Journal of Hazardous Materials 175 (2010) 583–592

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Application of an enhanced spill management information system to inland waterways

Janey S. Camp[1], Eugene J. LeBoeuf*, Mark D. Abkowitz[2]

Department of Civil and Environmental Engineering, Vanderbilt University, VU Station B 351831, 2301 Vanderbilt Place, Nashville, TN 37235-1831, USA

ARTICLE INFO

Article history:
Received 2 September 2009
Received in revised form 9 October 2009
Accepted 12 October 2009
Available online 20 October 2009

Keywords:
Oil spill
Emergency response
TCE
GIS
Inland waterway

ABSTRACT

Spill response managers on inland waterways have indicated the need for an improved decision-support system, one that provides advanced modeling technology within a visual framework. Efforts to address these considerations led the authors to develop an enhanced version of the Spill Management Information System (SMIS 2.0). SMIS 2.0 represents a state-of-the-art 3D hydrodynamic and chemical spill modeling system tool that provides for improved predictive spill fate and transport capability, combined with a geographic information systems (GIS) spatial environment in which to communicate propagation risks and locate response resources. This paper focuses on the application of SMIS 2.0 in a case study of several spill scenarios involving the release of diesel fuel and trichloroethylene (TCE) that were simulated on the Kentucky Lake portion of the Tennessee River, each analyzed at low, average, and high flow conditions. A discussion of the decision-support implications of the model results is also included, as are suggestions for future enhancements to this evolving platform.

1. Introduction

Spill response managers have indicated the need for a decision-support system that provides advanced modeling technology within a visual framework [1]. Currently available models for spill response assistance include 1D and 2D modeling systems such as RiverSpill and ICWater [2], GNOME [3], and SMIS 1.0 [4]. While some of these models provide rough estimates of spill plume locations, often in a geographic information system (GIS) environment, the representation of plume location is presented as leading edge [2] or in bulk river segments [4]. Efforts to overcome these limitations led the authors to develop an enhanced version of the Spill Management Information System (SMIS 2.0).

SMIS 2.0 represents a user-friendly, state-of-the-art 3D hydrodynamic and chemical spill modeling system tool that provides for improved predictive spill fate and transport capability, combined with a geographic information systems (GIS) spatial environment in which to better inform and assist decision support for planning and response activities. Within SMIS 2.0, the 3D Generalized, Longitudinal-Lateral-Vertical Hydrodynamic and Transport (GLLVHT) model is employed to provide hydrodynamic information for contaminant transport modeling through the Chemical/Oil Spill Impact Model (COSIM) [5]. Utilizing a graphical user interface within ESRI's ArcMap, SMIS 2.0 enables users to edit the COSIM control file, execute the spill model, and load and format the output for viewing within GIS. Employment of SMIS 2.0 requires only experience with use of basic GIS tools, thus aiding in timely and effective spill response. Once the spill model results are placed in ArcMap, simple spatial queries can lead to identification of: (i) local emergency response personnel such as hospitals, fire departments, and police within a specified distance of the spill event location; (ii) schools or other sensitive populations (e.g., nursing homes) that may need to be evacuated; (iii) sensitive species that may be impacted within or along the waterway; and (iv) spill response resources such as location of spill response contractors, and materials. In addition, using a pre-set template, maps can be produced for printing or display through other means such as screen projection within a spill response operations center, or distributed to spill response personnel in the field through email and/or website postings. SMIS 2.0 can also be used for training and planning of response strategies through development of plausible scenarios. Spill scenario output files can be saved in a common directory and added to ArcMap at any future time.

Abbreviations: BTEX, benzene, toluene, ethylbenzene, and xylenes; COSIM, Chemical and Oil Spill Impact Model; ERM, Environmental Resources Management, Inc.; ESRI, Environmental Systems Research Institute, Inc.; GLLVHT, Generalized, Longitudinal-Lateral-Vertical Hydrodynamic and Transport; GEMSS, Generalized Environmental Modeling System for Surface Waters; GIS, geographic information systems; RM, River Mile; SMIS, Spill Management Information System; TCE, trichloroethylene; TVA, Tennessee Valley Authority; USACE, U.S. Army Corps of Engineers.

* Corresponding author. Tel.: +1 615 343 7070; fax: +1 615 322 3365.
E-mail addresses: janey.v.smith@vanderbilt.edu (J.S. Camp), eugene.j.leboeuf@vanderbilt.edu (E.J. LeBoeuf), mark.d.abkowitz@vanderbilt.edu (M.D. Abkowitz).

[1] Tel.: +1 615 322 2739; fax: +1 615 322 3365.
[2] Tel.: +1 615 322 3436; fax: +1 615 322 3365.

0304-3894/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2009.10.045

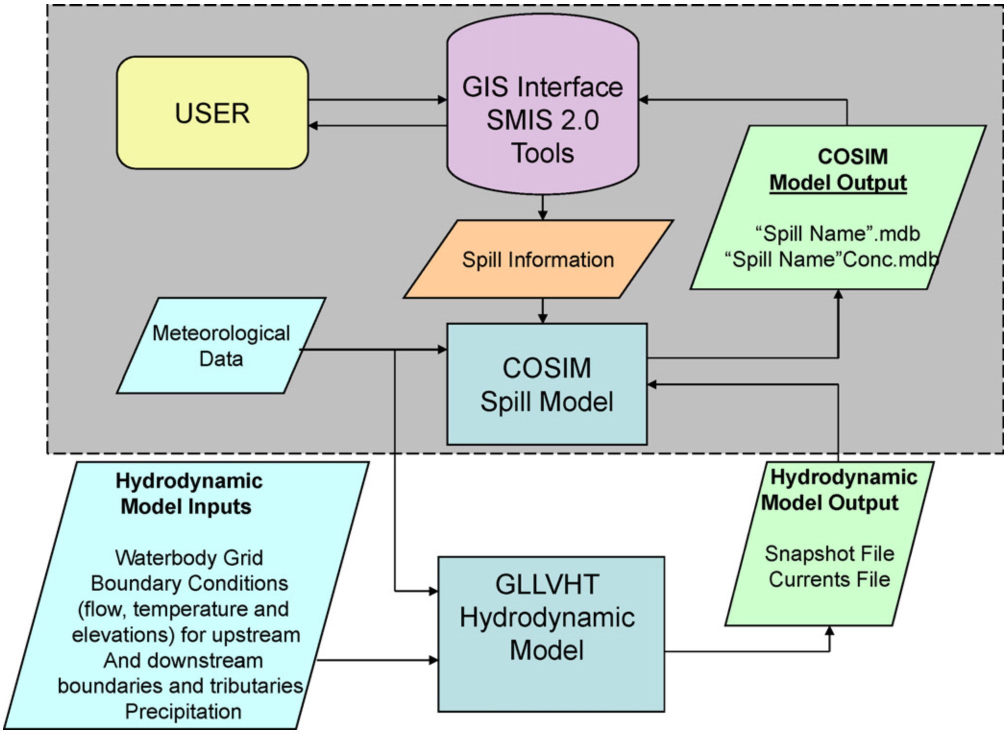


Fig. 1. System diagram. The items contained in the gray box are components of the SMIS 2.0 system. Those outside of the box are considered background information that is set up prior to a spill occurrence.

This paper focuses on the application of SMIS 2.0 as a decision-support tool in a case study of possible spill scenarios occurring near the Johnsonville, Tennessee fossil fuel electrical generating facility on Kentucky Lake. Three different spill scenarios are considered: (i) an average probable spill, (ii) a maximum probable spill, and (iii) a worst case spill, as defined by the Tennessee Valley Authority (TVA), under varying flow conditions [6]. SMIS 2.0 is used in creation of the scenarios and manipulation of the output for viewing in ArcMap. Presentation and comparison among simulation results for each scenario is provided, including a demonstration of querying capabilities within ArcMap to locate nearby schools. Placement of booms on the waterbody to assist with chemical spill recovery and protection measures is also evaluated. Boom interactions are of interest for: (i) developing pre-planned boom placement locations, (ii) evaluating containment and exclusion strategies, and (iii) determining resource needs for typical spill situations.

1.1. SMIS 2.0

As outlined in Camp et al. [1], SMIS 2.0 combines ArcMap 9.2 with Generalized Environmental Modeling System for Surface Waters (GEMSS) and COSIM modeling for enhanced spill response support. GEMSS contains multiple hydrodynamic models that can be used to provide water velocity information for COSIM spill modeling. The 3D GLLVHT model was selected for use in SMIS 2.0 to enable advanced (3D) hydrodynamic modeling for more accurate representation of flow characteristics in a waterbody that may impact spill plume migration. A diagram of the components involved with the flow of information identified and the corresponding SMIS 2.0 toolbar are shown in Figs. 1 and 2, respectively.

COSIM is capable of modeling numerous chemical constituents, including benzene, toluene, ethylbenzene, and xylenes (BTEX) hydrocarbons and their chemical sub-components [5,7]. In this application, a diesel fuel spill is simulated. In addition, COSIM can represent many physical and chemical interactions between the spilled chemical and the environment, including advection, dispersion, biodegradation, and evaporation. Volatilization, mixing, and degradation processes are also considered in the COSIM model. Additional information on the model's capabilities for simulating the physical and chemical processes associated with specific chemicals can be obtained from the developers [7]. Wind effects in the *x*- and *y*-directions on the water body hydrodynamics and plume migration are considered to be either all on or all off. Wind direction and speed are provided in the meteorological data input file.

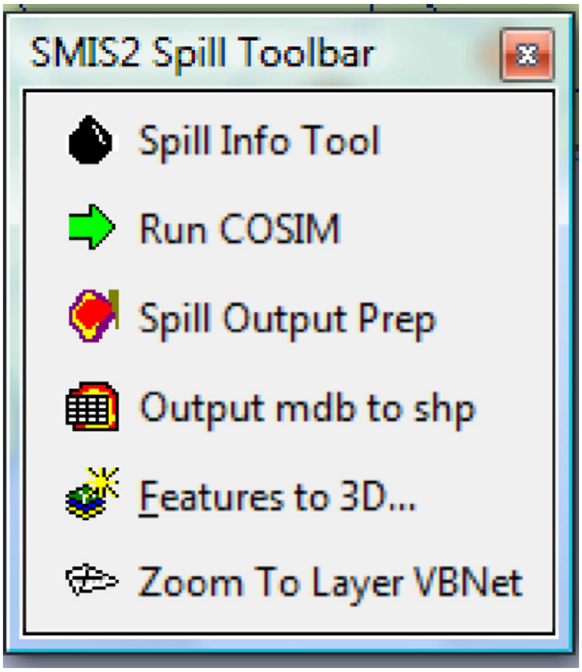


Fig. 2. SMIS 2.0 system toolbar.

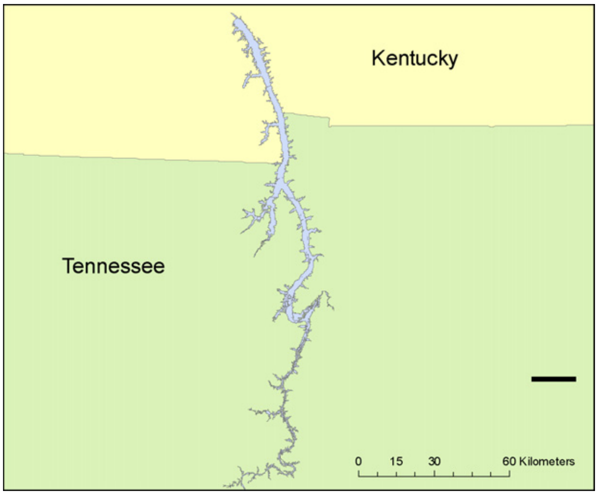


Fig. 3. Kentucky Lake project area.

Wind may contribute to the evaporation of volatile portions of the spill or shift the plume direction.

1.2. Case study region

The Tennessee River represents a major navigation pathway, connecting the southeastern United States region with the Ohio and Mississippi rivers. Due to its size, location, and amount of chemical barge traffic, Kentucky Lake, which comprises 184 miles of the Tennessee River situated west of Nashville, was chosen as the study region.

The lake area is bounded on the upstream end by Pickwick Dam at River Mile (RM) 202.3 and downstream by Kentucky Lake (RM 22.4), both managed by the Tennessee Valley Authority (TVA) (see Fig. 3). At normal operating level, the lake covers approximately 160,300 acres [8,9]. This includes tributaries such as the Duck and Big Sandy rivers, and a man-made canal linking Kentucky Lake to the Lake Barkley and the Cumberland River.

The river is narrow and sinuous downstream of Pickwick Dam before opening to a wide and deep reservoir behind Kentucky Dam, which serves as a sink for sediments, nutrients, and possible pollutants such as metals and organic compounds [10]. The depth of the river ranges from 8.3 m (elevation 353.4 ft) at the tail waters of Pickwick Dam to 25.6 m (elevation of 296.6 ft) at Kentucky Dam. The average flow in 2006 was 1033 m^3/s for Pickwick Dam and 1074 m^3/s for Kentucky Dam [11].

2. Experimental

The boundary area for GIS reference layers was defined as counties adjacent to the Tennessee River between the Pickwick and Kentucky dams. Base layers for counties, cities, and landmarks were obtained from U.S. Tiger Files [12]. The shapefiles for highways, streams, bridges, and other transportation features were obtained through the National Transportation Bureau data clearinghouse [13]. A national fire department shapefile was created using fire department addresses from the National Fire Department Census [14] and address matching the locations. Both the layers for schools and police/sheriff departments were developed by using online Yellow Pages (Yellowpages.com LLC, AT&T, 2008) and local online searches. Sensitive species information and addresses of subcontractors who provide response and clean up equipment were provided by TVA [6,11]. A sample map view of the GIS reference layers is shown in Fig. 4.

2.1. Hydrodynamic modeling with GLLVHT

River flow data for 2006 was selected as a base case since this annual data represented typical flow conditions for Kentucky Lake [15]. Available data included flows, temperatures, and tailwater elevations of Pickwick Dam, headwater elevation with temperatures and flows from Kentucky Dam, flow data for Barkley Canal, and intake and discharge volumes for the Johnsonville Fossil Fuel Plant (JOF), located at RM 99 on Kentucky Lake [11]. Barkley Canal, located near RM 25.0 just upstream of Kentucky Dam, links Lake Barkley on the Cumberland River with Kentucky Lake on the Tennessee River. Depending on the elevation difference between the two lakes, the water exchange between Kentucky Lake and

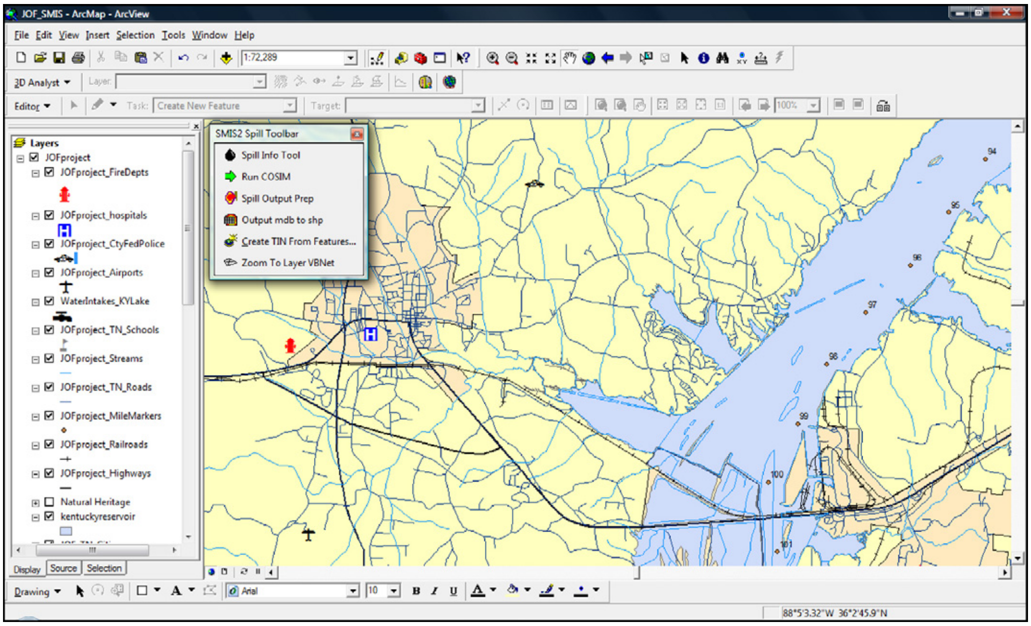


Fig. 4. Sample of Kentucky Lake project GIS layers. Items shown include a fire department, police department, hospital, an airport, the Tennessee River, railroads and highways, and river mile markers.

Table 1
Spill scenarios.

Scenario	Amount (gal)	Time to discover (min)	Time to stop (min)	Flow rate (gpm)	Additional spillage (gal)
Average probable	500	480	5	1	–
Maximum probable	3,200	30	5	85	225
Worst case	68,200	5	15	3400	225

Barkley Canal may be flowing to or from the canal at a given time. JOF, which is operated by TVA, withdraws water for cooling and then discharges it back into Kentucky Lake. Bathymetric data was obtained from both the TVA and the U.S. Army Corps of Engineers (USACE). The data from USACE was collected in the mid-1990s using an electronic echo-depth sounding device, Ratheon Model DE-1719B Fathometer Depth Sounder [16]. GEMSS's grid generation tool (GridGEN) was employed to create the hydrodynamic grid [17]. Meteorological data was obtained from the U.S. Climatic Data Center records for the Nashville airport [18]. Additional details on how this information was prepared and employed as input files to GEMSS are provided in [17].

The Kentucky Lake watershed comprises a very large region that encompasses many tributaries to the Tennessee River existing as either small streams or rivers. Tributaries with significant watershed areas contributing to flow into Kentucky Lake were identified using the Watershed Modeling System (WMS 8.1) developed by Environmental Modeling Systems, Inc. Two tributaries, the Duck River (RM 110.0) and Big Sandy River (RM 67.0), were considered significant because each represented greater than 1% of the total drainage area for Kentucky Lake. Flow data for these rivers were obtained from US Geological Survey records [19,20].

The GLLVHT hydrodynamic model was calibrated for both high and low flow conditions through use of the model's Head Correction tool [1,17], which calculates the amount of distributed flow required to close the difference between the model's estimated elevation and the measured elevation at a specified point. The elevation at Kentucky Dam was used as the calibration point. Sensitivity analysis was performed on the Chezy coefficient, the location of cells to which the distributed flow was applied, and the frequency of the Head Correction calculations. Calibration and sensitivity analysis efforts resulted in modeled elevation at Kentucky Dam within 0.3% of the measured elevation for the entire year.

2.2. COSIM set-up

Among the activities required in setting up COSIM are creation of a rectilinear spill grid (*.osg) for use in the COSIM model and preparing the shoreline characteristics data (if used). The spill grid overlays the hydrodynamic grid created in GEMSS for use with GLLVHT. The following discussion describes the various spill scenarios considered in the case study, as well as set-up of COSIM inputs not included as part of the GLLVHT model.

Three spill scenarios were evaluated, each involving leakage of diesel fuel on or adjacent to the waterway during a barge fuel unloading operation (see Table 1). Each of these scenarios was evaluated for three different flow conditions (low, average, and high flow), so that altogether nine different cases were evaluated. For the year 2006, a low flow period was determined to begin on March 30 with an average flow of 416 m^3/s over a three-day period. The average flow simulation period began on April 12 with an average flow rate of 1354 m^3/s over a three-day period. The high flow period began on November 18 with a three-day average flow of 2548 m^3/s.

Since each of the scenarios represents a different amount of diesel fuel spilled for a different release duration, a fourth scenario was added later for comparative purposes. This included the same spill amount as the "Worst Case" scenario (68,200 gal) but with an 8 h release duration similar to the "Average Probable" spill scenario, entitled "Worst 8 Hour Spill."

2.3. Spill grid

The spill grid was established in much the same manner as the grid for the hydrodynamic model in GEMSS. The main difference is that the grid is rectilinear instead of orthogonal/curvilinear, and must cover the entire area of interest (including shoreline), not just the waterbody region. Due to the size of Kentucky Lake and computational requirements of the spill model, it was deemed impractical to capture the entire region with a single grid without the use of very large grid cells of widths similar to the width of the river (an obviously undesirable condition for spill modeling). Smaller spill grids were thus employed, with defined areas for their use. The spill grid for the scenarios under consideration here ranged from river mile (RM) RM 112 to RM 65 and was 100 cells by 100 cells. Each cell covers 1520 m × 1980 m [17].

2.4. Shoreline classification

COSIM allows for modeling the amount of oil adhered to the shoreline of the waterbody; therefore, the bank area material type must be defined. This is done either by designating the shoreline as 100% reflective, 100% sorptive, or using ESI shoreline classification codes [21]. Selection of the shoreline classification is performed in the "Spill Information Tool" within SMIS 2.0. If the ESI Code option is chosen, a spill classification file is required. For the case study, due to lack of soil classification information for the region, a shoreline classification code of four was used, representing sand.

2.5. SMIS 2.0 application to spill scenarios

The front-end GIS-to-COSIM interface tool, known as the "Spill Info Tool", was used to edit the COSIM control file. The spill location was identified by clicking on the map. Here, the spill was assumed to occur at latitude 130700.00 and longitude 630875.60 (1983 NAD Tennessee State Plane Feet). Output file names created using this tool included the scenario name and flow level (e.g., avg_lowflow, worst_highflow) as part of the file path to assist in data management. Next, the "RunCOSIM" tool was used to execute COSIM in batch mode for each scenario.

The "Spill Output Prep" tool was used to manipulate the main output database file (*.mdb) produced by COSIM and separate the information into individual databases for each time step of the model simulation for the first 36 h after a spill. Times of 2, 4, 12, and 24 h after the spill were selected for conversion, first to XYEvent layers and then to shapefiles for each scenario.

The "Create TIN from Features" tool was used to generate contours for the surface mass point shapefiles. This tool is a built-in command for ArcMap when the 3D Analyst Extension is activated. In this application, the field "C5", representing surface mass in kilograms, was used as the height source and triangulated as mass points. The resulting tin was assigned a file name, saved, and added to the map. The tin symbology was modified for optimal representation of the contours.

Table 2
Summary of spill scenario results.

Scenario	Flow level		
	Low	Average	High
Average probable (500 gal/485 min)			
Maximum surface mass (kg)	11.14	9.74	10.76
Maximum plume length (m)	2215	4013	6500
Plume area at 24 h (km^2)	3.086	5.641	8.367
Maximum probable (3200 gal/35 min)			
Maximum surface mass (kg)	3.126	2.6	2.98
Maximum plume length (m)	2835	4297	7254
Plume area at 24 h (km^2)	4.115	6.238	9.27
Worst case (62,800 gal/20 min)			
Maximum surface mass (kg)	47.56	40.04	43.86
Maximum plume length (m)	3204	3710	6307
Plume area at 24 h (km^2)	4.574	5.49	8.499
Worst case 8 h (62,800 gal/485 min)			
Maximum surface mass (kg)	–	1648	–
Maximum plume length (m)	–	4119	–
Plume area at 24 h (km^2)	–	5.92	–

3. Case study results

Results of the nine spill simulations representing the three scenarios at each of three flow levels are presented in Table 2, shown as the maximum surface mass in kilograms and maximum length of the plume. Plots representing 2, 4, 12, and 24 h after the initial spill release for the three scenarios at average flow rates are also provided (see Figs. 5–7). Additional plots for scenarios at low and high flows are presented in Camp [1].

As shown in Fig. 5, the average probable spill represents the smallest quantity of oil released over the simulation period. For the average probable spill under average flow conditions, the mass on the surface ranges from 2.912 to 5.313 kg in the first 12 h. As expected, the surface mass decreases as the plume spreads and degradation processes take place. Within 24 h, the plume spreads approximately 4054 m from its source. The area covered by the plume at 24 h after the spill is 5.6 km^2.

Spill plots for the maximum probable spill scenario for the four selected times are shown in Fig. 6. Compared to the average probable spill, the maximum probable spill represents six times the amount of diesel fuel released in one-sixteenth of the time. Surprisingly, the plume is not much larger than the average probable spill or the worst case scenario for low flow conditions, but it exceeds both spill scenarios for average and high flow conditions. For all flow conditions, the maximum probable spill has a lower surface mass. The fuel oil on the surface drops from 2.60 kg to 1.27 kg in the first 24 h after the spill began. With the short release time, there is no continued source to supply the plume and therefore the amount of oil on the surface is reduced by dispersion and possible volatilization effects.

The worst case scenario presents a spill of very large quantity (68,200 gal) released over approximately 20 min (see Fig. 7). As expected, the plume possesses very high masses compared to the other scenarios. While the spill amount is 20 times greater than for the maximum probable spill, the mass observed on the surface is only greater by a factor of 15. Similar to the maximum probable spill, the source does not sustain the spill, but the high mass takes longer to dissipate.

Oil reactions and spill plume spread have been found to be a function of the thickness of the oil, which is proportional to the

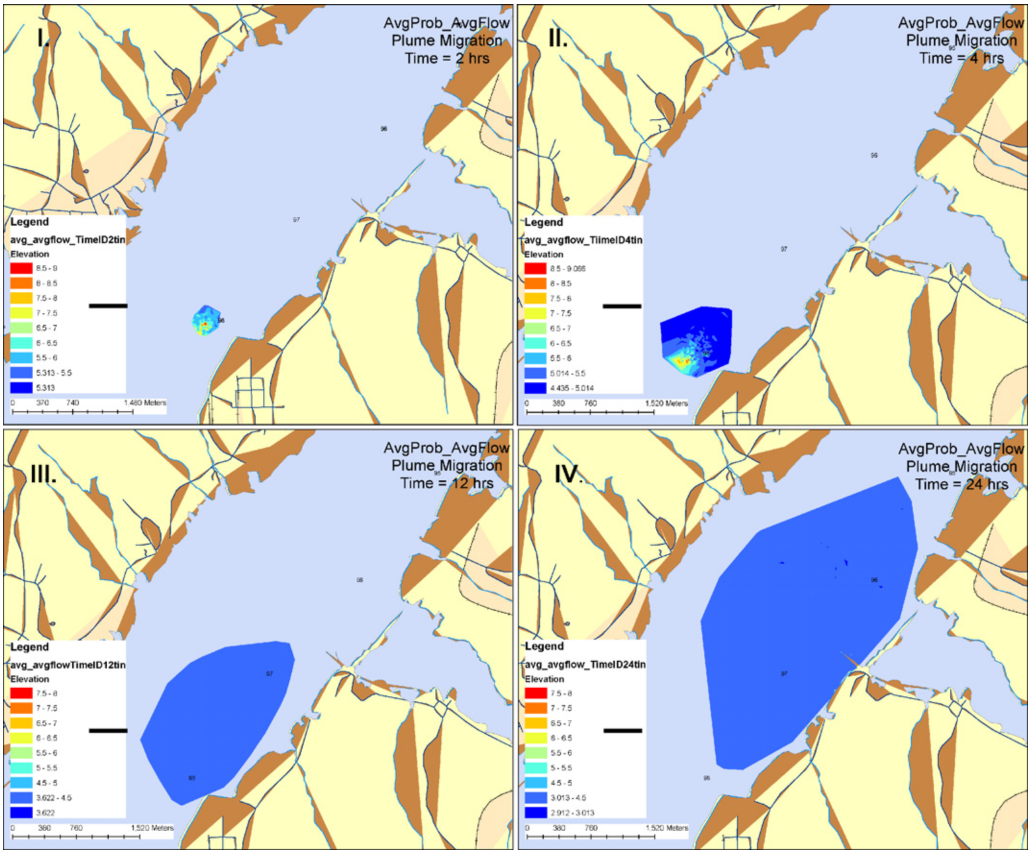


Fig. 5. Average probability, average flow scenario plots at $t = 2$, 4, 12, and 24 h after spill. Red/yellow colored areas represent high concentrations while dark blue colored areas are low concentrations of diesel fuel. Parts I–IV represent snapshots of the plume migration at $t = 2$, 4, 12, and 24 h after the spill initiation, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

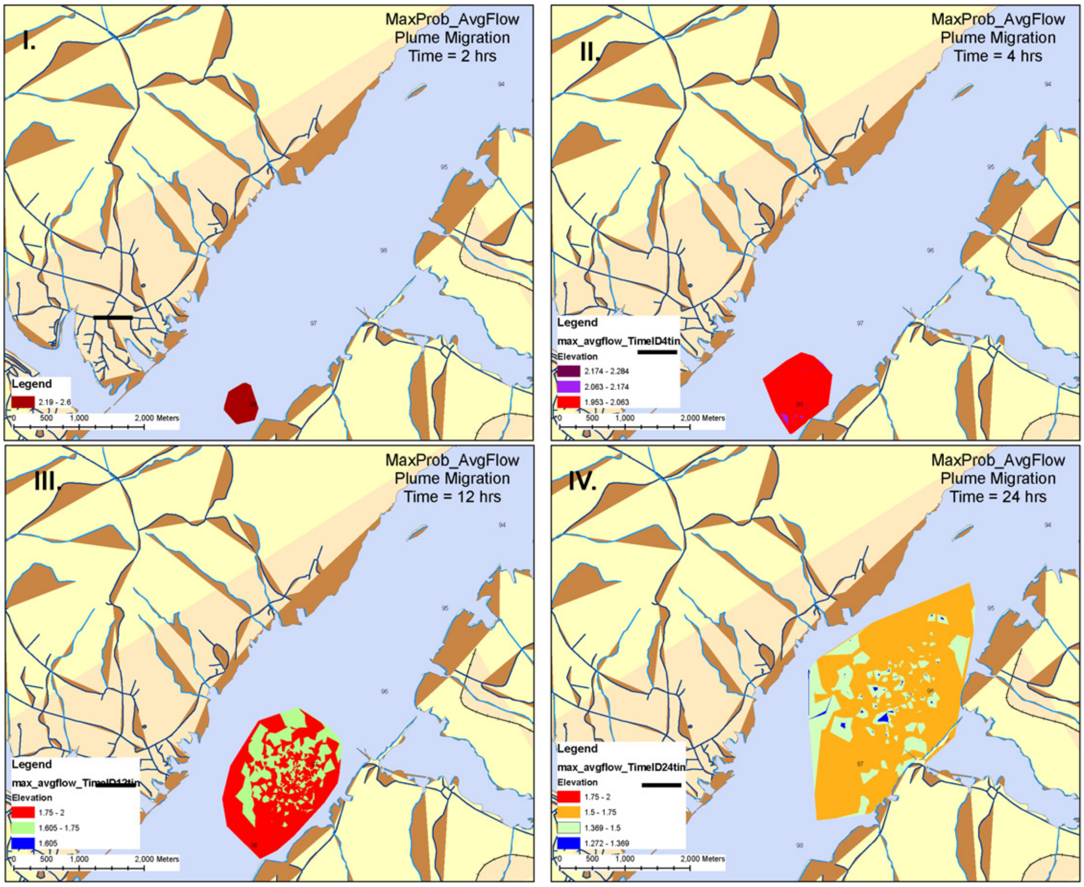


Fig. 6. Maximum probable, average flow scenario plots for $t = 2$, 4, 12, and 24 h after spill. Red colored areas represent high concentrations while yellow/orange colored areas are low concentrations of diesel fuel. Parts I–IV represent snapshots of the plume migration at $t = 2$, 4, 12, and 24 h after the spill initiation, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

surface mass [22]. The large quantity of oil spilled may in fact lead to reduced dispersion and evaporation effects. Thicker oil slicks are easier to skim off the surface with weir skimmers [23]. Therefore, while it may seem counterintuitive, a larger spill may be easier to clean up in terms of percent of spill recovered due to the reduced spread and improved recovery with booms and skimmers.

As mentioned previously, the “Worst Case 8 Hour Spill” was evaluated at average flow, representing a spill of 68,200 gal over an 8-h period. The plume plots are provided in Fig. 8. The continued release over approximately 8 h leads to much higher masses on the surface under these conditions than for any other scenario considered. The maximum plume length and area, however, are similar to that observed in both the average probable spill and worst case spill at average flow. As expected, it appears that the spread of the oil is primarily a function of flow in the waterbody.

3.1. Querying capabilities

An added benefit of using GIS as a fundamental component of SMIS 2.0 is the ability to perform spatial queries. The average probable scenario with average flow at hour 2 was used to demonstrate this functionality. In this instance, a query was made to identify the locations of schools within 25 miles of the spill plume. School gymnasiums may be used as command centers during a spill event if they are in relatively close proximity. As shown in Fig. 9, 12 schools are located within 25 miles of the average plume 2 h after the release. The attributes for the GIS layer for schools include the school address, principal name, email (if available), and phone number. This information could be important during a spill event, especially for highly volatile and hazardous chemical spills where schools may need to be locked down to minimize exposure to volatilized gases.

Similar queries can be performed to locate water intakes, fire departments, police stations, hospitals, sensitive species, and airports. The possibilities are limited only to the amount of available spatial information that can be represented as reference layers in GIS. Maintenance of the GIS reference layers with up-to-date information is important, however, to ensure accuracy and usefulness during a spill event.

3.2. Other considerations

An additional feature of COSIM modeling, not presently included as an automated function in SMIS 2.0, is the ability to model the effects of remediation and recovery efforts. For demonstration purposes, the worst case scenario under high flow conditions was modeled with booms deployed at seemingly strategic locations in an attempt to contain a portion of the plume. Fig. 10 shows the migration of the plume under normal conditions (Part I) and with a boom deployed (Part II) at 12 h after the release. As shown, the boom contains a portion of the spill.

It is obvious that adding boom deployment functionality to SMIS 2.0 would be of great benefit to spill response in gauging the effectiveness of containment and exclusion strategies. Currently, the boom simulations require the user to create the boom in GIS and then convert points outlining the boom into a spatially referenced, comma-delimited text file for use in COSIM.

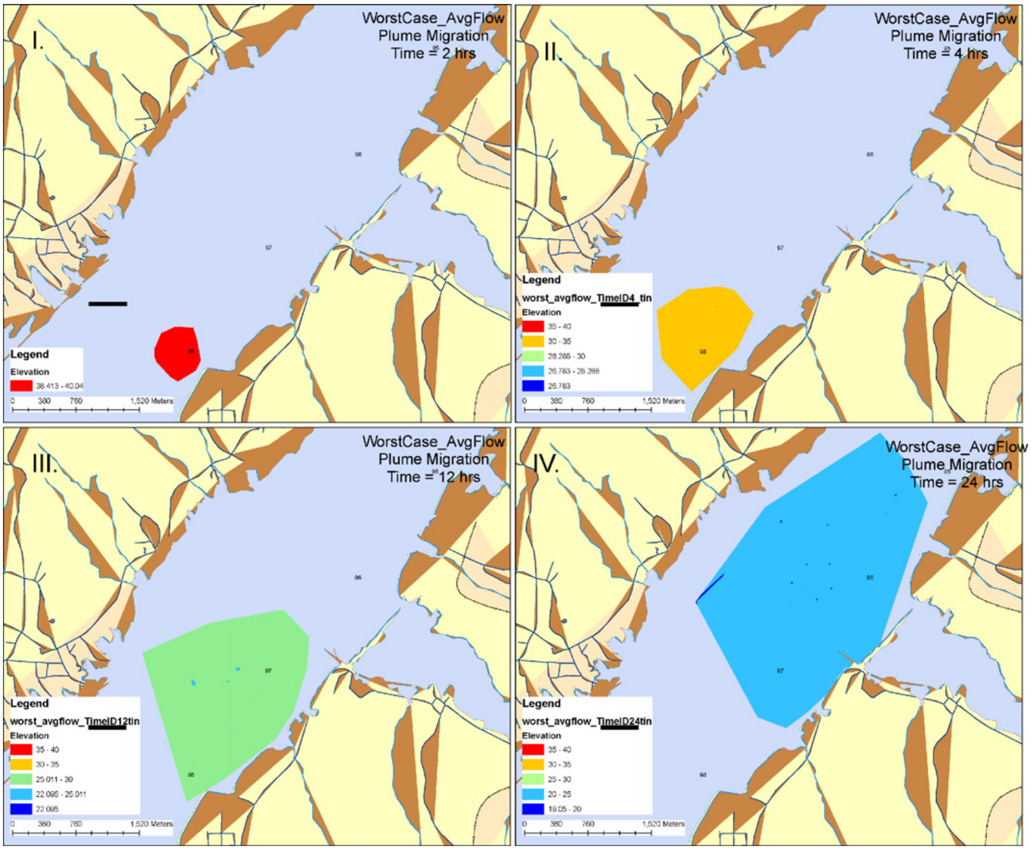


Fig. 7. Worst case, average flow scenario plots at t = 2, 4, 12, and 24 h after spill. Red colored areas represent high concentrations while blue colored areas are low concentrations of diesel fuel. Parts I–IV represent snapshots of the plume migration at *t* = 2, 4, 12, and 24 h after the spill initiation, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

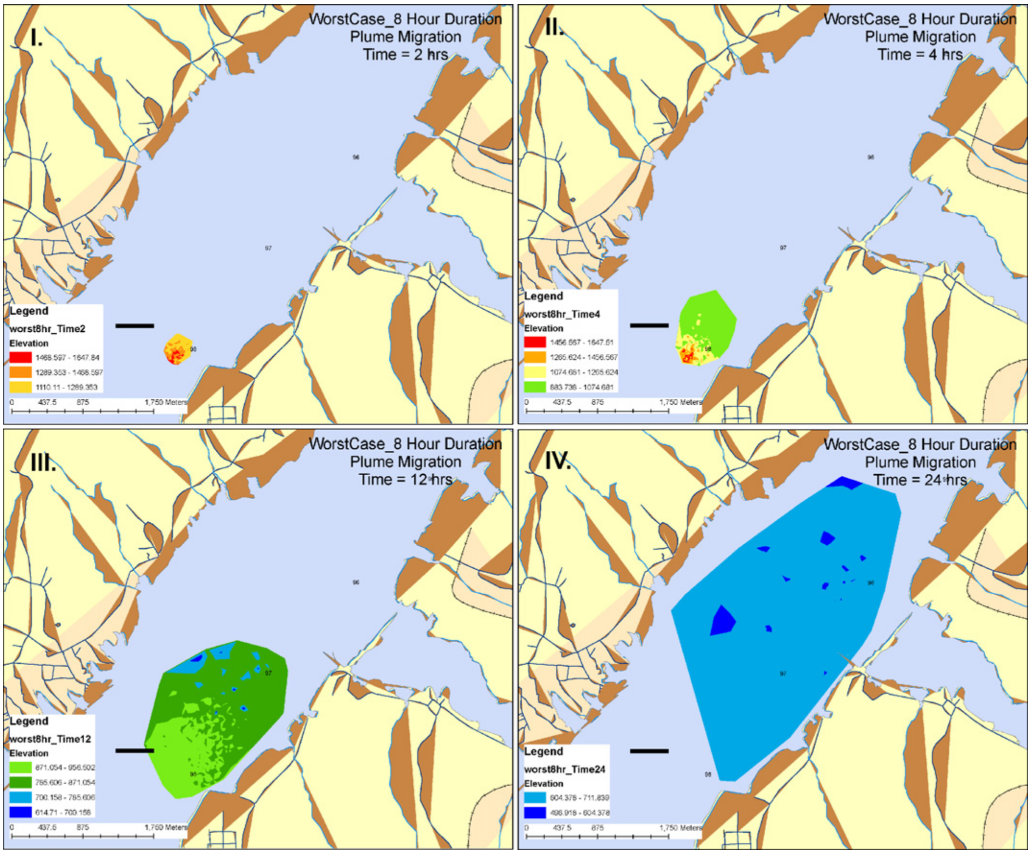
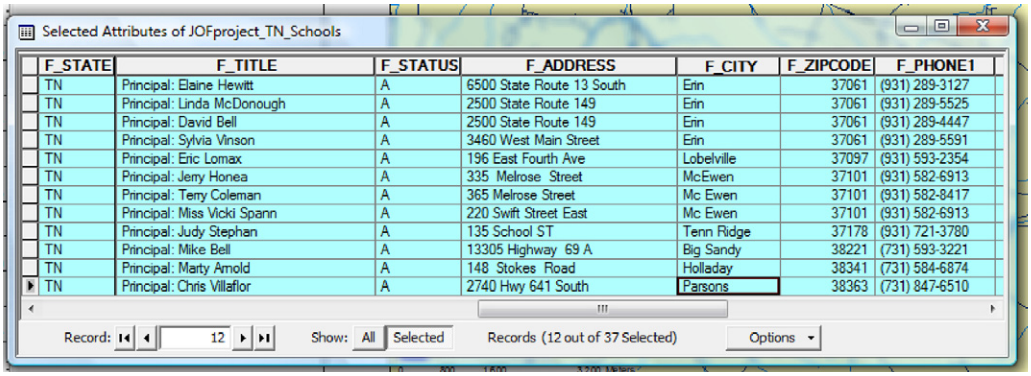


Fig. 8. Worst case spill with an 8-h duration at average flow conditions. Red colored areas represent high concentrations while blue colored areas are low concentrations of diesel fuel. Parts I–IV represent snapshots of the plume migration at *t* = 2, 4, 12, and 24 h after the spill initiation, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)


Selected Attributes of JOFproject_TN_Schools

F_STATE	F_TITLE	F_STATUS	F_ADDRESS	F_CITY	F_ZIPCODE	F_PHONE1
TN	Principal: Elaine Hewitt	A	6500 State Route 13 South	Erin	37061	(931) 289-3127
TN	Principal: Linda McDonough	A	2500 State Route 149	Erin	37061	(931) 289-5525
TN	Principal: David Bell	A	2500 State Route 149	Erin	37061	(931) 289-4447
TN	Principal: Sylvia Vinson	A	3460 West Main Street	Erin	37061	(931) 289-5591
TN	Principal: Eric Lomax	A	196 East Fourth Ave	Lobelville	37097	(931) 593-2354
TN	Principal: Jerry Honea	A	335 Melrose Street	McEwen	37101	(931) 582-6913
TN	Principal: Terry Coleman	A	365 Melrose Street	Mc Ewen	37101	(931) 582-8417
TN	Principal: Miss Vicki Spann	A	220 Swift Street East	Mc Ewen	37101	(931) 582-6913
TN	Principal: Judy Stephan	A	135 School ST	Tenn Ridge	37178	(931) 721-3780
TN	Principal: Mike Bell	A	13305 Highway 69 A	Big Sandy	38221	(731) 593-3221
TN	Principal: Marty Arnold	A	148 Stokes Road	Holladay	38341	(731) 584-6874
TN	Principal: Chris Villaflor	A	2740 Hwy 641 South	Parsons	38363	(731) 847-6510

Record: 12 Show: All Selected Records (12 out of 37 Selected)

Fig. 9. Query results for schools within 25 miles of the spill.

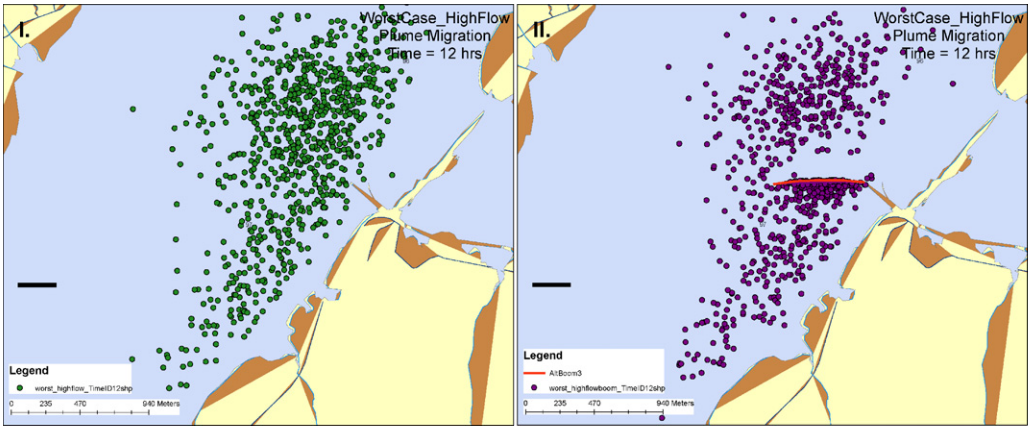


Fig. 10. Comparison of worst case scenario with and without boom deployment at $t = 12$ h. The red line in Part II represents the boom that has been simulated. Points in each part represent model output points for the worst case scenario at high flow conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

The current version of SMIS only provides tools for evaluation of diesel fuel/oils on the surface. However, COSIM can be used to predict concentrations of other chemicals both on the surface and within the water column. For comparison, a separate chemical spill simulation was performed to model the release of trichloroethylene (TCE) under average flow conditions (3200 gal released over 35 min).

Additional features of COSIM include the ability to track the distribution of the released chemical in different phases and identify impacted shoreline areas. These are currently not automated within SMIS 2.0. Fig. 11 shows the output for both shoreline impact and a bar chart for the distribution of the diesel fuel into separate phases for the average probable spill at average flow 12 h after the release. In the figure, darkened spill grid cells identify the shoreline areas where diesel fuel may be adsorbed. Using the output database table "tblMassBalance," the distribution of diesel fuel for each of the three scenarios at 2, 12, and 24 h after the release were obtained. The distribution of TCE between phases 12 h after the release was also evaluated. The resulting distributions for both substances are presented in Table 3. Fig. 12 shows the distribution of diesel fuel for each of the three spill scenarios at average flow 12 h after the initial release. For all scenarios, the majority of the fuel has been volatilized at this time and only a small amount has migrated into the subsurface/water column through dissolution. In all cases, at least 20% remains on the surface. This implies that efforts to contain/recover the fuel at this time would be limited because most of the fuel has been volatilized, adsorbed to the shoreline, or mixed in the water column.

Another attribute of COSIM is the ability to model dissolved/subsurface concentrations of spilled chemicals. Due to its chemical properties, TCE is more likely to mix in the water column and be dispersed than to float on the surface. Therefore, the surface results only show the initial release and nothing exists after the first time step. Within the output database created by COSIM,

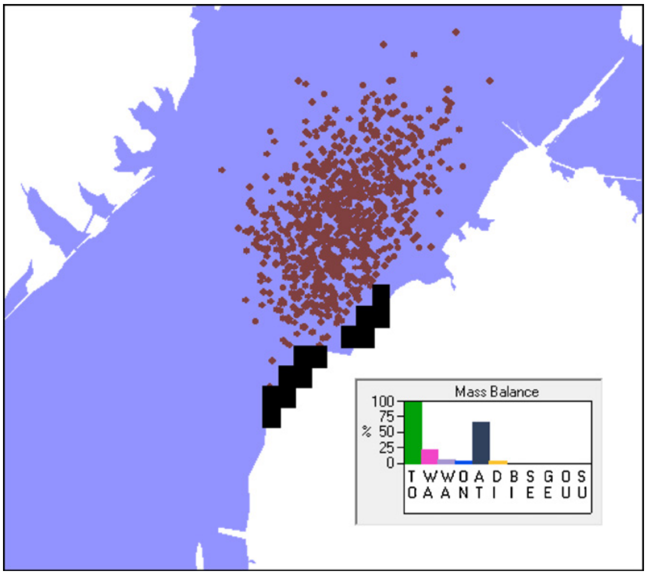


Fig. 11. Example of mass balance and impacted shoreline display at $t = 12$ for average probable spill at average flow. Black rectangles indicate impacted shoreline. The bars in the mass balance chart represent from left to right: total amount, water surface, water column, on shore, atmosphere, dissolution, biodegradation, and sediments.

Table 3
Mass balance distribution for diesel fuel for three spill scenarios at average flow ($t = 2$, 12, and 24 h).

Distribution as percentages of total mass released	Average probable – average flow	Maximum probable – average flow	Worst case – average flow
Diesel fuel			
At $t = 2$ h			
Water surface	50.439	41.884	56.96
Water column	0	0.1676	0
On shore	0	0	0
Atmosphere	48.619	55.866	42.69
Dissolution	0.939	2.075	0.338
Biodegradation	0	0	0
Sediments	0	0	0
At $t = 12$ h			
Water surface	27.433	21.948	31.283
Water column	3.082	3.872	1.152
On shore	2.361	4.028	5.451
Atmosphere	63.534	66.141	59.348
Dissolution	3.545	4.0945	2.724
Biodegradation	0	0	0
Sediments	0	0	0
At $t = 24$ h			
Water surface	18.66	15.332	20.8765
Water column	2.136	2.493	0.933
On shore	6.117	7.879	8.938
Atmosphere	68.238	69.188	65.8042
Dissolution	4.631	5.228	3.4028
Biodegradation	0	0	0
Sediments	0	0	0
TCE			
At $t = 12$ h			
Water surface	–	3.89	–
Water column	–	47.071	–
On shore	–	0	–
Atmosphere	–	0.002	–
Dissolution	–	47.018	–
Biodegradation	–	0.0197	–
Sediments	–	0.002	–

Values represent the percentage of total mass released.

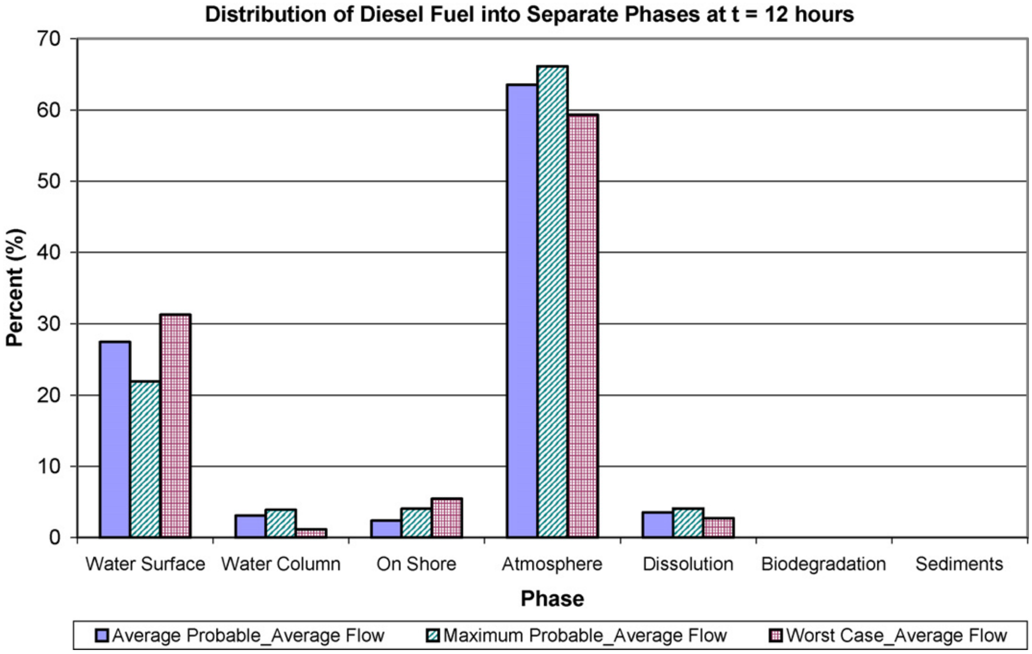


Fig. 12. Comparison of diesel fuel distributions for the three spill scenarios at average flow 12 h after the initial release.

the "tblSubSurface" contains information about the concentrations of chemicals within the water column. This can also be generated for oil/diesel fuel, but only the water soluble fractions of the fuel are available for analysis. The chemical concentrations can be used similar to the surface mass plots; however, the depth of the concentrations is not represented well in 2D, which limits the ability to discern the true location of the contaminants (e.g., with respect to water intakes or sensitive species below the surface). ESRI's ArcScene utility can be used to view the output in 3D [17]. In doing this, the waterbody can be rotated and a users may "dip" below the surface to see the depth and locations of points representing subsurface concentrations. Viewing the output in ArcScene allows one to determine the proximity of the subsurface plume to water intakes and possibly sensitive species. This analysis, provided in [17] but not shown here due to difficulties in representation in 2D black and white imaging, allows the user to view the concentration points below the surface in relation to depth. Display of subsurface COSIM outputs in 3D allows spill response personnel to identify the proximity of the plume to water intakes, the depth at which the majority of the concentration occurs, and the maximum concentration for comparison to water quality standards and sensitive species requirements. Both chemicals were plotted at hour 12 after the spill release and viewed in ArcScene. A long narrow vertical tube was used to represent a water intake to demonstrate decision-support capabilities of SMIS 2.0. For the diesel fuel spill, hexane is located primarily near the surface and surrounds the water intake at $t = 12$ h. The maximum concentration, presented as grams solute/100 grams solvent (gms), at this time is 1.31×10^{-2} g. The maximum concentration of TCE is 19,791 gms after 12 h. The area covered by TCE is only slightly larger, but the concentration is much higher.

4. Conclusions

SMIS 2.0 was developed to assist in spill response efforts on inland waterways by providing timely visualization of spill propagation and identification of impact locations and response resources in proximity of the spill. To demonstrate its use, several spill scenarios were simulated on the Kentucky Lake portion of the Tennessee River, each analyzed at low, average, and high flow conditions. As expected, the worst case scenario resulted in the highest surface mass. However, due to the large amount of diesel fuel released, plume migration was limited and dispersed in a similar manner to an average spill scenario at average flow conditions.

The usefulness of performing spatial queries in ArcMap to locate resources for assistance in spill response was demonstrated by identifying schools and contact information within a 25-mile range of the spill site. Such information could be vital for immediate notification during a spill event. Other response resources can also be queried, limitations being the availability of the data in a spatial format. The ability of SMIS 2.0 to convert spill output into shapefiles and tins for enhanced viewing and querying abilities was also demonstrated.

Extended applications illustrating the ability of COSIM to simulate boom interactions with a plume, surface and subsurface fate and transport modeling for other chemicals and determination of impacted shorelines and distribution of a chemical among various physical phases were also performed. While these functions are not currently automated within SMIS 2.0, future work could involve incorporating these options.

Acknowledgements

This research was supported in part by the Tennessee Valley Authority and Vanderbilt University, Department of Civil and Environmental Engineering. The contents of this document reflect solely the views of the authors. TVA assumes no liability for the contents or use of this document.

References

[1] J.S. Camp, M.D. Abkowitz, E.J. LeBoeuf, Inland Waterway Resource and Spill Management Needs of Southeastern U.S., Disaster Prevention and Management, in press.
[2] W.B. Samuels, D.E. Amstutz, R. Bahadur, J.M. Pickus, Riverspill: a national application for drinking water protection, J. Hydraul. Eng. 132/4 (2006) 393–403.
[3] C.J. Beegle-Krause, General NOAA oil modeling environment (GNOME): a new spill trajectory model, in: International Oil Spill Conference, Tampa, FL, 2001.
[4] P.H. Martin, E.J. LeBoeuf, E.B. Daniel, J.P. Dobbins, M.D. Abkowitz, Development of a GIS-based spill management information system, J. Hazard. Mater. 112/3 (2004) 239–252.
[5] J.E. Edinger, Generalized environmental modeling system for surface waters (GEMSS), J.E. Edinger Associates, Inc., Wayne, PA. http://www.erm-smg.com/gemss.html (accessed 2009).
[6] R. Majiros, Personal communication, Environmental response team director, Tennessee Valley Authority, Muscle Shoals, AL, 2007–2009.
[7] ERM, Chemical and oil spill impact model (COSIM): Technical Manual (Draft), Environ. Resour. Manag., Inc., Exton, PA, 1994.
[8] L. Lubbers, Kentucky Lake, Lake Lubbers, Raub's Internet for Business. http://www.lakelubbers.com/kentucky-lake-64/ (accessed 2008).
[9] KLProductions, Explore Kentucky Lake, Kentucky Lake Productions, Murray, KY. http://www.explorekentuckylake.com/weather.htm (accessed 2008).
[10] J.A. Kingsbury, A.B. Hoos, M.D. Woodside, Environmental settling and water quality issues in the lower Tennessee River Basin, in: Water Investigations Report U.S. Geol. Survey, 99-4080, 1999.
[11] TVA, Kentucky Lake GIS layers, Elevation, Flow, and Temperature Data, Tennessee Valley Authority River Operations, Knoxville, TN, 2006.
[12] USCB, Topologically Integrated Geographic Encoding and Referencing (TIGER) system, United States Census Bureau, 2005, http://www.census.gov/geo/www/tiger/.
[13] BTS, National Transportation Atlas Database (NTAD), U.S. Bureau of Transportation Statistics, 2008, http://www.bts.gov/publications/national_transportation_atlas_database/2008/.
[14] USFA, U.S. Fire Departments Census, U.S. Fire Administration, Federal Emergency Management Association. http://www.usfa.dhs.gov/application/census/ (accessed 2008).
[15] B. Hadjerioua, Personal communication, Civil and water resources engineering specialist, River Operations, Tennessee Valley Authority, Knoxville, TN, 2007–2009.
[16] J. Gregory, Personal communication, Hydrology division, U.S. Army Corps of Engineers, Nashville, TN, 2008–2009.
[17] J.S. Camp, Design and implementation of an advanced spill management information system for surface waters, Dissertation, Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, TN, 2009.
[18] NCDC, National climatic data center climate-radar data inventories. http://www4.ncdc.gov/cgi-win/wwcgi.dll?wwDI~StnSrch~StnID~200118355 (accessed 2008).
[19] USGS, USGS 03598000 Duck River Near Shelbyville, TN, U.S. Geol. Survey Online Data System. http://waterdata.usgs.gov/usa/nwis/uv?site_no=03598000 (accessed 2008).
[20] USGSa, USGS 03606500 Big Sandy River at Bruceton, TN, U.S. Geol. Survey Online Data System. http://waterdata.usgs.gov/tn/nwis/uv/?site_no=03606500&PARAmeter_cd=00065,00060 (accessed 2008).
[21] J.R. Jensen, E.W. Ramsey, J.M. Holmes, J.E. Michel, B. Savitsky, B.A. Davis, Environmental sensitivity index (ESI) mapping for oil spills using remote sensing and geographic information system technology, Int. J. Geog. Inf. Sci. 4/2 (1990) 181–201.
[22] M. Reed, O. Johansen, P.J. Brandvik, P. Daling, A. Lewis, R. Fiocco, D. Mackay, R. Prentki, Oil spill modeling toward the close of the 20th century: overview of the state of the art, Spill Sci. Technol. Bull. 5/1 (1999) 3–16.
[23] A.H. Hammoud, Enhanced oil spill recovery rate using the weir skimmer. http://www.epa.gov/OEM/docs/oil/fss/fss06/hammoud.pdf (accessed 2009).