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Mitigation of Oil Moving Along the Waterway Bottom

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Mitigation of Oil Moving Along the Waterway Bottom

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16. Abstract (MAXIMUM 200 WORDS) In 2016, the U.S. Coast Guard (USCG) Research and Development Center (RDC) determined a need to advance the science of spill response technologies for non-floating, or sunken oil. Since 2017, RDC designed, fabricated, and tested underwater barrier systems that can mitigate the adverse impacts of moving, sunken oil along the bottom of inland and offshore environments as well as large lakes. Mitigation is achieved by containing the spread of oil on the bottom and deflecting it to a collection area for recovery, or away from sensitive areas. RDC tested two different inland mitigation systems in the Kalamazoo River in April 2018 and April 2019, and an offshore mitigation system in Lake Huron in May 2018. For each mitigation system prototype, RDC explored several different anchoring, deployment, and retrieval methods. RDC also monitored each system for position, motion, sag, scour, and tension. RDC deployed the mitigation systems in areas of low to high current velocities in both the Kalamazoo River and Lake Huron. In this compilation report, RDC's summaries, conclusions, and recommendations for future research are provided with respect to the prototypes developed.					
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EXECUTIVE SUMMARY

The rise of oil sands production in Canada has been a major contributing factor to the overall growth of crude oil production in North America. Spills of oil sands products have occurred in the past, and real world experience demonstrates that they behave differently than conventional crude oil during an incident. In 2010, approximately a million gallons of diluted bitumen flowed into the Kalamazoo River from a damaged pipeline. Over 20 miles of shoreline were affected, making it one of the largest inland spills in U.S. history. EPA made the following statement on the overall initial response activities in the Kalamazoo River, “...there exists a great need for ongoing research and development into effective submerged oil containment devices and tactics.”

The U.S. Coast Guard Research and Development Center (RDC) created a research project that included the development of prototypes with potential to respond to these difficult non-floating oil spills. RDC developed and tested three oil spill response prototypes designed to mitigate the impacts of oil sands products in the inland and offshore environments.

RDC’s first inland mitigation system prototype consisted of three separate 25-foot boom-like sections linked together with slide connectors for a total length of 75 feet. Each 25-foot section weighed approximately 500 pounds with the flotation and weights covered with polyvinyl chloride (PVC) material. The system’s primary purpose is to divert moving, sunken oil from a faster part of the river towards the shoreline where current velocity is less.

The CLAMShell system was RDC’s second inland mitigation system, designed to be deployed as part of a long-term cleanup strategy instead of a first response option. The prototype consisted of four sections (27 feet each) for a total length of 108 feet. The purpose of this mitigation system is to promote deposition of moving, sunken oil along the length of the system.

RDC’s third prototype, for offshore mitigation, was made of semi-rigid high-density polyethylene (HDPE) panels covered with PVC. The system was approximately 3 feet high and was 200 feet in total length. Its primary objective was to collect sunken oil rather than diverting it to a specific location.

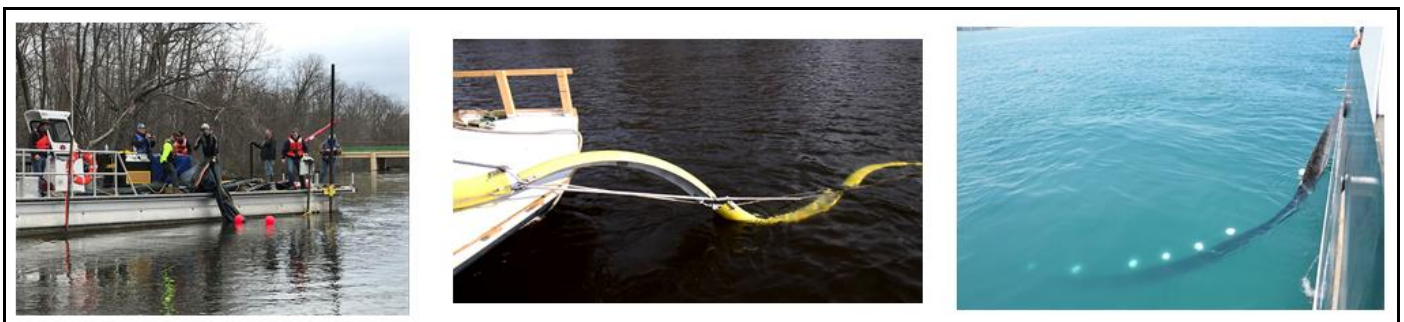


Figure ES-1. The figure shows images of the two inland and one offshore prototypes being deployed.

RDC captured lessons learned and developed recommendations to improve the designs of these prototypes. The research, development, test, and evaluation (RDT&E) conducted on these prototypes will contribute to a future final report on oil sands products spill response.

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

CFD	Computational Fluid Dynamics
DAQ	Data Acquisition System
Dilbit	Diluted Bitumen
EPA	United States Environmental Protection Agency
FOSC	Federal On-Scene Coordinator
ft	Feet
GLRI	Great Lakes Restoration Initiative
HDPE	High-Density Polyethylene
kt	Knot
OSC	On-Scene Coordinator
OSRO	Oil Spill Removal Organization
PVC	Polyvinyl Chloride
R&D	Research and Development
RDC	United States Coast Guard Research and Development Center
RFP	Request for Proposal
RHIB	Rigid Hull Inflatable Boat
ROV	Remotely Operated Vehicle
USCG	United States Coast Guard
USCGC	United States Coast Guard Cutter



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1 INTRODUCTION

Improved response to non-floating oil spills has been a U.S. Coast Guard Research and Development Center's (RDC) priority since 2008, when it carried out projects to identify, design, and test new methods for detecting and responding to sunken oil on the bottom of a water body and oil suspended in the water column. With these projects complete, RDC shifted its focus to oil sands products spills, which have recently garnered national attention. With partial funding support from the U.S. Environmental Protection Agency (EPA) through its Great Lakes Restoration Initiative (GLRI) program, RDC sought to advance the science of spill response technologies for moving, sunken oil. RDC developed and tested three separate oil spill response prototypes designed to mitigate the impacts of spilled oil sands products (or other non-floating oil) in the inland and offshore environments. The work to mitigate the impacts of spilled oil sands products or other heavy oil types is part of a larger research and development (R&D) effort at the RDC to develop enhanced decision-making tools for responding to this particular type of oil spill. From 2016 to 2017, RDC carried out the Concept Development phase (Phase I). From 2018 to 2019, RDC developed the actual prototypes during the Fabrication and Test phase (Phase II).

The first of the two inland mitigation system prototypes was deployed in April 2018 within the upstream portion of Morrow Lake on the Kalamazoo River in Michigan. The second inland prototype was deployed in the same location the following April in order to take advantage of the water depth and river current velocities that were available only in the springtime. The third mitigation system and the sole offshore prototype was deployed from the U.S. Coast Guard Cutter (USCGC) Hollyhock in Lake Huron near Port Huron, Michigan in May 2018. RDC selected both locations due to their proximity to the Great Lakes where GLRI stakeholders would have an opportunity to observe the equipment and engage with RDC's project teams.

1.1 Objective

RDC's primary objective with the development and testing of three mitigation systems was to advance the science of response technologies for moving sunken oil. This report captures findings and lessons learned, and makes recommendations from the three mitigation prototype tests that RDC carried out from April 2018 to April 2019 in the Kalamazoo River and Lake Huron. Although RDC did not use actual oil, field tests validated whether or not the prototypes met RDC's performance requirements, and how easily they can be deployed and recovered. RDC also monitored the mitigation systems while deployed, and recorded measured and observational data.

1.2 Background

In the past decade, the rise of oil sands production in Canada has been a major contributing factor to the overall growth of crude oil production in North America. Oil sands generally consist of extra heavy crude oil or crude bitumen trapped in unconsolidated sandstone along with sand, clay and water. Bitumen is extremely dense and viscous, with a consistency ranging from that of molasses to peanut butter at room temperature, making extraction difficult. As a result of oil sands' high viscosity and their abundance in landlocked Alberta, the future of oil sands as a reliable energy source is dependent on how they can be transported to distant refineries.



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Oil sands can be transported if they are heated or diluted with lighter hydrocarbons or natural gas condensates (diluent). Diluted bitumen (dilbit) is typically comprised of 70 percent bitumen and 30 percent diluent and is one type of oil sands products. Producers normally transport them by rail or pipeline; however every transportation method carries with it an inherent risk of spillage. Spills of oil sands products have occurred in the past, and real world experience demonstrates that they behave differently than conventional crude oil during an incident. To this day, scientists and researchers continue to study dilbit's properties as well as its fate and behavior if spilled into the environment.

In 2010, approximately 877,000 to 1 million gallons of dilbit flowed into the Kalamazoo River from a damaged pipeline owned by Enbridge, Inc. Over 20 miles of shoreline were affected, making it one of the largest inland oil spills in U.S. history. Responders faced the atypical challenge of trying to mitigate the impacts of moving, sunken oil. During the early stages of spill response, Enbridge, EPA On-Scene Coordinators (OSCs) and Oil Spill Removal Organizations (OSROs) tried several approaches to recovering the oil with varying degrees of success. Some approaches included the use of air curtains, silt curtains, gabion baskets with snare booms (see Figure 1), surface booms with sediment curtain using X-tex® material, and sedimentation basins.



Figure 1. Gabion basket with snare booms in the Kalamazoo River during 2012 cleanup efforts (Enbridge Energy, 2016).

In the Federal On-Scene Coordinator (FOSC) Report on the Kalamazoo River spill, EPA noted that “use of sediment curtains, X-tex® curtains, gabion baskets, and air curtains all demonstrated some level of effectiveness in containing submerged oil early in the response” (Enbridge Energy, 2016). EPA also observed that placing equipment in high velocity areas of the Kalamazoo River “resulted in significant scouring of the river bed sediment, resulting in less effective capture of submerged oil” (Enbridge Energy, 2016). EPA deemed that the surface booms with sediment curtains and the use of X-tex® material were promising approaches for collecting submerged oil in higher flow velocity areas while air curtain techniques were the least effective. In conclusion, EPA made the following statement on the overall initial response activities in the Kalamazoo River, “...there exists a great need for ongoing research and development into effective submerged oil containment devices and tactics” (Enbridge Energy, 2016). RDC recognized this need for better mitigation approaches for non-floating oil spills in rivers and streams as well as nearshore and large lake environments, and sought to develop prototypes to address this need.



1.3 RDC Prototype Requirements¹

RDC included a list of mitigation system requirements in its Request for Proposals (RFPs) based on lessons learned from the Kalamazoo River spill. The requirements are categorized by oil containment, system configuration, and deployment and retrieval. Each set of requirements differ between a system designed for the inland environments and a system for the offshore and large lake environments. Table 1 includes numeric, operating environment and configuration parameters for a full-scale sized solution, and Sections 1.3.1 and 1.3.2 list specific requirements for what a full scale sized system should include, as well as prototype development requirements, for both inland and offshore/large lake mitigation systems.

Table 1. Operating environment and configuration parameters for inland and offshore/large lake mitigation systems.

System	Depth	Current Velocity	Wave Height	Section Length	Total Length
Inland	3-50 feet	2-8 knots	0-1 feet	25-50 feet	100-200 feet
Offshore/Large Lakes	20-200 feet	0.5-4 knots	3-6 feet	50-100 feet	1,000-2,000 feet

1.3.1 Inland Mitigation System Requirements

1.3.1.1 Oil Containment Requirements

- The system shall be designed to mitigate sunken oil within the parameters in Table 1 for inland systems. The mitigation could include recovery or capture by the material in the system, deflection away from sensitive areas, and deflection or corralling to a known location for recovery by skimmers or underwater systems.
- The system shall mitigate droplets and tar balls moving along the bottom.
- If the system utilizes a material that absorbs or binds to the sunken oil, the system shall allow for the exchange of that component as they are oiled.

1.3.1.2 System Configuration Requirements

- The system shall meet the section length and total length parameters in Table 1 for inland systems.
- The system shall be deployable in a deflection configuration that moves the oil in a preferred direction, potentially to a recovery mechanism.
- The system shall be adjustable and have a manual that provides guidance for adjustment as environmental conditions change within the parameters in Table 1 for inland systems.
- The system shall provide outlets/escapes for animals/wildlife between the river/stream/small pond bottom and the water's surface.
- The system shall minimize impact to the bottom by limiting the portion of the system impacting the bottom from fluctuating (fluttering) by no more than 6 inches.
- The system shall have anchoring options for silt, sandy and rocky bottoms.
- The system shall have a method of marking its location on the surface such as options for buoys, poles, or other oil spill booms. As a minimum, both ends shall be marked for quick location and recovery.
- The system approach shall have a method to observe and monitor any sunken oil accumulation without retrieving entire system such as video, sonar or sampling.
- The system shall be able to be shipped on standard 40-inch by 48-inch pallets by no more than 50 inches high.

¹ The term "requirements" is used in context to the desired functional characteristics of a future and prototype system vice an "acquisition requirement."



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1.3.1.3 Deployment and Retrieval Requirements

- The system shall be designed to be deployable or recoverable within the parameters in Table 1 for inland systems.
- The system shall be safely deployable or recoverable in less than two hours for 200 linear feet of barrier.
- Recovery of the system shall require no more than the use of small crane (1,000 pound capacity) crane and/or small winch (500 pound line pull). A hand deployment is preferred.
- The system shall have a method and associated equipment for decontamination of the system upon retrieval.
- The system shall be reusable after decontamination and/or reconditioning to include the replacement of barrier material.

1.3.1.4 Prototype System Requirements

- The prototype system shall meet all requirements in Sections 1.3.1.1 to 1.3.1.3 with the following exceptions and replacements:
 - The prototype shall have a total length between 50 feet and 100 feet.
 - The prototype shall be deployable and recoverable in up to 10 feet of water.
 - The prototype shall be deployable in waves of 0.5 feet or less.
 - The prototype shall be deployable and recoverable in currents up to two knots.
 - The prototype shall have an anchoring system for a sandy bottom only.
 - The prototype shall be deployable in less than two hours.
 - The prototype shall have a data recording system that can track prototype performance in terms of positioning, shape, and loads on the system.

1.3.2 Offshore/Large Lakes Mitigation System Requirements

1.3.2.1 Oil Containment Requirements

- The system shall be designed to mitigate sunken oil within the parameters in Table 1 for offshore/large lake systems. The mitigation could include recovery or capture by the material in the system, deflection away from sensitive areas, and deflection or corralling to a known location for recovery by skimmers or underwater systems.
- The system shall mitigate droplets and tar balls moving along the bottom.
- If the system utilizes a material that absorbs or binds to the sunken oil, the system shall allow for the exchange of that component as they are oiled.

1.3.2.2 System Configuration Requirements

- The system shall meet the section length and total length parameters in Table 1 for offshore/large lake systems.
- The system shall be deployable in a “surround” configuration to corral the oil from moving in any direction.
- The system shall be deployable in a deflection configuration that moves the oil in a preferred direction, potentially to a recovery mechanism.
- The system shall be adjustable and have a manual that provides guidance for adjustment as environmental conditions change within the parameters in Table 1 for offshore/large lake systems.
- The system shall provide outlets/escapes for animals/wildlife between the ocean or lake bottom and the water’s surface.



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- The system shall minimize impact to the bottom by limiting the portion of the system impacting the bottom from fluctuating (fluttering) by no more than 6 inches.
- The system shall have anchoring options for silt, sandy and rocky bottoms.
- The system shall have a method of marking its location on the surface such as options for buoys, poles, or other oil spill booms. As a minimum, both ends shall be marked for quick location and recovery.
- The system approach shall have a method to observe and monitor any sunken oil accumulation without retrieving entire system such as video, sonar or sampling.
- The system shall be able to be shipped on standard 40-inch by 48-inch pallets by no more than 50 inches high.

1.3.2.3 Deployment and Retrieval Requirements

- The system shall be designed to be deployable or recoverable within the parameters in Table 1 for offshore/large lake systems.
- The system shall be safely deployable or recoverable in less than four hours for 500 linear feet of barrier.
- Final positioning of the system shall be accomplished by no more than two divers in 25-100 feet of water or by remotely operated vehicle (ROV) in 100-200 feet of water.
- Recovery of the system shall require no more than the use of small crane (2,000 pound capacity) crane and/or small winch (5,000 pound line pull).
- The system shall have a method and associated equipment for decontamination of the system upon retrieval.
- The system shall be reusable after decontamination and/or reconditioning to include the replacement of barrier material.

1.3.2.4 Prototype System Requirements

- The prototype system shall meet all requirements in Sections 1.3.2.1 to 1.3.2.3 with the following exceptions and replacements:
 - The prototype shall have a total length between 100 feet and 200 feet.
 - The prototype shall be deployable and recoverable in up to 50 feet of water without the assistance of divers or ROV.
 - The prototype shall be deployable in waves of two feet or less.
 - The prototype shall be deployable and recoverable in currents up to two knots.
 - The prototype shall have an anchoring system for a sandy bottom only.
 - The prototype shall be deployable in less than two hours.
 - The prototype shall have a data recording system that can track prototype performance in terms of positioning, shape, and loads on the system.

2 PROTOTYPE DEVELOPMENT AND DESCRIPTIONS

RDC awarded contracts to carry out Phase I (Concept Development) and Phase II (Fabrication and Test) for three mitigation system prototypes. One contractor developed both inland and offshore mitigation systems while the other developed an inland mitigation system only. Sections 2.1 to 2.3 below describe each mitigation system prototype.



2.1 Inland Mitigation System 1

RDC developed its first inland mitigation system working with Alion Science and Technology Corporation. This prototype was developed consisting of flotation, a proprietary fabric blend called X-tex®, weights along the bottom, and scour flaps on both sides of the system to provide a seal against the river bottom in high current areas. The primary purpose of the system is to divert moving, sunken oil from a faster part of the river towards the shoreline where current velocity is less (see Figure 2). In a spill scenario, responders will need to place the system at strategic locations in a river or other inland environments where the oil can be diverted to an area for easy recovery with mechanical spill response equipment. The angle of the system deployment relative to the shoreline depends on the current velocity. The higher the current velocity, the more parallel to the shoreline the system should be so that the stress acting on the system from the current is reduced.



Figure 2. A potential layout of the inland mitigation system 1 prototype in a river to divert oil to the shoreline.

The prototype consisted of three separate 25-foot sections linked together with slide connectors for a total length of 75 feet. Each 25-foot section weighed approximately 500 pounds, with the flotation and weights covered with polyvinyl chloride (PVC) material. The majority of the weight of the prototype was in the ballast chains, which were sized to limit movement of the bottom of the system (Michel, et al., 2017). The system panels were made of X-tex® fabric designed to allow water to flow through but retain oil. In theory, this would help to reduce the stress on the system from the river current. Each section was approximately 3 feet high but the section closest to shoreline was 2 feet to account for the shallower depth and slower current velocity. This helped reduce the overall weight. One section was constructed with Velcro to allow easy replacement of the X-tex® fabric panel. This was based on an idea that the entire system did not have to be pulled out of the water if portions of it were excessively oiled and needed cleaning. Figure 3 displays the system's specifications. The right photo of Figure 3 shows the fiberglass ribs embedded in the PVC material for the scour flaps to ensure they stayed rigid during underwater deployment.

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Figure 3. Inland mitigation system 1 prototype.

This prototype can be deployed with two different anchoring methods, one for shallower waters with sandy bottoms and one for deeper waters with harder substrates. The anchor post approach is used for shallow waters, which in RDC's case is interpreted to be less than 10 feet, and can be driven in with pole drivers. The system is then deployed with the upstream end attached to an anchor post, and the downstream end tied to a tree or a heavy object on the shoreline. The other anchor posts in between support and keep the system upright from the downstream side. In deeper waters or in areas with harder bottom substrates, one end of the system can be tied to a submerged Jersey barrier with the other end tied to a tree or a heavy object on the shoreline similar to the anchor post approach. Figure 4 depicts the two anchoring methods for this prototype system.



(a)



(b)

Figure 4. (a) Anchor post approach shown for shallow water deployments, (b) Jersey barrier approach shown for deeper water deployments.



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The prototype was also designed for easy deployment and compact storage with disjointed floats that allow the prototype to be folded accordion-style and stowed on standard 40 by 48 inch sized pallets. For deployments, the scour flaps were folded up and wrapped with a truss line. Once the prototype is released in the desired location underwater, the truss line can be pulled free to allow the scour flaps to drop down in a “falling apron” approach (Michel, et al., 2017).

2.2 Inland Mitigation System 2

RDC developed its second inland mitigation system working with American Systems Corporation (ASC). Designed to be deployed as part of a long-term cleanup strategy instead of a first response option, the CLAMShell system mimics naturally-occurring bottom features that can trap oil, such as depressions or large rocks. The design theory is the shell shape will generate an oscillation of the water flow path and create eddy pools that will capture/transfer oil sands products, which will then be carried by the osculation around the shell shapes down the array (Croom et al., 2019). Osculation is defined as the point where two curves come into contact. The system is intended to be deployed in a cascading formation and does not use sorbent materials of any kind. The purpose of this mitigation system is not to serve as a barrier in the river to collect moving, sunken oil as it migrates downstream a river, but to promote deposition of it along the length of the system. Figure 5 shows a concept design of the full scale system.

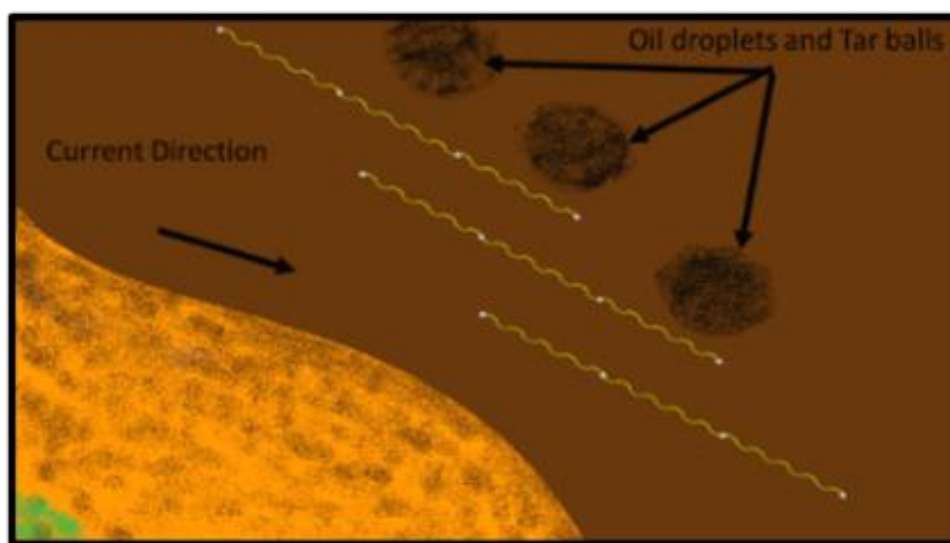


Figure 5. Conceptual configuration of CLAMShell layout in a spill scenario (Oates, 2017).

Figure 6 shows a detailed diagram of the CLAMShell system components. The prototype version of this mitigation system consisted of four sections (27 feet each) for a total length of 108 feet. Each section was comprised of nine 36-inch shell segments and when deployed, each shell segment was horizontally opposed. Originally, Kevlar was specified for the system material but due to cost considerations, the equipment was instead constructed with schedule 80 PVC electrical conduit with preformed 90 degree arcs (Oates, 2017). Each CLAMShell segment measured 6 inches high and they were attached to upper and lower strength members, which is a common technique used in towed arrays system (Croom et al, 2019). The upper line was Sampson Amsteel Dyneema while the lower line was a Vectran aramid fiber. Both ropes were low weight, high strength, and highly flexible.



Mitigation of Oil Moving Along the Waterway Bottom

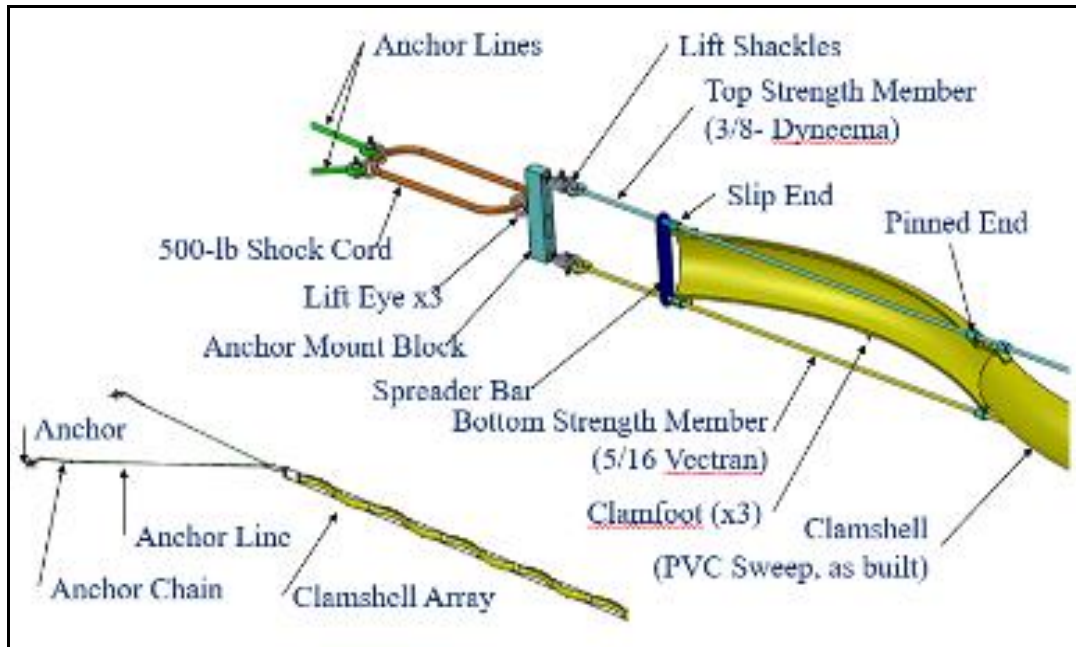


Figure 6. CLAMShell system components with labels (American Systems Corporation, 2019).

The CLAMShell prototype system with all four sections was stowed in a 40 by 48 by 40-inch (length, width, height) container and is loaded “last in, first out” similar to how a parachute is deployed. Figure 7 depicts how the system fits together in a clamshell fashion when stowed (Oates, 2017).

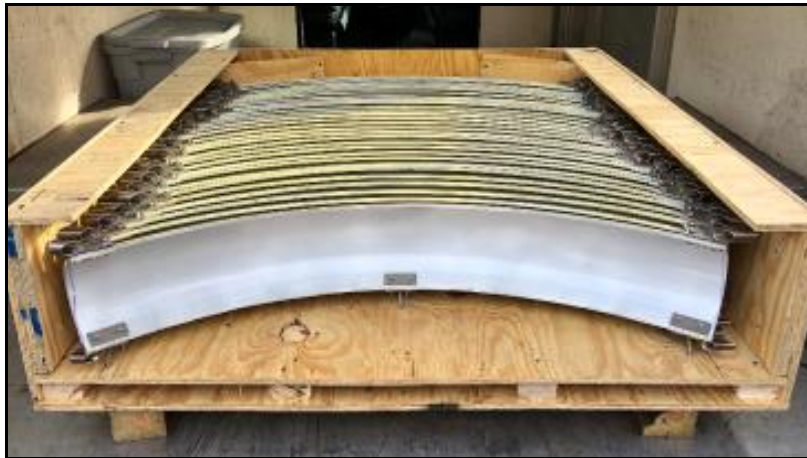


Figure 7. CLAMShell system in a stowed position (Oates, 2017).

The system’s flexibility allows it to be laid over uneven ground, debris and other various elements that can be found on river bottoms (Croom et al., 2019). Figure 8 displays the prototype being deployed. Each CLAMShell segment was pinned on one side of the shell to both the upper and lower rope strength members. The opposite side was not pinned, which allowed each shell to float on the ropes, creating additional flexibility. The floating techniques prevented the buildup of tension in the cable between CLAMShell ends and allowed strength members the ability to stretch when under tension. The floating CLAMShell mount approach removed stress transfer from one shell to the next, and additional segments down the array (Croom et al, 2019).





Figure 8. CLAMShell system being deployed.

The anchor lines were attached to a shock cord to allow system loading and tensioning once the leading anchors were set, and allowed for the ropes to maintain tension in the strength members while the array was deployed in the field. There were three CLAMFoot spikes on each CLAMShell segment that can dig into the bottom of the river bed when the system was deployed. The three CLAMFoot spikes created a tripod effect, which provided more stability because the shells lock into place on the river bed, significantly improving each CLAMShell vertical deployment configuration. (American Systems Corporation, 2019). The system is envisioned to be deployed with one end at an upstream area of the river attached to two Danforth anchors from a boat platform. Once the anchors are secured, the system can be launched into the river until the other end is reached. At that point, responders will be able to determine the system's curvature by pulling the downstream end in a direction perpendicular to the system's length. Once the curvature is deemed appropriate, responders can drop in the other two Danforth anchors to secure the system on the river bottom. Figure 9 shows the slight curvature of the system underwater.

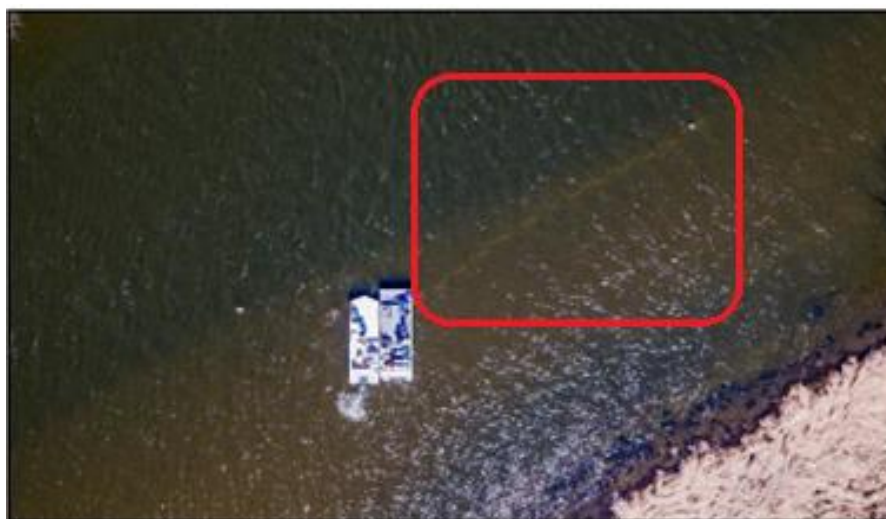


Figure 9. Overhead shot of the CLAMShell system's slight curvature while deployed underwater.

2.3 Offshore Mitigation System

Responders need a similar but different mitigation system for response to spills of oil sands products in the offshore and large lake environments. Generally, there are expanded response options for these types of environments since responders have access to larger boats with deeper drafts and response equipment can be larger and handled with additional supporting equipment. RDC developed its sole offshore mitigation system working with Alion. Its primary objective is collecting sunken oil rather than diverting it to a specific location. The prototype was designed to be deployed in an U-shaped configuration strategically placed to collect sunken oil moving with the prevailing current to allow recovery of accumulated oil at the apex of the system. Figure 10 shows this conceptual layout.



Figure 10. Conceptual layout of the offshore mitigation system.

RDC specified the prototype to be deployed in depths of 25 to 100 feet and in areas with a current velocity of up to 2 knots. It was made of semi-rigid high-density polyethylene (HDPE) panels covered with PVC; stress on the fabric material is less of a concern in this particular environment than inland regions since the prototype is expected to encounter lower current velocity. The prototype's height was approximately 3 feet and was 200 feet in total length when four 50-foot sections were linked together with slide connectors. Although the bottom part of the prototype was weighted with chains to limit movement, the prototype was still relatively lightweight compared to its inland mitigation system counterpart. Figure 11 (c) shows one of the many openings for posts to be driven into the lake bottom by divers and then tied with guy lines to help keep the system upright. Polyform A1 buoys attached to the system's grommets ensured that the system did not twist as it was being deployed, or fall flat on the bottom before the divers installed posts. Both ends of the system could be secured with Danforth anchors. This prototype is meant to be deployed in areas with sandy bottoms. For storage and ease of transport, this prototype can be folded accordion-style on two separate standard 48 inch by 40 inch pallets.

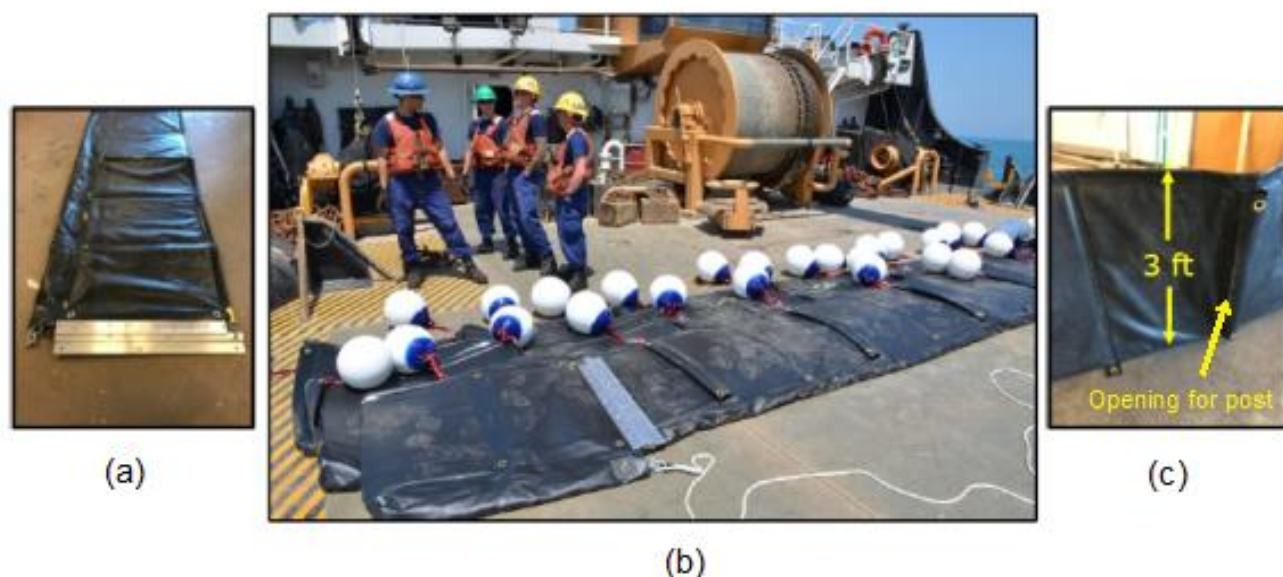


Figure 11. Offshore mitigation system prototype.

3 FIELD TESTS

3.1 Test Locations

3.1.1 Kalamazoo River for Inland Mitigation Systems

RDC tested its two inland mitigation system prototypes at the mouth of Morrow Lake on the Kalamazoo River near the town of Galesburg, Michigan. This site was chosen for a number of reasons: it was close to a public boat launch, the river bottom was publicly owned and mostly sandy, the water depth ranged from four to nine feet, the current was estimated to be two to three knots in April, and this was also a site that was heavily impacted from the Enbridge pipeline spill in July 2010. Figure 12 shows a map of the test location; the actual test sites are near the 35th Street Bridge where the river confluence is narrow and where RDC expected the current to be the highest. This is shown in the red circle. Figure 13 captures the test site with a picture from an aerial drone. The area in the bottom of Figure 13 was where most of the testing took place.

Mitigation of Oil Moving Along the Waterway Bottom

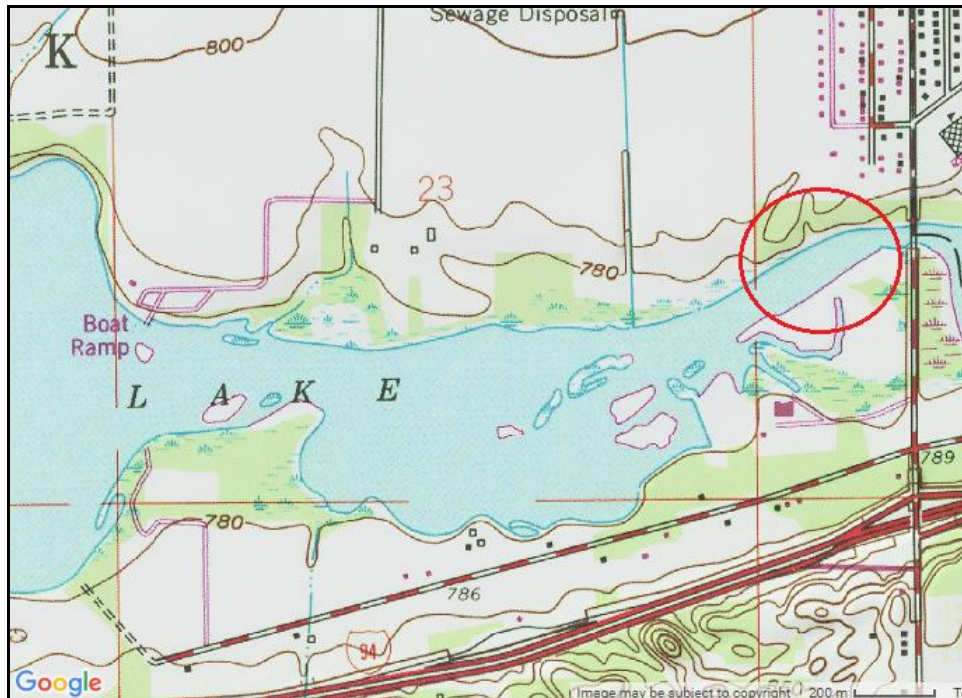


Figure 12. Close-up map of test area in the Kalamazoo River.



Figure 13. Kalamazoo River test area (Morrow Lake is in the background).

RDC tested the first inland river prototype during the third week of April 2018. RDC took depth soundings and current velocity readings at various points in the river and determined the maximum water depth to be seven to eight feet and the maximum current velocity to be approximately 1.4 knots. The tests proceeded with these conditions. Due to project constraints, RDC delayed the testing of its second inland river prototype until the following year during the first week of April 2019. RDC's intent was to test the prototype in deeper waters and in swifter currents with the earlier start date so that the system could be tested closer to its operating limits. However, conditions were mostly unchanged from the previous year. The deepest depths that RDC encountered were seven to eight feet and the fastest current velocity remained at 1.4 knots.



Mitigation of Oil Moving Along the Waterway Bottom

3.1.2 Lake Huron for Offshore Mitigation System

RDC's objective for this test was to deploy the offshore mitigation system prototype in an offshore (lake) environment with little to no current in 30 to 50 feet of water with sandy bottom. RDC chose Lake Huron due to the close proximity of Coast Guard Cutter Hollyhock's (Figure 14) homeport of Port Huron, Michigan and availability of sandy bottom with 20 to 50 feet water depth. RDC worked with the Hollyhock's crew to determine suitable locations for the tests nearest to the homeport and found several sites on the United States' side of the lake approximately three to five miles north of Port Huron close to the shoreline. Figure 15 shows the approximate location of the tests held in Lake Huron. The red circle shows the test area.



Figure 14. Coast Guard Cutter Hollyhock used to deploy the offshore mitigation system in Lake Huron.

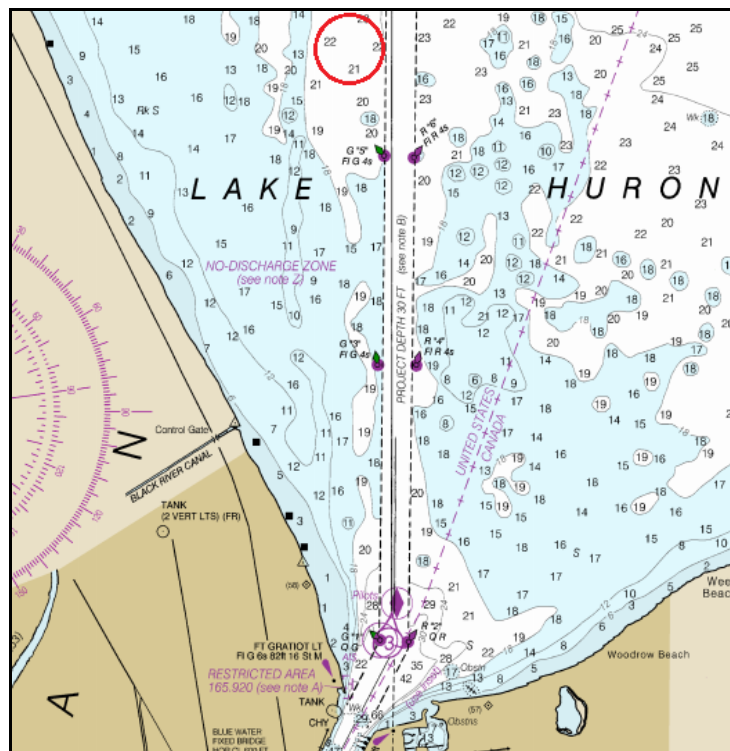


Figure 15. Map of approximate location for test sites for the offshore mitigation system prototype in Lake Huron.



Mitigation of Oil Moving Along the Waterway Bottom

RDC attempted to reach the first identified site that was approximately eight nautical miles north of Port Huron, and on the west side of the lake. RDC estimated this site to be 20 to 25 feet deep with a sandy bottom and a bottom current velocity of 0.5 knots. However, the dive boat was unable to reach the site due to rough wave conditions (three to five feet wave heights with short periods), so a second location was chosen closer to the homeport and near the shipping channel. The average depth at this site was 20 feet but the bottom current velocity exceeded 2 knots, which was discovered at the time of the dive. Divers had a difficult time as they needed to crawl/crouch in order to stay in position on the lake bottom. They were unable to effectively carry out the required work of securing the prototype to the bottom. RDC aborted the deployment, and located a third area closer to homeport and nearer the shoreline. This time, the bottom current velocity was determined to be less than 1 knot (kt), and the average water depth remained at approximately 20 feet. The lake bottom was mostly sandy and proved to be suitable for a test deployment of the offshore prototype system.

3.2 Inland Mitigation System 1

3.2.1 Pre-Deployment Setup

RDC carried out testing of the first inland mitigation system prototype with two vessels: (a) a 38-foot barge with two 14 foot spuds, a flat deck, a davit crane rated up to 1,500 pounds, and shallow draft and (b) a 20-foot jet-outboard boat (see Figure 16).



Figure 16. (a) 38 foot barge for deployment/retrieval operations and (b) 20 foot jet-outboard boat for supporting operations.

The barge with open deck space and rollers at the bow facilitated system deployment and retrieval, while the jet-outboard boat supported other test-related activities such as measuring current, depth, and GPS reading as well as deploying and retrieving anchors.

3.2.1.1 Anchor Post Method

RDC carried out the anchor post approach for its first test run with the inland mitigation system 1 prototype. Based on a river current velocity of 1.4 knots, RDC determined that an appropriate deployment angle for the system was 30° from the shoreline using the angle deployment chart that is dependent on current velocity and spacing distance between anchors.



Mitigation of Oil Moving Along the Waterway Bottom

Using measurements based on a 30° deployment angle for the prototype, RDC established markers on the shoreline to help the project team determine where to strike the three anchor posts into the river bottom. However, since the water depth was extremely shallow near the shoreline, the project team decided to offset the system approximately 20 feet from the shoreline (Michel, et al, 2018a). Using the barge, the project team installed three posts into the river in approximately 1.5 hours. One was located upstream, the other midstream, and the third and final post was downstream of the other two (see Figure 17).



Figure 17. Three anchor posts driven into the Kalamazoo River in advance of the shallow water deployment test run.

This work involved two people: one to hold the post and the other to drive it in with the pole driver although there was a rotation of personnel throughout due to fatigue (Michel, et al, 2018a). The project team encountered difficulties with driving in the second anchor post. There was high concentration of rock/gravel in the area but the project team was able to get enough length of the post driven in to serve the test's purpose. Once the anchor posts were in place, the project team was ready to commence with the system deployment.

3.2.1.2 Jersey Barrier Method

For RDC's second test run with the inland mitigation system 1 prototype, the same location and geometry (deployment angle) as the previous test run was used with the assumption that the river bottom was made of a harder substrate and that the anchor posts could not be driven into the bottom. In preparation, RDC filled the plastic Jersey barrier with 750 pounds of wet sand. With this approach, the setup time was shorter than the anchor post method since the prototype system itself was connected to the barrier (see Figure 18). Deployment of the prototype system could proceed at the same time with deployment of the Jersey barrier.



Figure 18. Jersey barrier connected to the inland mitigation system 1 prototype.

3.2.2 Deployment

3.2.2.1 Anchor Post Method

Once the posts were in place, the project team proceeded to fake out the prototype on the barge to prepare for actual deployment. The scour flaps were folded up and tied with a truss line as can be seen in Figure 19.



Figure 19. Compressed inland mitigation system with the scour flaps up and tied with a truss line.

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The project team then returned to the first anchor post upstream, and connected one end of the prototype to the post by way of sliding the prototype's two loops over the post. Once the loops were in place, the project team tied an anchor line to the prototype's end, and dropped it further upstream to ensure the post stayed upright. The project team added a load cell to measure the tension of this anchor line, and another to measure the tension line of the rope between the first post and a tree on shore. The project team secured a data acquisition system (DAQ) box to record the load cell measurements to the top part of the anchor post (see Figure 20). Load cell measurements would help the project team understand the tension limit of the anchor lines if they fail during deployment. With this in place, the project team maneuvered its way down to the second post downstream while paying out the prototype from the barge's starboard side into the water (see Figure 21).



Figure 20. Data Acquisition System attached to anchor post on upstream side to collect tension data from load cells.



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Figure 21. Inland mitigation system 1 prototype being deployed using the anchor post method.

The project team was careful to ensure that the prototype stayed on the upstream side of the second post. However, the limited maneuverability of the barge, the river current, and the short distance between the two posts made this operation somewhat challenging.

At the second post, the project team continued to drop the prototype into the water on the upstream side of the post, tied another anchor line to the post to keep it upright, and inserted a third load cell on the line. This load cell was connected to the existing DAQ box attached to the first post upstream. The project team then continued downstream to the third post and dropped the rest of the prototype into the water (see Figure 22).



Figure 22. Inland mitigation system 1 prototype continues to be deployed on upstream side of anchor posts.



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Since the water depth near the shoreline was very shallow, the project team agreed to let the other end of the system sit approximately 10 feet from the shoreline instead of bringing it in closer. A team of two to three personnel manually pulled the system towards the shoreline to straighten out the prototype before pulling out the truss line to allow the scour flaps to fall down. However, the project team had a difficult time pulling the truss line completely free due to friction between the PVC loops and the polypropylene rope material itself.

Once the truss line was pulled free and the scour flaps were fully extended, the project team tied a rope from the prototype's end to a nearby tree. The line was tensioned to approximately 350 pounds using a winch. Figure 23 shows the securing of the prototype to a tree, and Figure 24 shows the overall inland mitigation system deployed with the anchor post approach. The mitigation system is not visible in Figure 24; it is laid out underwater along the three anchor posts.



Figure 23. Inland mitigation system 1 prototype tied to a tree.



Figure 24. Final deployment of Inland mitigation system 1 prototype.



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For this shallow water deployment, there were a total of four anchor lines, two Danforth anchors, and three anchor posts for a 75-foot long prototype angled at 30° from the shoreline in a river current velocity of 1.4 knots.

3.2.2.2 Jersey Barrier Method

Once the prototype using the anchor post method was recovered, RDC proceeded with deploying the system using the Jersey barrier method. The anchors were left in place from the previous deployment. One 25-foot section of the prototype was replaced since in the previous deployment, the anchor line attached to the tension line of the prototype was ripped out of the top pocket. With the replacement section attached to the other two existing sections, the project team maneuvered the barge to the original upstream location for the second deployment.

During deployment, RDC quickly learned that handling the Jersey barrier with the davit crane at the barge's bow was difficult. The project team outfitted the Jersey barrier with slings and straps for the davit crane, but the crane was barely high enough to lift the barrier off the barge (see Figure 25).



Figure 25. Inland mitigation system 1 prototype being deployed with barge's davit crane.

When the Jersey barrier was placed in the water, the river current forced it sideways. It was the project team's intent to place the long side of the system on the bottom of the river roughly in line with the length of the prototype. After some time, the project team accomplished the objective and secured the upstream end of the Jersey barrier with two anchor lines, one attached to a Danforth anchor further upstream and the other tied to a tree on shore. With the Jersey barrier in place, the project team moved downstream along the 30° curve while paying out the system into the river (see Figure 26).



Mitigation of Oil Moving Along the Waterway Bottom



Figure 26. Inland mitigation system 1 prototype being deployed off the bow of the barge.

Two additional anchor lines were tied to the two-way slings rigged onto slide connectors in between panel sections to ensure the system stayed upright against the river current.

Since the project team had difficulties with the truss line in the previous deployment, it compressed only one section of the prototype system with the truss line (section closest to shoreline) while the other two sections remained free with the scour flaps already down during deployment (see Figure 27).



Figure 27. Compressing one section of the inland mitigation system 1 prototype with the truss line.

Once the project team completed deployment, it pulled the truss line but again, there was difficulty in getting it free. After some time, the project team decided to leave the line where it was, letting the scour flaps stay up.

The shore end of the prototype system was again connected to a tree on shore and tensioned with a come-along winch. Figure 28 shows the complete deployment of the Jersey barrier method. The float balls indicate the approximate position of the system; the river current displaced the floats by approximately 5 feet downstream.





Figure 28. Inland mitigation system 1 prototype deployed with the Jersey barrier method.

For this particular deployment, there were a total of five anchor lines, two Danforth anchors, and one Jersey barrier for a 75-foot long prototype angled at 30° from the shoreline in a river current velocity of 1.4 knots.

3.2.3 Monitoring

Both times when the inland mitigation system 1 prototype was deployed underwater, RDC captured videos using a hand-held video camera mounted to the end of a pole (see Figure 29).



Figure 29. Video capture of Inland mitigation system 1 deployed in the Kalamazoo River.

Mitigation of Oil Moving Along the Waterway Bottom

RDC carried out video recording immediately after deployment, and before retrieval the next day after the system was left in place overnight. The purpose was to capture visual evidence of whether or not the prototype was deployed correctly and was sealed against the bottom with sufficient tension. RDC observed and measured other parameters during the monitoring periods of both deployments including position, motion, sag, scour, and tension (Michel, et al, 2018a).

3.2.4 Recovery

3.2.4.1 Anchor Post Method

In retrieving the system with the anchor post method, the project team started with the two anchor posts closest to the shoreline. Unlike the post at the furthest upstream location, the two downstream posts did not have the system loops attached to them. Instead, the posts served to brace the system from migrating further downstream. The project team disconnected the anchor lines from the posts and two people on the barge pulled each post out of the water and onto the vessel. The davit crane was used in some instances to pull the post free.

The next step was to disconnect the anchor line between the downstream shoreline end of the prototype and the tree on shore. With the system now slack, the project team maneuvered the barge towards the system end near the shoreline and used the vessel's hydraulic capstan to pull the system onto the vessel. This process required three to four people on the barge to handle the prototype and fold it for re-deployment. Figure 30 shows the hydraulic capstan retrieving the prototype and Figure 31 shows the labor required to retrieve the system back onto the barge.



Figure 30. Hydraulic capstan (center) used to retrieve prototype back onto the barge.





Figure 31. Prototype retrieval taking place on the barge.

Once most of the system was retrieved and the barge made its way to the remaining anchor post, the project team proceeded to remove the DAQ box attached to the post and released the anchor lines. The upstream end of the prototype was then pulled onto the barge with help of the hydraulic capstan. The project team removed the remaining post to end the retrieval process.

3.2.4.2 Jersey Barrier Method

Retrieval of the prototype with the Jersey barrier method was similar to that of the anchor post method. The prototype was first de-tensioned at the downstream end by disconnecting the rope between the end of the prototype and the tree on shore. Then starting at the downstream end of the prototype, the project team retrieved the system with aid of the hydraulic capstan. When the end of the first 25-foot section came up on the barge, the project team disconnected the anchor line attached to the slide connector. This was repeated until the project team reached the Jersey barrier where it faced difficulties.

The project team attempted to lift the Jersey barrier with the davit crane but the combined weight of sand in the Jersey barrier and the force of lifting the barrier in water exceeded the davit crane's 1,500 pound capacity. As a result, the project team removed the plug in the Jersey barrier and turned it upside down to let the sand out. Also adding to the difficulties was the fact that the spuds could not be adequately fixed onto the river bottom to maintain stationary position on the river. The project team encountered rocky areas of

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the river bottom where retrieval operations needed to be carried out. As a result, the barge operator was constantly adjusting vessel speed to maintain position.

3.3 Inland Mitigation System 2

3.3.1 Deployment

The project team carried out three deployments of the CLAMShell system in three locations with varying water depths and current velocities. Since no extensive setup was necessary, the project team was able to carry out three deployments and retrievals within the test period. The project team also carried out site surveys to determine current velocities, water depths, and whether or not the bottom was sandy enough for the Danforth anchors to properly set. Data from the survey is shown in Table 2.

Table 2. Kalamazoo River survey results.

Upstream Anchor	First Test Site	Second Test Site	Third Test Site
Position	42° 16.789' N, 85° 25.833' W	42° 16.807' N, 85° 25.827' W	42° 16.802' N, 85° 25.780' W
Water depth (ft)	3.75	8.00	5.00
Current velocity (kts)	0.64	0.83 to 1.13	0.97
Downstream Anchor	First Test Site	Second Test Site	Third Test Site
Position	42° 16.781' N, 85° 25.880' W	42° 16.779' N, 85° 25.866' W	42° 16.800' N, 85° 25.800' W
Water Depth (ft)	3.00	4.50	5.00
Current Velocity (kts)	N/A	N/A	1.17 to 1.36

The project team used two vessels: a 24-foot Hurricane flat bottom boat to serve as the deployment/retrieval boat and a 24-foot Harris Sunliner boat to serve as an observation deck (see Figure 32). The two were lashed together throughout the test series.



Figure 32. Observer boat (left) and deployment/retrieval boat (right) for the inland mitigation system 2 prototype test.



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RDC carried out each of the three deployments following detailed deployment and retrieval procedures. Starting at one of the upstream locations identified during site surveys, the project team deployed the upstream anchors from the bow of the Hurricane vessel. The project team then slowly unspooled the mitigation system as the lashed vessels reversed downstream (see Figure 33).



Figure 33. CLAMShell mitigation system being deployed into the Kalamazoo River.

Once the end of the 108-foot (ft) section was reached, the project team maneuvered the vessels while holding on to the mitigation system to achieve the desired angle relative to the shoreline. Once satisfied, the project team dropped the system into the water and deployed the last two anchors.

3.3.2 Monitoring

During each of the three deployments, the project team recorded the mitigation system laid out on the river bottom with a video camera attached to the end of a pole to give visual representations of how well the system rested on the river bottom (see Figure 34). The project team also established a GoPro camera on the Hurricane vessel directly behind the storage box to capture each deployment and retrieval process. For the third deployment, the project team hired a flying drone to capture photos from above (see Figure 9). The project team took numerous photographs throughout each test run.





Figure 34. Capturing video evidence of CLAMShell mitigation system on the river bottom.

3.3.3 Recovery

RDC performed the retrieval operation in the reverse manner in which the system was deployed. Starting at the downstream location, two responders first picked up the two Danforth anchors and stowed them on the Hurricane work deck. Next, they hauled in the CLAMShell sections while the vessel operator proceeded slowly up the river (see Figure 35). Close coordination between the retrieval team and the vessel operator was crucial in ensuring that the responders were lifting the slack sections up and onto the vessel instead of pulling at it, which can damage the prototype system and quickly fatigue the responders.



Figure 35. Project team retrieving the CLAMShell mitigation system.

As the shells were being hauled in, a third team member near the storage box ensured that the system was being repacked properly, with the bottom strength members falling under the two metal bars at the bottom of the storage container to facilitate ease of future deployments. However, in the last test run, the project team simplified the recovery operation by removing the storage container and recovering/packing the system directly onto the work deck (see Figure 36). After returning to shoreside, the project team could then properly repack the system into the storage container for the next deployment.



Figure 36. Retrieving and packing the CLAMShell mitigation system.

Once all the CLAMShell sections were recovered, the project team pulled out the two remaining anchors in the upstream end to complete the recovery operation.

3.4 Offshore Mitigation System

3.4.1 Deployment

Immediately prior to deployment, the project team conducted a survey of the lake bottom using a sonar survey with the USCGC Hollyhock's Rigid Hull Inflatable Boat (RHIB) (see Figure 37). The project team conducted this survey to ensure there was no debris that could interfere with the system deployment, and also to capture potential evidence of historical shipwrecks that RDC could provide to the Michigan State Historic Preservation Office. However, none was found during this particular survey. Once the project team confirmed that the lake bottom at a pre-selected location was free and clear of debris, the project team proceeded with deployment.



Figure 37. Project team conducting sonar survey of lake bottom to ensure it is free of debris.

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The 200-foot offshore mitigation system was laid out on the ship's deck with each end connected to a Danforth anchor. It was outfitted with a buoy every third grommet on the upper part of the prototype to allow for a slow descent with the system standing vertical (Michel, et al, 2018b). Once the ship was in position, the project team set the first anchor by throwing it overboard, and then slowly payed out the system as the buoytender moved sideways (see Figure 38).



Figure 38. USCGC Hollyhock crew assisting with deployment of the offshore mitigation system.

Deployment in this manner required minimal effort as the project team “fed” the system into the water while the ship moved sideways. Once the end of the system was reached, the project team held the anchor line on the other end to help tension the system. Communication between the deployment team and the ship operator was crucial at this stage as positioning was important to ensure that the system would be deployed in an U-shape position. After approximately 15 minutes of the ship moving forward and sideways to create the desired U-shape configuration, the second and final anchor was dropped into the water (see Figure 39).



Figure 39. Second and final anchor dropped into Lake Huron after positioning system into an U-shape configuration.



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With the prototype system sitting loosely, but vertically on the lake bottom, the project team deployed a single diver to affix the system. He installed posts through sleeves attached to the system all along its length to keep it in position. The diver was able to drive the posts into the sandy lake bottom with a post driver. Once that was completed, he tied guy wires to the posts and installed stakes to fix the guy wires to the lakebed on the up-current side of the system. The diver indicated this was very easily done especially with CamJam cord tighteners and straight stakes (see Figure 40). The diver deployed for approximately 90 minutes and used up three tanks of air, but much of the time was dedicated to retrieving equipment that the dive team dropped to the bottom for installation (Michel, et al, 2018b).

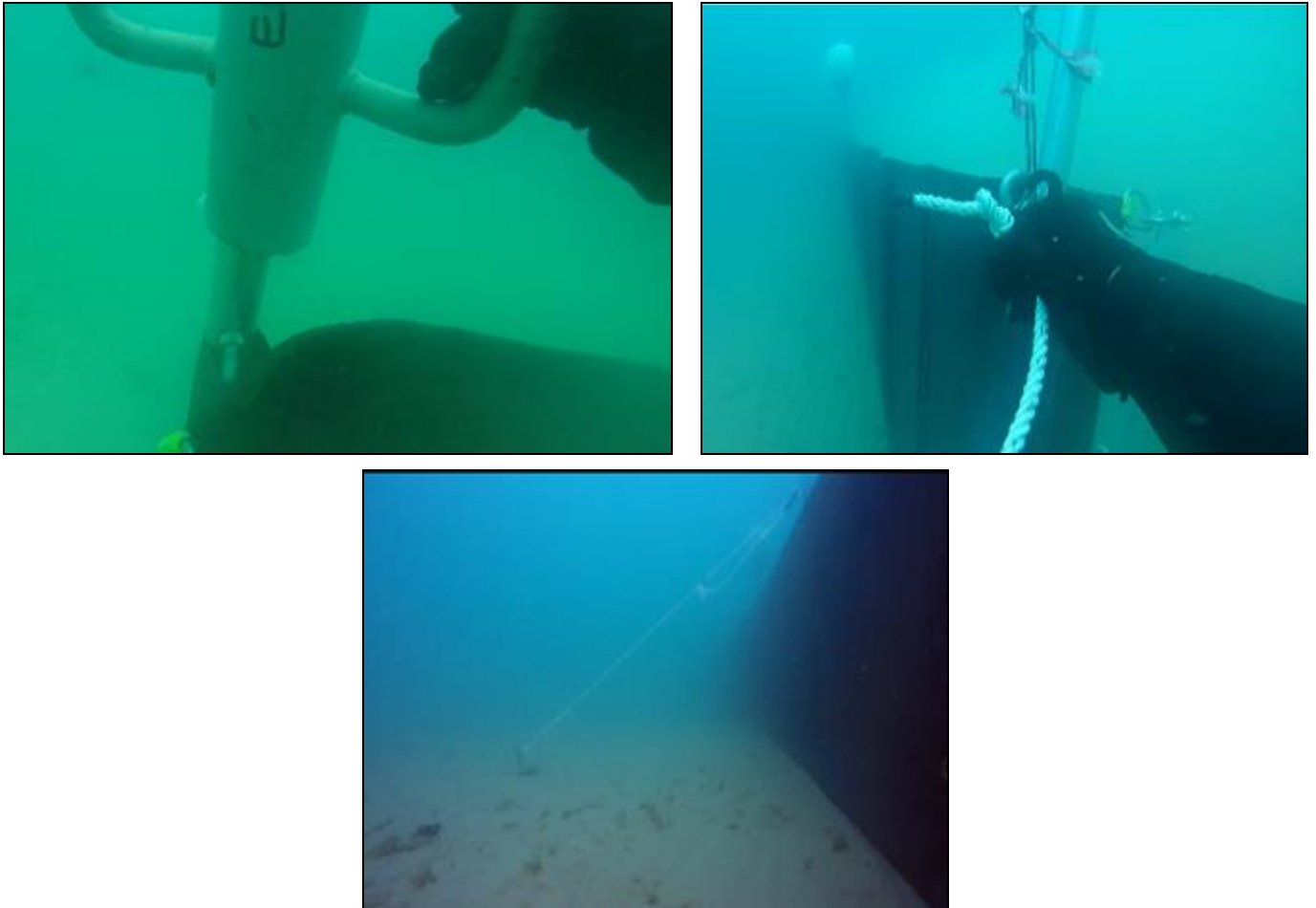


Figure 40. Diver driving post into the lake bottom with a post driver (left), diver attaching guy wire to post (right), and final result with guy wire tied from post to stake on the lake bottom (bottom).



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Overall, the deployment operation took approximately 1 hour and 40 minutes, and resulted in a shape as seen in Figure 41. The diver drew the picture after surfacing, and this shows that the system was not deployed in a more pronounced U shape that the project team was hoping for.

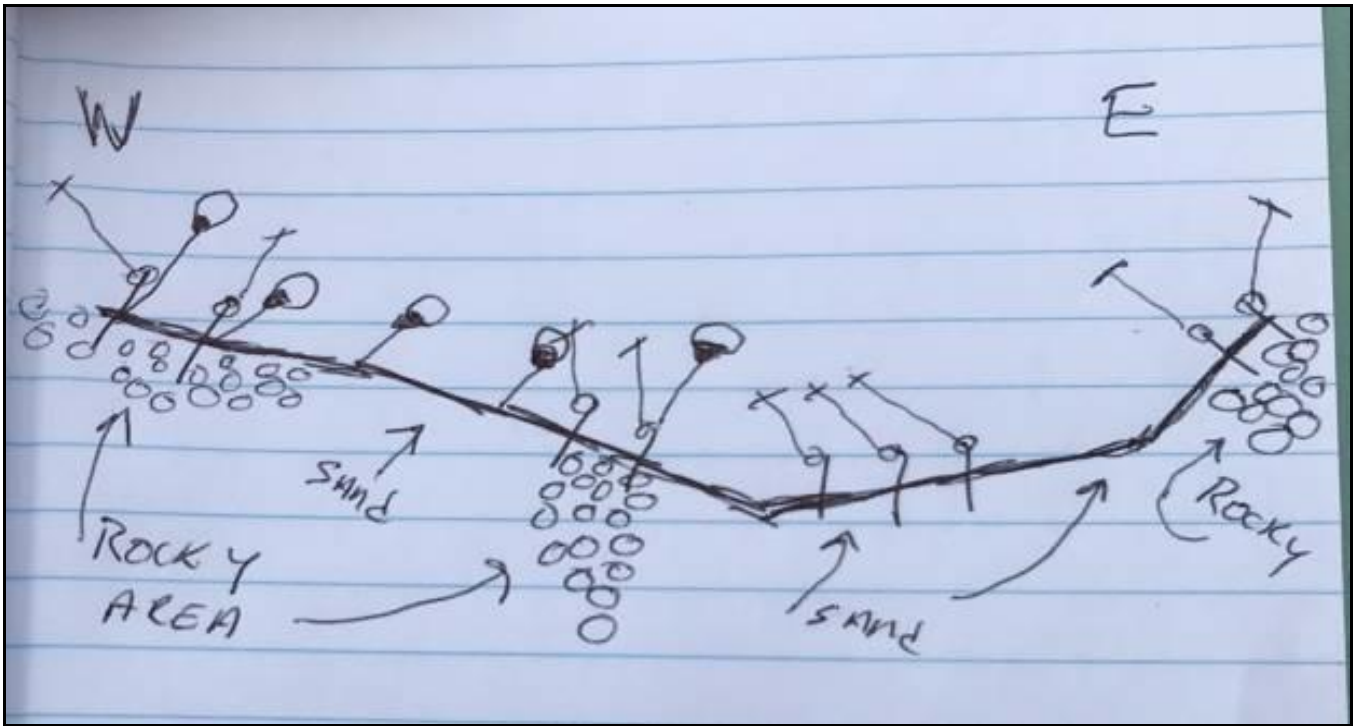


Figure 41. Diver's drawing of the prototype's layout on the lake bottom immediately after his dive.

3.4.2 Monitoring

After the system was deployed, the project team used a remotely operated vehicle (ROV) from the deck of USCGC Hollyhock to record underwater video along the system's length. The ship maintained its position above the center of the system, which made it easier for the ROV operator to maneuver the equipment in both directions of the prototype system. The ROV carried its onboard video and a higher resolution GoPro camera, which gave clear videos of the deployed mitigation system (see Figure 42). The diver also carried a GoPro camera for additional photos and videos.

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Figure 42. USCGC Hollyhock crew deploying a ROV (left), ROV image of mitigation system on the lake bottom (right).

The mitigation system was left in place overnight to test for its movement for an extended period of time. Before the ship returned to port after deployment, the project team conducted a sonar survey from the RHIB and confirmed the shape of the system that the diver drew (see Figure 43).

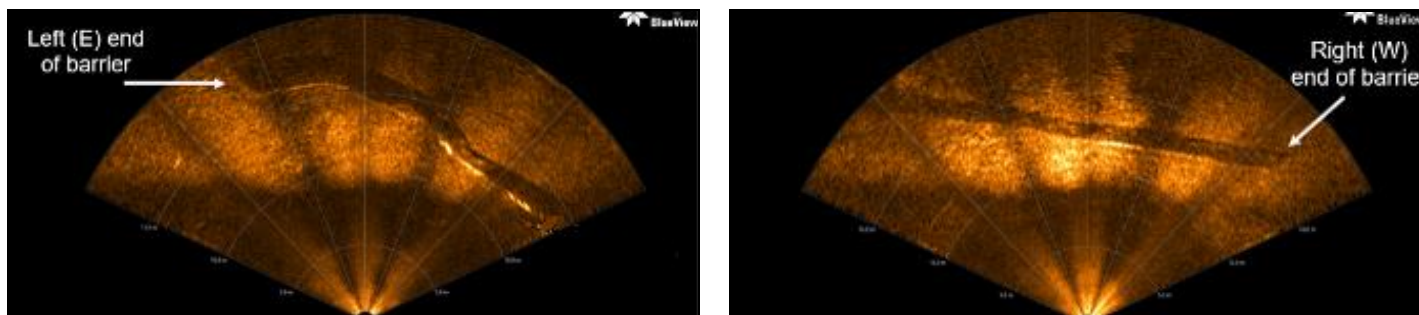


Figure 43. Sonar images of left and right sides of the offshore mitigation system while deployed on the lake bottom.

The next morning, the project team returned to the deployment site and repeated the video recording operation with the ROV to note changes from the day before. The project team also performed another sonar survey with the RHIB before commencing with the recovery operation. Other data collected during the monitoring period included GPS positions of anchors, water depth, photographs and videos from all vessel platforms, and notes from hotwashes held at the end of each operational day.

3.4.3 Recovery

Once the project team completed all the necessary monitoring operations, the diver deployed from the Hollyhock to the lake bottom for stake and post removal. Once completed, the Hollyhock moved in position at one end of the system and began hauling in the prototype, section by section. At first, the project team attempted to retrieve it with the ship's crane but when one section of the system was held aloft, the wind caught it and quickly made the situation unsafe for those on the ship's deck (see Figure 44).



Figure 44. Attempt to recover the offshore mitigation system with crane during high-wind conditions.

The crane approach was quickly abandoned. Instead, the project team decided to use the ship's cross deck winches. This made for an easier and safer operation as each section of the system was pulled up, wrapped with a canvas sling, and then dragged across the ship's deck. Once the system was stretched along the full width of the ship's deck, the canvas sling was relocated to the end of the system closest to the water, and the operation was repeated until the project team retrieved the entire 200 feet of the system (see Figure 45 and Figure 46).

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Figure 45. Start of recovery process with cross-deck winch approach.

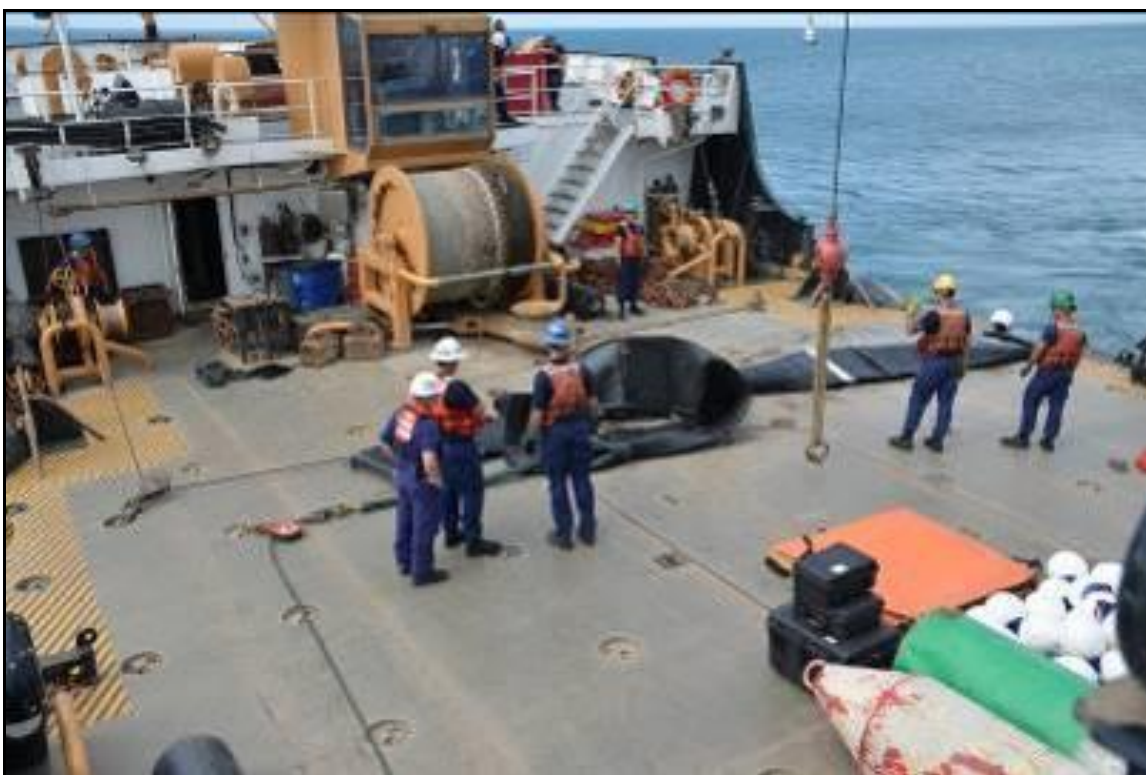


Figure 46. Mitigation system being recovered with the cross-deck winch approach.



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Similar to the inland mitigation system retrieval process, careful communication was needed between the recovery team and the ship operator to ensure that the ship was moving in the correct direction and at the appropriate velocity as the system was being pulled aboard. The project team then disconnected each of the four 50-foot sections, folded them, and stacked two sections to a 40-inch by 48-inch pallet (see Figure 47).

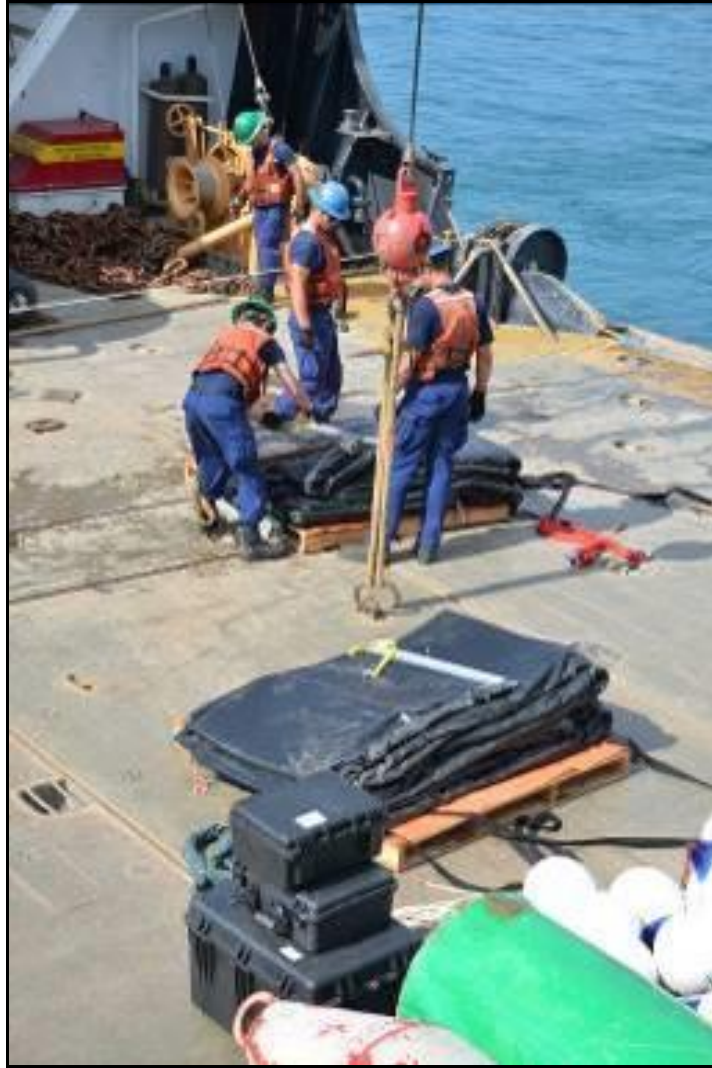


Figure 47. 200 feet of the offshore mitigation system packed on two 40 x 48 inch pallets.

4 ANALYSIS, CONCLUSIONS AND RECOMMENDATIONS

4.1 Analysis

In Sections 1.3.1.4 and 1.3.2.4, RDC specified a list of requirements that inland and offshore mitigation system prototypes should strive to attain during field testing. Table 3 summarizes RDC requirements for both the inland mitigation system prototypes, and specifies whether or not each system achieved the requirement. Table 4 is similar to Table 3 except it summarizes RDC requirements for the offshore mitigation system prototype.



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Table 3. Summary of RDC's requirements that were or were not met for the two inland mitigation systems.

Prototype System Requirement	Inland Mitigation System 1	Inland Mitigation System 2
Section length of 25 to 50 ft	✓	✓
Total length of 50 to 100 ft	✓	✓
Deployable and recoverable up to 10 ft water depth	✓	✓
Deployable in waves up to 0.5 ft	✓	✓
Deployable and recoverable in currents up to 2 kts	Unknown*	Unknown*
Anchoring system for sandy bottom	✓	✓
Deployable in less than 2 hrs	✓	✓
Data recording system to track performance	✓	Unmet

*Unknown - Project team did not encounter river current greater than 1.4 knots.

Table 4. Summary of RDC requirements that were or were not met for the offshore mitigation system.

Prototype System Requirement	Offshore Mitigation System
Section length of 50 to 100 ft	✓
Total length of 100 to 200 ft	✓
Deployable and recoverable up to 50 ft water depth without assistance of divers or ROV	Unmet
Deployable in waves up to 2 ft	✓
Deployable and recoverable in currents up to 2 kts	✓*
Anchoring system for sandy bottom	✓
Deployable in less than 2 hrs	✓
Data recording system to track performance	✓

*Project team did not encounter lake current at approximately 2 knots.

The inland mitigation system 1 prototype met all of RDC's requirements. The inland mitigation system 2 prototype met all of the requirements as well, although it provided only a video camera to record the system's performance while underwater. Additional performance tracking equipment such as GPS or tension cells could have been used to further quantify the prototype performance in terms of positioning, shape, and loads on the system over time. Therefore, RDC gave this an unmet rating. For the last test trial, an aerial drone was used to capture overhead pictures of the system when it was deployed.

All but one requirement was met with the offshore mitigation system, which is to deploy and recover a prototype without the use of divers or a ROV. RDC's goal with this requirement was to move away from manned recovery operations as they pose inherent safety risks to responders. During the contract bidding process, RDC did not receive a viable proposal with a system design that did not require the use of divers or a ROV.

The following sections describe RDC's assessment for each of the three prototype deployments. RDC also makes conclusions and suggests recommendations for how each prototype may be improved.

4.1.1 Inland Mitigation System 1

The 38-foot spud barge was the project team's primary work vessel during equipment deployment in the Kalamazoo River. The project team quickly learned that overall deployment and recovery operations could



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have been made easier with better vessel maneuverability to manage the river current and the short distances between posts for the anchor-post deployment approach. In some areas of the river, the spuds could not penetrate the gravel bottom deep enough so the barge was unable to stay in place on the river. Without side thrusters to help maintain position, the barge operator was forced to constantly drift downstream and then motor upstream back to the original location. However the spuds were effective with sandy bottoms, and the large deck space on the barge was conducive to the system deployment and recovery operations.

Overall, the anchor post deployment method worked well but it took a large amount of physical effort from the project team to achieve a successful deployment. The mitigation system itself weighed approximately 500 pounds per 25-foot section and it contained float sections that sometimes made it difficult or awkward to fold over itself. Project team members took turns with the slide hammer in installing the posts, which required good physical fitness to carry out the task. Two to three people were needed to pay out the mitigation system although sliding the upstream end of the system onto the post was a fairly easy task.

During the first deployment, the tension line ripped out of the pocket at the top of the mitigation system near the first anchor post upstream. The project team discussed two possibilities as to why the tension to the anchor attached to the upstream end of the system was pulling at an approximately 30 degree angle (horizontally) instead of being directly in line with the system. The first is that the anchor line could have been fouled by a large rock, which caused a change in the pull angle. The second possibility is that there could have been a design flaw in how the tension line was woven into the mitigation system.

The amount of effort to get the mitigation system prototype deployed with the Jersey barrier approach was similar to that of the anchor post approach. The davit crane on the barge's bow was barely high enough to lift the barrier off the barge. When the Jersey barrier was placed in the water, the river current forced it sideways. It was the project team's intent to place the long side of the barrier on the bottom of the river roughly in line with the length of the prototype. After some time, the project team accomplished the objective and secured the upstream end of the Jersey barrier with two anchor lines: one attached to a Danforth anchor further upstream and the other tied to a tree on shore. In western rivers of similar water depths, it may be difficult to obtain a vessel with shallow draft that is capable of deploying and recovering a Jersey barrier.

Once the mitigation system was finally deployed into the water, the next step was to tie the rope at the shoreline end of the system to a tree. The project team used a come-along winch to pull the system towards shoreline, stretching it out from its original slack position immediately after deployment. However, the current pushing against the Jersey barrier and the Jersey barrier weight itself made it difficult so one project team member waded into the water and pulled on the rope. This was effective although this is not recommended in oil-contaminated rivers.

Once the system was in place on the river bottom, the final step was to pull out the truss line to unfold the scour flaps. The project team encountered difficulties with this both times the system was deployed. This may be attributed to the friction between the PVC loops and the polypropylene rope material itself. The long length of the rope and the shape of the loops may have also contributed to this difficulty. Once the system was finally fully deployed and secured, a project team member commented that deployment was more difficult than it should have been. The project team also noted that a river current of four knots is most likely the extreme upper working limit for the inland mitigation system. Even a full-scale sized system of this design would be difficult to deploy in a river with currents between four and eight knots, which was a RDC objective.



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Video evidence of the system proved that it did not change position after remaining in the water overnight, and that scour flaps sealed well around small to medium cobblestones. The anchors upstream of the mitigation system proved to be useful in straightening out the system. There was sediment buildup on the upstream side of the mitigation system, indicating that had there been moving sunken oil, it would have accumulated up against the prototype system. There were gaps under the flap when the system was laid on larger rocks, however, and in between sections above and below slide connectors.

During recovery with the anchor post deployment approach, two of the downstream anchor posts were removed before the system was de-tensioned (the anchor post at the upstream end, which the system was connected to remained in place until after the system was recovered). During this time, the project team noted that the prototype continued to stay upright. RDC anticipates that fewer anchor posts may be required for future deployments with this mitigation system.

Overall, recovery of the inland mitigation system 1 prototype was a smoother process than deployment since the project team had use of a hydraulic capstan. Three to four people were needed for this recovery operation and the project team agreed that without the capstan, work would have been very difficult. Recovering the Jersey barrier, however, proved to be an obstacle for the project team. The davit crane capacity on the barge was only 1,500 pounds, which did not give much margin over the weight of the water and sand-filled barrier (Michel, et al, 2018a). It also could not lift the barrier high enough to put it on the deck so sand and water had to be released from the barrier before bringing it back onboard.

4.1.2 Inland Mitigation System 2

The 24-foot Hurricane flat bottom boat with a customized work deck on its bow proved to be a good working platform for the deployment and retrieval of the CLAMShell system. There was adequate deck space for two responders. Overall, operations can be carried out with three people including the vessel operator. Vessel maneuverability did not prove to be much of an issue during the test week. The project team carried out anchor and system deployment relatively quickly so the vessel did not need to maintain position on the river for an extended amount of time. However for an actual oil spill response operation when multiple deployments of the system are needed, side thrusters for the vessel would be beneficial to help maintain position.

The deployment and retrieval of the system went fairly smoothly and quickly without major issues. The system was found to be misaligned during the first deployment, and the project team concluded that it may have been due to excessive and unnecessary handling during deployment. Another potential reason was that the system may have been laid out too tautly, which did not allow it conform with the natural features on the river bottom. The project team handled the system more gently in subsequent deployments, allowing it to deploy more freely with minimal intervention. It also ensured there was sufficient slack in the elastic cords on the anchor lines. With those changes, the system laid out properly each time.

The CLAMShell system anchored and retained location without concern of drift, even when the system was deployed at an angle across the current. Video evidence also confirmed that the CLAMFoot properly self-anchored into the river bed as anticipated and maintained position in currents up to two knots (American Systems Corporation, 2019). However, RDC anticipates that the system may not be laid properly if it encounters medium to large cobblestones on the river bed.

The project team also learned that the safety catches installed on the system to halt run-away conditions (allowing the system to deploy rapidly all at once) proved to be a hindrance to the overall deployment



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operation, and may have been a contributing factor to the misalignment of the system during the first deployment. In future deployments, the project team removed safety lines and the system deployed smoothly and without incidents. After three deployment and recovery cycles over two days, there was minimal wear and tear to the system.

Recovery of the CLAMShell system was made slightly complicated when the project team repacked it into the CLAMShell “magazine”, or storage box with twin metal bars that separate the bottom strength members from the system to prevent entanglement for the next deployment. This process required the assistance of a third project team member (bringing the total number of personnel to four for recovery) to help facilitate the process by ensuring the bottom strength members remained below the twin metal bars. During the third test trial, the project team decided to forego the storage box and recovered the system directly onto the Hurricane vessel. It made for a much simpler operation, and did not require the assistance of the third person. The system was then repacked properly while shoreside.

The project team quickly learned during the first test run that good communication between the responders and the vessel operator was needed to ensure minimal physical labor during recovery. Recovering the system is easier if the responders are simply pulling the system straight up from the river, instead of pulling at it to bring it onboard. If the vessel is moving upstream at a velocity that the responders are comfortable with, then responders can simply pull up the slack system and repack as the vessel moves upstream towards the first anchor point. If the vessel moved too slowly, then responders needed to hold on to the system, which can be a taxing effort over time and potentially damaging the system. This occurred during the first test run but the project team quickly overcame this issue by ensuring good communication with the vessel operator.

4.1.3 Offshore Mitigation System

RDC quickly learned that site conditions and type of vessels play a large role in determining whether or not a successful deployment is possible. When the project team got underway on Lake Huron on the first day of the test week, the project team attempted to transit to a pre-identified location approximately eight miles offshore from Port Huron with USCGC Hollyhock and a pontoon boat that the divers rented. The further away from shore, the higher the waves were. The dive team observed three to five foot high waves that day, which eventually forced them to turn back. Since the first location was no longer a feasible option, the project team proceeded to the alternative location closer to Port Huron and to shoreline as well. From existing current velocity charts, the project team estimated underwater current velocity at this alternative location would be less than one knot. However, when divers reached the bottom, they had difficulty standing upright and were forced to a crawl/crouch position just to maintain position. Later, they estimated the underwater current velocity was approximately three knots, which was one knot higher than what RDC deemed to be the upper limit for a deployed offshore mitigation system prototype. The dive team also indicated that dive operations for its Navy or Army Corp of Engineers work are generally not permitted at this current velocity.

The project team deployed the offshore mitigation system prototype at this alternative location, and while it ultimately did not succeed, the project team learned many lessons. At a depth of 20 feet with mostly sandy bottom and minimal rock outcrops, the initial anchor did not properly set to the lake bottom due to improper attachment of the yellow buoy line with the anchor (see Figure 48).



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Figure 48. Improper anchoring method with the yellow buoy line that was corrected after the first deployment.

The anchor line was also 100 feet long, which gave it enough slack to wrap itself around the anchor, furthering inhibiting the anchor's ability to properly set into the lake bottom (see Figure 49).



Figure 49. Anchor tangled up with anchor and buoy lines on the lake bottom during first deployment.

As a result of improper anchor setting, the diver noticed the mitigation system was “skipping” off of the lakebed with the current (Meskill, 2018). Since the line from the anchor to the boom was very long (100 feet), the diver's shorter tether length prevented him from gaining access to the system. The diver went down a second time, this time closer to the boom but with a visibility of 10 feet and strong current, the diver was unable to locate the mitigation system prototype. After some time, the operation was aborted and the project team retrieved the system back onto the Hollyhock.

The next day, in a different location with a measured bottom current of less than 1 knot, the project team successfully deployed, monitored, and retrieved the mitigation system. The project team learned that attaching buoys to every third grommet on the top of the prototype was sufficient to allow a slow descent to the bottom while maintaining its vertical position. The deployment the previous day proved that the full set of 42 buoys (one buoy per grommet) made the overall system more buoyant than expected. When the diver deployed to secure the system to the lake bottom, he noted that the buoys helped to keep the system upright before the posts were driven in (Meskill, 2018). After the posts were installed, the diver removed buoys from one half of the system and left the other half with buoys since the project team was curious if the



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buoys would help to keep the system upright. The next day, the diver determined there was no difference in how the system was standing between the two halves, which leads to the project team's belief that all buoys can and should be removed after the posts are installed. This would also help to ensure that the system do not lift from the bottom especially in heavier wave conditions (Michel, et al., 2018b).

While the diver worked to secure the system, he noted that the posts to keep the system fully upright did not need to be driven the full 2 feet into the bottom substrate; they were solid and actually proved somewhat difficult to remove during recovery. The use of guy wires and stakes to provide additional stability to the posts were also deemed unnecessary in this low current environment. Stakes to secure the bottom of the system to the bottom were not necessary as well except for the ends where the taut anchor lines caused the system to lift from the lakebed (see Figure 50). However, the bottom stakes could be useful if the system was laid on top of rocks or large gravels to reduce the gap between the system bottom and the lakebed.



Figure 50. Tension of anchor line lifted the end of the mitigation system slightly.

Although deployment of the system was successful and it stayed in position, the diver noted that the desired U-shape was not as pronounced (see Figure 41 of diver's drawing). It appeared that during deployment, the Hollyhock moved straight sideways and did not go forward as much as what was needed to give the system the project team's desired curvature. As it was, the diver positioned the system in a U-shape as best as he could while on the lake bottom. However, the heavier anchors (approximately 125-pound buoy chain) that the project team added to the system after the failed first deployment may have played a role in ensuring the first anchor set properly. This in turn helped the diver to locate the system and manipulate it to the desired position as best as he could before driving in posts and stakes to secure the system.

The project team agreed that with strong winds, the use of the ship's crane in retrieving the system posed a safety hazard to the crewmembers. The ship's cross-deck winches enabled the system to be pulled flat across the deck. It made for a slower recovery operation than the crane approach but it was the safer and more sensible approach.

4.2 Conclusions and Recommendations

Since RDC did not use oil in any deployments, it cannot state whether the prototypes are actually effective in responding to moving, sunken oil.



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4.2.1 Inland Mitigation System 1

Based on the Kalamazoo River field tests, RDC makes the following conclusions and recommendations to improve the inland mitigation system 1 design and the handling of it:

Design

- Designers need to carefully consider tradeoffs between material weight and system performance. Reducing weight will improve ease of deployment and recovery operations but may reduce performance, especially in higher current areas. RDC does not recommend deploying this particular system design in currents above four knots, which was RDC's original projected operating environment. In higher current areas, the deployment angle would be smaller and thus a longer mitigation system will be needed to reach the middle of a river.
- Since the heavy weight of the mitigation system proved to be cumbersome for the project team during manual deployment and recovery operations, future system design should consider a different deployment approach such as including an air bladder. It would enable the mitigation system to float to where it should be positioned for most efficient oil collection and then sunk. This design feature would also enable the system to be deployed with a boom reel, which would reduce the amount of physical labor for responders. The current system design with flotation pieces does not allow the system to be deployed from a boom reel, nor does it make it easy for responders to manually fold during recovery operations.
- To prevent another occurrence of a tension line rip from the mitigation system, one possibility is to attach the anchor line to the upstream anchor post instead of the tension line built within the system. An alternative solution is to change the design of how the tension line is integrated into the mitigation system.
- Releasing the truss line after deployment proved to be a challenge for the project team. If future design iterations continue to include the use of a truss line, then RDC recommends metal rings and smoother lines such as a braided cord to reduce the amount of friction and facilitate ease of release to allow scour flaps to fold down.
- RDC recommends further research to determine how truly advantageous X-tex® fabric is over other system materials in fast water environments in terms of cost, reducing stress on the mitigation system itself, and capturing oil.
- The mitigation system should be a brighter color or include retroreflective tape for easier identification through the water column while it is deployed.

Operations

- Though the 38-foot spud barge provided a good working platform for the responders, better vessel maneuverability is needed for more efficient deployment and recovery operations, especially when spuds are ineffective with gravelly or rocky river bottoms. RDC recognizes that compared to offshore environments, there is less access for barge platforms or large vessels for Western rivers and other smaller tributaries; this inland mitigation system design may need to be deployed from shore and then towed upstream to its position to overcome the smaller deck footprint available on river/stream boats.
- Responders would find it difficult to include a Jersey barrier as a part of its inland mitigation system since it is unwieldy, may not have sufficient holding power for its weight and size, and may not be suited for smaller response vessels that can access shallower waters. Alternative solutions include rock rakes or plow anchors.



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- Cleaning the mitigation system after contact with oil may be challenging with limited deck footprint availability on vessels suited for the riverine and other inland environments; RDC anticipates oily decks during recovery and high risk/potential for responders to be contaminated with oil.
- The mitigation system needs additional cover above and below slide connectors between sections to prevent potential oil from flowing past. There was a very good seal between the bottom of the mitigation system and the river bottom except when the system was laid on top of large rocks. RDC recommends fully ensuring that the river bottom is mostly free of large rocks before setting down the mitigation system.

4.2.2 Inland Mitigation System 2

Based on the Kalamazoo River field tests, RDC makes the following conclusions and recommendations to improve the inland mitigation system 2 design and the handling of it:

Design

- The purpose of this mitigation system is not to serve as a barrier in the river to collect moving, sunken oil as it migrates downstream a river, but to promote deposition of it along the length of the system. In an actual oil spill scenario, multiple CLAMShell systems in a cascading formation are envisioned to slow its migration and allow responders time to recover the oil. However, this particular capability was not tested during RDC field tests. Thus, further work is needed to assess the effectiveness of CLAMShell system in promoting deposition of moving, sunken oil along its length. One way of doing so is to conduct computational fluid dynamics (CFD) modeling or to test the system in a large flume tank with actual oil.

Operations

- Deploying and recovering the system from the bow of a modified 24-ft Hurricane vessel proved to be effective. The system was deployed quickly and with ease, which did not require the vessel to maintain a stationary position on the river for an extended amount of time. This in turn reduced the need for additional vessel maneuverability. However, during actual oil spill response operations, RDC anticipates that future vessels should be equipped with side thruster capabilities to maximize flexibility for when the vessel needs to maintain position for an extended amount of time.
- There was minimal manpower needed to deploy and retrieve the system. The project team was able to carry out its operations with three people at the most, two to work directly with the system and one to operate the vessel. The project team encountered several issues during the test trials but were able to overcome them with minimal modifications to how operations should be carried out.
- The CLAMShell system was able to maintain its position in river currents up to two knots, and with enough slack in the elastic cords on anchor lines can be made to conform to natural features on the river bottom. However, the system may be misaligned when laid on top of medium to large cobblestones so a careful site survey would be needed prior to deployment. It appeared that the system is capable of enduring higher river current velocity but further tests would confirm this.

4.2.3 Offshore Mitigation System

Based on the Lake Huron field tests, RDC makes the following conclusions and recommendations to improve the offshore mitigation system design and the handling of it:

Design



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- RDC does not recommend employing human divers as a necessity to complete installation of a mitigation system.
- A self-deployable mitigation system in higher current areas would be a more feasible option to eliminate placing divers in dangerous work environments. An example would be the incorporation of an air bladder or additional foam material into the top of the mitigation system instead of the A1 buoy attachments. This would also remove the need of divers to detach buoys after the system is established on the bottom. Removal of buoys would also allow the mitigation system to be spooled onto a reel, which would significantly speed up deployment and recovery times. Another example is for an anchoring system to be integrated into the mitigation system that can set itself once the system reaches the lakebed. This feature would further obviate the need for divers.
- Responders would benefit from better attachment points on the system itself to improve ease of equipment handling during deployment and recovery. Larger loops on the system would also allow the responders to handle the equipment with hooks instead of their hands, which would reduce safety risk and the amount of oil contamination on the responders.
- Responders should grease slide connectors between system sections after recovery from the water to facilitate disconnection during breakdown.
- The addition of an acoustic pinger on the system itself would help the responders to quickly locate the system with a sonar instrument.
- Brighter colored fabric or the use of retroreflective tape on the mitigation system itself would improve diver visibility, especially in murky underwater environments.

Operations

- If a mitigation system requires the use of divers to complete installation, dive platforms should be stable.
- In higher current areas, buoyancy of the system proved to be a challenge; employing the use of heavier anchors would help to secure the mitigation system to the bottom of the lake.
- In areas with current less than 1 knot, posts without additional guy wires or bottom stakes are sufficient to keep the system upright. The posts do not need to be driven the full 2 feet; 12 to 18 inches are enough and would significantly decrease dive time during deployment and recovery.
- Deploying the system sideways from a vessel may be easily carried out on a Coast Guard buoytender, but it would be difficult to do the same from a vessel of opportunity. RDC recommends deploying the mitigation system from the stern; a vessel with ample aft work deck space would be the most ideal platform for deployment and recovery of this mitigation system.
- If use of divers cannot be avoided, stakes to secure the bottom of the system to the lake bottom are recommended since taut anchor lines may lift the system ends slightly. RDC also recommends stakes if the system is laid on rocks or in regions with large amounts of gravel. Sandbags may also be helpful in these scenarios to cover system gaps.
- Using a crane to recover the system may be a practical approach in very low-wind conditions but alternative methods such as the use of cross-deck winches or boom reels are safer and thus recommended.
- Careful consideration of how lines are tied to anchors is needed to prevent entanglement and improper setting during deployment. There should be a variation of options for anchoring to adapt to multiple conditions that responders may encounter in the open water, such as heavier anchors, types of anchors, and shorter anchor lines to name a few. Additionally, varying anchoring options would allow the system to be more accessible to a wider range of vessels of opportunity.



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- A second anchor is needed to control or position placement of the mitigation system endpoint.
- Good communication is needed between responders and the vessel operator to ensure the system is laid out in a pronounced U-shape for a more efficient oil collection.

4.2.4 Overall Conclusions and Recommendations

RDC sought to advance the science of response technologies for moving sunken oil with the development and testing of three mitigation systems. After reviewing results and lessons learned, RDC recommends further developmental efforts and testing with oil to determine actual effectiveness for all three mitigation systems before they can be used as response tools for real world oil spill incidents that involve moving sunken oil.

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