presumably be slowed or halted by the northern Traverse River breakwater (still present).

**Quantification of Stamp Sand Breadth**

The widths of the stamp sand shoreline measured from each of the twenty sample points transects are shown in Figure 3. Each measurement was the average of five readings with the on-screen measurement tool.

The shoreline of the first section (transects 2 through 6) has been narrowing and the main mass of stamp sand has shifted southwestward (right on the graph) from about transect 5 to transect 6. Transect 8 shows widening in 1986 and 1997 due to the southward migration of the stamp sand. From transects 9 to 13, the stamp sand is narrower in 1997 than previous years, while breadth at transect 12 shows a slow increase. The width is relatively constant at transect 13. Along transects 14 through 20 the stamp sand is shown to gradually advance as far as the Traverse River breakwater by 1978, though the southwestern-most extent reached only transect 15 in 1938.

**Quantification of Stamp Sand Surface Area**

It should be noted that only the area of stamp sand above the water line is defined, according to the scope of this project. The initial area of stamp sand in 1938 was approximately 225.08 ha and decreased by 1997 to about 217.88 ha. The change was not, however, along a constantly decreasing vector because of the difference of Lake Superior water levels from 1938 (183.4 m in April; Fig. 4) to 1964 (183.1 m in April). This likely accounted for the slight increase in area of about 7.4 ha from the 1938 base to approximately 232.5 ha in 1964. The stamp sand area is similarly decreased by about 11.4 ha between 1964 and 1978 in relation to greater water levels (183.3 m in April). Apparent correspondence to water levels decreased past 1978 as there was a slight increase by about 1.5 ha between 1978 and 1986, though the 1986 water levels were highest among the years sampled (183.7 m in April). Rather, the southwestward extension of the stamp sand boundaries substantially influenced the surface area. There was a decrease of 4.3 ha between 1986 and 1997 to the final sampled area of 217.9 ha. Overall, the fluctuations in stamp sand area have been relatively minor (approximately 6% of maximum in 1964) through the 59 years.

**DISCUSSION AND CONCLUSIONS**

The primary goal of this research was to create a series of maps that would graphically illustrate and allow measurement of long-term changes in the coastal geomorphology of the Keweenaw shoreline south of Gay, Michigan caused by the presence and dynamics of man-made sediment. The methodology is relatively simple and repeatable for other shoreline reaches with access to GIS and tools for spatial reference. There is no attempt to comprehensively define the geophysical processes and conditions forcing the dynamics of the Gay shoreline, or to provide an inventory (by volume, for instance) of the resource represented by the mass of stamp sands. Results provide a geographic and temporal record of context for further studies or application in this field.

Spatial error affecting our measurements may have been contributed by the distribution and reliability of selected GCPs using GPS and the DRGs. The GCP labeled as Gay07 (Fig. 2) was associated with a road junction near the west of the photographed areas, and produced the largest accepted East RMS error value (–60.1 pixels) on the corresponding photo from the 1938 PAN set. However, the transformation of that image produced RMS sums of error of 0.0 pixels East and –0.1 pixels North. The resulting stamp sand polygon (inshore boundary) was not misregistered by more than the 4 m (approximately 3 pixels) from the 1938 polygon reference boundary from which breadth measurements were anchored. The largest North RMS error value accepted (–13.8 pixels) from the 1954 IR set was associated with a GCP at a point bar in river.
bend from the DRG and produced RMS sums of error of 0.0 pixels East and –0.1 pixels North. Among individual transformations, the total RMS values were all less than 0.1 pixels East and North, with the exception of the 1938 PAN photo (–3.3 pixels East and –6.8 pixels North) covering the northeastern portion of the study area at Gay. While a small number of consistently identifiable GCPs, from either GPS field visits or available topographic map data, presented less than optimum multitemporal registration of the shoreline study area, the stamp sand polygons still allowed effective measurement and historical documentation of the coastal dynamics.

The relevance of this approach and acquired information is strongest to end users in land mapping, appraisal, planning, management and use in context of the surface area of the unique stamp sand shoreline materials (in the Great Lakes and elsewhere), in agreement with comments from Stafford (1971). To date, lagging property values and aesthetic inferiority of stamp sand to native sands have been the primary concerns leading to interest in sediment transport patterns for this specific research area. Associated environmental degradation, while making headlines elsewhere, has received little attention, although in the future this may be a significant application of this type of research.

A number of environmental factors may have an impact on defining the shore/water boundary and consequently may affect the accuracy of polygon delineation from air photos. The critical factor of water levels at the time of photo acquisition is influenced by seasonal lake levels, interannual variations, and acute events such as tides and seiches. Dorr and Eschman (1970) noted that Great Lakes tides range from 2.5 to 7.6 cm and the more significant seiches range from 1.5 to 2.7 m. The geometric relationship between water levels and shoreline gradients is also a critical factor delineating the water line, and is difficult to ascertain with reasonable vertical resolution from historical photos not associated with ground truth.

Although a potential error of 3.5 m was calculated for a 0.6 m change in water level on a conservative 10% grade, the observed stamp sand beach profile varies from a nearly vertical wave-cut bluff at the waterline to a gently sloping (> 10%) abrasion (or wave cut) platform beyond. Rising lake levels meet the vertical face of stamp sand halting the water line’s shoreward movement. However, in conditions of a lowering lake level the waterline recedes a greater distance across the platform. Thus, an event that lowers water level has a greater impact on polygon delineation than a seiche that is piling water into Keweenaw Bay. Assessing bathymetry beyond the waterline is beyond the scope and intent (and available ground truth resources) of this project.

Monitoring coastal change is important because over 60% of the world’s population lives within (and affects or is affected by) a few kilometers of a coastline (Pethick 1984, Viles and Spencer 1995). The coastline of any lake or ocean is a dynamic zone undergoing continual modifications due to natural processes (Viles and Spencer 1995). Some large-scale events occur during a short time-span that attracts public attention. For example, in February 1995, at the Sleeping Bear Dunes National Lakeshore, a 488 m section containing more than 991,086 m³ of sand slumped into Lake Michigan overnight (Jaffe et al. 1998). However, what appears in the short term to be very dynamic may exhibit characteristics that are part of a relatively stable system balance over the long-term thus the importance of a historical survey of changes (Pethick 1984). The historical sequencing of the development of shoreline features suggests the forces at work in a geographic context. Geomorphologic features, such as stamp sand or native sand and sediments, can be mapped as areas of sources or sinks saving coastal researchers time and resources (Komar 1976, Viles and Spencer 1995).

A strict engineering or resource approach to studying shorelines may discount the impacts of or on human populations using the shoreline with various values (economy, industry, natural areas, real estate, recreation, residences, tourism). The presence of stamp sand along the Gay shoreline does have an aesthetic impact on the area, currently accompanied by lower real estate values. One anticipated beneficiary group of this type of study may well be local land-use planning commissions. Maps illustrating long-term sources and sinks of sediment might prompt local planning commissions to reevaluate how they use some stretches of shoreline. Rather than having blanket regulations for shoreline construction, it may be appropriate to establish construction setbacks for particular stretches of shoreline based on historical zones of erosion or deposition. Some areas may have an erosion rate great enough that constructing dwellings may be unadvisable and, therefore, the “best use” may be to set aside some areas for recreational purposes. Environmental planners may be able to use this infor-
mation to plan shoreline habitat conservation or restoration programs over the stamp sand bases.

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