The case for geomorphic impairment of MN Point by the Duluth Ship Canal

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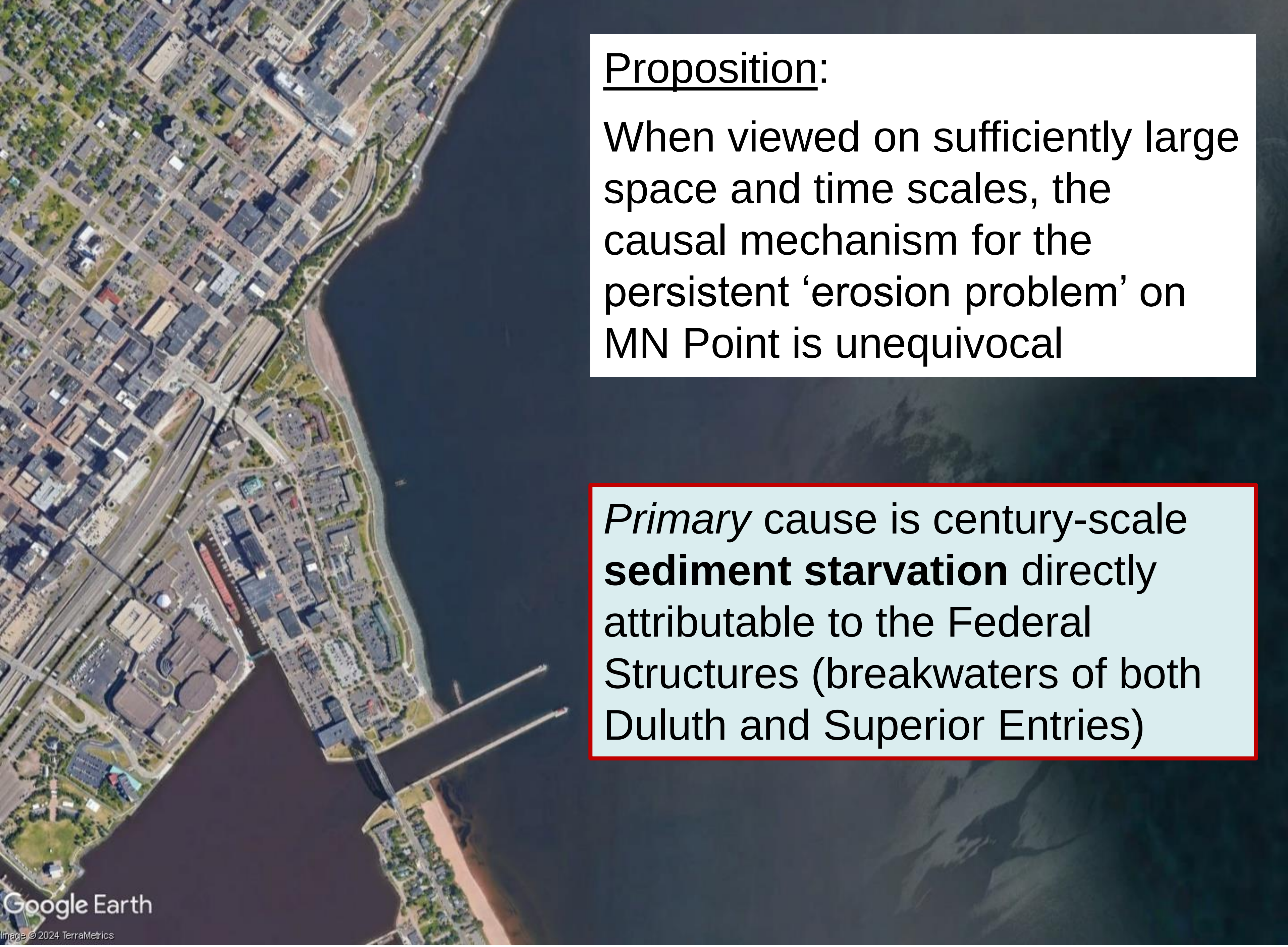
Photo: USACE (2021)



Proposition:

When viewed on sufficiently large space and time scales, the causal mechanism for the persistent ‘erosion problem’ on MN Point is unequivocal

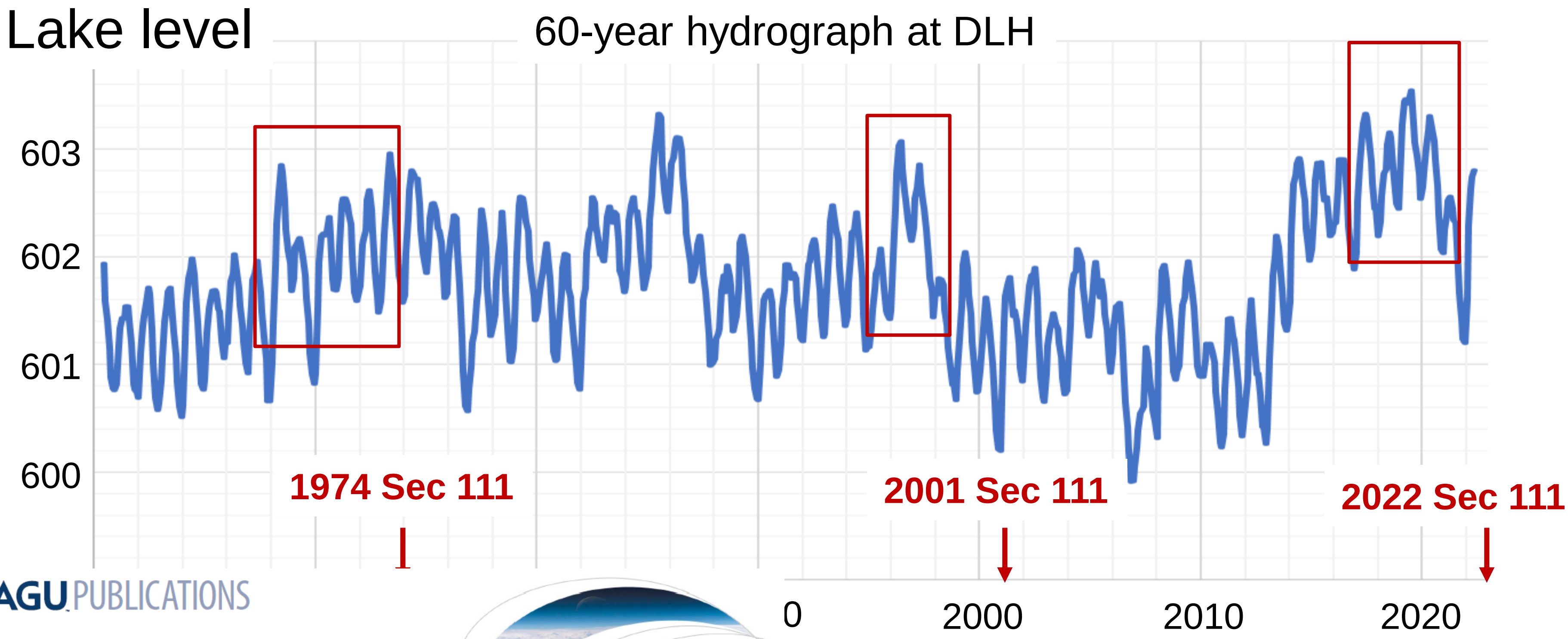
Primary cause is century-scale **sediment starvation** directly attributable to the Federal Structures (breakwaters of both Duluth and Superior Entries)

Overview

- **Lake level** changes: Century/millennial scale vs. decadal scale
- Sediment **sources** and sinks in the far western arm of Lake Superior
- Long-term changes in sediment source
- Large-scale lake **circulation** and associated **littoral drift**: Sediment pathways
- Sediment **sink**: MN Point and its precursor
- Recent **north-shore sediment supply**

Approach

- **Summarize** our understanding of the system
  - Defer supporting **evidence** for later discussion
- Frequent appeal to **Occam's Razor**
- Acknowledge **confirmation bias**
- Encourage construction of **alternative hypotheses**



AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2013GL058679

Key Points:
- A climatically driven decadal oscillation dominates the regional water cycle
- The oscillation is governed by (P − E) and a stage-dependent runoff flux
- A recent change in oscillation may mark the onset of a new hydroclimatic regime

Supporting Information:
- Readme
- Relationship between total evaporation (May-November) and summer evaporation (June, July and August) for the in-lake evaporation pan.
- Spectral analysis (FFT) of the time-series for: annual water level (A), annual change in water level (B), annual precipitation minus evaporation (C), annual precipitation (D), annual evaporation (E), annual water level pre-1998 (F), annual water level post-1998 (G) in the NHLD. (data detrended; cs2Hann window; PSD SSA: power spectral density as sum squared amplitude) Horizontal lines indicate the 50% (yellow), 90% (green), 95% (blue) and 99% (red) significance levels (white noise

Decadal oscillation of lakes and aquifers in the upper Great Lakes region of North America: Hydroclimatic implications

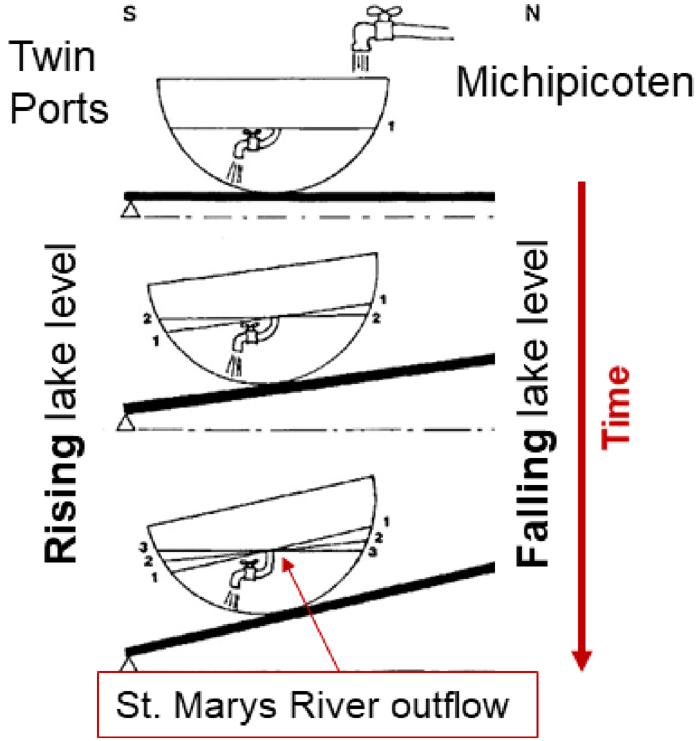
C. J. Watras[1,2], J. S. Read[3], K. D. Holman[4], Z. Liu[5,6], Y.-Y. Song[6], A. J. Watras[7], S. Morgan[8], and E. H. Stanley[2]

[1]Wisconsin Department of Natural Resources, University of Wisconsin-Madison Trout Lake Research Station, Boulder Junction, Wisconsin, USA, [2]Center for Limnology, University of Wisconsin-Madison, Madison, Wisconsin, USA, [3]Center for Integrated Data Analytics, U.S. Geological Survey, Middleton, Wisconsin, USA, [4]Center for Climatic Research, University of Wisconsin-Madison, Madison, Wisconsin, USA, [5]Department of Atmospheric and Oceanic Sciences and Center for Climatic Research, University of Wisconsin-Madison, Madison, Wisconsin, USA, [6]Department of Atmospheric and Ocean Sciences, Peking University, Beijing, China, [7]Department of Electrical and Computer Engineering, University of Wisconsin-Madison, Madison, Wisconsin, USA, [8]Wisconsin Valley Improvement Company, Wausau, Wisconsin, USA

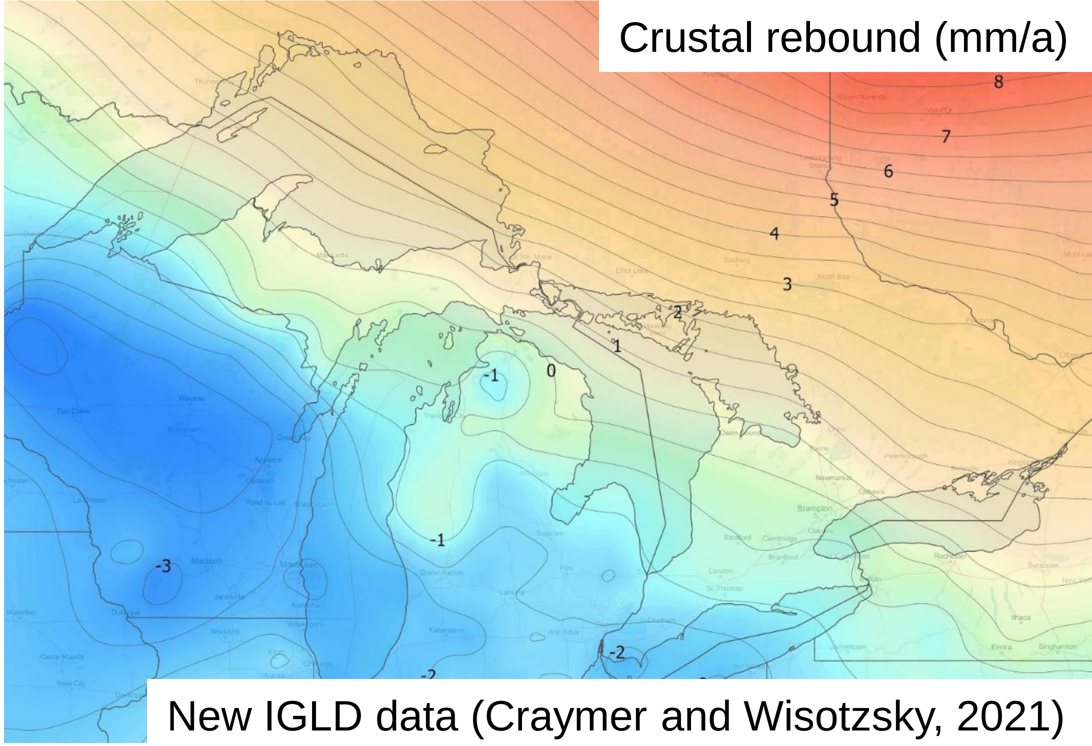
Abstract We report a unique hydrologic time series which indicates that water levels in lakes and aquifers across the upper Great Lakes region of North America have been dominated by a climatically driven, near-decadal oscillation for at least 70 years. The historical oscillation (~13 years) is remarkably consistent among small seepage lakes, groundwater tables, and the two largest Laurentian Great Lakes despite substantial differences in hydrology. Hydrologic analyses indicate that the oscillation has been governed primarily by changes in the net atmospheric flux of water (*P* − *E*) and stage-dependent outflow. The oscillation is hypothetically connected to large-scale atmospheric circulation patterns originating in the midlatitude North Pacific that support the flux of moisture into the region from the Gulf of Mexico. Recent data indicate an apparent change in the historical oscillation characterized by an ~12 years downward trend beginning in 1998. Record low water levels region wide may mark the onset of a new hydroclimatic regime.

These **climate-driven** fluctuations are superimposed on a long-term (millennial scale) lake-level rise driven by lithospheric dynamics, i.e. **differential post-glacial rebound**, and shifting drainage outlets.

Lake level (millennial scale)



Larsen (1987); extension of ideas in Goldthwait (1908)



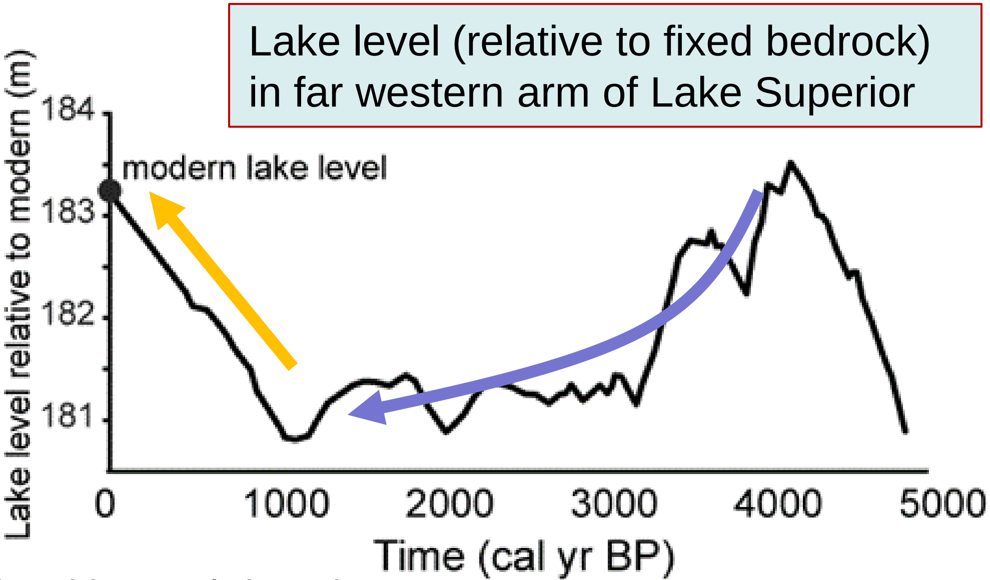
1200 BP – present:

Rapid rise (2.5 – 3.0 mm/yr)

4200 BP – 1200 BP:

Generally falling to stable

Some uncertainty in timing and magnitude; trends certain

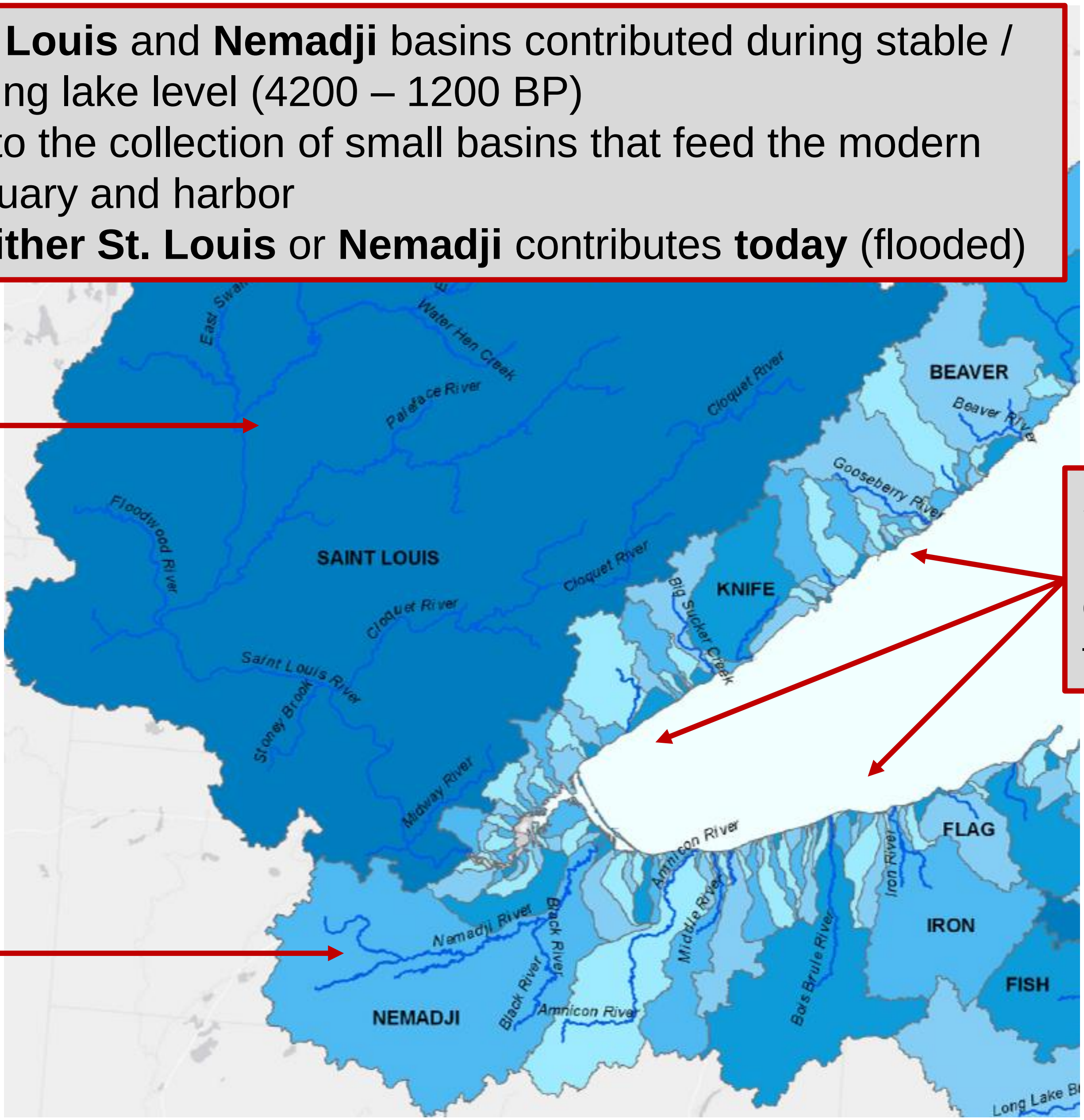


Breckenridge et al. (2016)

Sediment (sand & gravel) sources: **Riverine** input

- **St. Louis** and **Nemadji** basins contributed during stable / falling lake level (4200 – 1200 BP)
- Ditto the collection of small basins that feed the modern estuary and harbor
- **Neither St. Louis** or **Nemadji** contributes **today** (flooded)

We are not concerned with **mud**



Smaller basins feeding north and south shores contributed continuously from 4200 BP – present

Sediment sources: **Bluff retreat (erosion)**

South shore

- **South-shore** bluffs immediately east of Superior are composed entirely of **glacial sediments** (till)
- Fundamentally driven by **long-term** (millennial scale) **lake-level rise**
- Homogeneous
- **High** retreat rate; representative rate ~**50 cm/yr**
- Mud-dominated material (~15% sand)

- Bluff erosion likely was insignificant during stable / falling lake level (4200 – 1200 BP)
- Bluff erosion ignited when lake level began to rise rapidly (1200 BP – present)

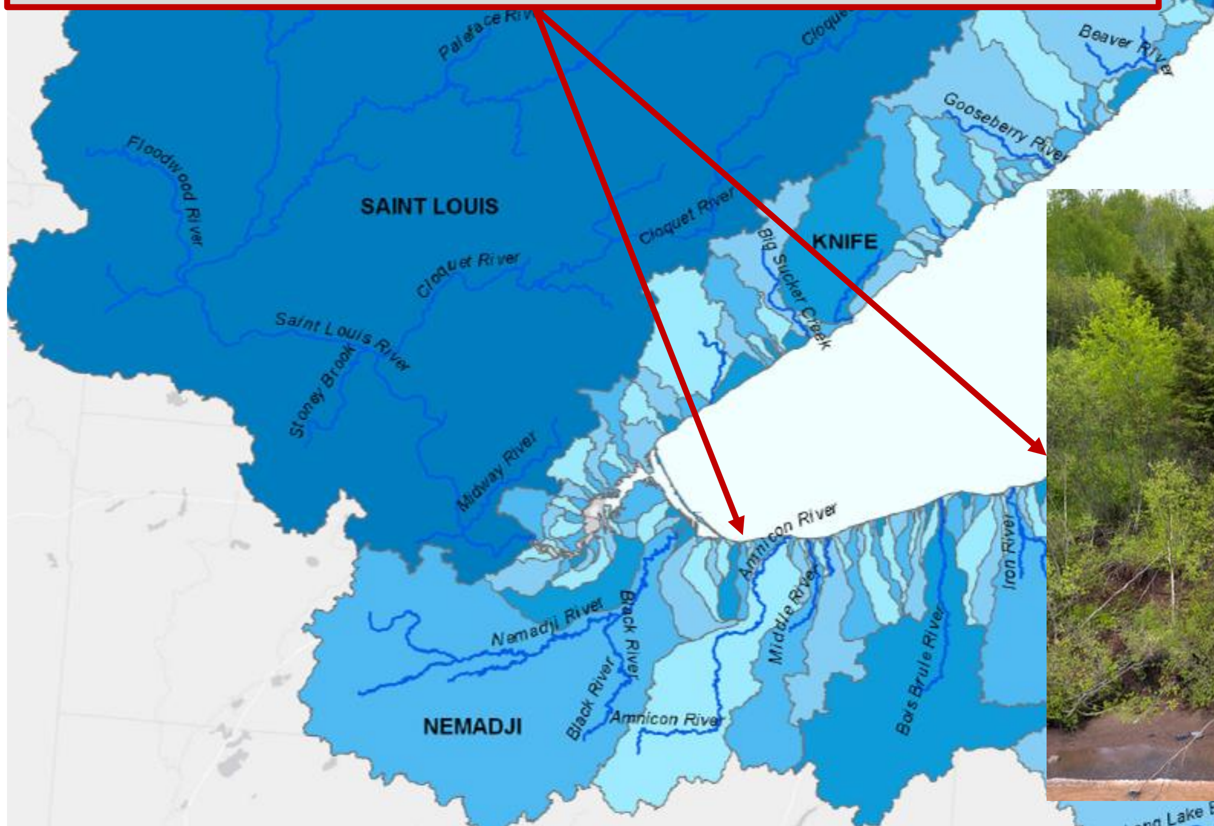
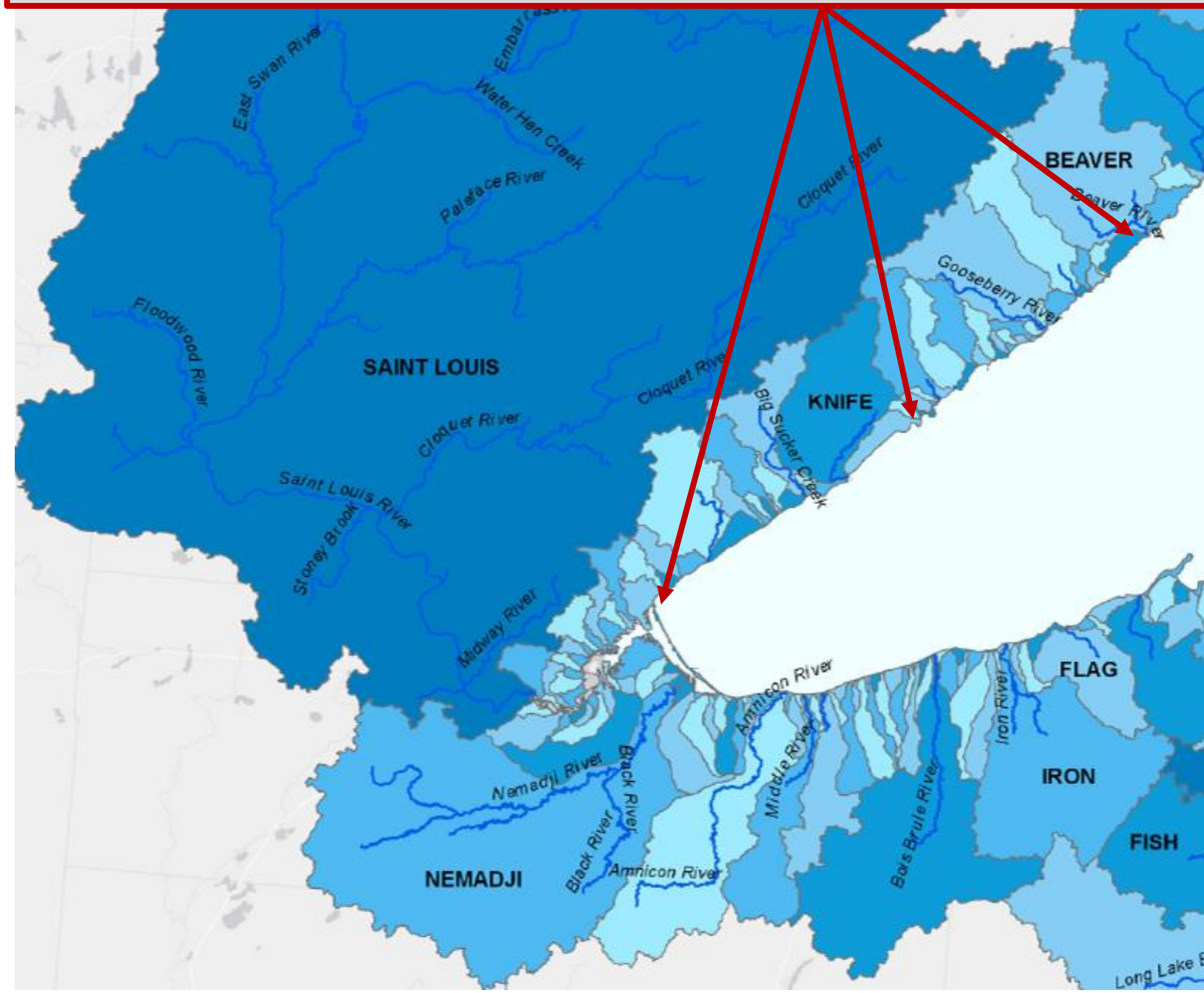


Image: Star Tribune

Sediment sources: **Bluff retreat (erosion)**

North shore

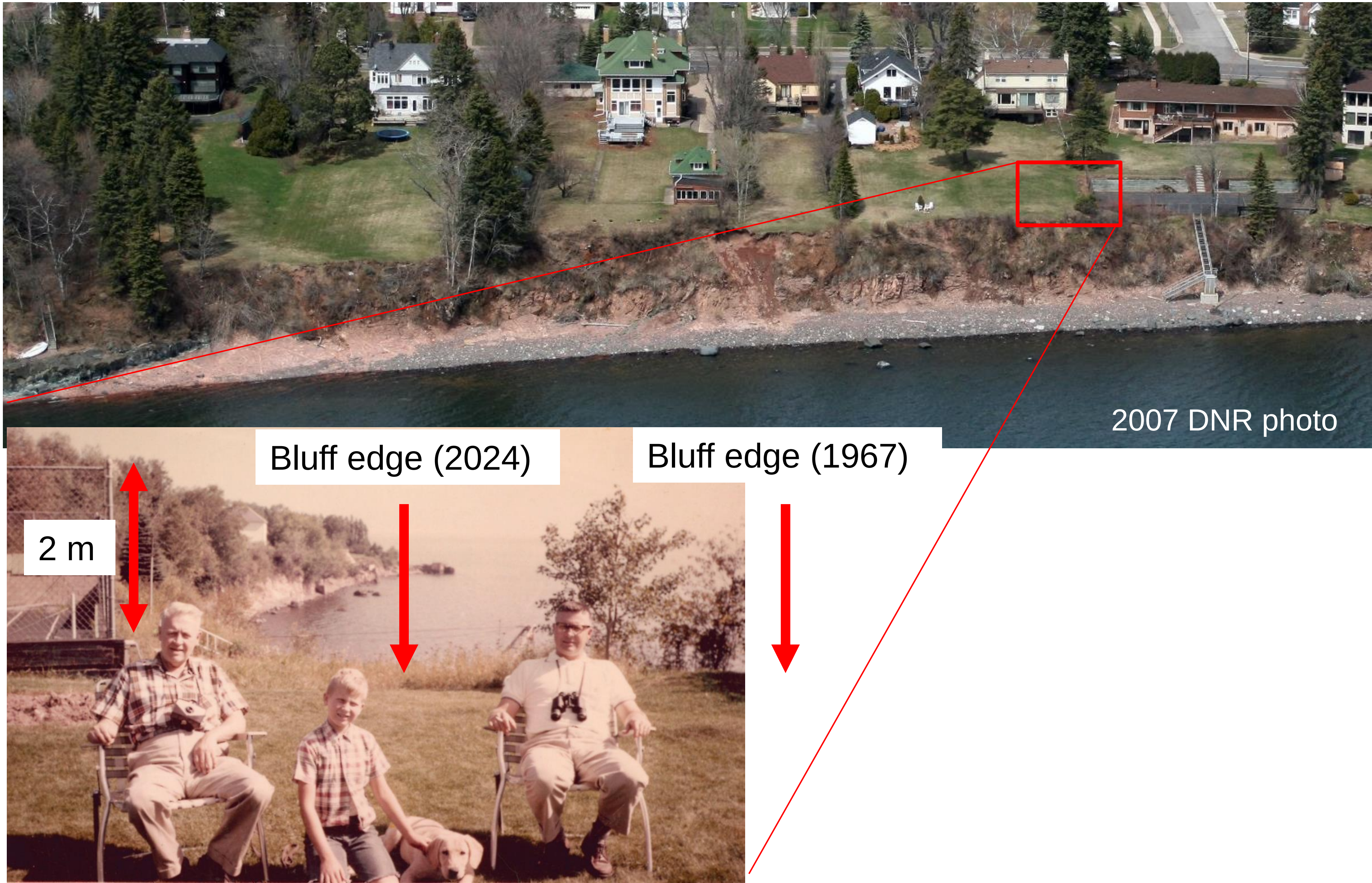
- Entire north shore is **bedrock cored** w/ veneer of **glacial sediments** (till)
- Fundamentally driven by long-term (millennial scale) lake-level rise
- Lower retreat rates (limited by **bedrock weathering**)
- Representative retreat rate ~**5 cm/yr**



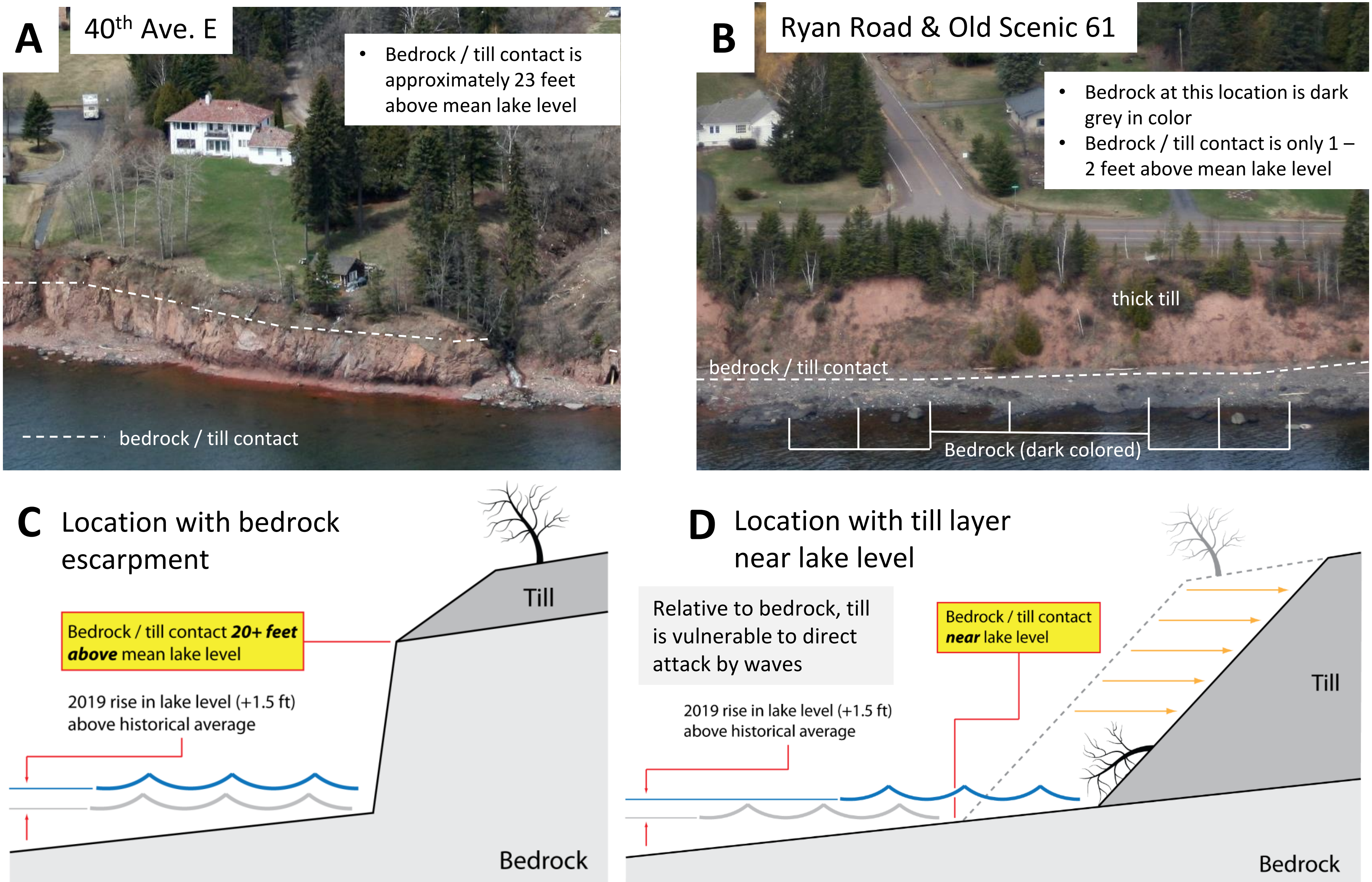
- Bluff erosion likely was insignificant during stable / falling lake level (4200 – 1200 BP)
- Bluff erosion ignited when lake level began to rise rapidly (1200 BP – present)

North Shore Bluff Retreat

5100 Block, East Duluth

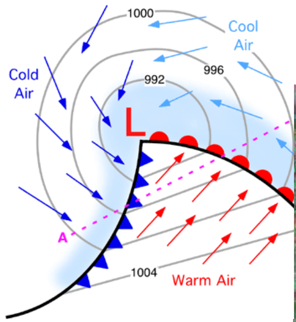


North Shore Bluff Retreat: **Variability**

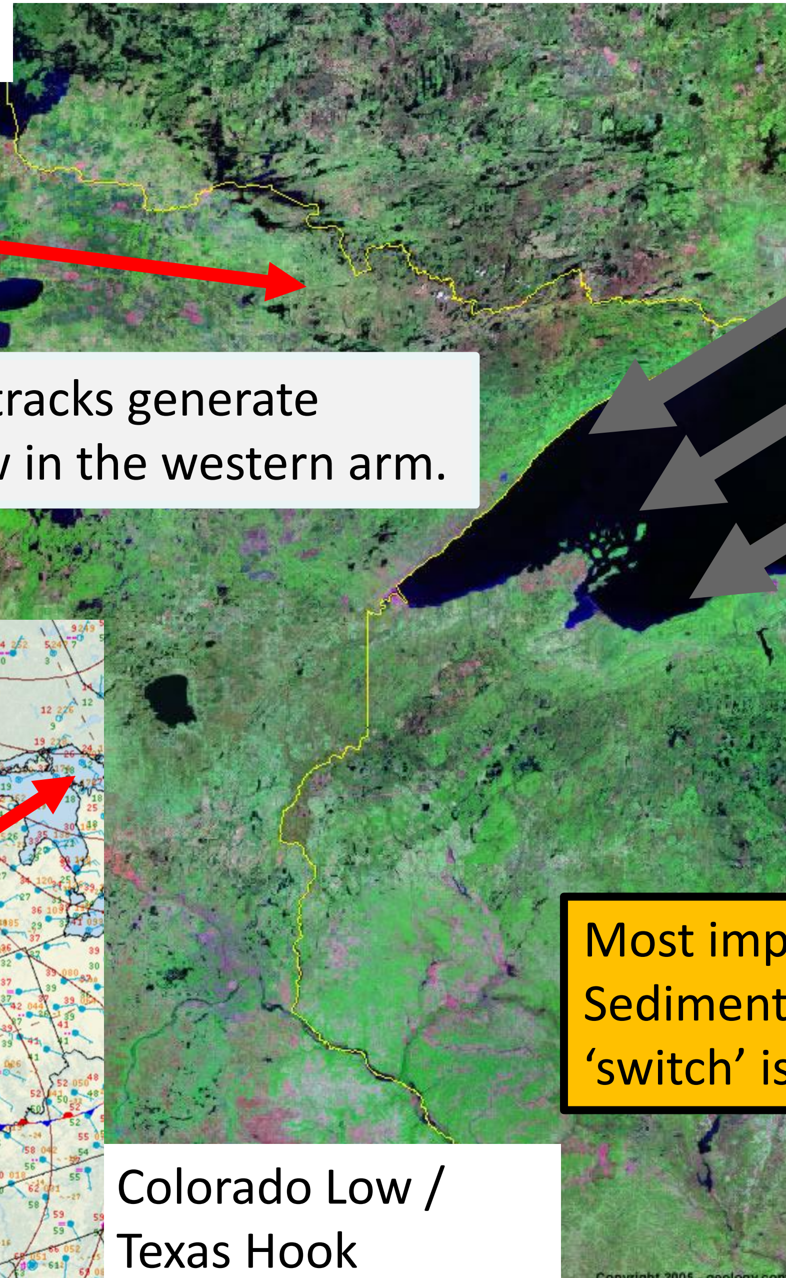


Swenson (2022)

Transport pathways: Sand and gravel transported during ‘storms’ (cyclones)

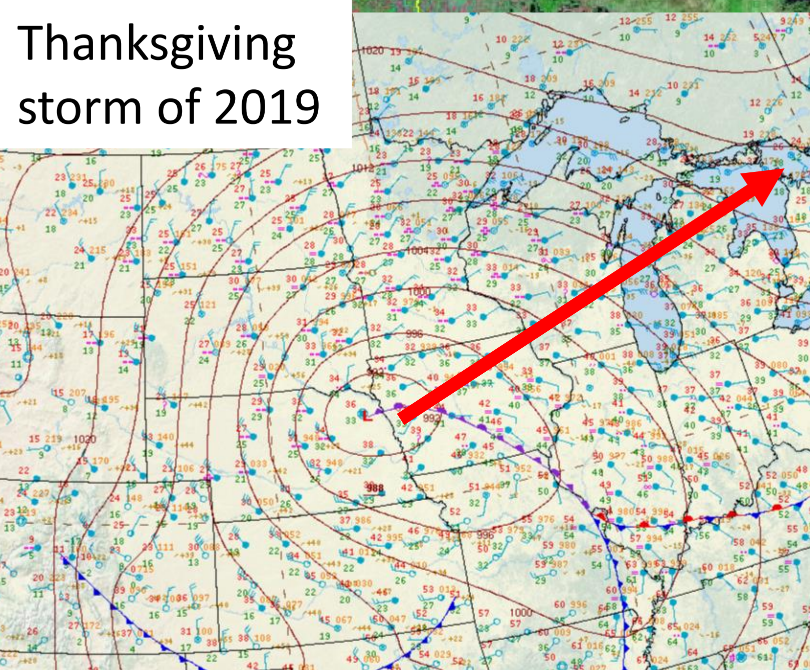


Alberta Clipper



Nearly all extratropical cyclone tracks generate period of **long-fetch**, **E – NE** flow in the western arm.

Thanksgiving storm of 2019



Colorado Low / Texas Hook

Most important, by far. Sediment transport ‘switch’ is fully ON.

Fig. 3. Conceptual diagram of the resulting flow. Surface wind stress from the northeast acts uniformly across the surface of the water and dominates flow in shallow areas. An opposing pressure gradient works throughout the water column and dominates flow in deeper areas, driving the plume off-shore. [Color figure can be viewed at wileyonlinelibrary.com]

Lake circulation on the 'front end' of extratropical cyclones

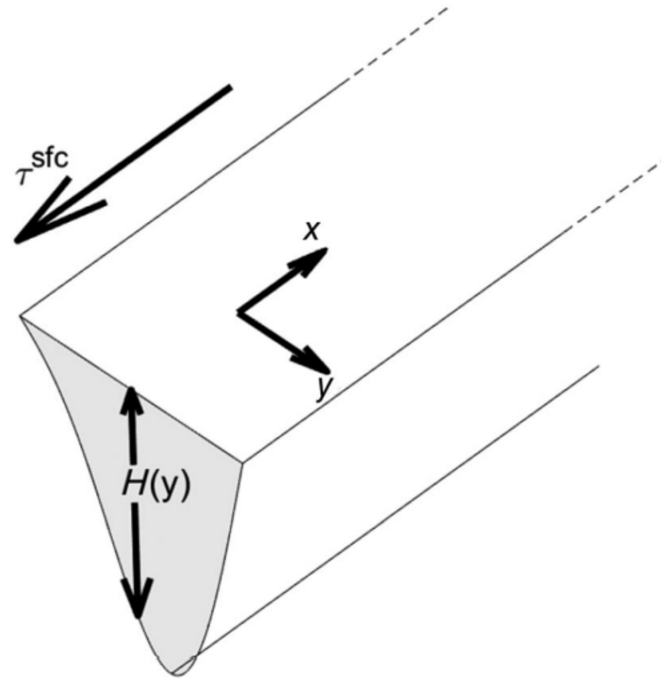


Fig. 2. Schematic figure of analytical model setting. The along-channel dimension is x, and the cross-channel dimension is y, with the sides of the channel at $y = \pm L$. Bottom bathymetry is designated $H(y)$. The wind stress τ is entirely in the along-channel direction.

LIMNOLOGY and OCEANOGRAPHY

ASLO

Limnol. Oceanogr. 64, 2019, 1309–1322

doi: 10.1002/lno.11117

The wind-driven formation of cross-shelf sediment plumes in a large lake

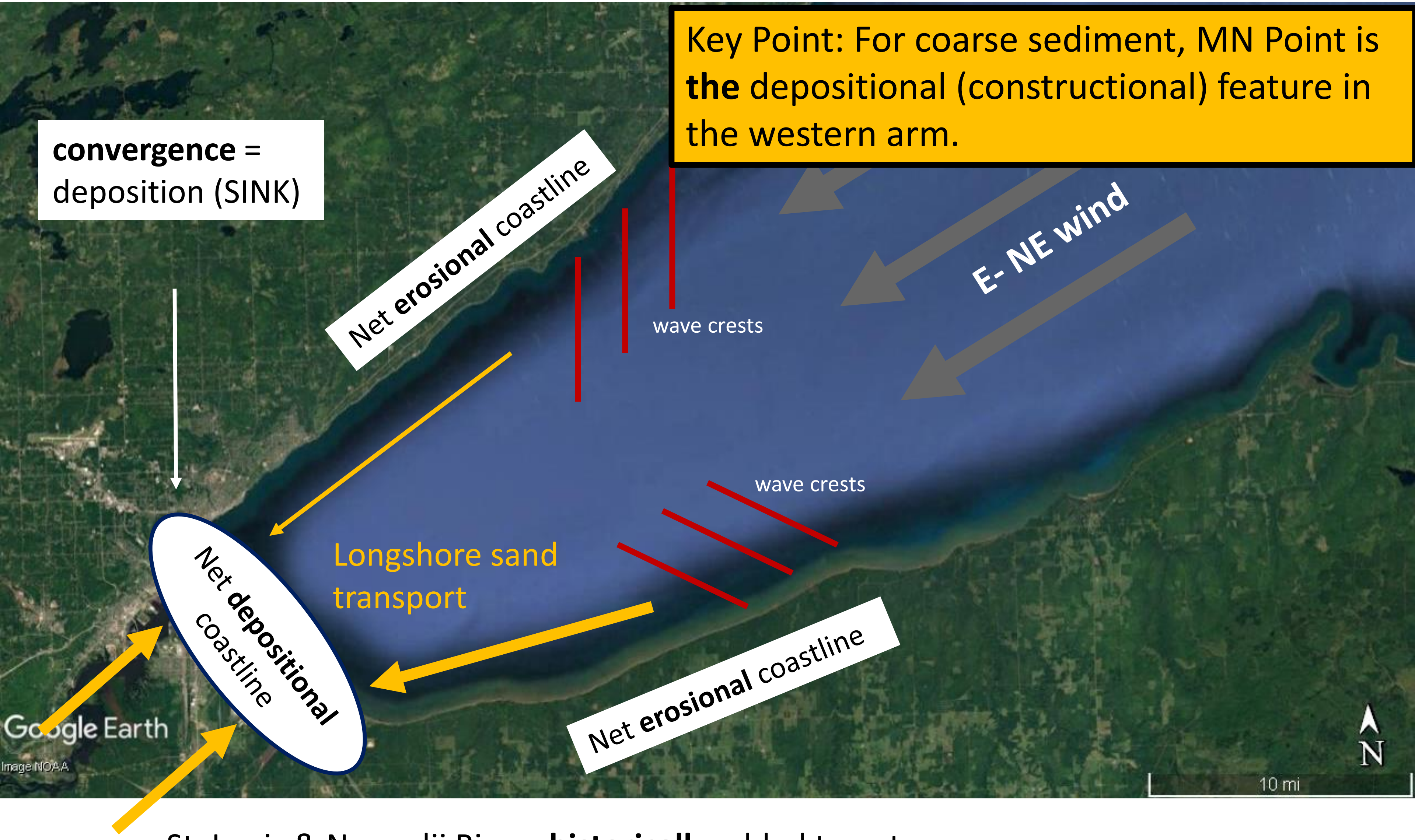
Paul McKinney,[1*] **Jay Austin**,[2] **Gills Fai**[3]

[1]National Research Council, U.S. Environmental Protection Agency, Office of Research and Development, Mid-Continent Ecology Division, Duluth, Minnesota
[2]Large Lakes Observatory and Department of Physics and Astronomy, University of Minnesota Duluth, Duluth, Minnesota
[3]Department of Physics and Astronomy, University of Minnesota Duluth, Duluth, Minnesota

Sydor, M. 1979. Red clay turbidity and its transport in Lake Superior. Great Lakes National Program Office, US Environmental Protection Agency, Region V.

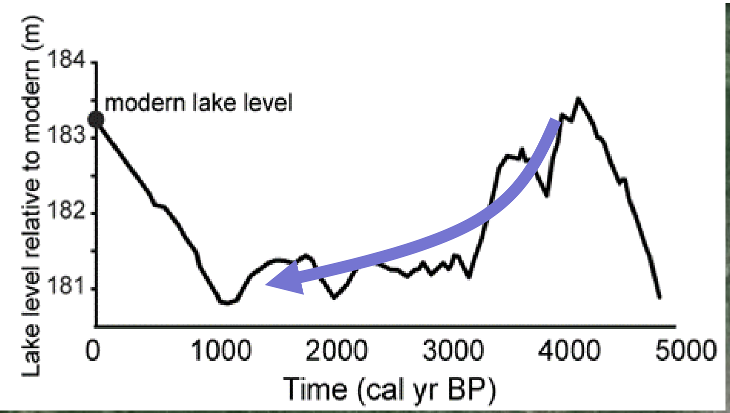
Offshore circulation patterns transport **mud** (plumes)
Corresponding **nearshore** circulation drives littoral transport of **sand / gravel**

Transport pathways: Net **longshore transport** of sand near Duluth



St. Louis & Nemadji Rivers **historically** added to net sediment convergence; not today (drowned)

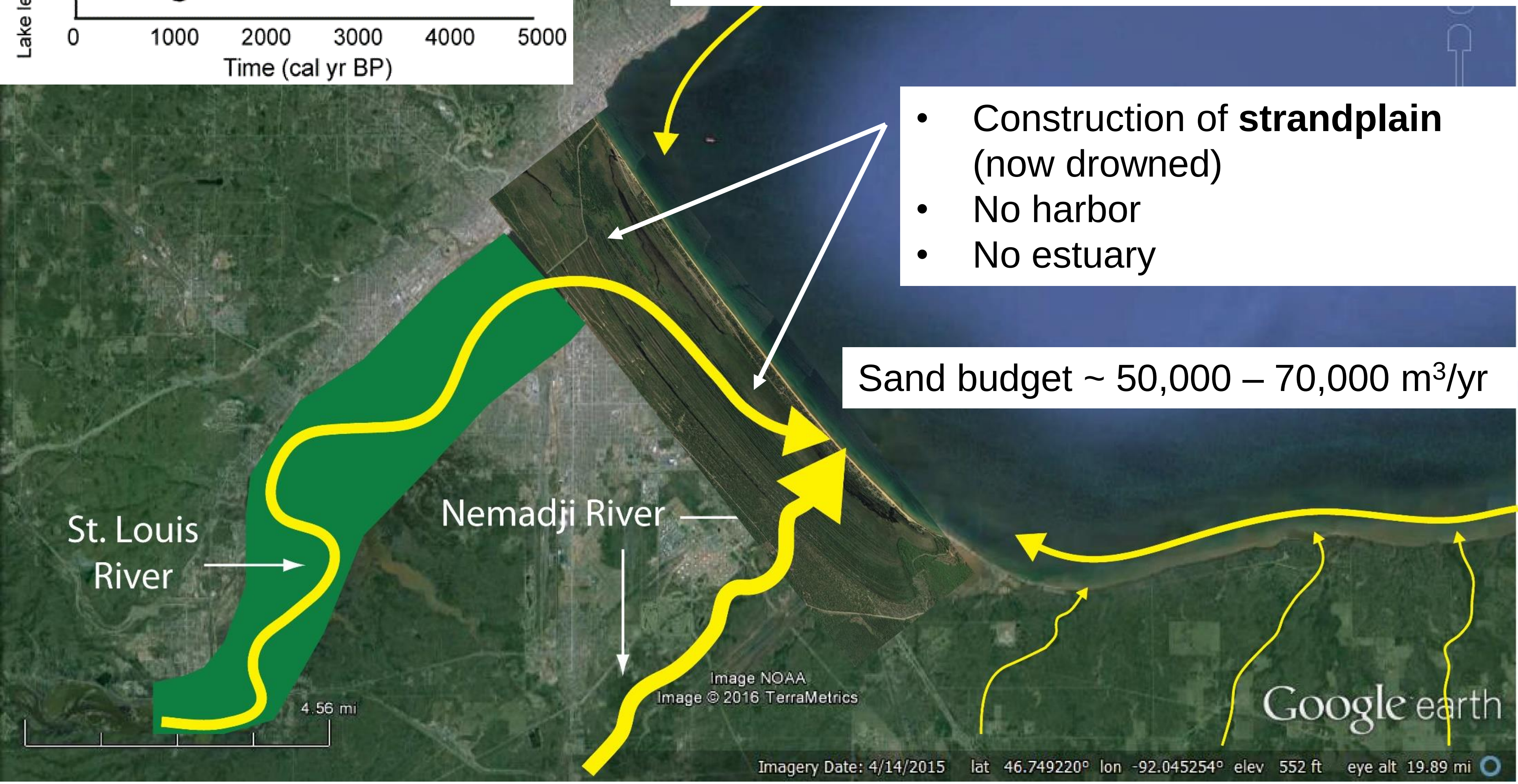
(Genetic model) **4500 – 1200** years BP: Slow lake-level **fall**



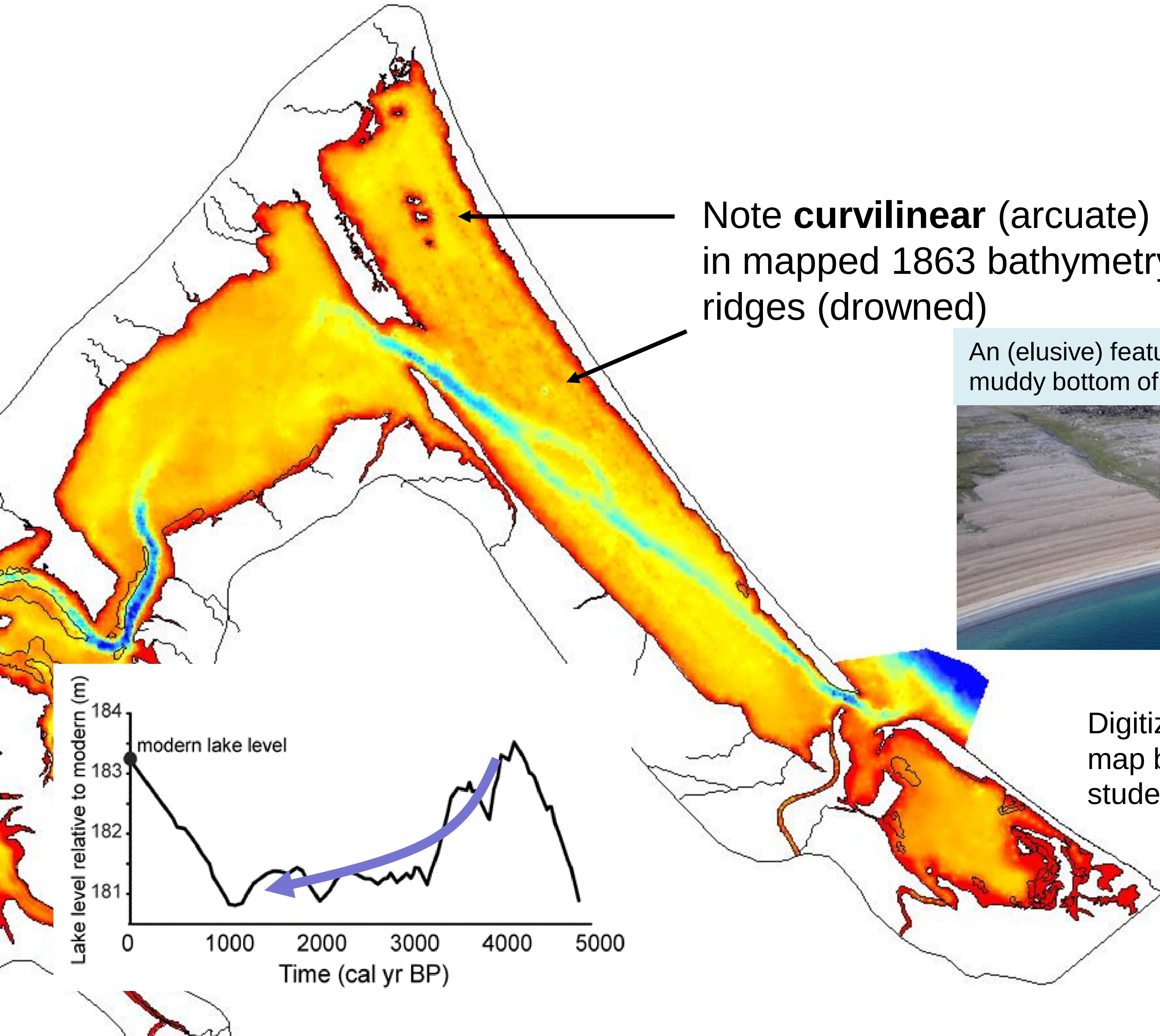
- Sand supply from **St. Louis** and **Nemadji** Rivers (connected to lake)
- Longshore transport of sand from north- and south-shore **rivers**
- Minor bluff erosion

- Construction of **strandplain** (now drowned)
- No harbor
- No estuary

Sand budget ~ 50,000 – 70,000 m^3/yr



Supporting evidence for **strandplain** beneath harbor



Note **curvilinear** (arcuate) **features** in mapped 1863 bathymetry = beach ridges (drowned)

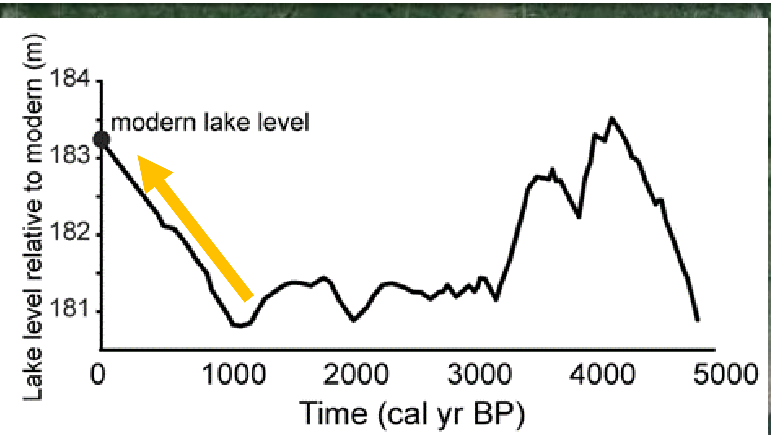
An (elusive) feature like this underlies the muddy bottom of the Duluth / Superior harbor

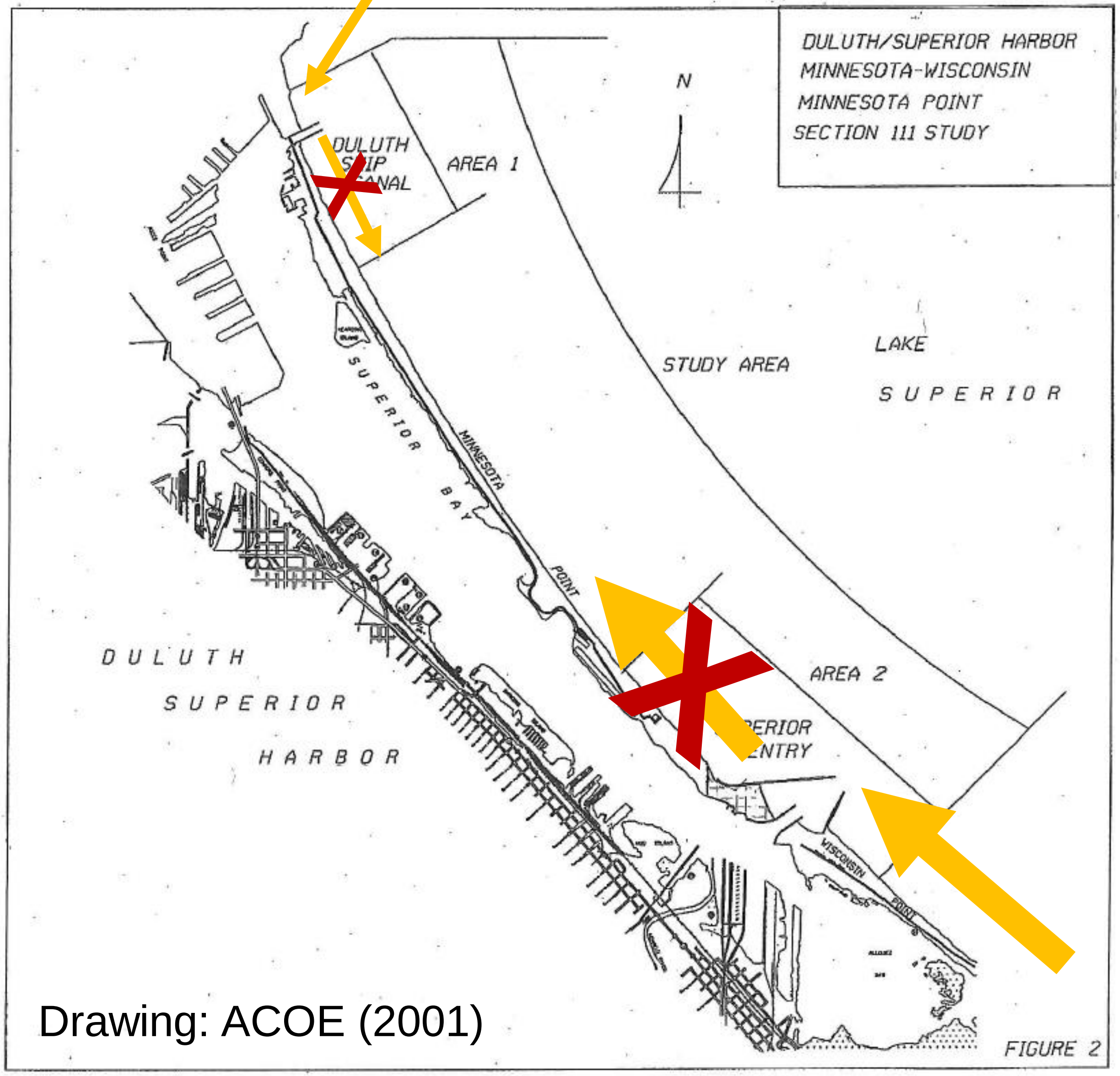
Digitization of 1863 Hearding map by Andy Breckenridge and students


Google Earth
Image © 2024 Airbus

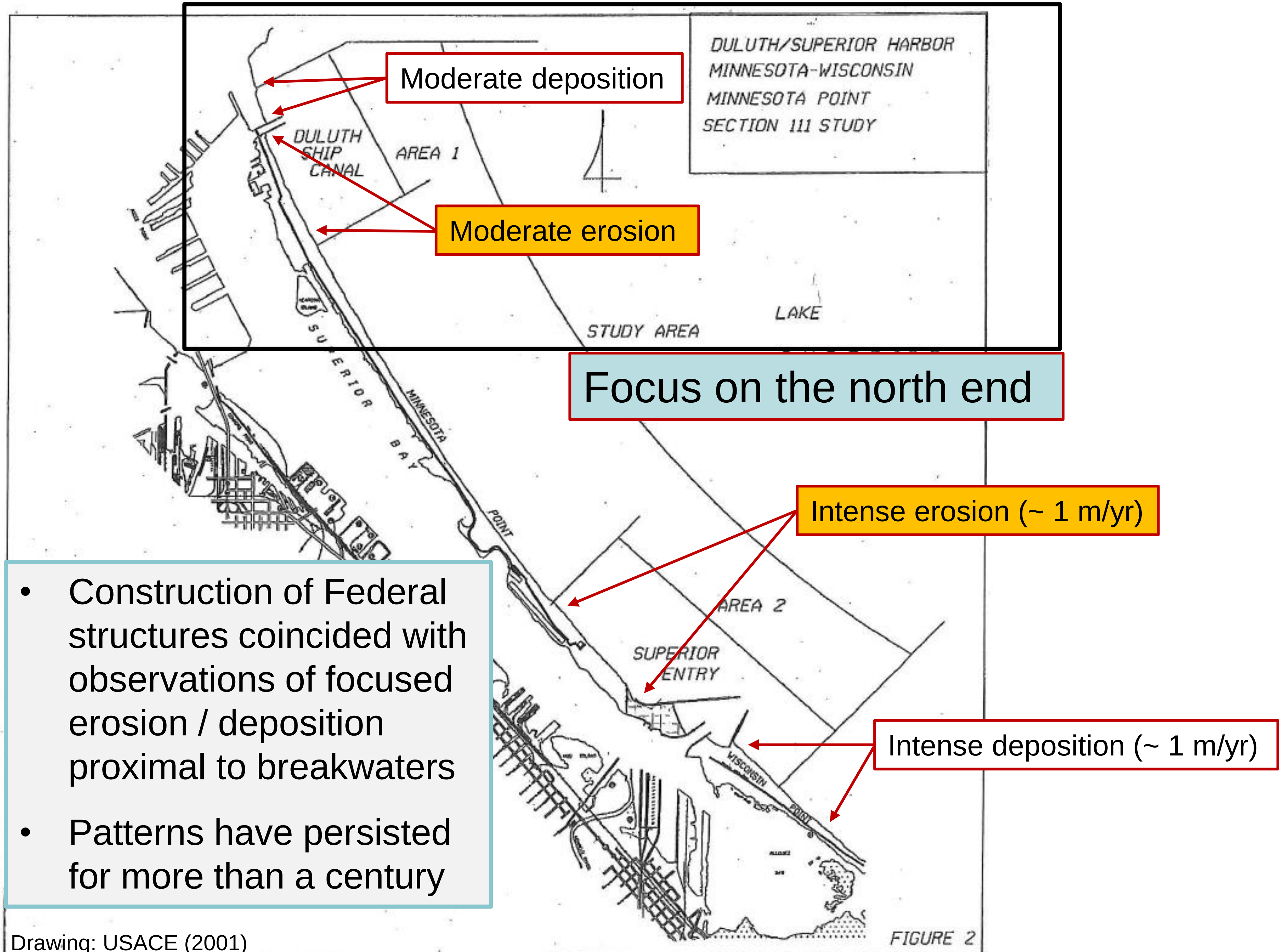
(Genetic model) **1200** years BP - present: Rapid lake-level **RISE**

- Rise ignites **bluff erosion**
- St. Louis and Nemadji Rivers contribute **relatively little** sand due to progressive **drowning** and trapping in estuary
- Strandplain is drowned





Drawing: ACOE (2001)

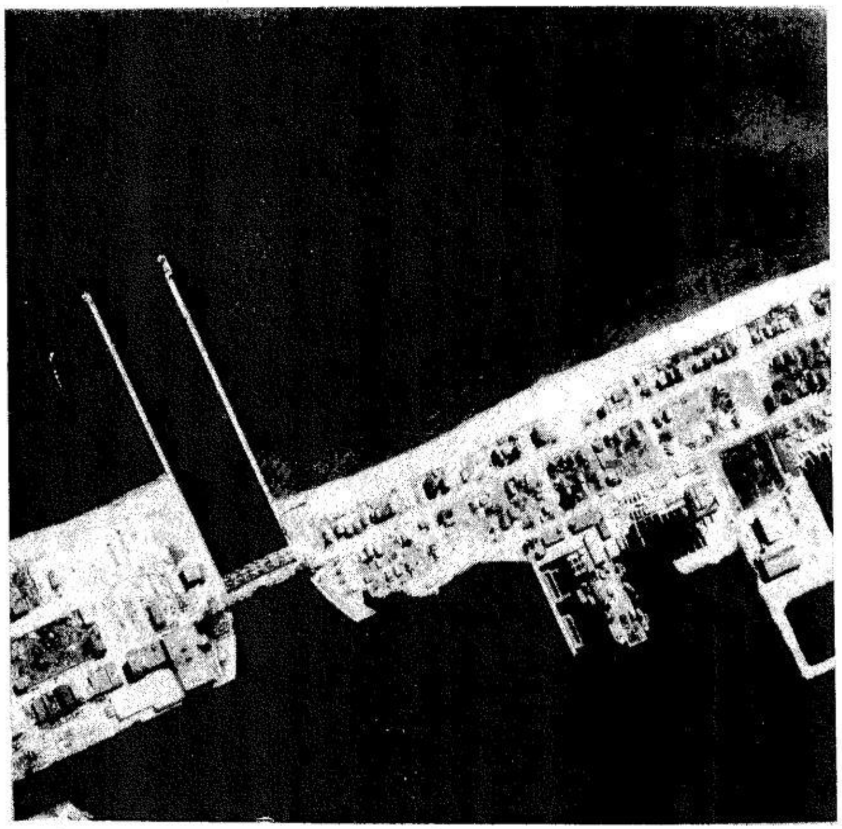


- Construction of Federal structures coincided with observations of focused erosion / deposition proximal to breakwaters
- Patterns have persisted for more than a century

Drawing: USACE (2001)

1974 Section 111 study

SECTION 111 DETAILED PROJECT REPORT
BEACH EROSION CONTROL ON
MINNESOTA POINT AT DULUTH, MINNESOTA



U.S. ARMY ENGINEER DISTRICT ST. PAUL
CORPS OF ENGINEERS
ST. PAUL MINNESOTA
NOVEMBER 1974

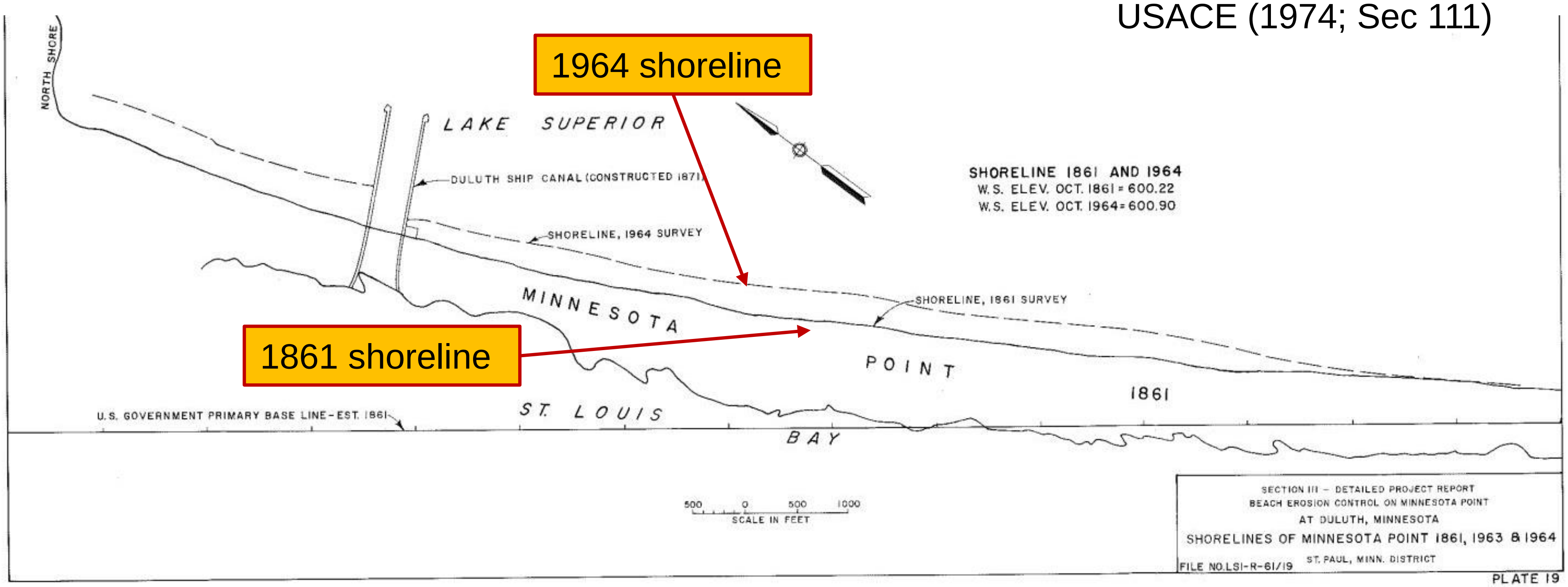
CONCLUSIONS

74. The construction of the Duluth Ship Canal and the Superior Entry piers has altered the natural processes affecting the lakeward shoreline of Minnesota and Wisconsin Points. Due to these changes, a potential erosion problem exists along a 3,000-foot strip of beach adjacent to and southeast of the Duluth Ship Canal. However, no actual shoreline damage attributable to the Federal navigation structures can be shown.

1974 conclusions:

- Federal structures have created a “potential” erosion problem downdrift of Duluth Ship Canal
- No actual damage can be attributed to the Federal structures

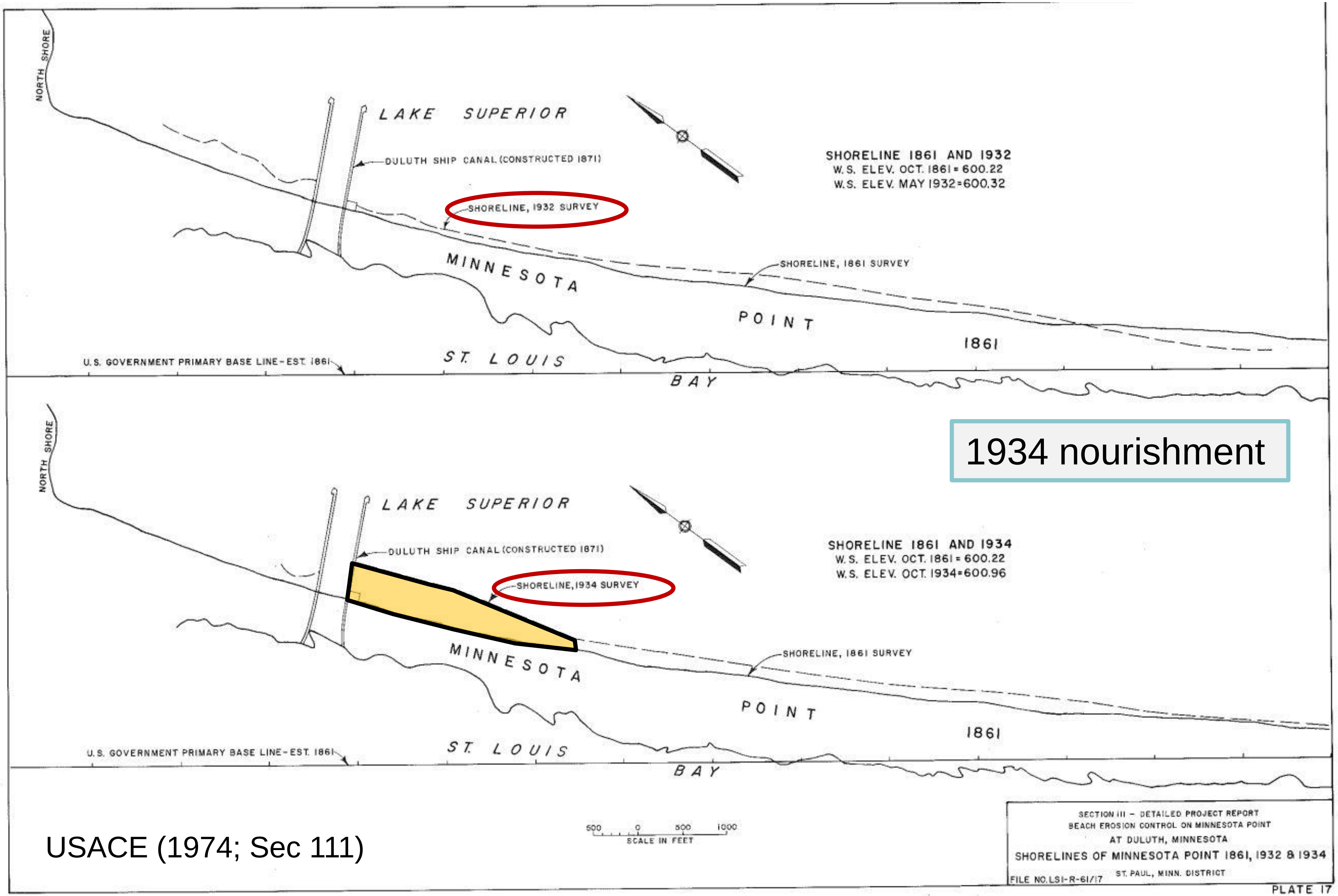
USACE (1974; Sec 111)



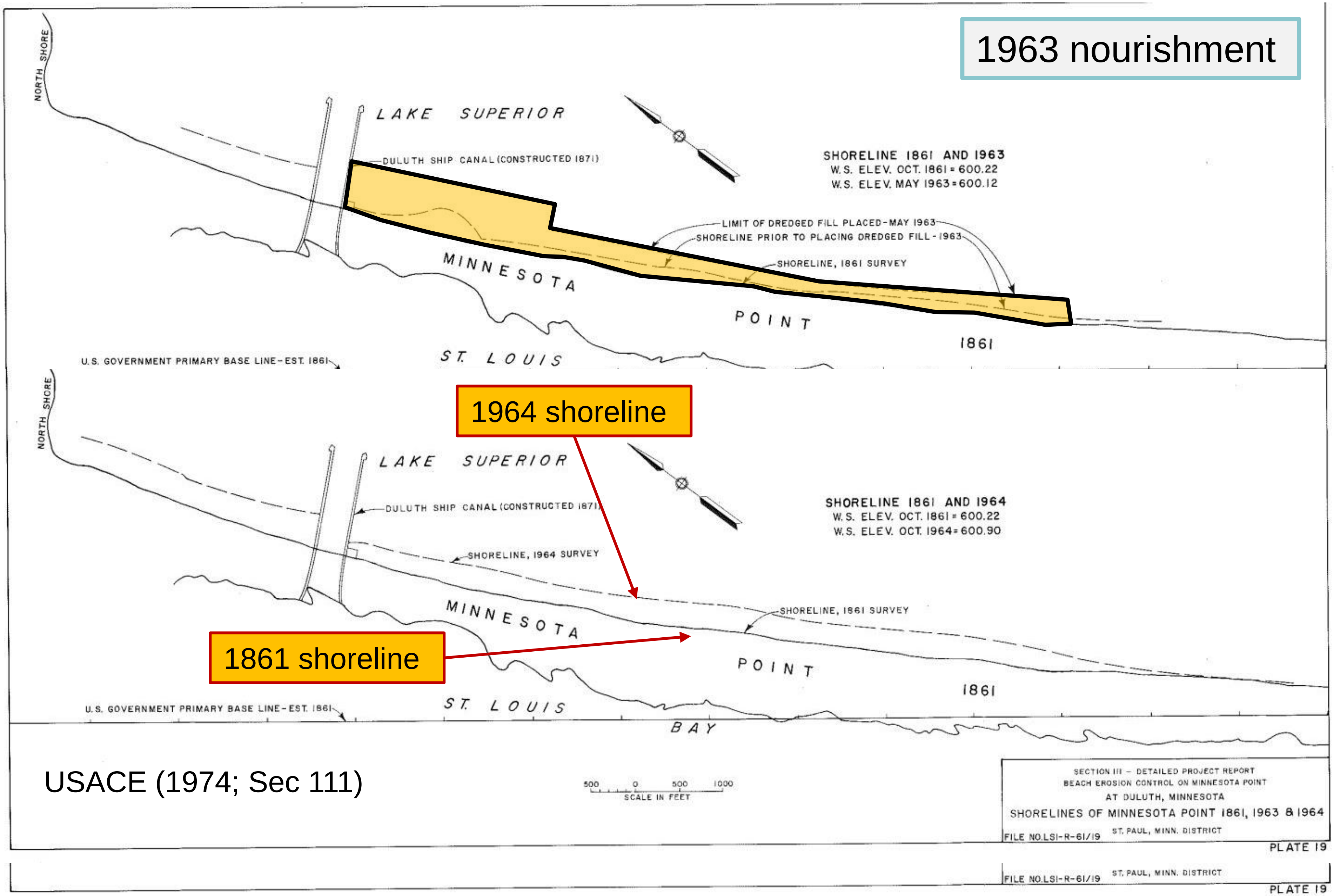
USACE Rationale: 1964 shoreline is **lakeward** of 1861 shoreline.

Therefore, no loss of shoreline.

Therefore, no actual shoreline damage can be attributed to the Federal structures.



USACE (1974; Sec 111)



USACE (1974; Sec 111)

Thought problem:

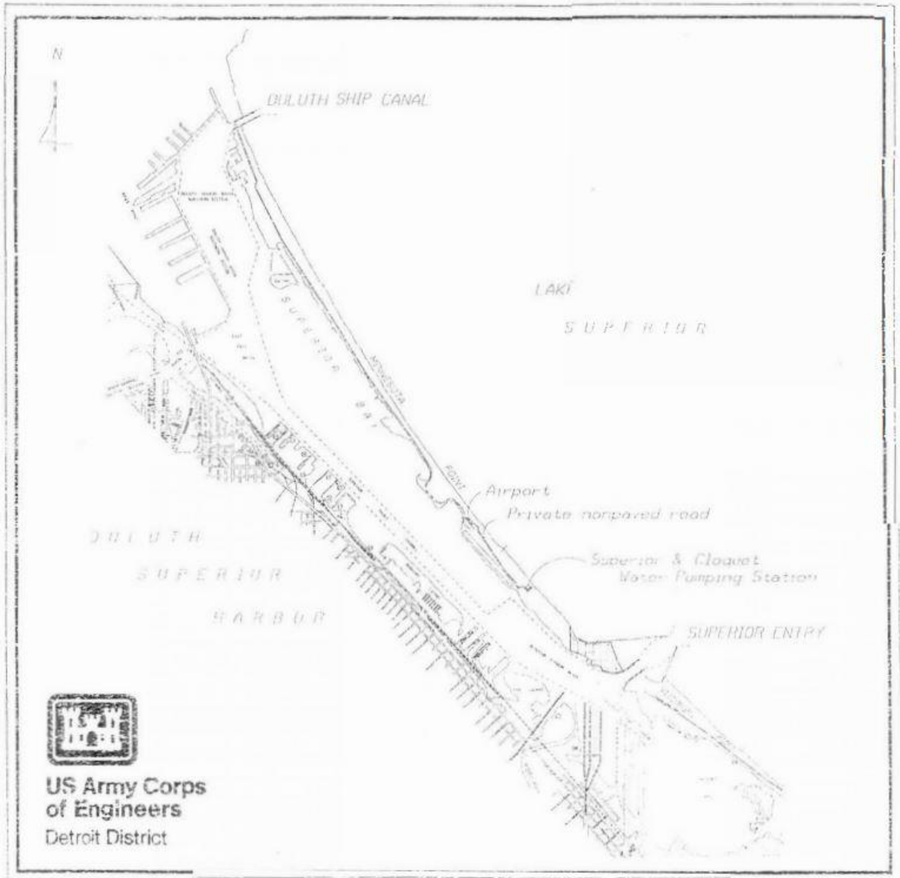
- My car’s oil sump holds 4 quarts;
- Bob borrows my car and damages the oil sump;
- Sump now leaks slowly;
- Without frequent monitoring / maintenance, sump will run dry, destroying the engine;
- Before returning my car, Bob (over)fills the sump to 5 quarts volume.

Is Bob responsible for damage to my car?

2001 Section 111 study

DETAILED PROJECT REPORT
SECTION 111 STUDY
MINNESOTA POINT, DULUTH, MINNESOTA

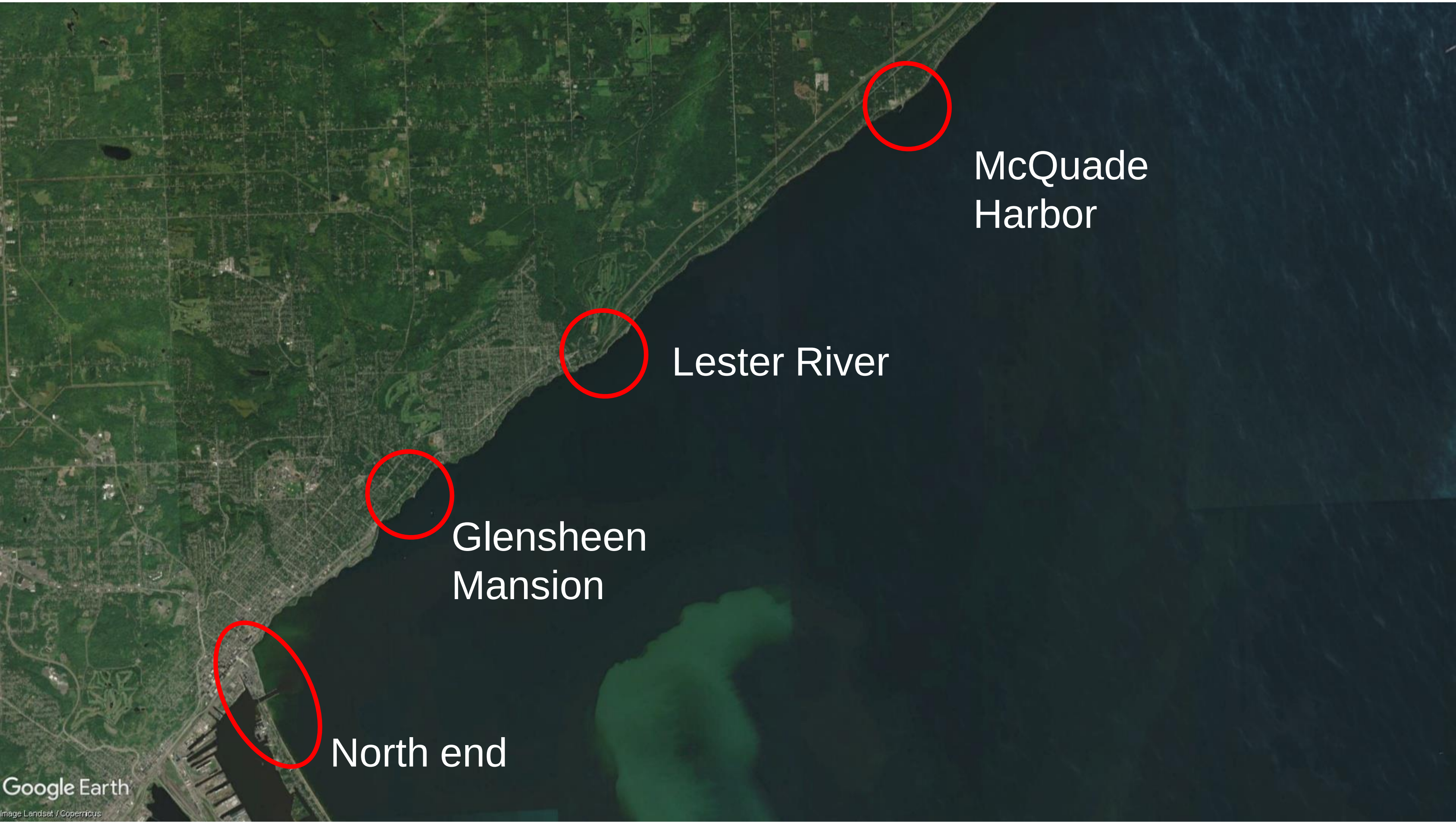
FEBRUARY 2001



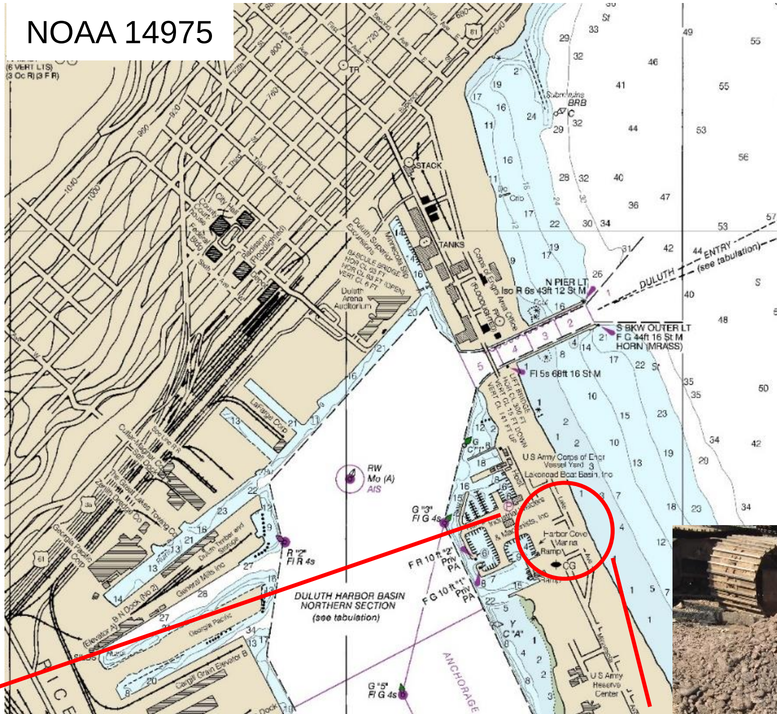
2001 conclusions:

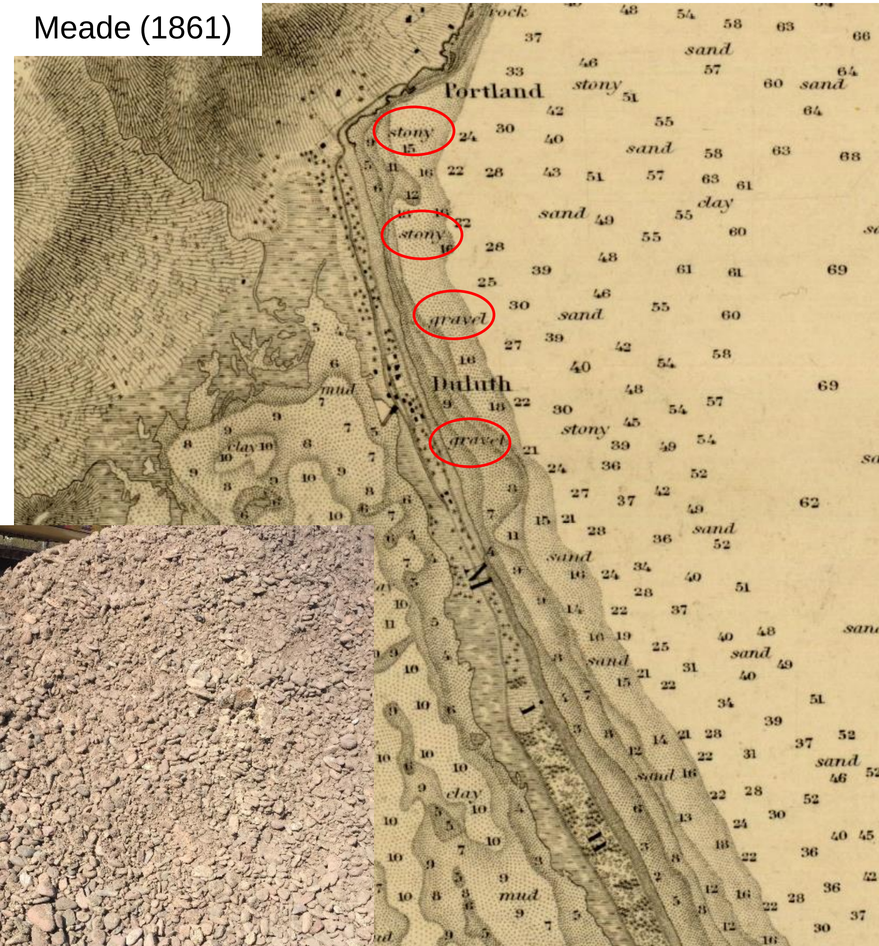
- Superior Entry is responsible for 'south end' shoreline damage
- No 'north end' damage can be attributed to the Duluth Ship Canal

- Key assumption: Sediment supply from the north shore was negligible


McQuade
Harbor
Lester River
Glensheen
Mansion
North end
Google Earth
Image Landsat / Copernicus

North end of barrier composed of cobbles, gravel, and coarse sand derived from **north-shore** bedrock weathering & transport





"Major D.C. Houston in his report to the Chief of Engineers in 1872, …, noted the **northern 2 miles** of Minnesota Point was covered in **gravel**."
(USACOE, 1974 Sec. 111 report)

North end is gravel-cored; source = north shore

No stratigraphic logs

Minnesota Unique Well Number

544042

County St. Louis
Quad Duluth
Quad ID 244D

MINNESOTA DE
WELL AND
Minnesota S

Well Name	Township	Range	Dir Section	Subsection
INTER CITY OIL	50	14	W 27	DABCBA

Elevation 609 ft. **Elev. Method** LiDAR 1m DEM (MNDNR)

Address

Well 307 CANAL PARK DR DULUTH MN 55802

Contact 1923 SOUTH ST DULUTH MN 55812

Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
COARSE GRAVEL	0	20	BROWN	MEDIUM

Minnesota Unique Well Number

564343

County St. Louis
Quad Duluth
Quad ID 244D

MINNESOTA DE
WELL AND
Minnesota S

Well Name	Township	Range	Dir Section	Subsection
BUCKEYE INC.	50	14	W 27	DDCABB

Elevation 608 ft. **Elev. Method** LiDAR 1m DEM (MNDNR)

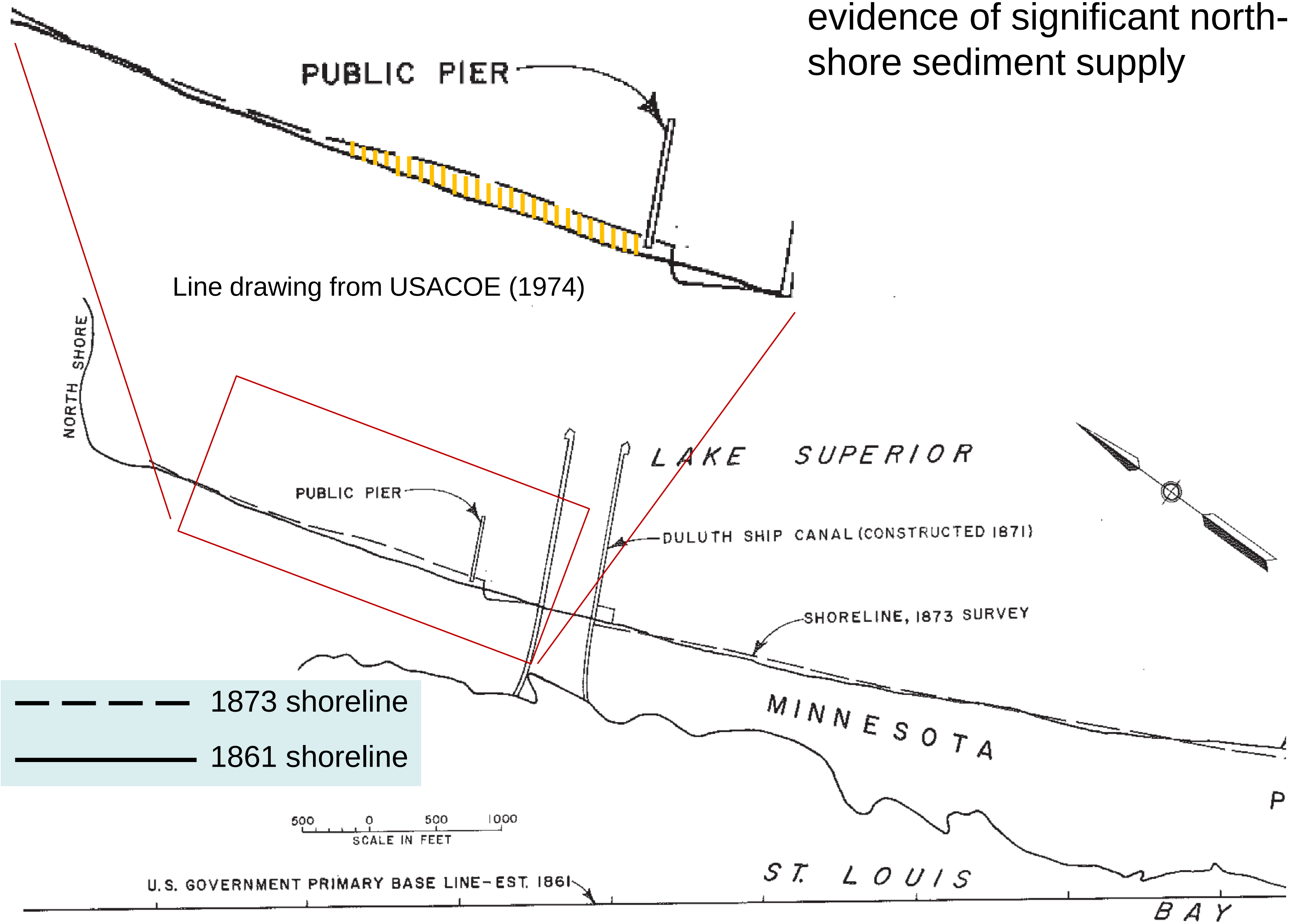
Address

Well 501 LAKE AV S DULUTH MN 55802

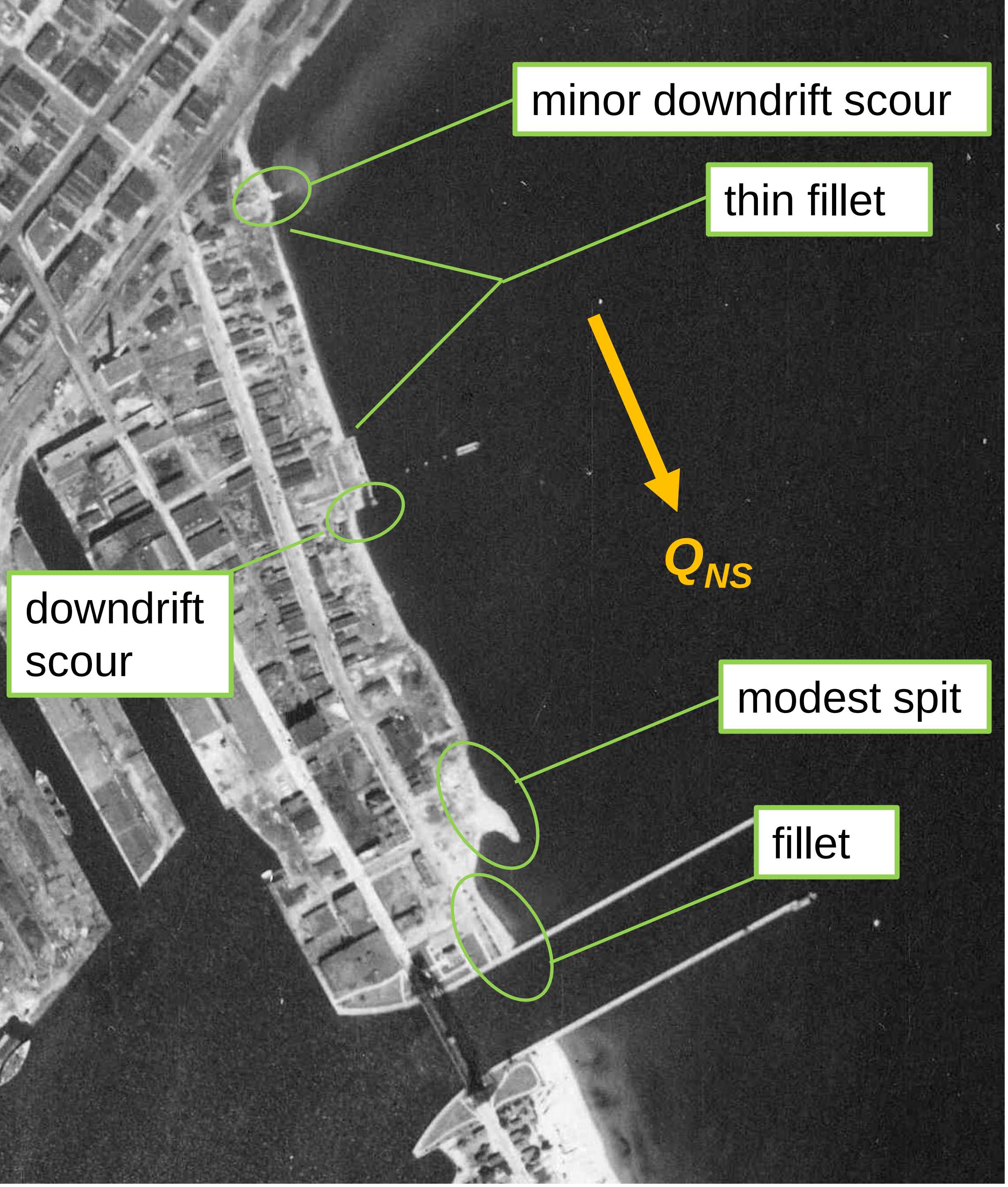
Stratigraphy Information

Geological Material	From	To (ft.)	Color	Hardness
GRAVEL	0	25	BROWN	MEDIUM
SAND	25	46	BROWN	MEDIUM

The Public Pier: Unequivocal evidence of significant north-shore sediment supply



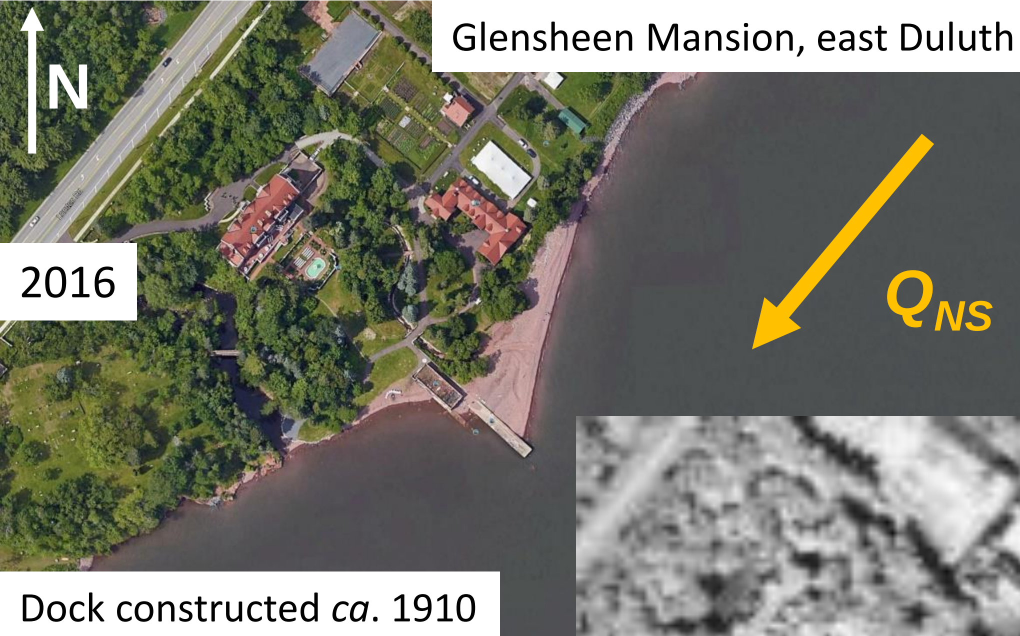
Line drawing from USACOE (1974)



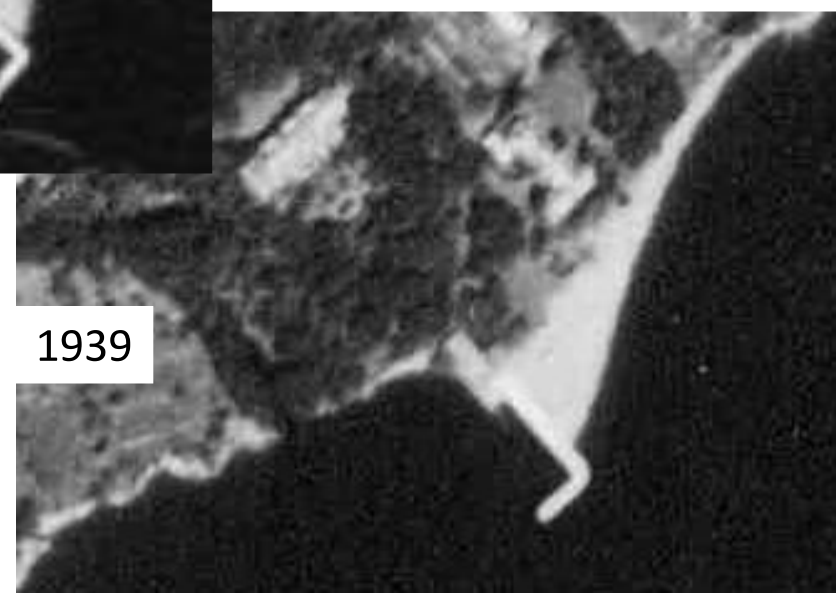
Morphologic features consistent with SSE littoral transport of north-shore sourced material.

'Built' environment—complicates interpretation

1939 air photo (MHAPO)



Well-developed fillet in east Duluth.



Multiple lines of evidence (historical air photos, etc.) support non-trivial north-shore supply of cobbles / gravel / sand

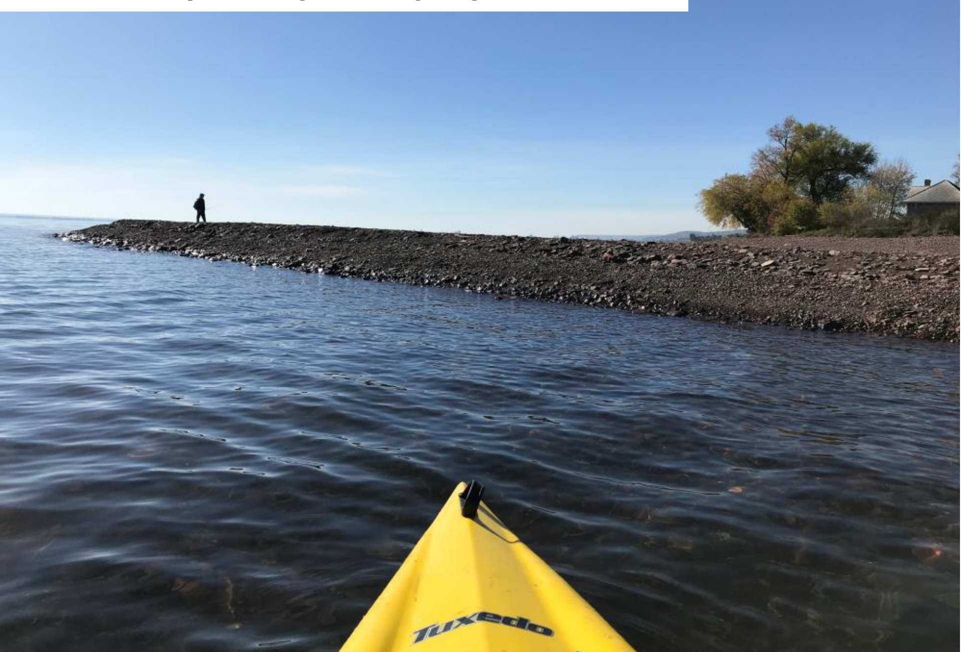
Oct 11

Looking southwest (downdrift)

Lester River

4” (convective) rain event on Sept 25

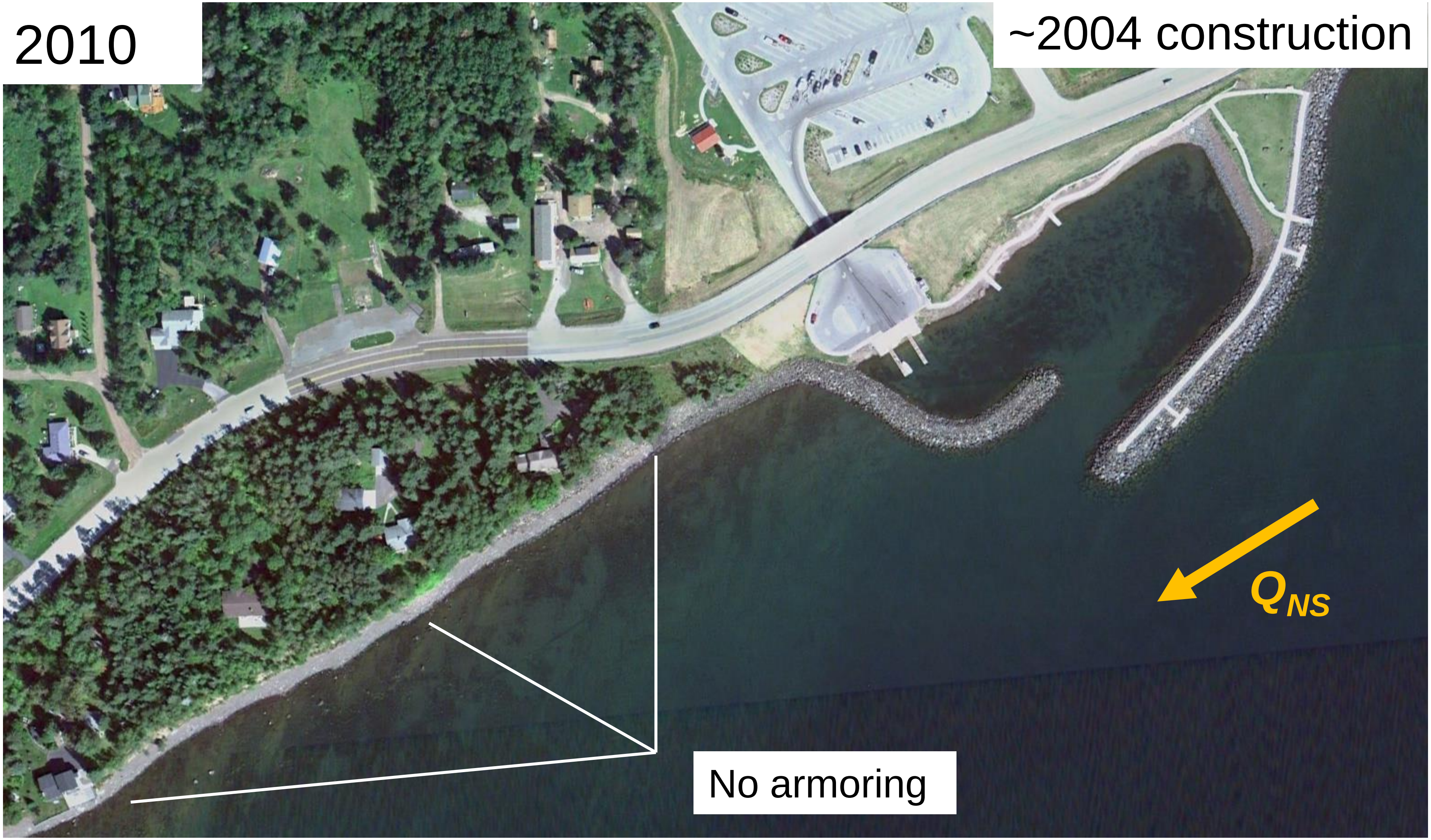
Oct 17: post (weak) cyclone

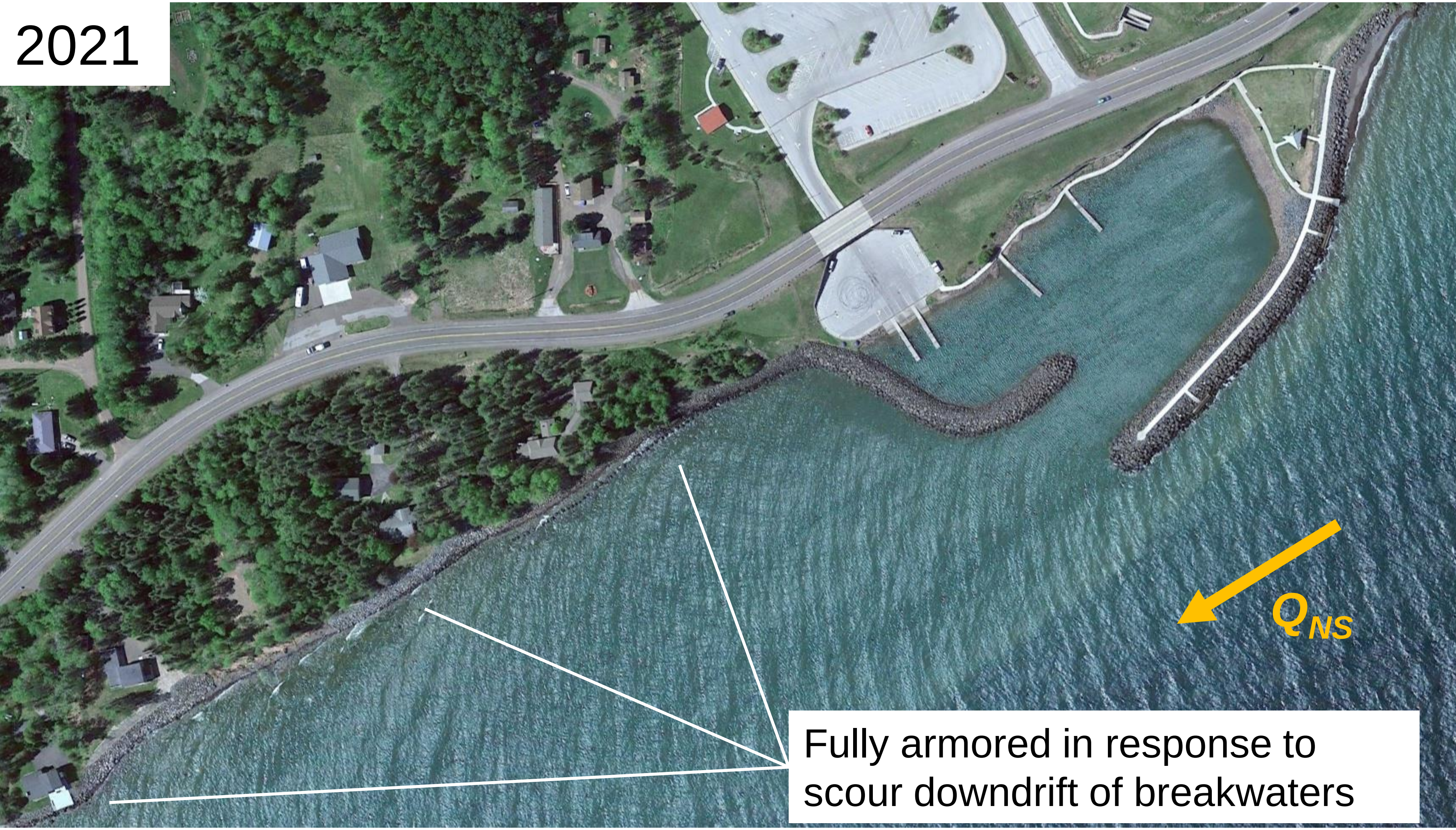


Oct 27: after another cyclone

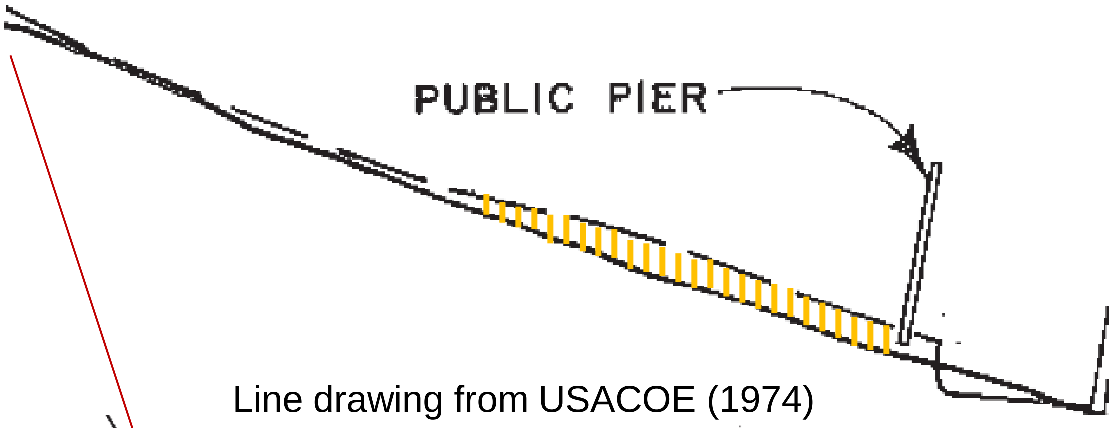

Mar 14
Looking southwest (downdrift)
Mar 14
Q_{NS}
Apr 6
SETTING FIRES PROHIBITED
Apr 6
Q_{NS}

McQuade Harbor: Erosion downdrift of structure




2021
Q_{NS}
Fully armored in response to
scour downdrift of breakwaters

Quantitative constraint on **north-shore** gravel / sand supply (Q_{NS}):



Line drawing from USACOE (1974)

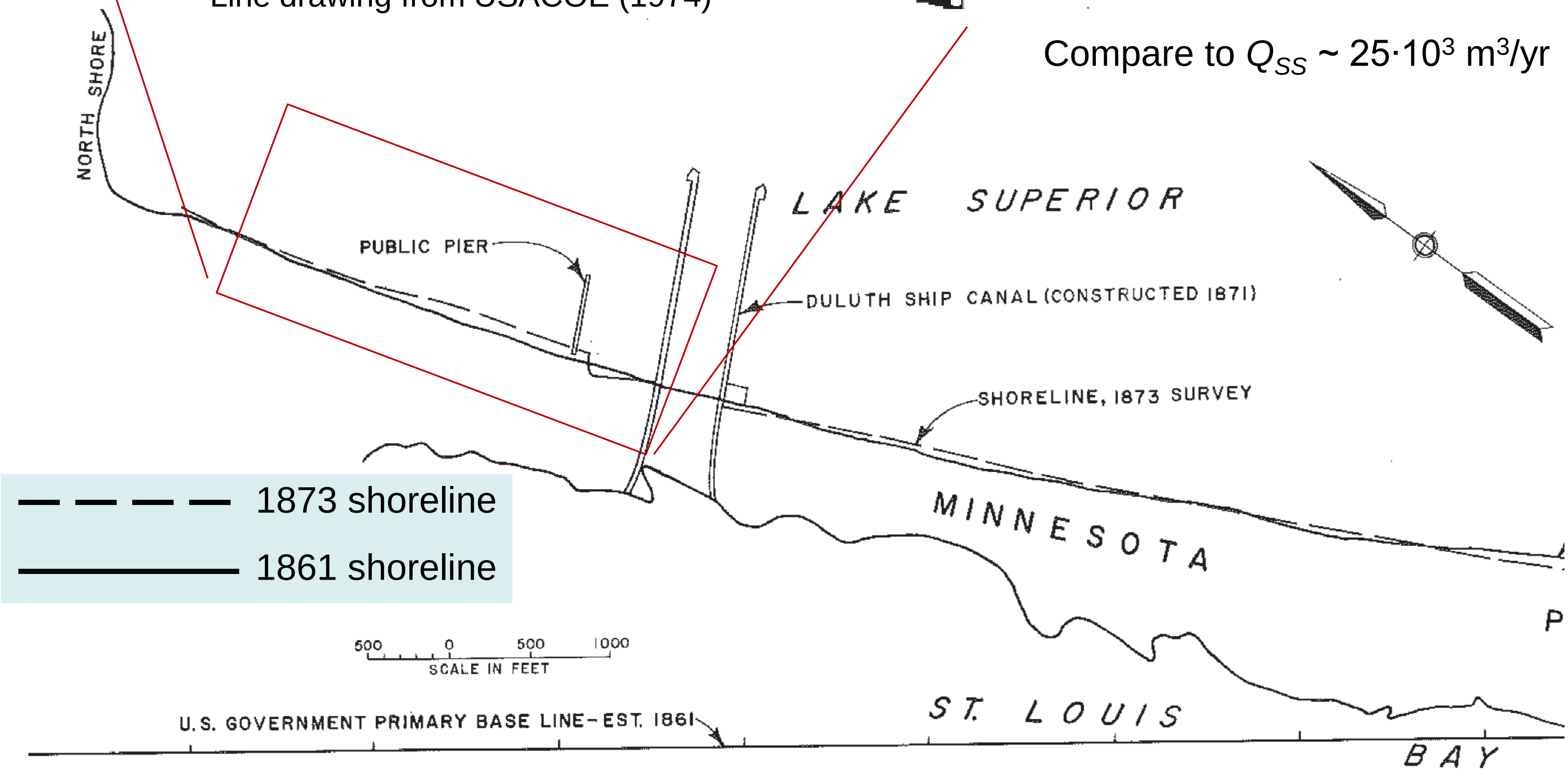
$A_{fillet} \sim 8 \cdot 10^3$ m²

$H_{shore} + H_{beach} \sim 12$ m

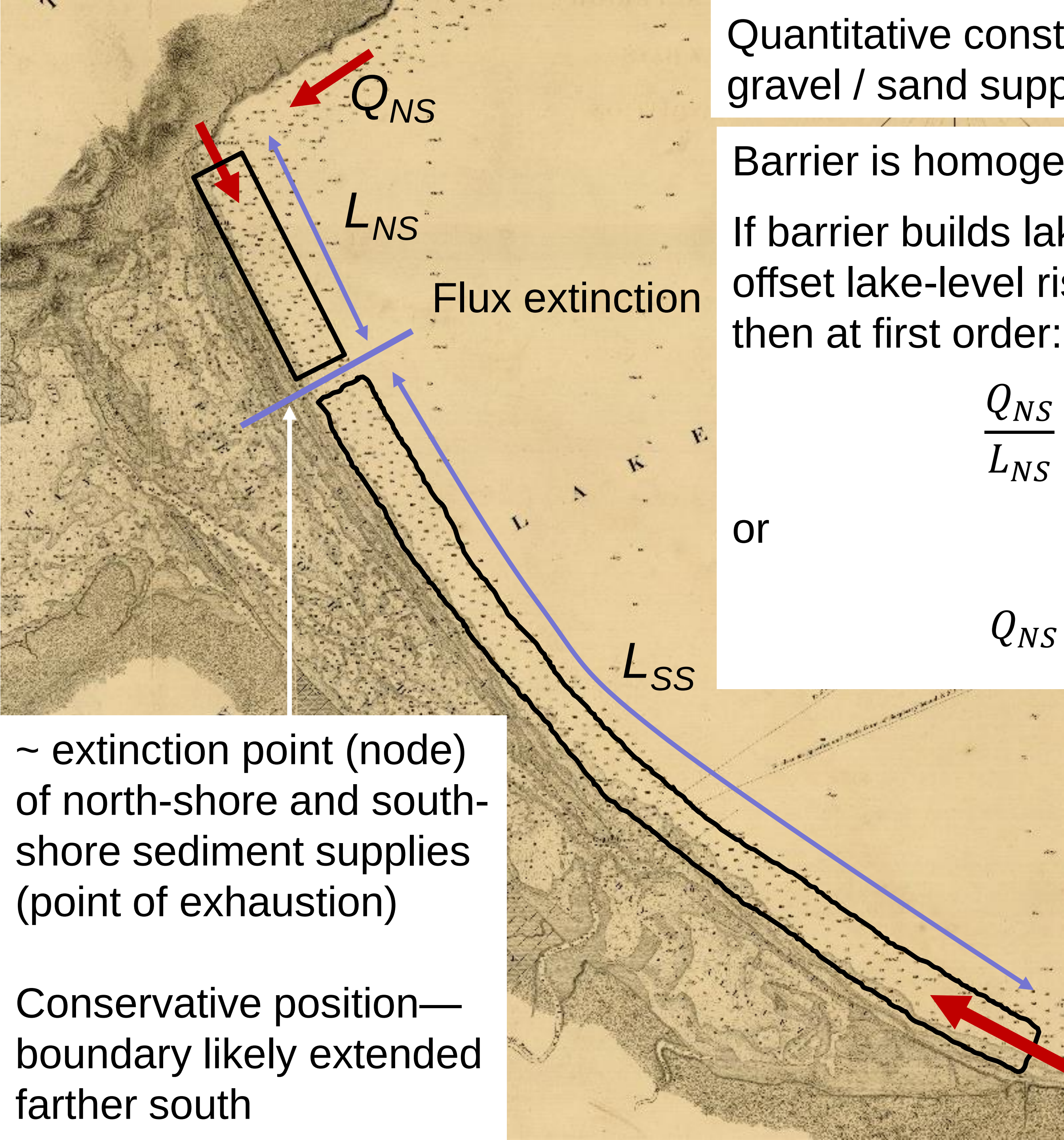
$T_{accum} \sim 12$ yr

$Q_{NS} \sim 8 \cdot 10^3$ m³/yr

Compare to $Q_{SS} \sim 25 \cdot 10^3$ m³/yr



Quantitative constraint on **north-shore** gravel / sand supply (Q_{NS}):



Barrier is homogeneous in structure

If barrier builds lakeward and upward (to offset lake-level rise) uniformly at rate R, then at first order:

$$\frac{Q_{NS}}{L_{NS}} = \frac{Q_{SS}}{L_{SS}} \propto R$$

or

L_{NS} ~ 2 mi
L_{SS} ~ 8 mi

$$Q_{NS} = Q_{SS}\frac{L_{NS}}{L_{SS}}$$

Q_{NS} ~ 0.25·Q_{NS}

If Q_{SS} ~ 25,000 m^3/yr

then Q_{NS} ~ 6,000 m^3/yr

~ extinction point (node) of north-shore and south-shore sediment supplies (point of exhaustion)

Conservative position—boundary likely extended farther south

Summary

- North end of MN Point is constructed of cobbles, gravel, and sand sourced from north-shore sources
- Coarse material was ‘active’ at time of breakwater construction
- Today, negligible gravel observed on beach south of south breakwater
- Beaches ‘updrift’ of north breakwater are composed of gravel
- Multiple lines of evidence for southwestward transport of north-shore gravel flux after construction of breakwaters – present

Quick swipe of Occam’s Razor:

Duluth entry breakwaters prevent north-shore gravel flux from feeding north end of MN Point