

Supplemental Material

Supplemental SA: Lake height over time

Data describing lake height over time was acquired from the National Oceanic and Atmospheric Administration's Great Lakes Environmental Research Laboratory using the Great Lakes Dashboard. The tool pulls data from water level monitoring stations operated by NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) [85]. Because these data are updated occasionally to reflect new findings and observations, Table B1 provides an excerpt from this dataset to document the lake levels used in this analysis. Underlined values indicate the lake levels relevant to the 1955 and 2016 datasets used in the analysis.

Table SA1. Lake Michigan-Huron monthly lake-wide average water levels (1918-2021)

Lake Michigan-Huron:

Monthly Lake-Wide Average Water Levels (1918 - 2021) in meters (m)

Source: NOAA/NOS; CHS

year	jan	Feb	mar	Apr	may	Jun	jul	Aug	sep	Oct	nov	Dec
1955	176.83	176.78	176.76	<u>176.82</u>	176.88	176.91	176.88	176.79	176.64	176.54	176.46	176.38
1956	176.31	176.30	176.32	176.37	176.50	176.57	176.62	176.62	176.56	176.45	176.37	176.29
1957	176.22	176.19	176.17	176.20	176.28	176.35	176.43	176.38	176.33	176.24	176.21	176.16
1958	176.15	176.13	176.12	176.14	176.12	176.12	176.15	176.11	176.07	175.98	175.91	175.81
1959	175.75	175.75	175.79	175.92	176.06	176.11	176.12	176.12	176.10	176.10	176.13	176.12
1960	176.14	176.16	176.14	176.24	176.50	176.64	176.72	176.77	176.73	176.64	176.57	176.48
1961	176.38	176.31	176.33	176.36	176.42	176.44	176.46	176.45	176.43	176.38	176.32	176.24
1962	176.20	176.17	176.19	176.26	176.34	176.37	176.36	176.32	176.26	176.17	176.06	175.97
1963	175.89	175.85	175.85	175.94	176.02	176.06	176.04	176.03	175.98	175.90	175.80	175.71
1964	175.63	175.59	175.58	175.61	175.74	175.76	175.78	175.77	175.76	175.70	175.65	175.62
1965	175.60	175.62	175.67	175.77	175.94	176.00	176.02	176.04	176.07	176.10	176.07	176.09
1966	176.10	176.08	176.13	176.20	176.26	176.30	176.28	176.24	176.17	176.08	176.01	176.08
1967	176.07	176.07	176.06	176.23	176.35	176.45	176.50	176.48	176.40	176.34	176.34	176.32
1968	176.29	176.30	176.27	176.35	176.40	176.47	176.55	176.58	176.60	176.57	176.50	176.48
1969	176.47	176.47	176.45	176.54	176.70	176.82	176.94	176.95	176.86	176.78	176.73	176.64
1970	176.59	176.56	176.53	176.58	176.68	176.76	176.80	176.78	176.77	176.73	176.69	176.67
1971	176.63	176.62	176.68	176.76	176.86	176.94	176.96	176.96	176.90	176.84	176.76	176.75
1972	176.73	176.65	176.65	176.72	176.88	176.93	176.99	177.05	177.07	177.03	177.00	176.96
1973	176.98	176.95	176.98	177.10	177.20	177.30	177.30	177.29	177.21	177.13	177.04	177.00
1974	176.95	176.97	177.00	177.07	177.19	177.28	177.32	177.26	177.15	177.04	176.98	176.91
1975	176.87	176.86	176.87	176.92	177.06	177.14	177.15	177.10	177.07	176.95	176.87	176.82
1976	176.76	176.75	176.87	177.02	177.11	177.15	177.15	177.08	176.95	176.80	176.64	176.51
1977	176.42	176.38	176.44	176.56	176.57	176.55	176.56	176.54	176.53	176.50	176.50	176.51
1978	176.48	176.45	176.43	176.51	176.61	176.67	176.69	176.68	176.71	176.70	176.62	176.54
1979	176.51	176.48	176.54	176.71	176.88	176.95	176.98	177.00	176.96	176.88	176.83	176.81
1980	176.78	176.72	176.68	176.77	176.84	176.90	176.93	176.93	176.90	176.82	176.72	176.65
1981	176.59	176.56	176.60	176.67	176.75	176.80	176.82	176.81	176.80	176.73	176.66	176.59
1982	176.51	176.46	176.45	176.56	176.62	176.66	176.69	176.69	176.65	176.62	176.60	176.67
1983	176.67	176.66	176.68	176.76	176.90	177.02	177.02	176.98	176.93	176.87	176.77	176.74
1984	176.70	176.70	176.72	176.81	176.91	177.01	177.06	177.04	177.02	176.96	176.93	176.88
1985	176.88	176.86	176.98	177.14	177.24	177.25	177.23	177.19	177.20	177.16	177.19	177.20

1986	177.14	177.11	177.12	177.23	177.28	177.33	177.39	177.39	177.38	177.50	177.38	177.26
1987	177.18	177.10	177.06	177.07	177.06	177.07	177.04	176.99	176.90	176.79	176.70	176.68
1988	176.63	176.60	176.57	176.67	176.70	176.67	176.61	176.57	176.48	176.42	176.43	176.42
1989	176.38	176.33	176.32	176.41	176.44	176.56	176.57	176.54	176.47	176.34	176.27	176.18
1990	176.15	176.16	176.19	176.27	176.35	176.44	176.51	176.49	176.45	176.41	176.39	176.39
1991	176.36	176.31	176.33	176.48	176.60	176.66	176.64	176.59	176.48	176.40	176.38	176.40
1992	176.38	176.36	176.38	176.44	176.53	176.52	176.54	176.53	176.52	176.49	176.52	176.54
1993	176.54	176.51	176.48	176.58	176.70	176.82	176.91	176.88	176.83	176.76	176.70	176.64
1994	176.57	176.56	176.59	176.63	176.70	176.72	176.82	176.81	176.78	176.71	176.66	176.59
1995	176.53	176.49	176.47	176.49	176.58	176.64	176.63	176.64	176.55	176.46	176.44	176.41
1996	176.37	176.39	176.39	176.46	176.63	176.76	176.83	176.84	176.82	176.80	176.79	176.77
1997	176.79	176.82	176.89	176.95	177.07	177.13	177.19	177.16	177.12	177.02	176.89	176.78
1998	176.74	176.71	176.74	176.89	176.91	176.90	176.88	176.80	176.68	176.55	176.44	176.36
1999	176.27	176.28	176.24	176.25	176.28	176.34	176.40	176.36	176.24	176.14	176.04	175.99
2000	175.92	175.87	175.90	175.92	176.00	176.10	176.13	176.13	176.09	175.98	175.89	175.81
2001	175.77	175.78	175.78	175.85	175.95	176.06	176.05	176.03	176.01	176.03	176.05	176.05
2002	175.99	175.95	175.99	176.06	176.19	176.29	176.33	176.32	176.24	176.14	176.01	175.91
2003	175.82	175.75	175.73	175.82	175.92	176.00	176.04	176.02	175.94	175.87	175.89	175.90
2004	175.87	175.84	175.90	175.98	176.12	176.31	176.37	176.33	176.28	176.15	176.10	176.08
2005	176.08	176.10	176.10	176.14	176.19	176.21	176.19	176.17	176.09	176.00	175.93	175.88
2006	175.88	175.92	175.93	176.01	176.09	176.14	176.14	176.13	176.04	175.99	175.94	175.98
2007	176.00	175.91	175.92	176.02	176.06	176.08	176.05	176.00	175.95	175.88	175.77	175.68
2008	175.70	175.76	175.78	175.92	176.04	176.16	176.24	176.22	176.18	176.09	176.00	175.97
2009	176.01	176.01	176.09	176.20	176.34	176.42	176.44	176.44	176.37	176.29	176.27	176.22
2010	176.15	176.11	176.09	176.11	176.13	176.19	176.26	176.24	176.16	176.07	175.96	175.86
2011	175.81	175.78	175.81	175.91	176.10	176.21	176.26	176.24	176.13	176.08	176.07	176.04
2012	175.99	175.96	176.00	176.03	176.05	176.07	176.04	175.97	175.86	175.74	175.68	175.61
2013	175.57	175.61	175.63	175.75	175.93	176.05	176.09	176.08	176.04	176.01	176.01	175.97
2014	175.95	175.95	175.95	176.06	176.27	176.38	176.46	176.48	176.51	176.54	176.54	176.53
2015	176.51	176.50	176.48	176.53	176.59	176.69	176.73	176.72	176.70	176.58	176.54	176.55
2016	176.57	176.56	<u>176.61</u>	176.77	176.82	176.84	176.84	176.82	176.78	176.69	176.59	176.51
2017	176.47	176.48	176.53	176.66	176.80	176.88	176.99	177.00	176.93	176.87	176.85	176.79
2018	176.73	176.74	176.76	176.79	176.92	176.98	176.98	176.95	176.94	176.90	176.86	176.83
2019	176.81	176.83	176.86	176.96	177.17	177.32	177.37	177.32	177.27	177.29	177.26	177.25
2020	177.26	177.25	177.22	177.30	177.38	177.45	177.46	177.42	177.34	177.25	177.20	177.14
2021	177.07	176.99	176.95	176.95	176.95	176.93	177.00	177.02	176.93	176.91	176.77	176.69

Supplemental SB: Landslide information

Table SB1 provides unit descriptions for select landslide features shown in the examples of this article. The comprehensive list of landslide units and descriptions can be found in [71].

Table SB1. Landslide features described in this paper 1

Landslide feature	Abbreviation	Description
<u>Deposits</u>		
Landslide deposits	DEP1, DEP2	DEP1 typically lobate with well-defined headscarp; inferred younger or more active than DEP2, which typically has more subdued features than DEP1; DEP2 inferred to be older or less active, or thinly covered by slope wash or colluvium
Shallow landslide complexes	SLC	Complexes of shallow slope failures and flows; exhibited evidence of recent slope movement on either, or both, of the 2012 and 2015 aerial imagery
Older shallow landslide complexes	OSLC	Similar to SLC, but on completely forested to partly re-vegetated slopes; slightly more subdued, geomorphic expression than SLC
Alluvial fans	AF	Alluvial fans deposited by sand flows formed near shoreline or at the base of inland bluffs; mapped using the LeelanauCo 2015 topography; areas of recently active depositional areas on some alluvial fans (RADAAF) mapped using the 2012 HRO
Coalesced alluvial fans	CAF	Areas where two or more alluvial fans are coalesced; typically near shoreline
Colluvial aprons	CA	Broad areas of colluvial deposits forming an apron on the lower slope
Detached and displaced soil block zones	DDSBZ	Areas of detached and/or displaced soil blocks in close proximity to source area; equivalent to a DEP1
Clustered soil blocks	CSB	Area of clustered soil blocks with a wider block spacing than DDSBZ
<u>Source Areas</u>		
Narrow flow source areas	NFSA	Source area of alluvial fan or deposit sediments is solely narrow ravines or gullies
Flow source area shallow landslide complexes	FSASLC	Shallow landslide complex within larger drainage basin forming the primary source area of sand flows
Flow travel path channels	FTPC	Drainage channels of sand flows connecting source areas to alluvial fans or deposits

¹ Modified from information in Ashland (2022) [71]

Figure SB1 shows the views of the northwest point of South Manitou Island (example 1) and the southwest point of South Manitou Island (example 2) for each date of imagery. Visual analysis of each image provides additional information regarding the geomorphic changes that may have occurred for the landslide features in the view, which may be extrapolated to other similar features along the western bluff of South Manitou Island.



Figure SB1. View of landslide and other geomorphic features from each date of imagery at the northwest (example 1) and southwest (example 2) points of South Manitou Island.

Supplemental SC: Analysis of wind direction and water currents

Analysis of wind direction focused on the seasonality of wind strength and direction as a potential driver of aeolian transport of sand and other sediments on South Manitou Island. Understanding of the prevailing wind direction for specific times of the year, together with other environmental factors affecting erosion, such as precipitation events and ice, aided the study's investigation of the aeolian landforms on the island. This analysis was particularly relevant to assessment of sand dune movement and aeolian accretion factors. Figure SC1 shows a series of compass rose diagrams that indicate the average wind speed and direction recorded at Traverse City FAA Airport, MI between 1961 and 1990 [100]. The data used in these diagrams do not reflect wind gusts. From these diagrams it can be interpreted that the wind generally blows between 5 and 10 mph from the south-southwest during the late fall through winter months (October through January). In late winter (March) through early spring (April – May) the wind direction changes from the southwest to the north. Winds are highly variable, but strong in May, before subsiding during the summer (June–September) and returning to the southwesterly direction that is seen through late fall.

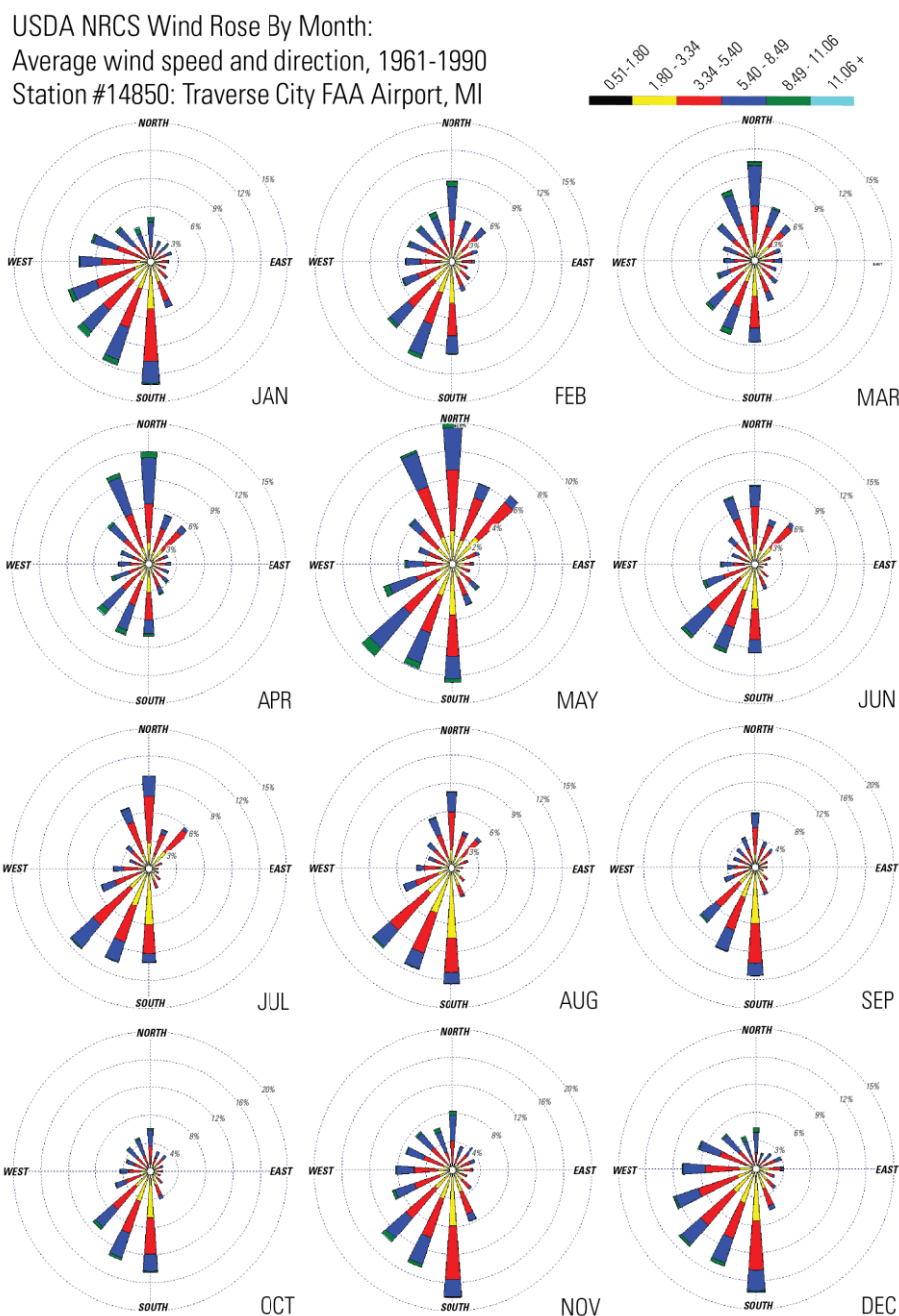


Figure SC1. Compass rose diagrams indicate average monthly wind speed and direction recorded at Traverse City FAA Airport, MI, between 1961 and 1990.

A second factor that greatly impacts erosion and deposition in coastal settings is the strength and direction of water currents. Currents strength and direction are affected by wind speed and direction, as well as by the proximity and distribution of land masses. Currents in the vicinity of South Manitou Island and other parts of Sleeping Bear Dunes National Lakeshore were analyzed qualitatively through review of the NOAA GLERL depth-averaged lake current maps [101]. Reproduction of these maps (figure SC2) enabled visual interpretation of seasonal water current conditions around South Manitou Island and provided better understanding about lacustrine erosion and deposition conditions. During the winter months, strong currents flow from the north and northwest. In spring, current strength diminishes and they switch direction, beginning to flow from the southwest. Current strength diminishes more over the summer until September, before increasing again in the fall. In fall, currents strengthen first between South Manitou Island and

North Manitou Island where they flow from the northwest, and then between the islands and the mainland where they flow from the northeast. Quantitative modeling of lake currents is beyond the scope of this project, but this basic understanding aids in determining potential zones of erosion and deposition.

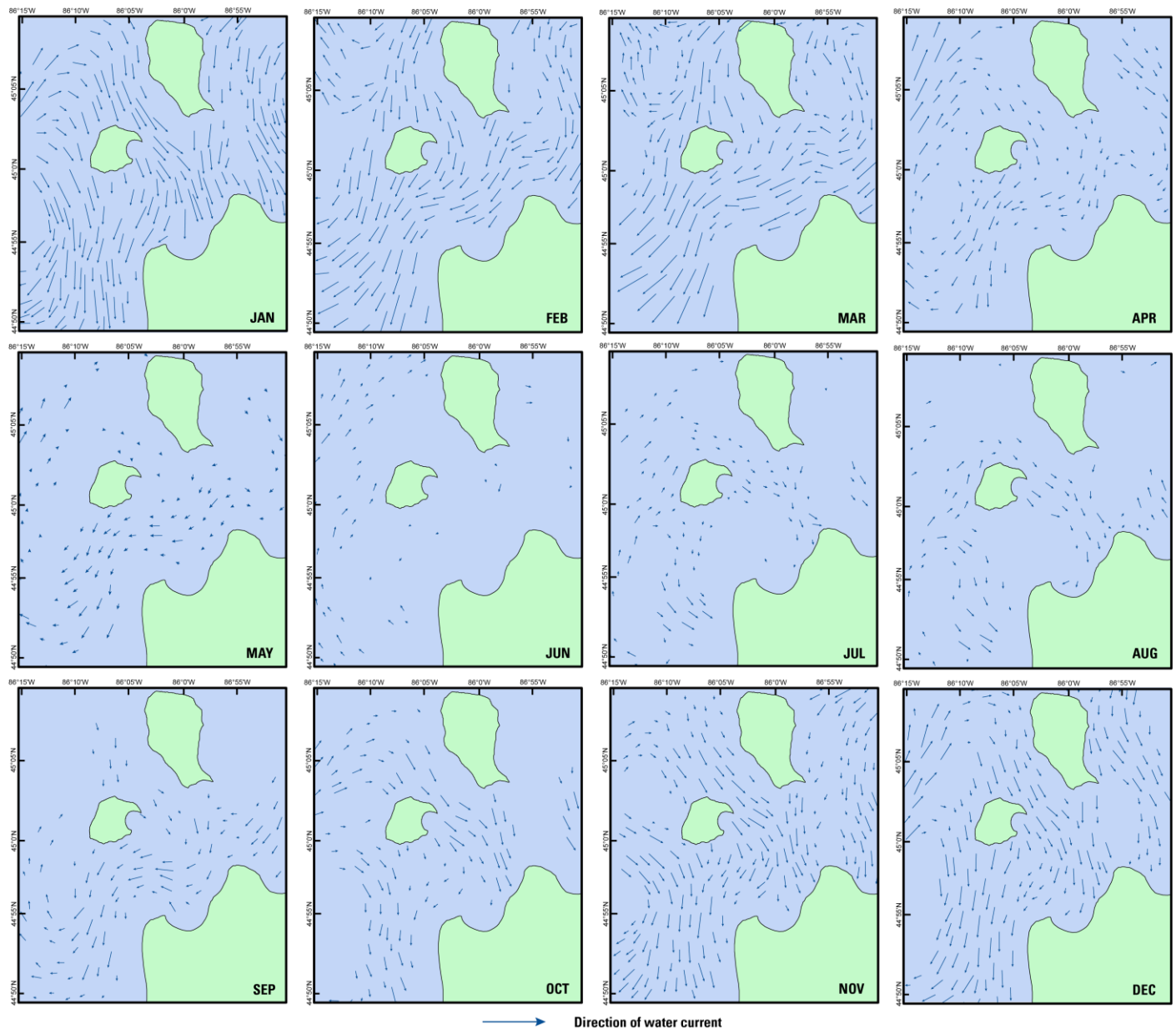


Figure SC2. Current maps indicate the direction and relative strength of water currents in the vicinity of South Manitou Island. Data for the maps was acquired from the NOAA GLERL depth-averaged lake current maps, which were created from lake current data in January 2013.

Supplemental SD: Ground control for SfM analysis

Table SD1 provides the GCPs used to geographically register the Structure from Motion (SfM) model developed from historical aerial imagery.

Table SD1. Ground control points (GCPs) used to geographically register the SfM model. Datum is NAD83(2011) StatePlane Michigan North, FIPS 2111 (Intl Feet) + NAVD88 geoid 12B.

Name	Easting	Northing	Elevation (m)
FID25	26,480,900	84,531.4	177.9
FID2	26,476,000	89,542.6	182.7
FID290	26,483,800	92,691.1	184.9
FID4	26,471,100	80,390.1	205.7
FID288	26,470,800	95,698.9	215.8
FID284	26,465,600	84,469.1	286.9