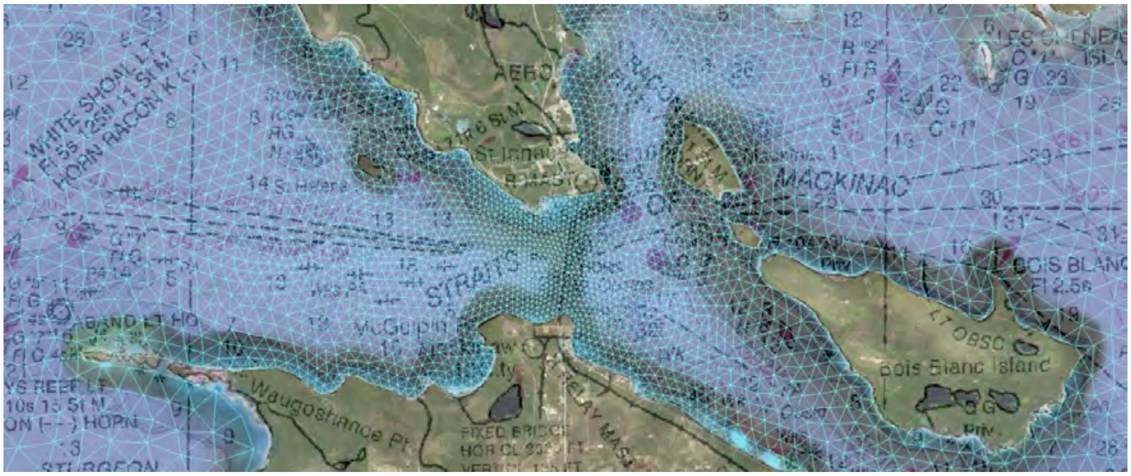
Straits of Mackinac Contaminant Release Scenarios: Flow Visualization and Tracer Simulations



Research Report for the National Wildlife Federation Great Lakes Regional Center

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The U-M Water Center is a center of the Graham Sustainability Institute, which fosters sustainability through translational knowledge, transformative learning, and institutional leadership.

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Project Report to National Wildlife Federation

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Introduction

The Straits of Mackinac is the roughly 10 km long section of waterway connecting Lakes Michigan and Huron into a single hydraulic system. It is spanned at its narrowest point (6 km) by the Mackinac Bridge which connects Michigan's upper and lower peninsulas. Tens of thousands of trucks pass over the bridge each year and hundreds of cargo vessels pass under it. Just west of the Mackinac Bridge, the Straits are also spanned by two submerged oil pipelines that carry up to 23 million gallons of crude oil and natural gas fluids each day (Ellison, 2014).

Currents in the Straits can be as strong as currents in the Detroit River (up to 1 ms^{-1}) and tend to reverse direction between eastward flowing and westward flowing every few days. Peak volumetric transport through the Straits can reach 80,000 $m^3 s^{-1}$ (more than 10 times the flow of the Niagara River). Flow through the Straits can play an important role in water quality, contaminant transport, navigation, and ecological processes.

To better understand and better communicate these unique flow conditions, the UM Water Center has used results from a recently published hydrodynamic model (Anderson and Schwab, 2013) of the connected Michigan-Huron system to produce computer simulations and animations of hypothetical tracer (dye) releases in the Straits. Since properties of various contaminants in water vary widely, we used 'neutral' tracers, which follow the ambient current and have no inherent tendency to float or sink. The tracers are released at three locations in the model, one near the south shore of the Straits, one near the north shore of the Straits, and one in the center of the Straits. At each location, tracers are released at three depths: surface, mid-depth, and near bottom. The tracers are released continuously over a 12 hour period at two different times of the year, and then tracked for 20 days as they are moved by the simulated currents. Animations were prepared for 6 cases corresponding to south, center, and north releases at the two different times of the year. Hopefully, these simulations and animations will be useful in understanding and preparing for potential impacts of an accidental contaminant release in the Straits.

Hydrodynamic model

The currents used to calculate tracer trajectories in this study are based on the results of Anderson and Schwab (2013). They developed a three-dimensional, unstructured mesh hydrodynamic model that extended over Lake Michigan and Lake Huron, including the Straits of Mackinac. The model is based on the Finite Volume Coastal Ocean Model (FVCOM; Chen et al., 2006), a free-surface, hydrostatic, primitive-equation hydrodynamic model that solves the continuity, momentum, and energy equations in three-dimensions on an unstructured, sigma-coordinate (terrain-following) mesh. FVCOM has been validated and implemented successfully in several coastal ocean applications as well as in the Great Lakes and connecting channels (see Anderson and Schwab, 2013 for numerous references). For the combined-lake model, three arc-second bathymetric and coastline data for the Great Lakes were obtained from the NOAA National Geophysical Data Center (NGDC) and interpolated to the unstructured mesh. The horizontal grid resolution of the mesh ranges from 100 m in the Mackinac Straits to 2.5 km in the center of the lakes (Fig. 1). Vertical resolution is provided by 20 uniformly distributed sigma layers.

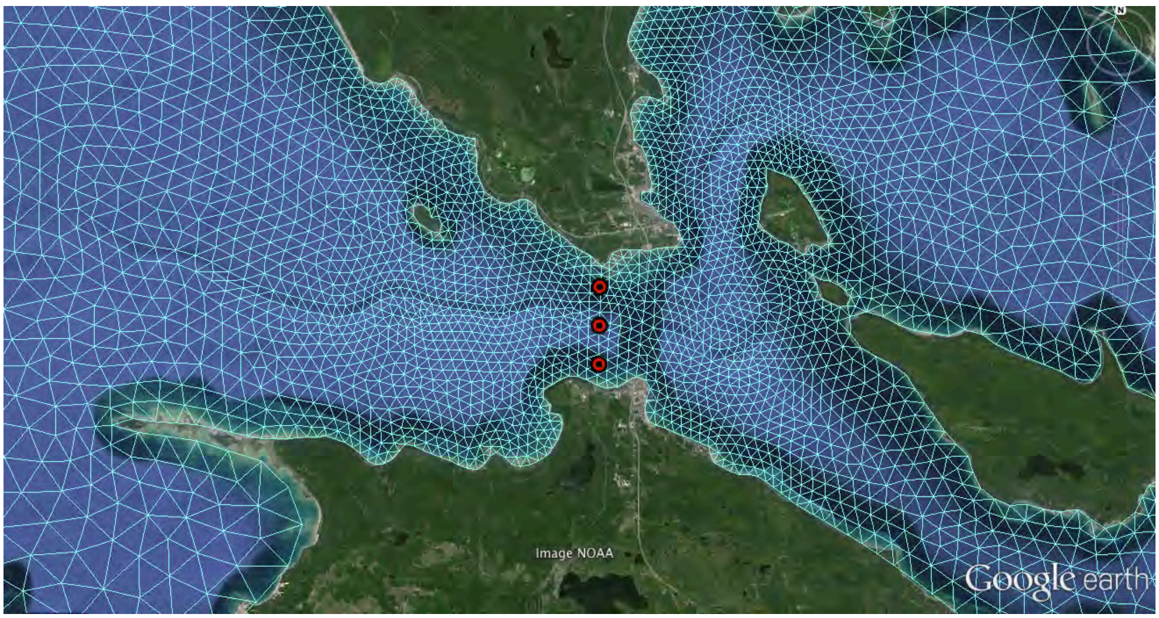

Figure 1. Section of computational mesh for hydrodynamic model (Anderson and Schwab, 2013) and 3 contaminant release points.

Simulations in Anderson and Schwab (2013) were carried out for the period April–December 1990 using realistic atmospheric forcing to drive the model. Validation was provided by the NOAA/NOS water level gauges for water levels, NOAA/NWS buoys for hourly surface water temperatures at 4 locations, and current measurements from two Acoustic Doppler Current Profilers deployed in the Straits during the simulation period (Saylor and Miller, 1991). A statistical analysis and spectral analyses were carried out comparing the observed and modeled variables and both showed very good agreement.

The main result of the Anderson and Schwab study was that the model accurately predicts oscillating flow at the Straits, and also simulates the vertically bidirectional currents that appear during the stratified period. The observed dominant flow oscillation occurs at a period of roughly 3 days, and current speeds can reach up to 1 m s^{-1} with a volumetric flow of 80,000 m^3s^{-1}. A comparison of water level records and atmospheric pressure changes, which indicate the passage of weather systems across the lakes, yielded similar periods for each, indicating that flow oscillations in the Straits are mainly caused by changing weather patterns.

Contaminant Release Scenarios

Two 20 day time periods were chosen for contaminant release scenarios. The first was August 1-21, 1990 (Day of year 213-233) and the second was September 23-October 13, 1990 (Day of year 266-286). As shown in Figure 2, the first release period started during a peak in eastward flow through the Straits and the second period started during a peak in westward flow. Both 20 day periods included 6-8 cycles of the oscillating flow through the Straits.

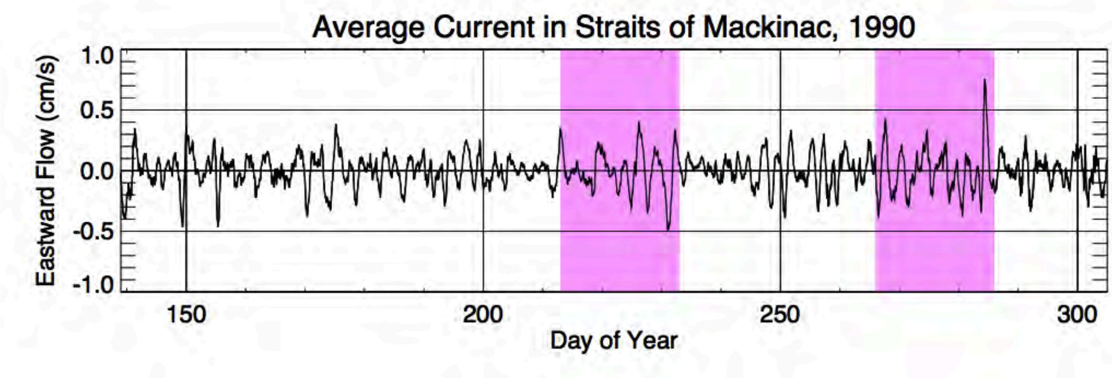

Figure 2. Average flow through the Straits of Mackinac as estimated by the model of Anderson and Schwab (1990). The two 20 day periods chosen for contaminant release scenarios are highlighted.

To simulate the trajectory of a contaminant release, we used 'neutral' tracers, which follow the ambient current and have no inherent tendency to float or sink. For each time period, three different scenarios are simulated. In each scenario, tracers are released at a rate of 100 per hour at one of three locations in the model, one near the south shore of the Straits, one near the north shore of the Straits, and one in the center of the Straits (Table 1). At each location, tracers are released at three depths: surface, mid-depth, and near bottom. The tracers are released continuously over a 12 hour period at two different times of the year, and then tracked for 20 days as they are moved by the simulated currents. The tracers are treated as discrete “particles” to better track the initial trajectory of the release when there is relatively little dispersion. The trajectory calculations for each tracer include a “random walk” component to simulate large-scale dispersion. The horizontal and vertical dispersion coefficients were set to 0.05 m^2s^{-1} and 0.0005 m^2s^{-1} respectively. If each tracer corresponded to 300 gallons, the contaminant release at each depth would be 360,000 gallons over a 12 hour period, or a total of 1.08 million gallons from all three depths. A particle tracking computer code based on Bennett et al. (1983) and Anderson and Phanikumar (2011) was used for calculating the trajectory of each tracer for the 20 day period. The particle tracking code is similar to the method used by the NOAA spill response team to predict the transport and fate of actual contaminant releases (http://response.restoration.noaa.gov/gnome). Animations were prepared for 6 cases corresponding to south, center, and north releases at the two different times of the year.

Location	Latitude (N)	Longitude (W)	Depth (m)
South	45.79482	84.75500	9.5
Center	45.81279	84.75500	42.8
North	45.83076	84.75500	3.8

Table 1. Locations and depths of tracer release locations in the Straits of Mackinac.

August Release Scenario

Tracers were released starting on August 1, 1990 00Z at the rate of 100 per hour at surface, mid-depth, and near bottom at three locations across the channel. Release was stopped 12 hours later (12Z). The tracers were allowed to move with currents (from the hydrodynamic model) and were tracked for 20 days. During this period, average currents in the Straits were initially eastward, but changed direction every day or two. Currents at mid-depth and bottom reverse direction sooner than at the surface and are moving tracers to the west after 2 days. Surface tracers from the southern release point have impinged on the southern shore of Lake Huron just east of the Straits within 12 hours. Surface tracers from the central release impinge on Bois Blanc Island after 2 days. Tracers from all depths at the northern release point are in the vicinity of Mackinac Island and Round Island after 12 hours, and near the northern shore of Bois Blanc Island after 2 days. Because of the initially strong eastward flow, surface tracers, and some of the tracers from mid-depth releases tend to be advected into Lake Huron and end up impacting the southern shoreline as far south as Rogers City after 10 days. Tracers from near-bottom and mid-depth tracers from the southern and central release points are mainly offshore in Lake Michigan after 20 days (Figure 3). Curiously, most mid-depth and many near bottom tracers from the northern release point end up in Lake Huron offshore of Rogers City after 20 days.

September Release Scenario

The second simulation began on September 23, 1990. Locations and duration of the release were the same as the August simulation. This case ended on October 13. Average currents in the Straits were initially westward, but again changed direction periodically throughout the period. The westward flow carried all tracers into Lake Michigan during the first 24 hours. After 2 days, tracers from the northern and central release points were evenly distributed between the Lake Michigan side and the Lake Huron side while most of the tracers from the southern release point were in Lake Huron and impinging on the Michigan shoreline from Mackinaw City halfway to Cheboygan. During this scenario, currents were more similar in direction from surface to bottom than in the August case. After 3 days, some surface particles from the northern release and particles from various depths from the central release were impinging on the southern shore of Bois Blanc Island. At 10 days, a large number of tracers were beginning to accumulate in an area halfway between the Straits and Beaver Island in Lake Michigan, and particles had been advected along the Michigan shoreline in Lake Huron past Cheboygan, but not as far as Rogers City. After 16 days, some tracers from the northern release have reached Beaver Island in Lake Michigan. At 20 days, the majority of tracers from mid-depth and near bottom releases at all three locations, as well as surface release tracers from the northern location, are in northern Lake Michigan, spread between the Straits and Beaver Island (Figure 3). Most of the surface release tracers from the center location have impinged on the shore of Bois Blanc Island.

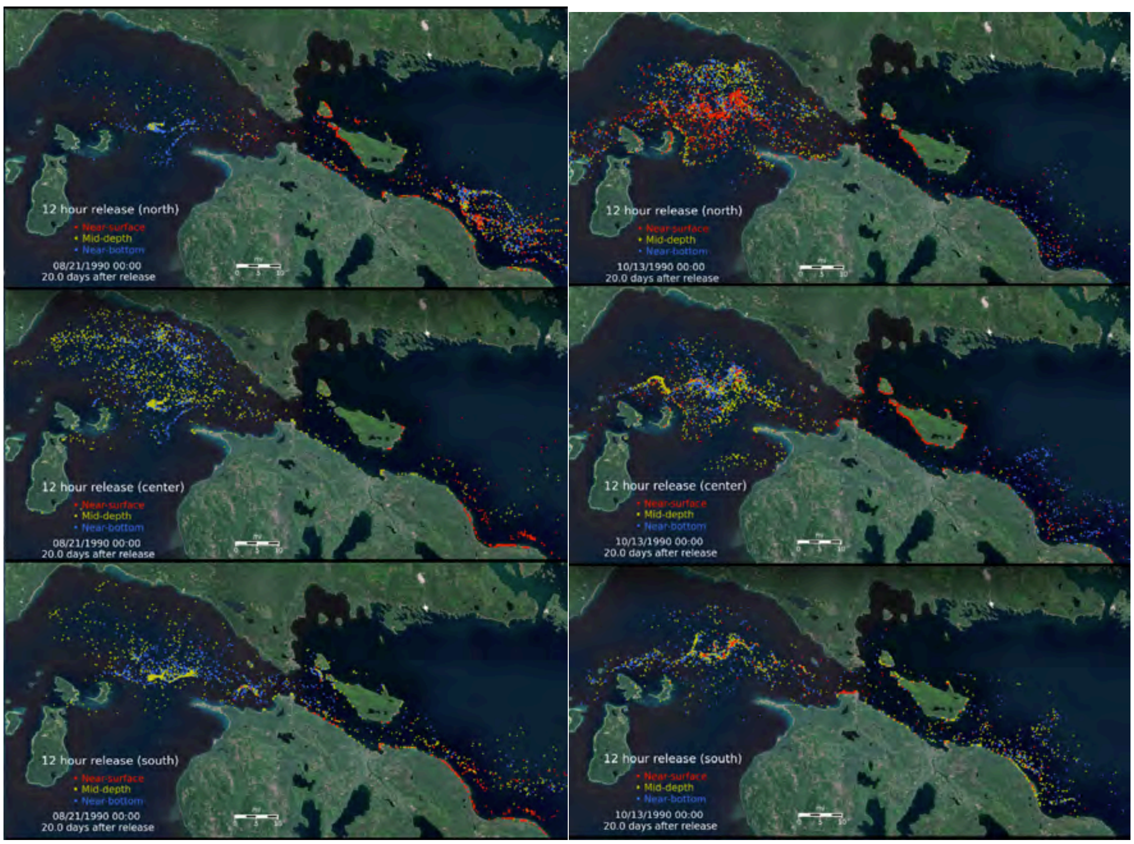

Figure 3. Location of tracers after 20 days for August release (left) and September release (right)

Summary

The oscillating currents in the Straits of Mackinac will have a strong influence on the transport and fate of any contaminant release in the Straits. Depending on the direction of the currents in the Straits at any particular time, material released into the Straits could be transported eastward into Lake Huron or westward into Lake Michigan and could move back and forth through the Straits several times. Because of the vertically bi-directional flow in the Straits in the summer and fall, material in the upper part of the water column preferentially flows eastward into Lake Huron, and material in the lower part of the water column preferentially flows westward into Lake Michigan. Within 20 days of a contaminant release in the Straits, material could be spread as far west as Beaver Island in Lake Michigan and as far southeast as Rogers City in Lake Huron. In the release scenarios considered here, the shoreline areas most likely to be impacted by a contaminant release in the Straits are Mackinac Island, Bois Blanc Island, and the Lake Huron shoreline from Mackinac City to Rogers City. Material released into the deep waters of the Straits has a tendency to accumulate in the offshore area of northern Lake Michigan.

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