USE OF TRAJECTORY MODELING TO ANALYZE VARIATIONS ON THE RESPONSE STRATEGIES FOR INLAND SPILLS

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ABSTRACT

This study presents a methodology for evaluating various mechanical containment and recovery-based response strategies for inland spills through the use of a trajectory, fate, and effects model (SIMAP). A case study demonstrates different spill impacts that may have resulted from several variations of response strategies, focusing on placement of and type of booms and oil removal equipment. The actual spill response to the April 2000 PEPCO pipeline spill of 138,600 gallons of a combination of No. 2 and No. 6 fuels into Swanson Creek at Chalk Point, MD, was modeled with SIMAP to recreate the oil movement and behavior. Several variations on the spill response, including alternative placement and timing of booms, were modeled to estimate different outcomes that may have occurred with the different responses. This particular case offers valuable lessons learned in that it demonstrates the importance of strategic boom placement and timing. The methodology is applicable to a broad spectrum of response planning and training situations, and for post-spill assessment for a more detailed evaluation of response strategy.

INTRODUCTION

Major oil spill events provide excellent opportunities for in-the-field strategic spill response planning and training as well as post-spill response evaluations. With decreasing frequency of these events in inland waterways (Etkin 2004), it is even more important to derive the greatest benefit from these “spills of opportunity” to increase response effectiveness and maintain well-trained preparedness. The use of SIMAP for simulating the path and behavior of oil while modeling various spill response methods for actual historical spills and for hypothetical spills allows for a state-of-the-art assessment of alternative spill response strategies for these purposes.

METHODOLOGY: SIMAP OVERVIEW

SIMAP is a computer modeling software application developed by Applied Science Associates (ASA), Inc., that estimates physical fates and biological effects of releases of oil. The model algorithms and assumptions of SIMAP are fully described in French McCay (2004), and summarized below. In SIMAP, both the physical fates and biological effects models are three-dimensional. There is also a two-dimensional oil spill model for quick trajectories and screening of scenarios and a three-dimensional stochastic model for risk assessment and contingency planning applications. The models are coupled to a geographic information system (GIS) that contains environmental and biological data, and also to databases of physical-chemical properties and biological abundance, containing necessary inputs for the models.

SIMAP contains several major components: physical fate modeling of surface distribution and subsurface concentrations of spilled oil and components over time; biological effect modeling of impacts resulting from a spill scenario on fish, shellfish, wildlife, and for each of a series of habitats (environments) affected by the spill; probability of impact from an oil discharge quantified using a three-dimensional stochastic model; modeling of currents that transport contaminant(s) and organisms using the graphical user interface or generated using a (separate) hydrodynamic model[1]; computation of fates and effects from environmental, chemical, and biological databases that supply required information to the model; and incorporation of user –supplied information about the spill (time, place, oil type, and amount spilled) and some limited environmental conditions at the time of the spill (such as temperature and wind data).

Physical Fates Model

The physical fates model estimates distribution (as mass and concentrations) of contamination on the water surface, on shorelines, in the water column, and in sediments. The model is three-dimensional, using a latitude-longitude grid for environmental data and projecting model results. A geographical information system (GIS) database supplies values for water depth, sediment type, ecological habitat, shoreline type, and ice cover throughout the gridded domain. The physical-chemical (oil property) database supplies physical and chemical parameters required by the model. The user supplies a wind-time series specific to the time and location of the spill.

The model estimates surface spreading, slick transport, entrainment into the water column, and evaporation, to determine trajectory and fate at the surface. Surface slicks interact with shorelines, depositing and releasing material according to shoreline type. In general, some fraction of any

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[1] Alternatively, existing current data sets may be imported.

contaminant spilled will exist in both water column and sediments. In the water column, horizontal and vertical transport by currents and turbulent (random) dispersion are simulated. A contaminant in the water column is partially adsorbed to particles and partially dissolved. Partitioning between these states is assumed to be in constant proportions (*i.e.*, based on equilibrium partitioning theory). The contaminant fraction adsorbed to suspended particulate matter is assumed to settle at a rate typical for the type of sediment. Contaminants at the bottom are mixed by benthic animals into underlying sediments according to a simple bioturbation algorithm. Degradation of water column and sediment contaminant is estimated assuming a constant rate of “decay” in each environment.

The model is designed to simulate fates of crude oils and petroleum products, which are complex mixtures of hydrocarbons. For modeling purposes, crude oils and petroleum products are represented by seven pseudo-components: three aromatic fractions considered toxic to organisms, three non-aromatic volatile and relatively insoluble fractions, and a nonvolatile insoluble (residual) fraction. Each has representative volatility and solubility characteristics for that component.

The physical fates model computes dissolved concentrations in the water column and sediments, and the area of water and shoreline covered by surface slicks in space and time. These results may be viewed and evaluated using the graphical user interface. The information is also passed to the biological effects model, which then calculates biological effects of those concentrations and areas of coverage.

Hydrodynamics

The transport of oil is dependent on inputs of high quality current (hydrodynamic) data for the area of interest. Model grids may be rectilinear or boundary-fitted (which better conforms to estuarine and river shorelines). Forcing may include tidal, pressure gradient, and wind driven motion of water. In coastal and marine applications, the hydrodynamic modeling includes and is often dominated by tidal currents, whereas for freshwater, either gradient or wind-driven flow is dominant. Currents in rivers are typically computed for mean flow conditions and stored in the database. These flows may be scaled up or down, depending on conditions during a spill. These water currents are in turn used to calculate transport of contaminants in and on the water.

Spill Response

SIMAP allows the user to apply various spill responses to spill scenarios, including location-specific mechanical containment (booming), oil removal (skimming or vacuum trucks), chemical dispersant applications, and *in situ* burning, with user-specified capabilities (minimum oil thickness, current velocity and wave height thresholds, wind conditions, and removal effectiveness) and timing. SIMAP follows the trajectory and fate of the oil, as well as the hydrodynamics, winds, and time. When conditions are within the set response parameters, SIMAP simulates the containment and removal of oil at the rates set by the user. When these parameters are exceeded (*e.g.*, wave and/or current thresholds exceed capabilities of booms), SIMAP simulates the behavior of the oil in the absence of the response (*i.e.*, the response is not effective).

Results and Output

SIMAP generates a large amount of output, including oil fate, biological effects, and oil removal effectiveness. For this study, only shoreline impacts and the amounts of oil that impacted various zones were derived to determine the effectiveness of various responses.

METHODOLOGY: CASE STUDY ASSUMPTIONS

A case study of a major oil spill to an inland waterway, the 7 April 2000 pipeline spill of 138,600 gallons of a mixture of No. 2 and No. 6 fuel oils into Swanson Creek and the Patuxent River at Chalk Point, Maryland was selected for evaluation of spill response strategies that were deployed as well as alternative responses that may have been implemented. This case is particularly instructive in that it involved extensive impacts to wetlands after failures to follow through on directives set forth by the federal on-scene coordinator (FOSC)[2], as well as deployment of defective, poorly-maintained boom. Misinformation on spill magnitude, along with the arrival of a storm on the second day after the spill created challenges for responders[3]. The actual response, five alternative responses[4], and one “no-response” scenario were

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[2] An extensive review of Incident Action Plans, Pollution Reports, spill photographs, spill documents (*e.g.*, EPA After-Action Report), weather and current records, and personal interviews with spill responders, observers, and federal on-scene coordinators were conducted to determine the actual course of events.

[3] Reports of the spill as “2,000 gallons” rather than the actual 138,600 gallons were received by the FOSC before arriving on-scene. Improperly maintained and poor-condition boom was installed without sufficient anchorage and in a twisted fashion. Several boom deployments directed by the FOSC were not carried out, including the installation of booms in Swanson Creek after initial booming efforts failed and installation of protective booms to exclude oil from sensitive downstream creeks and wetland areas.

modeled as in Table 1, with boom deployment as in Table 2[5]. Figures 1 and 2 show boom locations. Figure 3 shows oil removal locations (with shore-based vacuum trucks and on-water skimmers).

Table 1: Alternative Modeled Spill Scenarios

Scenario Name[6]	Response
ACTUAL (See Table 3)	Actual Response
FOSC (See Table 4)	Actual Response plus follow FOSC directives for Swanson Creek booming
A-GOOD (See Table 5)	Actual Response with all boom properly installed
NO RESP	No Response

Table 2: Boom and Condition/Deployment Effectiveness by Scenario for Alternative Modeled Spill Scenarios

Boom[7]	Boom Condition and Deployment Effectiveness by Scenario[8]			
	ACTUAL	FOSC	A-GOOD	NO RESP
A	actual	actual	good	none
B	actual	actual	good	none
C	actual	actual	good	none
C2	none	good	none	none
E	actual	good	good	none
F	actual	actual	good	none
G	actual	actual	good	none
H	none	good	none	none
TG	actual	actual	actual	none
BV	actual	actual	actual	none
BenBr-A-C	actual	actual	good	none
BenBr-1	actual	actual	good	none
InCr-A	actual	actual	good	none
InCr-B	actual	actual	good	none
TH-A	actual	actual	good	none
TH-B	actual	actual	good	none
Sandy	actual	actual	actual	none
Wash	actual	actual	actual	none
Sher	actual	actual	actual	none

The timing of boom deployment and boom condition (percent oil retention) for the scenarios are shown in Tables 3 – 5. Note that boom breaks in several cases. Booms are less than 100% effective if twisted and/or or improperly anchored. Booms are also less than optimally effective if in poor condition.

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[4] Alternative responses were assumed to use only those resources reported to have been on-scene.

[5] "Actual" response scenarios were compared to records of known oil trajectory and shoreline impacts to ascertain validity of modeling and to calibrate SIMAP. This would also validate results from alternate responses.

[6] Tables 3 – 5 give detailed descriptions of the use of booms in each scenario.

[7] Boom as shown and labeled in Figures 1 and 2. Tables 3 – 5 give detailed descriptions of the use of booms in each scenario.

[8] "Actual" boom deployment refers to the manner in which the boom was actually reported to have been deployed in the actual spill scenario, including boom condition and deployment effectiveness with regard to use of anchoring, angling, and presence of twists during deployment as reported. "Good" boom deployment refers to deployment of well-maintained boom, with proper anchoring and angling, and avoidance of twists during deployment.

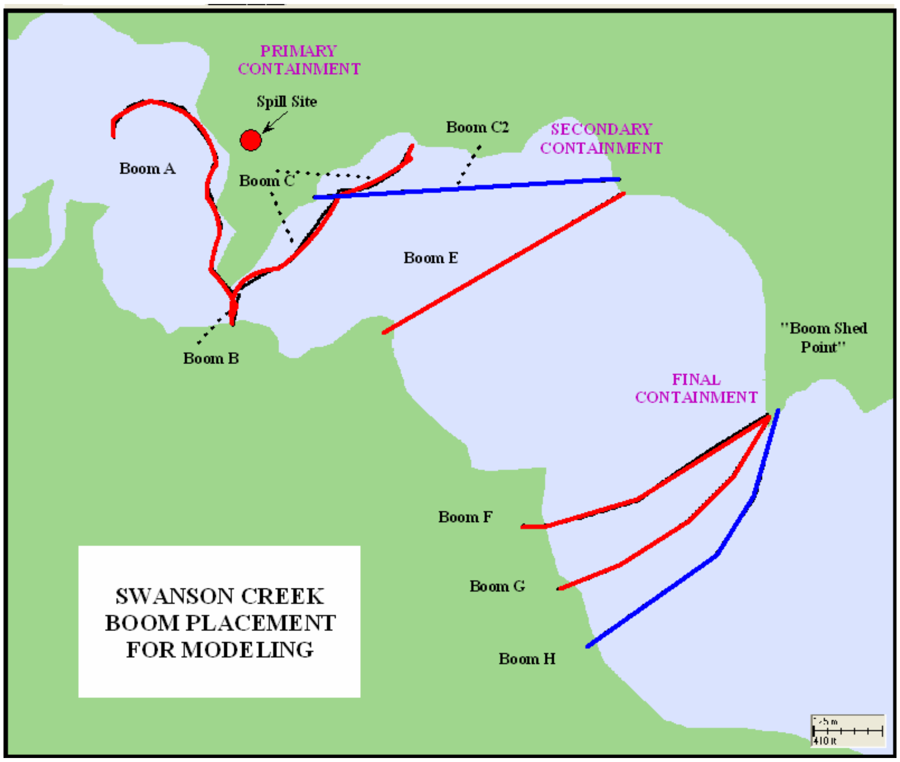

Figure 1: Boom Placement in Swanson Creek. Booms indicated in red are ones that were actually deployed in the spill response. Booms indicated in blue are ones that the FOSC ordered but were never deployed.

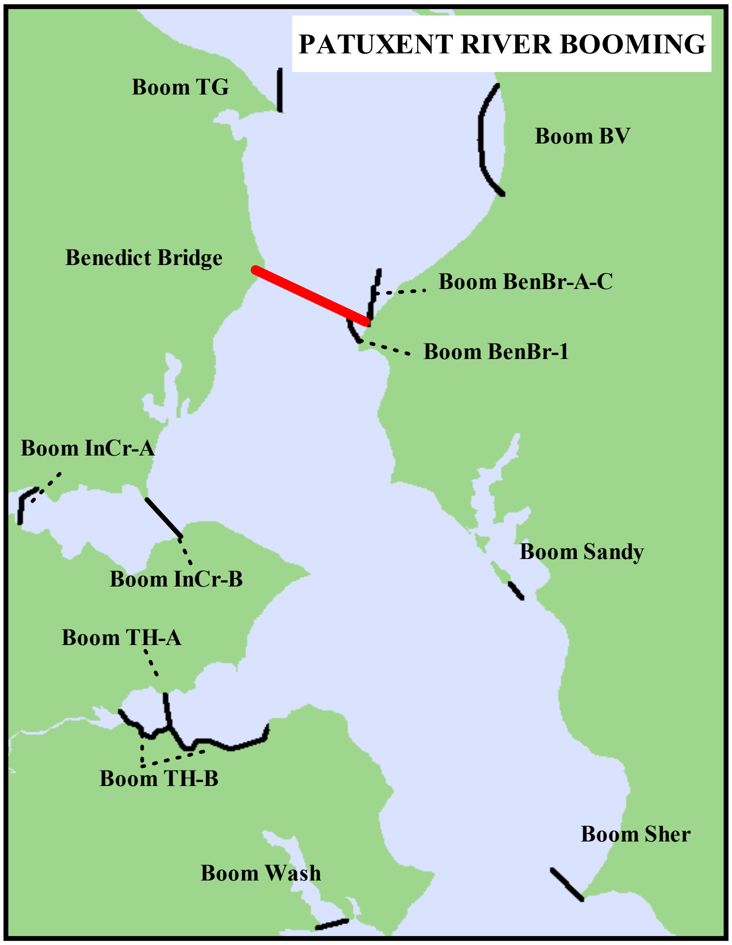

Figure 2: Boom Placement in Patuxent River (downstream from Swanson Creek). Benedict Bridge is shown in red.

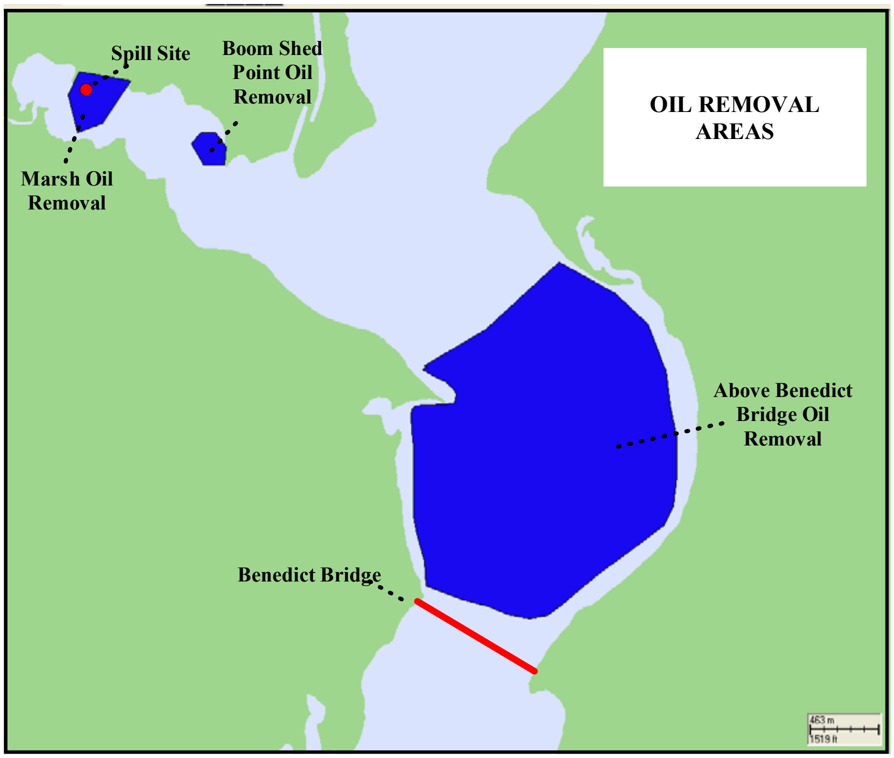

Figure 3: Oil Removal Areas. Oil removal occurred at the marsh near the spill site and at "Boom Shed Point" with vacuum trucks and with Navy skimmers in the Patuxent River north of the Benedict Bridge. Oil removal was assumed to take place with decreasing efficiency over time (Figure 4) due to the spread of oil and the greater difficulty in retrieving oil. Skimming capacities were based on the type of equipment reported to be present at each of these locations. It was assumed that the skimmers and vacuum trucks needed to be emptied when filled and that skimming did not occur during darkness when it would be too difficult to locate the oil.

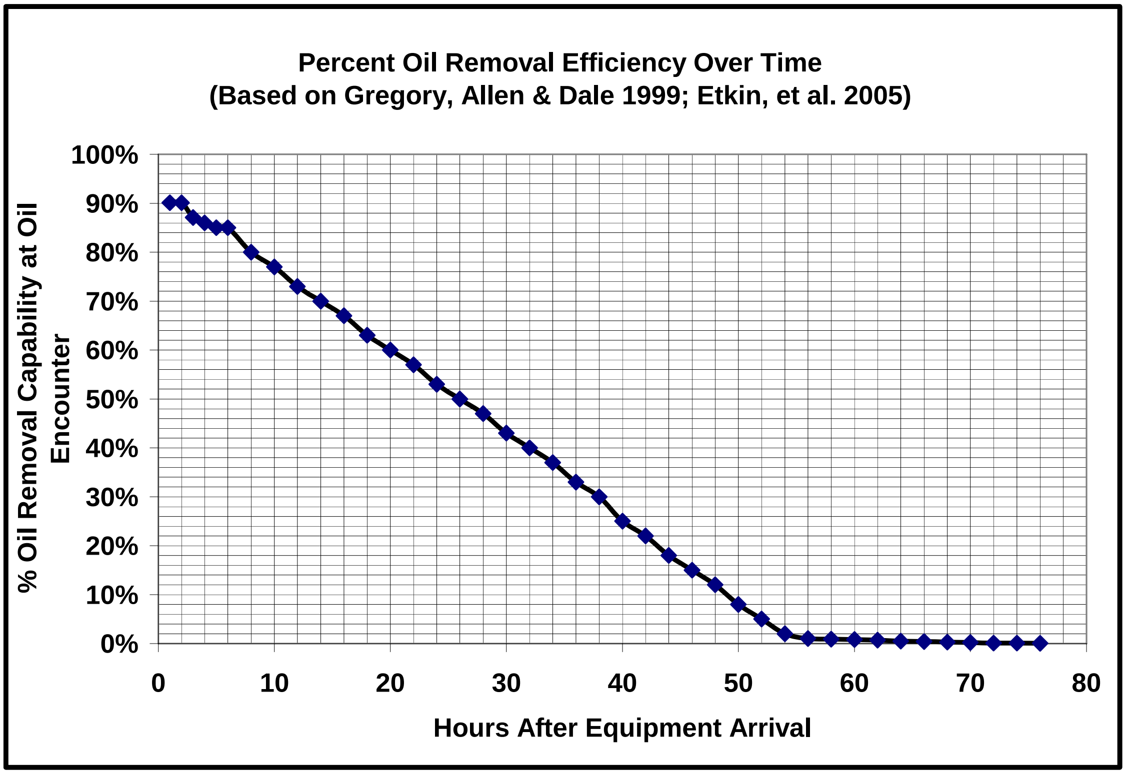

Figure 4: Assumed Percent Oil Removal Efficiency

Table 3: Scenario ACTUAL (Actual Response) Boom Deployment Assumptions

Boom	Deployment [9]	Boom Break	% Retention[10]	Current Threshold (kts)[11]	Wave Threshold (ft)[12]
A	4/7 11:00PM	4/8 6:00PM	25	0.7	3
B	4/7 11:00PM	4/8 2:00PM	25	0.7	3
C	4/7 11:00PM	4/8 2:00PM	25	0.7	1
E	4/8 2:00PM	4/8 6:00PM	25	0.7	3
F	4/7 7:00PM	4/8 6:00PM	50	0.7	1
G	4/8 2:00PM	4/8 6:00PM	50	0.7	3
TG	4/11 11:00AM	*No break*	100	0.7	3
BV	4/9 2:30PM	*No break*	100	0.7	3
BenBr-A-C	4/10 9:30AM	4/10 9:30PM	100	0.7	3
BenBr-1	4/10 9:30AM	4/10 9:30PM	100	0.7	3
InCr-A	4/11 11:30AM	4/11 4:30PM	50	0.7	3
InCr-B	4/11 11:30AM	4/11 4:30PM	50	0.7	3
TH-A	4/11 11:30AM	4/11 4:30PM	50	0.7	3
TH-B	4/11 11:30AM	4/11 4:30PM	50	0.7	3
Sandy	4/10 11:30AM	*No break*	100	0.7	3
Wash	4/11 11:30AM	*No break*	100	0.7	1
Sher	4/11 11:30AM	*No break*	100	0.7	3

Table 4 : Scenario FOSC Boom Deployment Assumptions

Boom	Deployment	Boom Break	% Retention	Current Threshold (kts)	Wave Threshold (ft)
A	4/7 11:00PM	4/8 6:00PM	25	0.7	3
B	4/7 11:00PM	4/8 2:00PM	25	0.7	3
C	4/7 11:00PM	4/8 2:00PM	25	0.7	1
C2	4/8 2:00PM	*No break*	100	0.7	3
E	4/8 2:00PM	*No break*	100	0.7	3
F	4/7 7:00PM	4/8 6:00PM	50	0.7	1
G	4/8 2:00PM	4/8 6:00PM	50	0.7	3
H	4/8 4:45PM	*No break*	100	0.7	3
TG	4/11 11:00AM	*No break*	100	0.7	3
BV	4/9 2:30PM	*No break*	100	0.7	3
BenBr-A-C	4/10 9:30AM	4/10 9:30PM	100	0.7	3
BenBr-1	4/10 9:30AM	4/10 9:30PM	100	0.7	3
InCr-A	4/11 11:30AM	4/11 4:30PM	50	0.7	3
InCr-B	4/11 11:30AM	4/11 4:30PM	50	0.7	3
TH-A	4/11 11:30AM	4/11 4:30PM	50	0.7	3
TH-B	4/11 11:30AM	4/11 4:30PM	50	0.7	3
Sandy	4/10 11:30AM	*No break*	100	0.7	3
Wash	4/11 11:30AM	*No break*	100	0.7	1
Sher	4/11 11:30AM	*No break*	100	0.7	3

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[9] Oil release began at 9:30am and continued for five hours. The spill was discovered and reported at 6pm on 7 April.

[10] % retention is the % of oil contained behind the boom. Less than 100% occurs if the boom is improperly deployed and/or the boom is in poor condition. Boom will not retain oil if current or wave threshold is exceeded.

[11] In the modeling, oil would pass under (entrain) the boom if the current threshold were exceeded.

[12] Wave threshold of one foot assumed for 6 – 18” “river-canal” boom and three feet for 18 – 42” “inland environment” boom. In the modeling, oil would pass under (or splash over) the boom if the wave threshold were exceeded.

Table 5 : Scenario A-GOOD Boom Deployment Assumptions					
Boom	**Deployment**	**Boom Break**	**% Retention**	**Current Threshold (kts)**	**Wave Threshold (ft)**
A	4/7 11:00PM	*No break*	100	0.7	3
B	4/7 11:00PM	*No break*	100	0.7	3
C	4/7 11:00PM	*No break*	100	0.7	1
E	4/8 2:00PM	*No break*	100	0.7	3
F	4/7 7:00PM	*No break*	100	0.7	1
G	4/8 2:00PM	*No break*	100	0.7	3
TG	4/11 11:00AM	*No break*	100	0.7	3
BV	4/9 2:30PM	*No break*	100	0.7	3
BenBr-A-C	4/10 9:30AM	*No break*	100	0.7	3
BenBr-1	4/10 9:30AM	*No break*	100	0.7	3
InCr-A	4/11 11:30AM	*No break*	100	0.7	3
InCr-B	4/11 11:30AM	*No break*	100	0.7	3
TH-A	4/11 11:30AM	*No break*	100	0.7	3
TH-B	4/11 11:30AM	*No break*	100	0.7	3
Sandy	4/10 11:30AM	*No break*	100	0.7	3
Wash	4/11 11:30AM	*No break*	100	0.7	1
Sher	4/11 11:30AM	*No break*	100	0.7	3

RESULTS

Shoreline oiling (in square meters) in the various zones shown in Figure 5 were determined. Results are shown in Table 6. Each response is compared to "no response" and alternate responses are compared to the actual response to see the extent to which the response was effective in keeping oil off shorelines in the various zones. The same results by oil volume that entered the various zones are shown in Table 7. The actual response reduced overall shoreline oiling by 29 percent over having done no response at all. The actual response reduced shoreline oiling outside Swanson Creek by 38 percent over what it would have been with no response. Following the FOSC or properly installing good boom in its original configuration would have eliminated any oiling of Zone 3 and much of Zone 4. Good booming would have reduced the shoreline impact to Zone 2 by 54 percent. Following FOSC directives would have reduced shoreline impact in Zone 2 by 23 percent. Following the FOSC or properly installing good boom in its original configuration would have eliminated almost all oiling of Zones 3 and 4. Good booming would have reduced the shoreline impact to Zone 2 by 16 percent. Following FOSC directives would have reduced shoreline impact in Zone 2 by 23 percent.

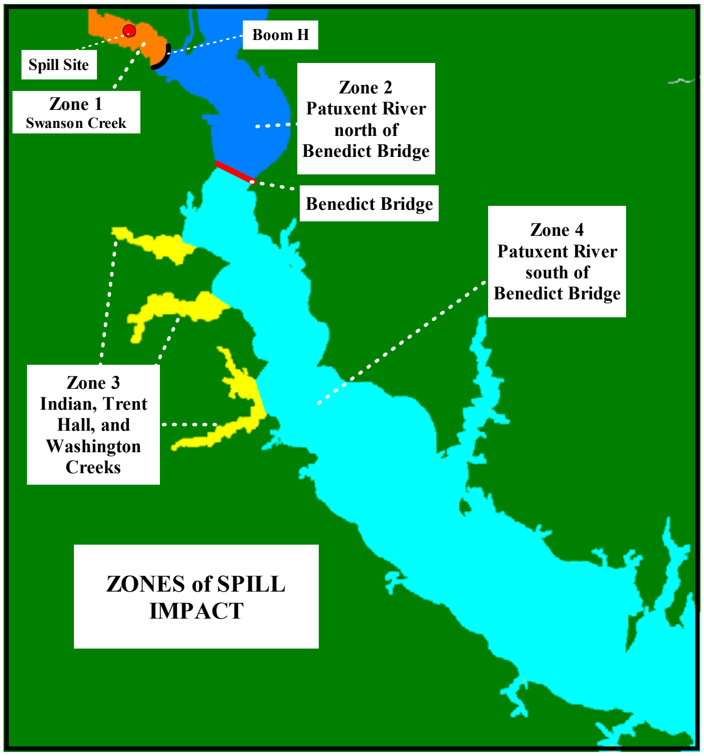

Figure 5: Zones of Impact. Indian, Trent Hall, and Washington Creeks contained significant wetland areas and impacts to these areas resulted in significant response costs.

Table 6: Shoreline Oiling by Zone Based on Spill Response

Scenario	Total Shoreline (m^2)					
	Total	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Outside Swanson Creek**
NO RESP (no response)	23,029	4,919	6,055	5,178	6,877	18,110
ACTUAL (actual)	16,277	5,026	5,947	1,118	4,185	11,250
Shoreline Oiling Avoided	**6,752**	**-107**	**108**	**4,060**	**2,692**	**6,860**
% Less than No Response	**29%**	**-2%**	**2%**	**78%**	**39%**	**38%**
FOSC	10,285	5,339	4,570	36	340	4,946
Shoreline Oiling Avoided	**12,744**	**-420**	**1,485**	**5,142**	**6,537**	**13,164**
% Less than No Response	**55%**	**-9%**	**25%**	**99%**	**95%**	**73%**
% Less than Actual	**37%**	**-6%**	**23%**		**92%**	**56%**
A-GOOD	9,543	6,573	2,808	9	152	2,969
Shoreline Oiling Avoided	**13,486**	**-1,654**	**3,247**	**5,169**	**6,725**	**15,141**
% Less than No Response	**59%**	**-34%**	**54%**	**100%**	**98%**	**84%**
% Less than Actual	**41%**	**-31%**	**53%**		**96%**	**74%**

The actual response reduced the volume of oil on shorelines outside Swanson Creek by 30 percent over what would have happened with no response at all. Figure 6 shows the shoreline oiling that occurred with the actual response. Figure 7 shows the “no response” scenario. Following the FOSC directives would have reduced shoreline oiling (by volume) by 61 percent. By applying good boom and good booming technique, 95 percent of shoreline oiling outside Swanson Creek could have been prevented.

Table 7: Volume of Shoreline Oiling by Zone Based on Spill Response

Scenario	**Gallons Impacting Shorelines by Zone**[13]					
	Total	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Outside Swanson Creek**
No Response	37,926	25,746	8,190	2,142	0	10,332
ACTUAL (actual)	29,862	22,554	6,342	294	672	7,266
Δ from No Response	8,064	3,192	1,848	1,848	-672	3,066
% prevented	**21%**	**12%**	**23%**	**87%**		**30%**
FOSC	40,362	36,288	4,032	0	42	4,074
Δ from No Response	-2,436	-10,542	4,158	2,142	-42	6,258
Δ from Actual Response	-10,500	-13,734	2,310	294	630	3,192
% prevented	**-6%**	**-41%**	**51%**	**0%**		**61%**
A-GOOD	38,388	37,842	504	0	0	546
Δ from No Response	-462	-12,096	7,686	2,142	0	9,786
Δ from Actual Response	-8,526	-15,288	5,838	294	672	6,720
% prevented	**-1%**	**-47%**	**94%**	**0%**		**95%**

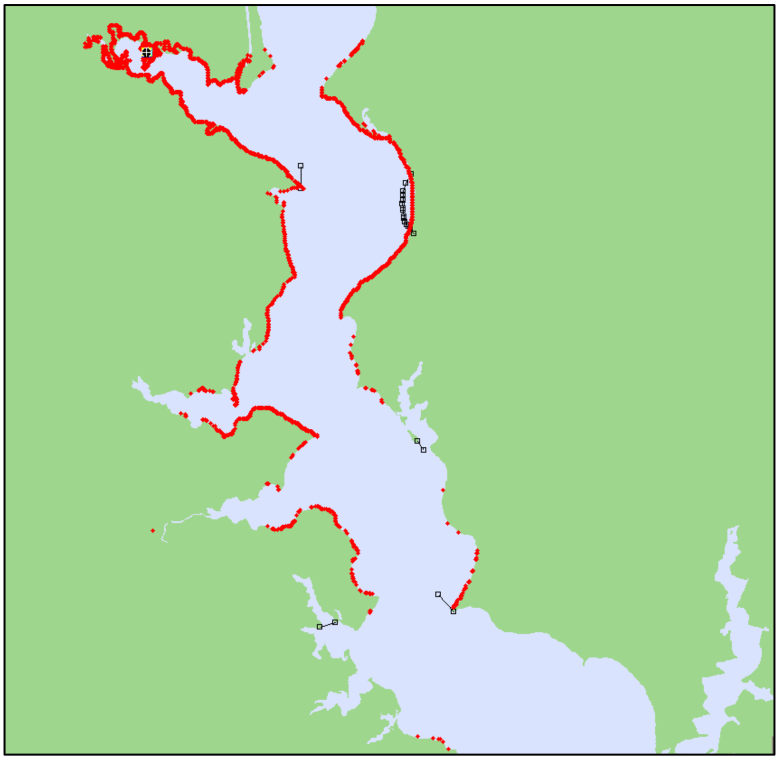

Figure 6: SIMAP depiction of ACTUAL scenario (actual oil spill response) showing shoreline oiling. Note that the shoreline impacts are not all of equal magnitude. (Black lines are booms.)

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[13] Keeping oil contained in Swanson Creek (with effective booming) would somewhat increase the area of shoreline oiling within the creek unless aggressive efforts were made to remove oil from the water surface before it lands on the shoreline. The modeling assumed that, despite any hypothetical changes in booming configuration, deployment technique, or boom condition, no additional oil removal efforts were made beyond that that was reported to actually have occurred.

By following the currents and winds, it was possible to show that current velocity thresholds for oil containment (generally considered to be 0.7 knots) were exceeded for only a few minutes in a minimal number of locations during the entire spill response. In addition, wave thresholds were never exceeded for the duration of the response, despite the storm that occurred on the second day after the spill. This meant that with effective booming techniques (angling and anchoring) and the use of well-maintained boom, it would be possible to contain much of the oil within Swanson Creek, as directed by the FOSC, and, at the very least, to keep oil out of vulnerable downstream wetlands and creeks once the oil had escaped Swanson Creek into the Patuxent River. Figures 8 – 9 show alternative responses.

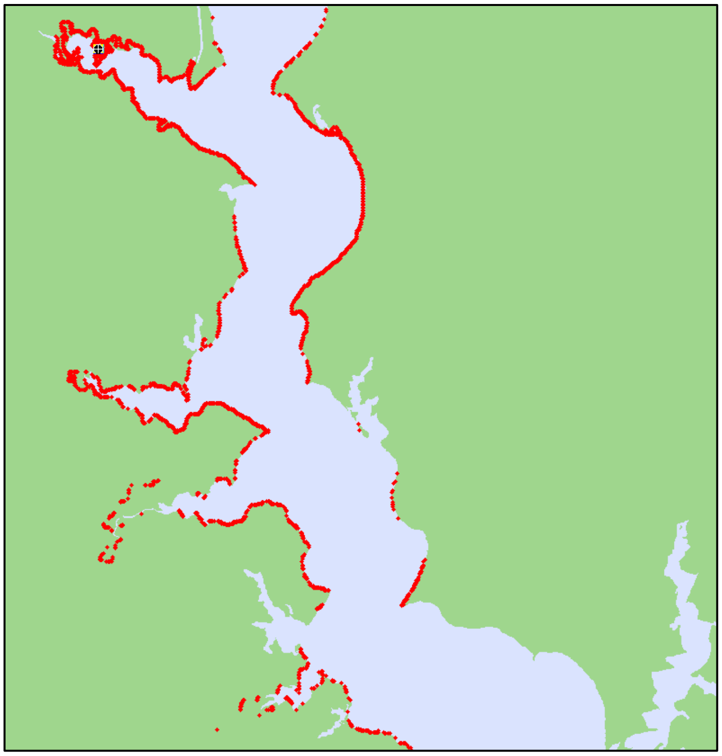

Figure 7: SIMAP depiction of NO RESP ("no response") scenario showing shoreline oiling. Note that the shoreline impacts are not all of equal magnitude.

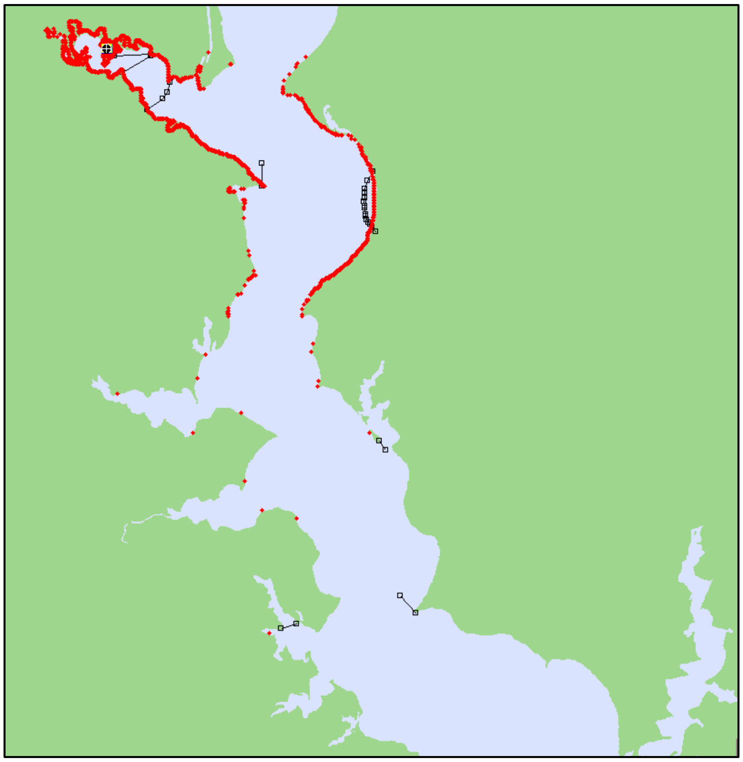

Figure 8: SIMAP depiction of FOSC scenario (actual plus following FOSC directives) showing shoreline oiling. Note that the shoreline impacts are not all of equal magnitude. (Black lines are booms.)

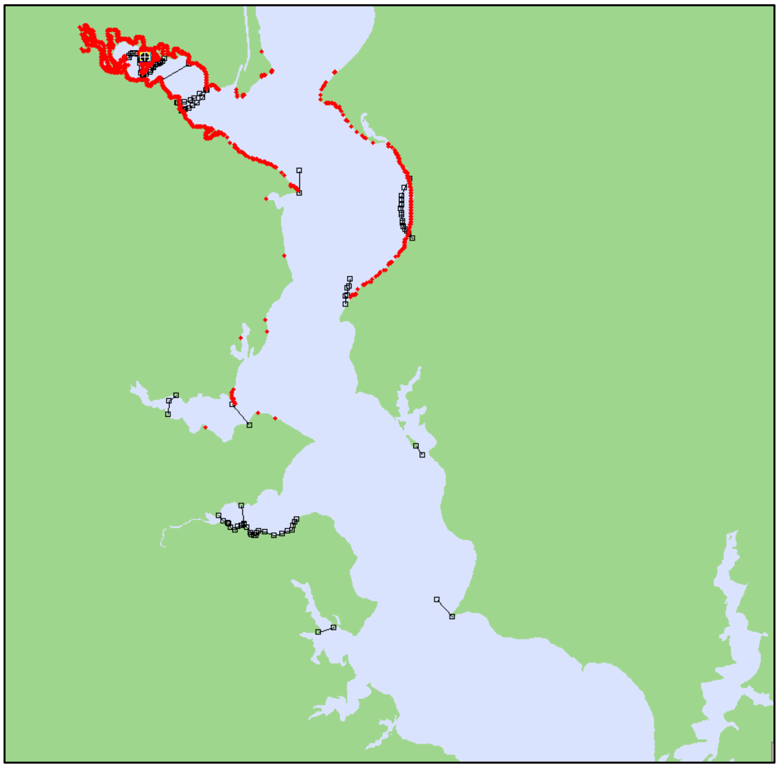

Figure 8: SIMAP depiction of A-GOOD scenario (actual response using good boom and good booming technique) showing shoreline oiling. Note that the shoreline impacts are not all of equal magnitude. (Black lines are booms.)

DISCUSSION

The April 2000 Pepco pipeline oil spill at Chalk Point, Maryland, provided some challenges to response personnel as well as to federal on-scene coordinators due to a storm and a series of errors that allowed oil to escape the marsh and creek into which the oil originally spilled. The impacts and costs of the spill were greater than one might anticipate from the volume of oil spilled. By using SIMAP modeling to “replay” the spill, comparing the actual response to “no response” and to varying alternative responses, it was possible to ascertain the effectiveness of the actual spill response and how response effectiveness might have been improved with different response strategies, including the following of actual FOSC directives at the time of the spill for booming in Swanson Creek near the spill site. In this case, it was possible to show that with the use of properly-maintained, good-condition boom and good booming technique or by following the FOSC’s directives to add additional boom once the initially-installed boom had failed and to install protective boom at sensitive downstream creeks, significantly less shoreline oiling and wetland impact would have occurred.

This type of review of a past spill response provides invaluable “lessons learned” to improve spill response in future incidents. This type of tool can also be used for training purposes to develop better response strategies and for developing contingency plans for inland facilities that may spill oil near sensitive natural or socioeconomic resources.

SIMAP can also be applied to develop estimates of biological impacts and compensatory restoration costs, and to estimate spill response costs and socioeconomic damage costs when coupled with ERC’s oil spill cost modeling.

ACKNOWLEDGEMENTS

Oil spill response consultant Charlie Huber and Steve Potter, SL Ross Environmental Research Ltd., provided invaluable assistance in determining specifications and capabilities of the booms and mechanical recovery equipment based on records of on-scene resources, data in SL Ross Environmental Research’s *World Catalog of Oil Spill Response Products,* and current research on spill boom capabilities.

BIOGRAPHY

Dagmar Schmidt Etkin received her B.A. in Biology from Univ. Rochester, and her A.M. and Ph.D. degrees in Biology (specializing in population biology, ecology, and statistical analysis) from Harvard

Univ. She has analyzed and modeled oil spill data and impacts for 17 years. Deborah French McCay received her B.A. in Zoology from Rutgers College and her Ph.D. in Biological Oceanography from Univ. Rhode Island. Dr. French McCay specializes in quantitative assessments and modeling of aquatic ecosystems and populations, pollutant transport and fates, and biological response to pollutants.

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