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Statistical Analysis of Straits of Mackinac Line 5: Worst Case Spill Scenarios

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Introduction

The Straits of Mackinac is the roughly 10 km long section of waterway that joins 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. Just west of the Mackinac Bridge, it is also spanned by a submerged section of the Enbridge Inc. Line 5 oil pipeline. Line 5 typically carries up to 20 million gallons of light crude oil, light synthetic crude oil, and natural gas liquids across the Straits each day (Alexander and Wallace, 2013).

Currents in the Straits can be as strong as currents in the Detroit River (up to 1 m/s) and tend to reverse direction between eastward flowing and westward flowing every few days (Saylor and Sloss, 1976). Peak volumetric transport through the Straits can reach 80,000 m^3/s (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, in 2014 the UM Water Center used a recently published hydrodynamic model (Anderson and Schwab, 2014) of the connected Michigan-Huron system to produce computer simulations and animations of hypothetical tracer (dye) releases in the Straits (Schwab, 2014). These simulations were carried out for two release periods, one in summer and one in fall. The simulations showed graphically for these two example cases how far and how fast an oil spill could spread from the Straits.

The purpose of this report is to expand on the results of the Schwab, 2014 study by using similar computer simulation technology to run a large number of oil spill simulation cases (840) covering a wide variety of weather conditions using realistic estimates of worst-case discharge spill parameters, including amount of oil released, oil characteristics of light crude oil (such as specific gravity and evaporation rate), and realistic oil spill dispersion properties. The spill simulation cases use currents from hydrodynamic simulations of flow in the Straits for 2014, based on the same hydrodynamic computer model used in Anderson and Schwab, 2014. The results of the cases are then analyzed to develop statistical distribution maps based on all cases for several parameters, which are relevant for quantitative risk assessment. These include time series of the open water area covered by the spill, time series of the length of impacted shoreline, time series of the beached volume and open water volume, probability maps of offshore impact area, probability maps of impacted shoreline area, and a map of the shortest time it would take to reach a specific area in any of the 840 cases. In all cases, it is assumed that no oil is contained or recovered by cleanup efforts. This assumption is consistent with the “worst case” scenario. The statistical approach used here is similar to the approach used in a recent report on the potential impact of a deep-sea oil spill on the coasts of New Zealand (Lebreton and Franz, 2013).

Hydrodynamic Model

The currents used to calculate trajectories in this study are based on the hydrodynamic model described in Anderson and Schwab (2013). That model is a three-dimensional, unstructured mesh hydrodynamic model that extends over Lakes Michigan and 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. The 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. 20 uniformly distributed sigma layers provide vertical resolution.

The Anderson and Schwab model was run using meteorological conditions from April-December, 2014. The required surface meteorological fields were extracted from the NOAA NCEP CFSR (National Oceanic and Atmospheric Administration, National Centers for Environmental Prediction, Climate Forecast System Reanalysis http://cfs.ncep.noaa.gov/cfsr/) hourly gridded fields for 2014. Results of the model run showed excellent agreement with actual currents measured in the Straits during this period (Anderson and Schwab, 2016).

Oil Spill Simulation Model

In this study, an oil spill is represented by a cloud of individual tracer particles, moving with the currents from the hydrodynamic model. The computer code used to simulate the particle motion is based on the Lagrangian particle tracking code supplied with the FVCOM hydrodynamic model. In this version of the particle tracking code, we have optimized the computational scheme by improving the algorithm for identifying the mesh element containing a particular particle location. In general, the particle tracking approach used here is very similar to the widely used GNOME (Generalized NOAA Oil Modeling Environment, http://response.restoration.noaa.gov/gnome), but has been optimized for carrying out a large number of simulations based on a single hydrodynamic model run. A random walk process is used to simulate subgrid-scale turbulent variability in the velocity field. We used a horizontal diffusion coefficient of 10 m^2/sec as recommended for the default GNOME setting.

For each spill simulation, the oil is represented by 10,000 discrete particles released on the surface of the water at a point just south of halfway between the north and south pipeline terminals in the Straits (45.81111°N, 84.76944°W). The particles are released at the surface since the specific gravity of the petroleum products currently carried in the pipeline would cause the product to quickly rise to the surface in the event of a pipeline breach. We expect that a release point near the center of the Straits is the "worst case" condition, particularly in terms of maximizing the area of potential impact. Three different spill volumes are considered: 1) 5,000 bbl, 2) 10,000 bbl, and 3) 25,000 bbl. The 5,000 bbl amount is close to the 4,500 bbl volume used in the multi-agency spill simulation exercise in the Straits in 2015. The 10,000 bbl volume is slightly more than the 8,583 bbl "worst-case discharge at the Straits," estimated by Enbridge in their response to the April, 2014 information request from the State of Michigan Attorney General. It's important to note that the estimated amount of oil released in the Kalamazoo River spill from Enbridge Line 6B in 2010 is 25,000 bbl.

For the three spill volumes — 5K, 10K and 25K — each discrete particle of oil in the cloud of 10,000 particles initially represents 0.5, 1.0, or 2.5 bbl of oil respectively. The tracer particles in these simulations are released simultaneously, but the results would not change substantially for release durations less than an hour or two. For longer release durations, the lower release rate would likely cause even more dispersion of the spill than the simultaneous release case.

Evaporation is an important process for most oil spills. The rate of evaporation depends primarily on the composition of the oil product, and secondarily on environmental conditions, such as temperature and waves. For this study, we assume a logarithmic function for the evaporation rate with coefficients appropriate for "Alberta Mixed Sweet Blend" crude oil (Fingas, 2013 and 2015):

$$\%\text{Evaporation} = (3.41 + 0.054T)\ln(t)$$

Here T is temperature in degrees C and ln(t) is the natural logarithm of the time in minutes. We use a temperature of 20 degrees C for all simulations. This results in 32% evaporation 1 day after release and 40% evaporation after 10 days. Although water temperature in the Straits is lower than 20°C in the early spring and late fall, which would slightly decrease the evaporation rate, it can also be higher than 20°C in the summer, which would slightly increase the evaporation rate.

When currents and random-walk diffusion carry a particle into the shoreline, the particle is considered "beached" and not allowed to move again. The amount of oil the particle represents is its initial value reduced by evaporation, according to the equation above.

Spill simulation cases were carried out for 840 overlapping 60-day periods with starting dates from March 31, 2014 and to October 27, 2014. The cases end in October to avoid extending into the Straits ice cover season. Little is known about the behavior of an oil spill under ice, so the winter period was excluded from the simulations. Each new case started 6 hours after the previous case. The 60 day duration of the cases was sufficient to establish the maximum extent of impacted shoreline in all but a few cases, and in these cases the low amount and low concentration of oil remaining in open water after 60 days was unlikely to cause further significant shoreline impact. Particle trajectories were recorded for each case and then analyzed statistically to develop the probability graphs and charts described in the next sections.

Sample Cases

Animations of particle trajectories for 6 of the cases were created to illustrate the wide variety of conditions encountered during spring, summer and fall in the Straits. In the animations, the oil tracer particles are shown as black dots. A magenta dot represents a beached particle. The legend in the animation indicates the amount of time that has elapsed since the beginning of the case, the percent of particles that have beached, and an estimate of the length of shoreline, exceeding a threshold impact level of 12 particles per km^2. Using a density for light crude oil of 850 kg/m^3, for the three release volumes of 5,000, 10,000, and 20,000 bbl this impact level corresponds to an oil density of 0.5, 1.0, or 2.5 gm/m^2 respectively. These values can be compared to the threshold value for "socio-economic impact on land" of 1 gm/m^2 cited by NOAA (2013), as "… that amount of oil would conservatively trigger the need for shoreline cleanup on amenity beaches." Fingas (2015) also suggests 1 gm/m^2 as the threshold for impacts to shoreline resources.

View the case animations online, see: http://graham.umich.edu/news/mackinac-straits-oil-lines

The start times and a brief description of the 6 selected cases follow.

- *Case 1:* 4/3/14 00Z: In this case, the released oil forms a patch moving westward, away from the Straits into Lake Michigan for almost 2 days without any significant beaching. After 2 days, water flow in the Straits reverses direction and the oil patch starts to move back toward the Straits. After 3 days, some oil has begun to impinge on the shores from Mackinaw City westward. Part of the patch separates and continues to move eastward, eventually impacting the southwestern shores of Bois Blanc Island. Meanwhile, the bulk of the spill moves back and forth through the Straits, impacting the Lake Michigan shores of both the Upper and Lower peninsulas west of the Straits, as well as the Lower peninsula shore of Lake Huron east of the Straits. After 10 days, 40% of the initial spill is still in the water. It gradually moves into Lake Michigan and slowly deposits along the northern shore as far west as Manistique over the next 30 days. In this case, it took almost 25 days before 90% of the oil was beached and it ultimately impacted over 100 km of shoreline.

- *Case 2: 4/14/14 00Z:* This case illustrates how quickly a spill could impact a large amount of shoreline. The initial oil patch in this case moves quickly southeastward into Lake Huron for 6 hours, but then reverses direction and moves back into the southern part of the Straits while depositing oil along the southern shoreline both east and west of Mackinaw City. After 1 day, more than 60% of the oil has beached and impacted 15 km of shoreline. In the next 12 hours, 30% more has beached and 22 km of shoreline are significantly affected.

- *Case 3: 4/16/14 06Z:* This case starts only 2 days after case 2, but has a vastly different outcome. Oil initially moves northeastward toward St. Helena Island in Lake Michigan, and is 90% beached on day 40 when 90 km of shoreline are impacted.

- *Case 4: 4/27/14 12Z:* This is one of the most extreme cases in terms of amount of impacted shoreline. This case starts similarly to Case 3, but after 5 days the oil patch has spread to both Lakes Michigan and Huron. By the time 90% of the oil has beached after almost 30 days, the oil has impacted 168 km of shoreline in both lakes.

- *Case 5: 7/1/14 06Z:* In this case, oil moves almost exclusively eastward, with more than 30% of the oil beached on Mackinac Island, Bois Blanc Island, and almost the entire Lake Huron shoreline from Mackinaw City to Cheboygan after 3 days. The oil travels as far south as Presque Isle on the Lake Huron shoreline in 15 days, and a small percentage of the particles reach northern Saginaw Bay on day 30. This case also illustrates the some of extreme distances in Lake Huron that could be reached in 30 days.

- *Case 6: 8/4/14 06Z:* Most of the oil in this case moves into Lake Michigan, but a substantial amount impacts the shores of Mackinac Island and St. Martin Bay. The bulk of the spill in Lake Michigan has impacted the entire north shore of Wilderness State Park by Day 3. Oil is beached on Beaver Island on Day 10, and has reached as far south as Little Traverse Bay by day 14. By day 30, a total of 116 km of shoreline have been impacted.

Statistical Analysis of Results

1. Time series

Maps of tracer particle locations from each of the 840 cases were analyzed at each hour after spill initiation to calculate 1) the open water area covered by the spill, 2) the fraction of the initial volume of oil still in the water, and 3) the fraction of the initial volume of oil on the beach. At any given time, the volume represented by 2) plus 3) equals the initial volume less evaporation.

Figures 1-3 show the hour-by-hour statistical distribution of these three parameters in terms of the median value (dark line), the 25th and 75th percentiles (light lines bordering the shaded area) and the 0 and 100th percentiles (bottom and top light lines). As shown in Figure 1, the median value of open water area covered by the spill increases to 300 km^2 after about 7 days, and then gradually decreases as more oil is beached. The maximum open water area affected by a single spill can reach 1600 km^2 at 35 days. Fifty percent of the cases have maximum open water areas between 200 and 400 km^2 with the peak occurring 5-7 days after the initial release. As shown in Figure 2, the median fraction of oil volume still on the water rapidly decreases to less than 10 percent after 5 days. The largest amount of oil remaining on the water after 35 days is about 10 percent of the initial volume. Figure 3 shows that in half of the cases, more than 65 percent of the initial volume of oil is beached after 7 days. In at least one case, 70 percent of the initial release volume is beached in less than 24 hours.

2. Offshore Impact

The next series of maps depict the distribution probability of oil at a particular time interval after the start of the case. The area around the Straits is divided into 1 km x 1 km square cells and the percent of cases that had at least one tracer particle in a cell is calculated. Maps are provided in Figures 4-11 for intervals of 6 hours, 12 hours, 1 day, 2 days, 4 days, 10 days, 30 days, and 60 days. The maps shows that in the first six hours after the release, oil is almost equally likely to be found east or west of the Straits, and could travel as far as 15 km in either direction (Figure 4). After 12 hours, there is a 10% chance that the shores of Mackinac and Bois Blanc Islands could be affected (Figure 5). At 1 day (Figure 6), it becomes clear that there is a higher likelihood for oil to be found in Lake Huron than in Lake Michigan, although it may have traveled further into Lake Michigan (up to 25 km) than into Lake Huron (20 km). After 2 days (Figure 7), the most likely location of oil is about 10 km east of the Straits with about half of the spill cases indicating the presence of oil there. The entire shorelines of Mackinac, Bois Blanc, and St. Helena Islands have been impacted in at least one of the cases. At 4 days (Figure 8), the most likely location to find oil has moved to 15 km east of the Straits and over 20% of the cases show impacts on Mackinac Island and Bois Blanc Island. Figures 9-11 show that after 4 days some oil continues to spread far into Lake Huron and to a lesser extent into Lake Michigan, but by this time most of the oil has beached or evaporated as shown in Figure 2.

An animation was created of the areal probability maps at hourly intervals for the first 5 days after release. The animation (available online, see: http://graham.umich.edu/news/mackinac-straits-oil-lines) shows that the most probable location for oil to be found is centered in the Straits for the first 12 hours after the initial release, but gradually moves toward the south shore of Lake Huron, south and east of Mackinac Island, during the next 24 hours. Over the next 3 days, the area where oil is present in at least 20% of the spill cases extends to the north of Mackinac Island, reaches 15-20 km west into Lake Michigan, and has moved as far south as Cheboygan in Lake Huron.

Figure 12 and Table 1 shows the percent of cases in which oil reached a particular area at *any* time during the 60-day duration of the case and Figure 13 depicts the *shortest* time (up to 10 days) that it would take oil to reach an area in any of the 840 spill cases.

As shown in Table 1, over 15% of Lake Michigan's open water (9,141 km^2) and almost 60% of Lake Huron's open water (35,264 km^2) could be affected by visible oil from a spill in the Straits. At least 60% of the cases affected an area of 207 km^2 in Lake Michigan and 1,953 km^2 in Lake Huron.

Table 1. Offshore area affected by any case. First column is the percentage range of cases, which affected this area. See Figure 12 for graphical representation.

Percent of cases	Total area (km^2)	L. Michigan area (km^2)	L. Huron area (km^2)
>0 %	44,405	9,141	35,264
>20%	12,931	1,688	11,243
>40%	5,684	518	5,166
>60%	2,160	207	1,953
>80%	635	64	571

3. Shoreline Impact

Figures 14-16 show the percent of cases that would result in the amount of beached oil exceeding "socio-economic impact" threshold of 1 gm/m^2 along each 1 km section of shoreline. The three figures are based on initial release volumes of 25,000, 10,000, and 5,000 bbl respectively. The total length of shoreline that could be impacted in any of the 840 cases is 1162, 835, and 709 km for the three release volumes respectively.

Tables 2 and 3 show the minimum arrival time (from Figure 13) and percent of cases exceeding the "socio-economic impact" threshold for the shoreline (from Figures 14-16) at a number of selected locations along the shorelines north and south of the Straits for the three initial release volumes.

Table 2. *Minimum arrival time (Column A) and percent of cases exceeding the "socio-economic impact" threshold for shoreline (Columns B, C, and D corresponding to initial release volumes of 25,000, 10,000, and 5,000 bbl respectively) for selected locations along the shore north of the Straits.*

North Shore	A	B	C	D
Garden Peninsula	29 days	1	<1	<1
Manistique	27 days	2	1	<1
Seul Choix Point	14.5 days	5	3	1
Naubinway	6 days	10	5	3
Brevort	40 hrs	25	20	16
Point Aux Chenes	18 hrs	40	32	30
St. Helena Island	6 hrs	58	52	50
Gros Cap	6 hrs	60	56	54
Point La Barbre	5 hrs	80	65	60
Bridge View Park	5 hrs	74	57	56
Graham Point	10 hrs	75	70	67
St. Ignace Ferry Docks	15 hrs	50	38	35
Castle Rock Campground	20 hrs	40	25	10
Mackinac Island South Shore	9 hrs	90	85	80
Mackinac Island North Shore	12 hrs	60	48	45
Round Island	8 hrs	92	88	85
Bois Blanc Island South Shore	10 hrs	90	85	82
Bois Blanc Island North Shore	12 hrs	70	65	60
Horseshoe Bay	24 hrs	20	12	10
Saint Martin Bay	30 hrs	10	6	5
Marquette Island	51 hrs	20	10	7
DeTour State Park	8 days	2	1	<1
Drummond Island	9 days	2	<1	<1
Cockburn Island	12.5 days	1	<1	<1
Manitoulin Island SW Shore	14.5 days	1	<1	<1

Table 3. *Minimum arrival time (Column A) and percent of cases exceeding the "socio-economic impact" threshold for shoreline (Columns B, C, and D corresponding to initial release volumes of 25,000, 10,000, and 5,000 bbl respectively) for selected locations along the shore south of the Straits.*

South Shore	A	B	C	D
Charlevoix	11 days	1	1	<1
Petoskey/Harbor Springs	10 days	1	1	<1
Beaver Island	9 days	2	1	1
Cross Village	4.5 days	10	5	2
Sturgeon Bay	4 days	8	5	2
Waugashance Island	30 hrs	20	16	14
Wilderness State Park North Shore	10 hrs	35	30	29
The Headlands	2.5 hrs	75	70	66
Old Mackinac Point	2.5 hrs	92	85	82
Mackinaw City Ferry Docks	3.5 hrs	85	80	74
Cadottes Point	6 hrs	90	80	75
Point Nipigon	15 hrs	85	78	72
Cheboygan	30 hrs	65	50	40
Hammond Bay	3 days	30	20	10
Rogers City	6 days	25	20	13
Presque Isle	7 days	20	10	5
Thunder Bay	10 days	5	2	1
Harrisville	21 days	1	<1	<1
Oscoda Twp.	27 days	1	<1	<1
Au Sable Point	29 days	1	<1	<1

The shortest arrival times are 2.5 hours on the south shore of the Straits near Mackinaw City, and 5 hours on the north shore. These times would be reduced if the oil release were closer to the north or south shore than the release point used in the simulations near the midpoint of the Straits. Mackinac Island could be impacted in as little as 9 hours, Round Island in 8 hours, and Bois Blanc Island in 10 hours. Locations that could be affected in less than a day extend from Point Aux Chenes to Horseshoe Bay north of the Straits and from the north shore of Wilderness State Park to a point northwest of Cheboygan on the south side of the Straits. Significant shoreline impact could still occur as far away as the Garden Peninsula and Charlevoix in Lake Michigan, and the western end of Manitoulin Island and AuSable Point in Lake Huron. At least 20 percent of the cases using a 25,000 bbl initial discharge showed significant shoreline impact at points from Brevort in Lake Michigan to Horseshoe Bay in Lake Huron along the north side of the Straits, and from Waugashance Island in Lake Michigan to Presque Isle in Lake Huron along the south side of the Straits.

Figures 17-19 show the statistical distribution of the amount of impacted shoreline as a function of time after the initial release for the three initial volumes of 25,000, 10,000, and

5,000 bbl. The median value is shown as a dark line; light lines bordering the shaded area below and above the median represent the 25th and 75th percentiles; and the bottom and top light lines are the 0 and 100^{th} percentiles.

Table 4 is a summary of the length of impacted shoreline for the three different initial release volumes in terms of 1) the length of shoreline that could be impacted by *any* spill, 2) the maximum length of impacted shoreline in a *single* case, and 3) the median length of impacted shoreline from *all* cases.

Table 4. *Length (km) of impacted shoreline for three initial release volumes*

Initial release volume	All Cases	Single Case	Median Case
25,000 bbl	1162	245	120
10,000 bbl	835	170	85
5,000 bbl	709	115	60

Conclusions and suggestions for future work

The main conclusion of this report is that a quantitative analysis of 840 oil spill cases in the Straits of Mackinac using a "worst-case discharge" from Line 5 shows that more than 1,000 km of Lake Huron-Michigan shoreline and specific islands are potentially vulnerable to an oil release in the Straits. This conclusion strongly supports the assertion that under the right weather conditions, a spill in the Straits could affect a significant amount of shoreline and open water area in either Lake Michigan or Lake Huron in a very short time. In the case of a 10,000 bbl release, the median length of impacted shoreline from all 840 cases is 85 km. Three quarters of all cases impacted more than 65 km of shoreline. The median size of an oil patch from a release in the Straits was 300 km^2 after 7 days. Three quarters of the 840 cases resulted in maximum open water oil patch sizes greater than 200 km^2 after as little as 5 days. The maximum open water area subject to oiling in any of the cases was over 1600 km^2.

Limitations of the Report and Results

The affect of ice cover in the Straits was not considered. Ice typically affects the Straits each winter from late December to April. Commercial vessel traffic continues during at least part of this period with assistance from U.S. Coast Guard icebreaking operations. The possibility of an oil spill from Line 5 also continues through winter, but little is known about how ice cover would affect an oil spill in the Straits. This is an area that requires further investigation.

One difference between the spill simulations carried out in this study and the methodology used in GNOME is that the GNOME software includes a provision for a "minimum regret" solution based on uncertainty in the assumed water currents. We did not include this factor in our calculations. If it were included, the "minimum regret" solutions would tend to encompass wider open lake areas and increase the amount of impacted shoreline, so the results presented in this report can be considered somewhat conservative.

The direct affect of wind on the spill trajectory was not considered. Including this affect would likely increase the affected open lake area and amount of impacted shoreline. So the results we present are conservative in this respect.

Finally, we have not considered processes by which oil would sink or be otherwise incorporated into the water column below the surface. For the type of petroleum products being carried by Line 5, this effect would probably be small, but in any case, our findings would still apply to oil remaining on or near the surface.

The results from this report are anticipated to provide guidelines for the development of a full risk analysis in the future.

Recommendations for Further Study

The spill scenario simulations in this study are only the first step in a complete risk analysis of a "worst case discharge" as called for in the State of Michigan Petroleum Pipeline Task Force Report (2015). Other considerations in a more complete risk analysis would include 1) analysis of environmental impacts, 2) cleanup costs, 3) restoration and remediation measures, 4) a natural resource damage assessment, and 5) Economic damage to public and private sector interests.

In addition, information about how ice cover would affect an oil spill in the Straits requires further investigation.

Acknowledgement
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Figures

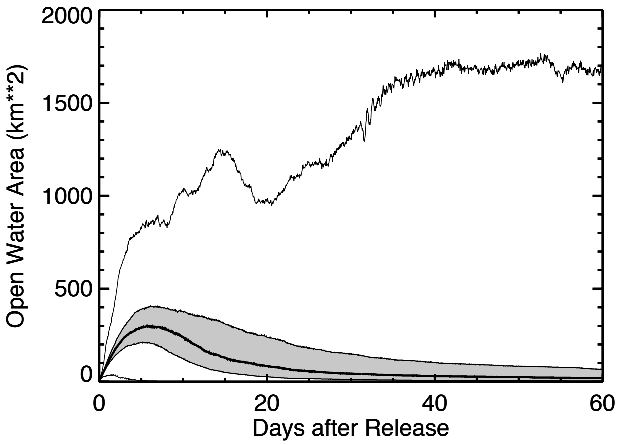

Figure 1. Time series of statistical distribution of affected open water area in each of the 840 spill cases. The dark line is the median value, the light lines bordering the shaded area are the 25th and 75th percentiles, and the lower and upper lines are the 0th and 100th percentiles.

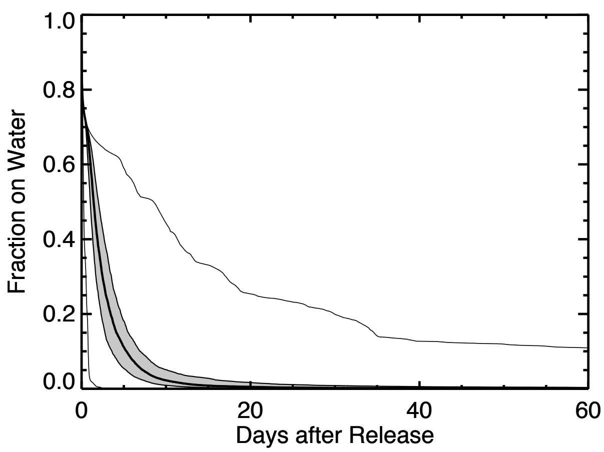

Figure 2. Time series of statistical distribution of fraction of initial oil release volume remaining on water in each of the 840 spill cases. The dark line is the median value, the light lines bordering the shaded area are the 25th and 75th percentiles, and the lower and upper lines are the 0th and 100th percentiles.

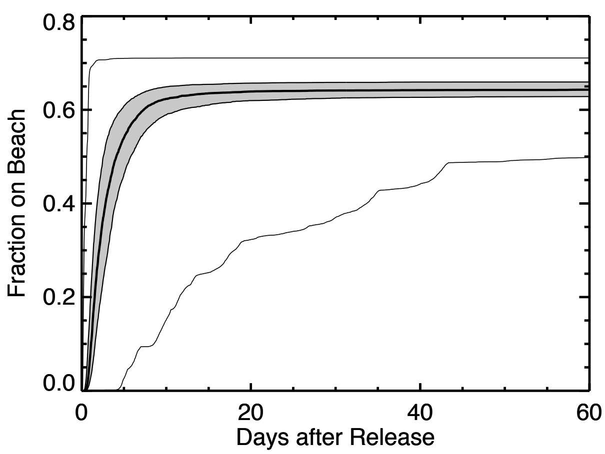

Figure 3. Time series of statistical distribution fraction of initial release volume that has beached in each of the 840 spill cases. The dark line is the median value, the light lines bordering the shaded area are the 25th and 75th percentiles, and the lower and upper lines are the 0th and 100th percentiles.

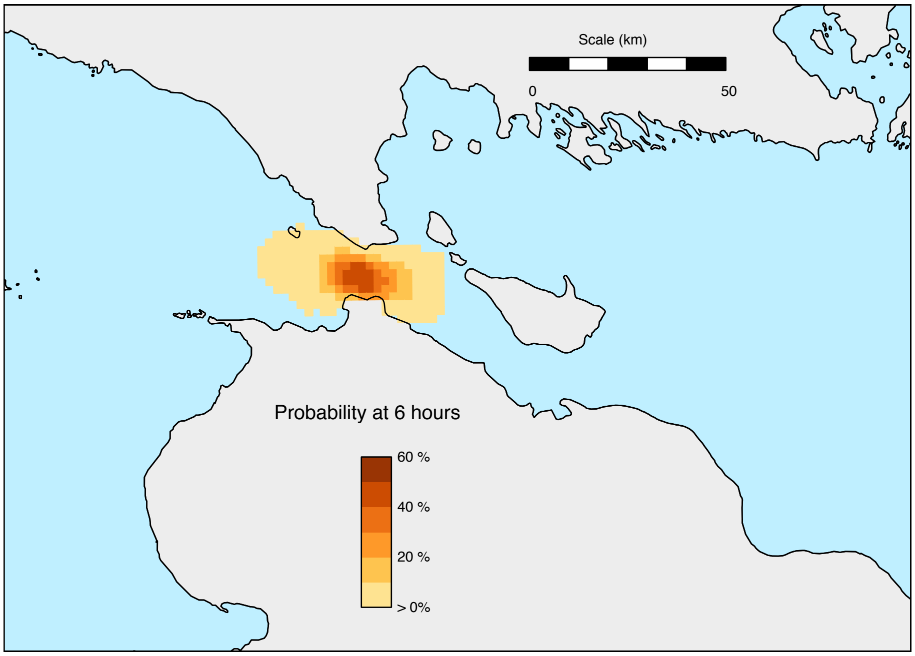

Figure 4. Probability of presence of oil (percent of cases) at 6 hours after initial release.

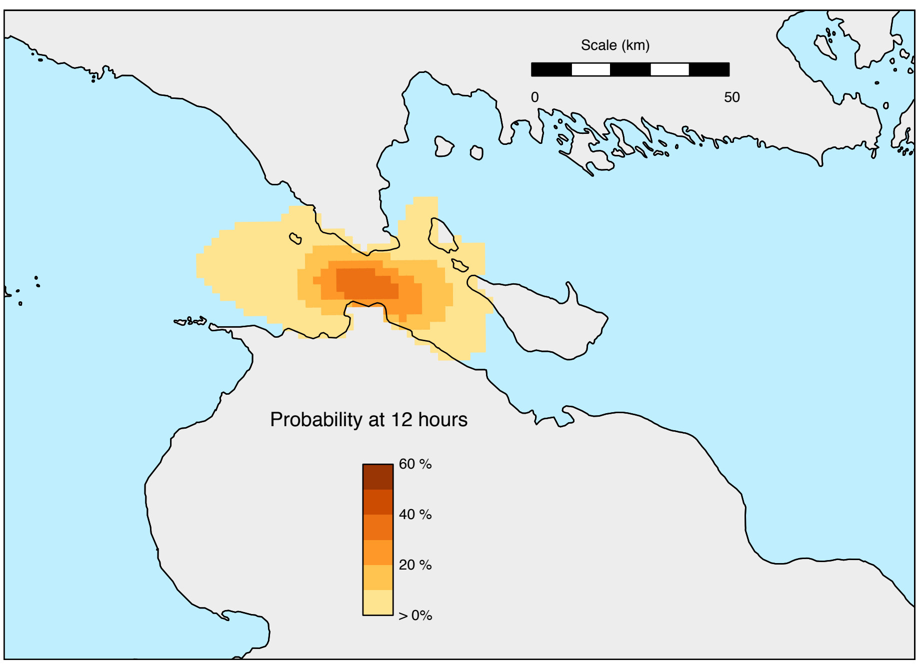

Figure 5. Probability of presence of oil (percent of cases) at 12 hours after initial release.

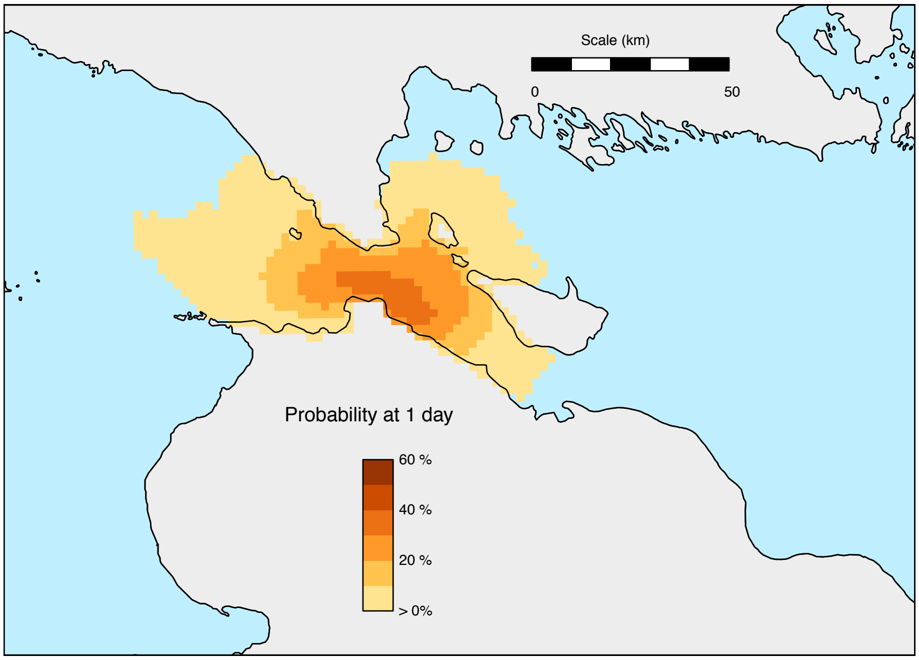

Figure 6. Probability of presence of oil (percent of cases) at 1 day after initial release.

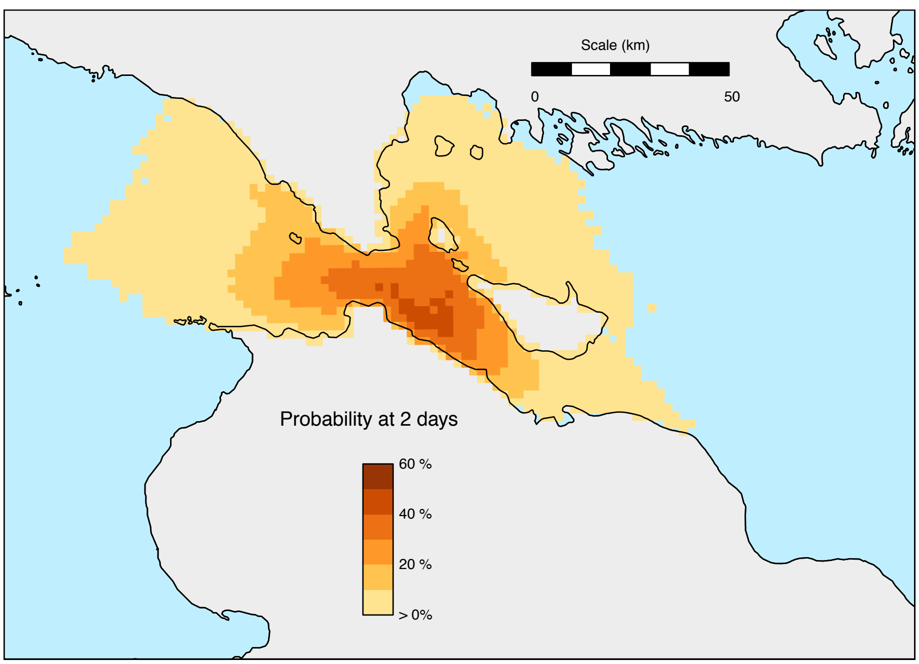

Figure 7. Probability of presence of oil (percent of cases) at 2 days after initial release.

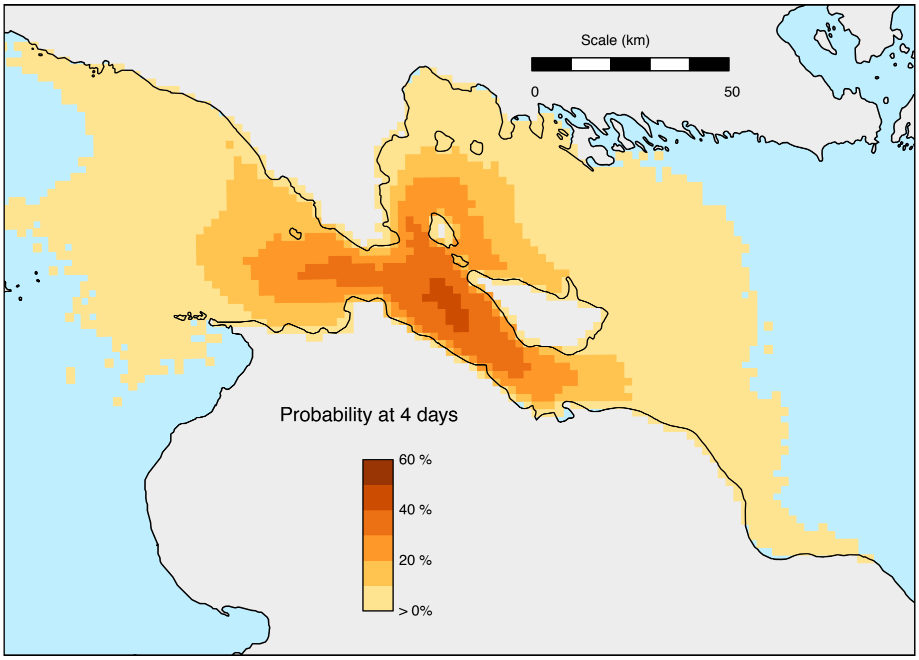

Figure 8. Probability of presence of oil (percent of cases) at 4 days after initial release.

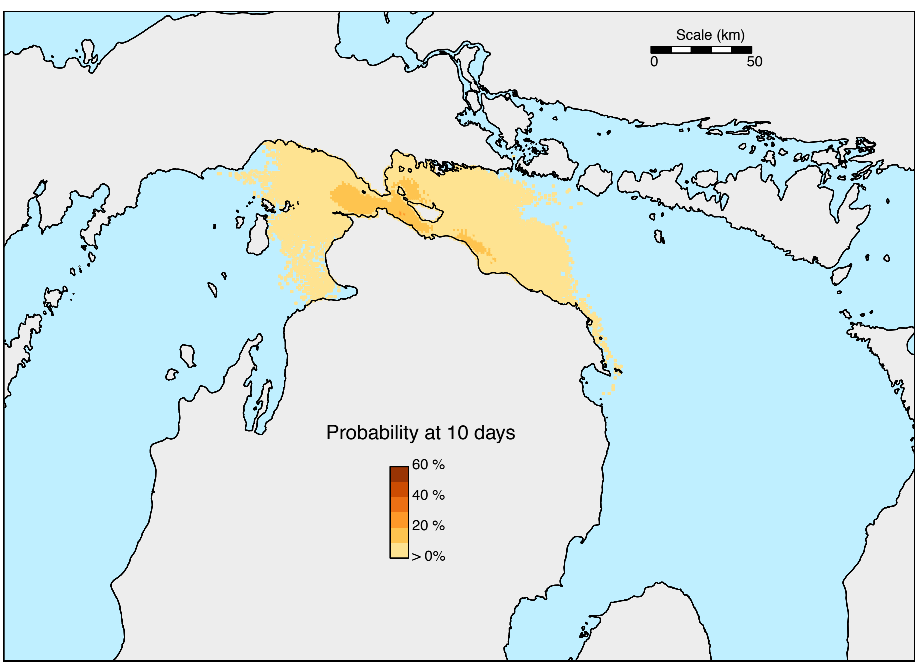

Figure 9. Probability of presence of oil (percent of cases) at 10 days after initial release.

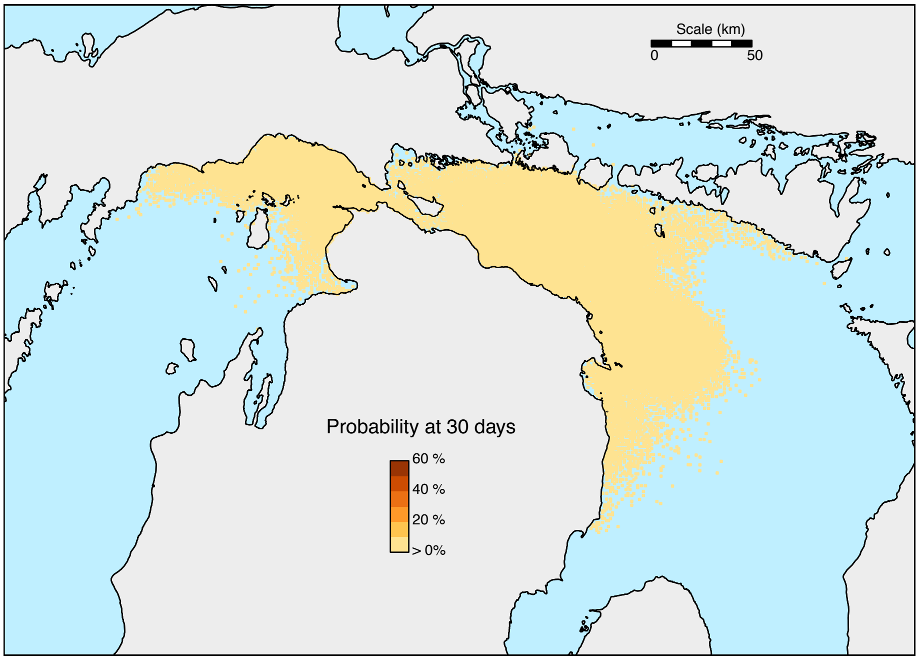

Figure 10. Probability of presence of oil (percent of cases) at 30 days after initial release.

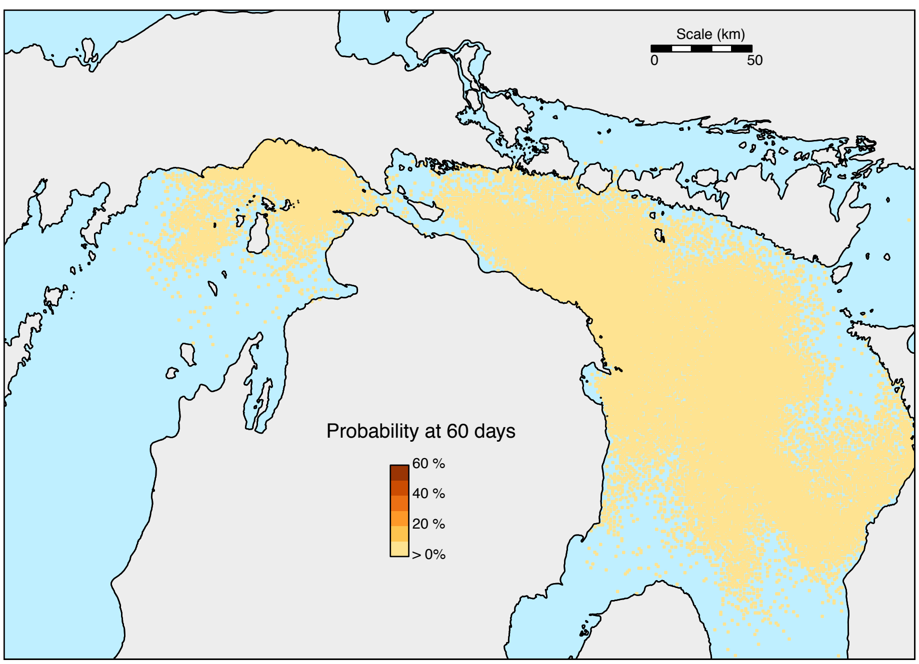

Figure 11. Probability of presence of oil (percent of cases) at 60 days after initial release.

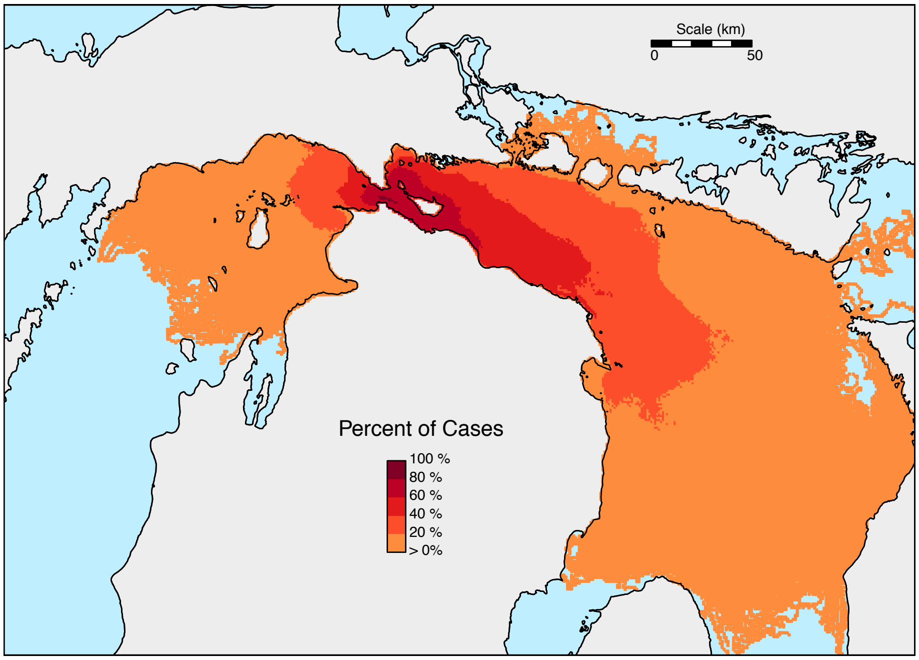

Figure 12. Percent of cases in which oil is present at *any* time after initial release.

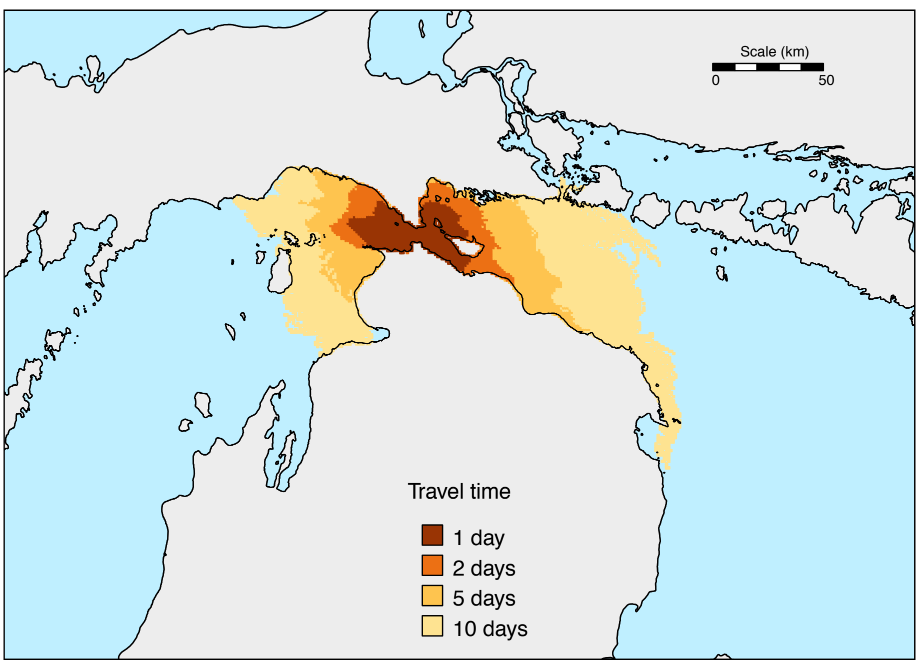

Figure 13. Minimum travel time (up to 10 days) to a location from *any* case.

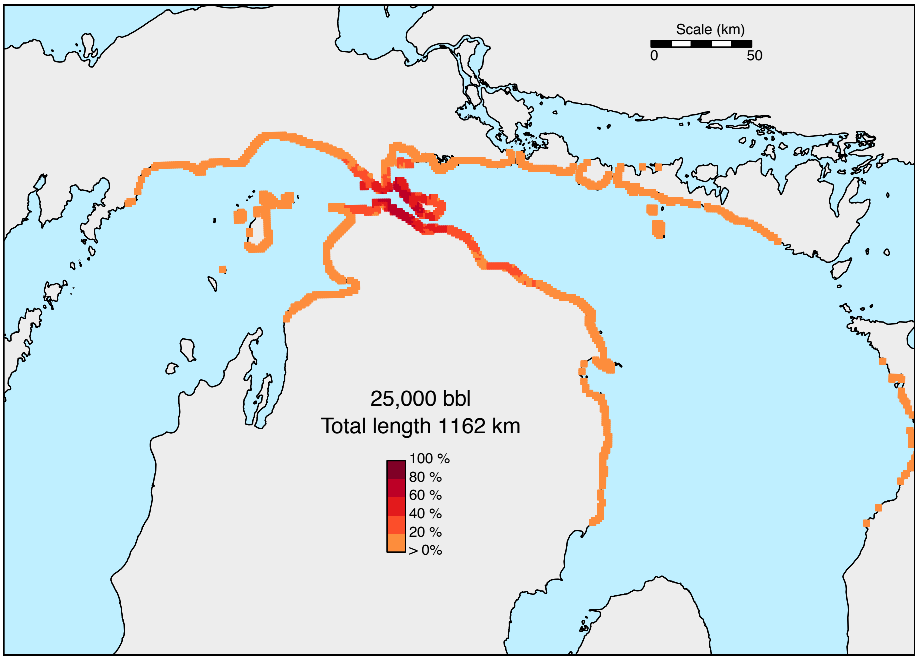

Figure 14. Probability (percent of cases) that beached oil concentration exceeds 1 gm/m^2 after 60 days from any spill case, based on an initial release volume of 25,000 bbl.

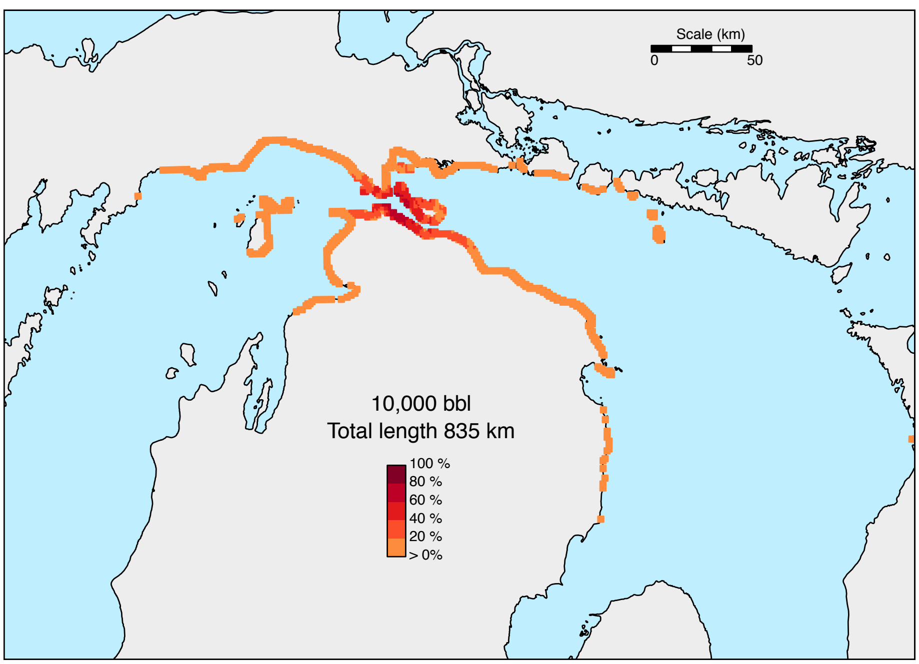

Figure 15. Probability (percent of cases) that beached oil concentration exceeds 1 gm/m^2 after 60 days from any spill case, based on an initial release volume of 10,000 bbl.

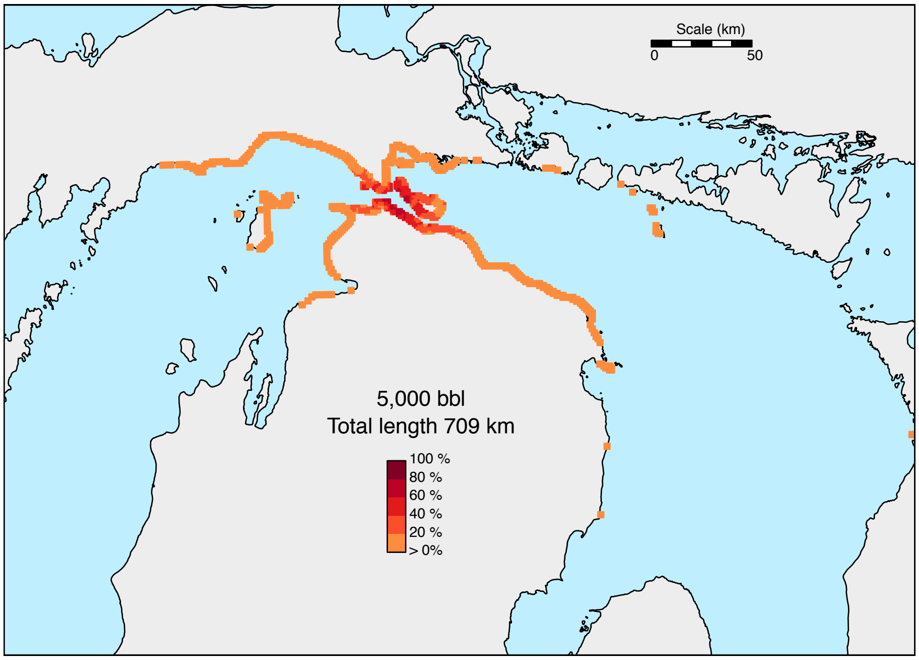

Figure 16. Probability (percent of cases) that beached oil concentration exceeds 1 gm/m^2 after 60 days from any spill case, based on an initial release volume of 5,000 bbl.

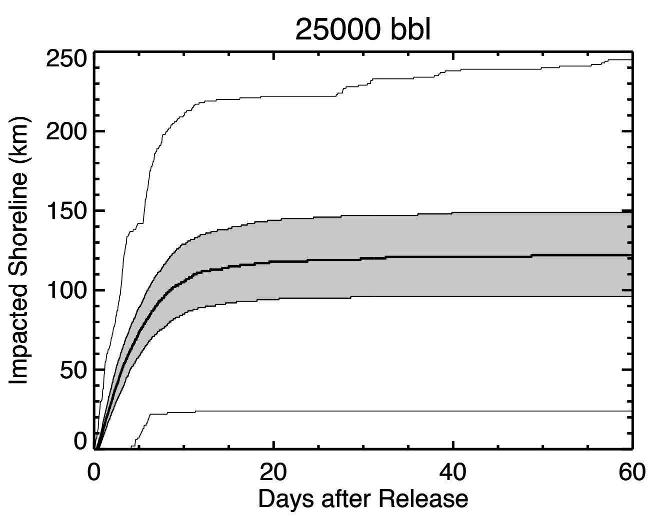

Figure 17. Time series of statistical distribution of length of impacted shoreline based on an initial release volume of 25,000 bbl. The dark line is the median value, the light lines bordering the shaded area are the 25th and 75th percentiles, and the lower and upper lines are the 0th and 100th percentiles.

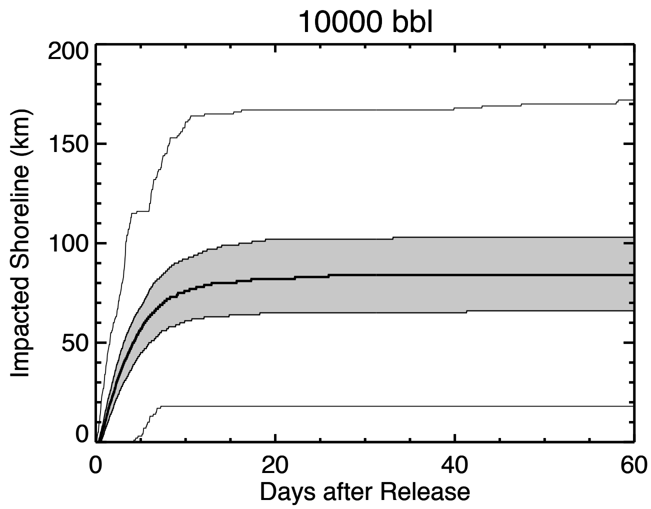

Figure 18. Time series of statistical distribution of length of impacted shoreline based on an initial release volume of 10,000 bbl. The dark line is the median value, the light lines bordering the shaded area are the 25th and 75th percentiles, and the lower and upper lines are the 0th and 100th percentiles.

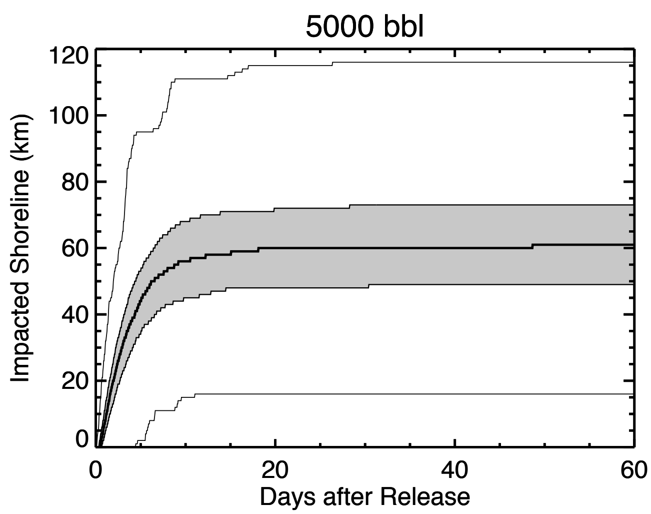

Figure 19. Time series of statistical distribution of length of impacted shoreline based on an initial release volume of 5,000 bbl. The dark line is the median value, the light lines bordering the shaded area are the 25th and 75th percentiles, and the lower and upper lines are the 0th and 100th percentiles.

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The Water Center engages researchers, practitioners, policymakers, and nonprofit groups to support, integrate, and improve current and future freshwater restoration and protection efforts. The Water Center conducts collaborative science, supporting Great Lakes restoration and coordinates the National Estuarine Research Reserve System (NERRS) Science Collaborative. The Water Center is part of the U-M Graham Sustainability Institute, which fosters sustainability through translational knowledge, transformative learning, and institutional leadership.