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Development of a GIS-based Spill Management Information System

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Abstract

Spill Management Information System (SMIS) is a geographic information system (GIS)-based decision support system designed to effectively manage the risks associated with accidental or intentional releases of a hazardous material into an inland waterway. SMIS provides critical planning and impact information to emergency responders in anticipation of, or following such an incident. SMIS couples GIS and database management systems (DBMS) with the 2-D surface water model CE-QUAL-W2 Version 3.1 and the air contaminant model Computer-Aided Management of Emergency Operations (CAMEO) while retaining full GIS risk analysis and interpretive capabilities. Live 'real-time' data links are established within the spill management software to utilize current meteorological information and flowrates within the waterway. Capabilities include rapid modification of modeling conditions to allow for immediate scenario analysis and evaluation of 'what-if' scenarios. The functionality of the model is illustrated through a case study of the Cheatham Reach of the Cumberland River near Nashville, TN.

Keywords: GIS; Spill Management Information System; CE-QUAL-W2; CAMEO

1. Introduction

In order to more effectively manage risks associated with accidental or intentional chemical releases into the environment, the Nashville District of the U.S. Army Corps of Engineers (USACE) engaged Vanderbilt University's Department of Civil and Environmental Engineering to develop a decision support system (DSS) to aid responders in identifying, responding to, and mitigating the effects of chemical release incidents. The project goal was to develop a Spill Management Information System (SMIS), coupling geographic information systems (GIS) with advanced water quality and air dispersion models to provide real-time information to emergency responders following an incident involving hazardous materials [1]. For this application, hazardous materials were defined as any commodity, including petroleum products that, if released, would pose considerable danger to human health and the environment. Additionally, the SMIS application was designed for short-term impact mitigation activities, as opposed to the evaluation of long-term chronic impacts of a contaminant spill.

SMIS was designed to overcome many of the communications and coordination challenges generated following a spill incident by providing responders with access to uniform information comprised of real-time incident information and maps, contaminant transport models, chemical response data, areal displays of contaminant procession, and locations of sensitive receptors. Proper utilization of this tool greatly reduces the time required to acquire and decipher pertinent chemical data, establish jurisdiction of responder responsibility, locate available waterbody access points, identify proximity of emergency response units (i.e., fire, police, U.S. Coast Guard (USCG)), and generate local contacts for community notification to protect against toxic vapor exposure.

Two types of information systems underpin SMIS: GIS and a database management system (DBMS). GIS is an information technology utilized to maintain and analyze geographic data capable of organizing data into layers and relating sets by geography. Certain relationships and operational trends are more easily conveyed in a geographic context than in a traditional tabular format [1]. GIS functionality may also be delivered through a standard Internet browser, a valuable feature enabling the distribution of uniform and current data [2]. GIS has been broadly adopted for use with predictive models providing functions for data storage, calculation of required parameters, data manipula-

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tion, and output processing [3]. GIS capabilities have also been employed to provide spatial decision support systems (SDSS) with output display, spatial data management, and interface functions [4–6]. The relatively weak user interface but strong computational capabilities of most water quality models [5] underscore the benefits garnered from employing GIS as the front-end application for SMIS. The review work of Martin et al. [7] elucidates the benefits realized by employing GIS with water resources predictive models, techniques of interface, and current trends in development.

DBMS refers to software that collects, manipulates, queries, and retrieves tabular data. Efficient database construction and combination of project-relevant datasets into a single application reduces instances of data redundancy, error, and computational lag time. Dobbins and Abkowitz [8] chronicle the development of a centralized response database for several modes of hazardous materials transport. This project was accomplished by identifying the most commonly used emergency response databases for all modes of transportation, developing relationships between the data, and building intuitive interfaces allowing for rapid information retrieval. Resultantly, facility and vessel operators benefit from having access to a comprehensive chemical database, rapidly accessible in the event of a release or human contact with the material [8]. Dobbins and Abkowitz [2] further explore the effectiveness of this approach through the development of a prototype decision support system (DSS) employing global positioning system (GPS), GIS, and the Internet for inland waterway barge accidents. In the event of an incident, this system enables en-route responders to view incident details via an Internet GIS map service.

This manuscript serves to provide a proof-of-principle demonstration of SMIS within a case study environment. Daniel et al. [9] detail the architectural requirements for SMIS and advancements in developing a decision support system (DSS) within the model. This paper begins with an overview of system components comprising SMIS, including the interfacing of surface water quality and air quality models. Data input and other pre-processing functions are then described, followed by methods of SMIS execution, data output, and results interpretation. A case study, highlighting the Cheatham Reach of the Cumberland River located in Nashville, TN is used to illustrate SMIS capabilities. The paper concludes with a summary of SMIS competencies, limitations, and plans for future phases of work.

2. System components

The impact of a waterway injection of a hazardous material is modeled for GIS display through two pathways: surface water and air. Although spill effects propagate through other pathways, the most acute and immediately dangerous short-term effects advance through these mediums [2]. The major components of SMIS include Environmental Systems Research Institute (ESRI, Redlands, CA) ArcView Version 8.2 GIS, the two-dimensional (2-D) surface water quality and hydrodynamic model CE-QUAL-W2 Version 3.1 developed by USACE, the atmospheric dispersion modeling suite Computer-Aided Management of Emergency Operations (CAMEO) developed by the U.S. Environmental Protection Agency (USEPA) and the National Oceanic and Atmospheric Administration (NOAA), and customized Visual Basic (VB) functions for data input, model execution, and results presentation (Fig. 1).

VB coding is a well-defined mechanism allowing user-developed routines to be called within the normal user in-

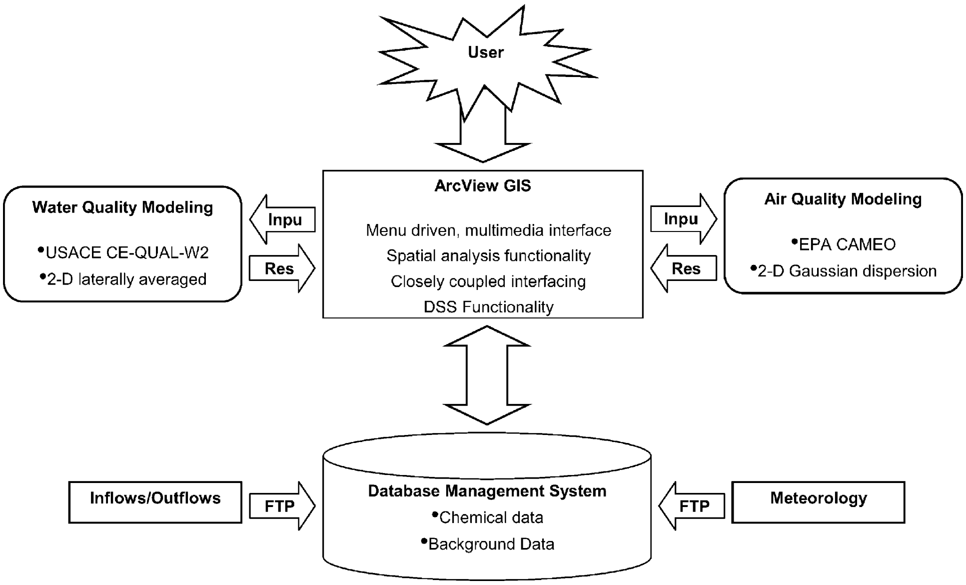


Fig. 1. Spill Management Information System (SMIS) architecture.

terface of GIS. Developed VB bridges enable users to input and view spill incident information and outputs within the impact area directly from the GIS graphical user interface (GUI). Within SMIS, GIS possesses three major functions: (i) providing an interface between the SMIS and its users; (ii) linking inputs, the predictive models, and outputs; and (iii) managing spatial and aspatial databases (DBMS). Application of risk analysis routines to GIS data layers provides opportunities to estimate the number of people residing within a spill isolation zone, predict concentrations and times of arrival/passage of pollutants at critical receptor regions, and locate responders and abatement resources within a user-specified distance from the incident. This plethora of data is located within a single outlet, providing responders with a wide range of potentially useful information including real-time incident information and maps, contaminant transport model outputs, and chemical response data. In addition, VB routines provide menu-driven GUIs, supporting neophyte users with prompts and guidance throughout the application.

Specific GIS layers utilized in this project include: (i) waterway network and water area; (ii) facilities (docks, launch ramps, locks and dams); (iii) demographic and environmental receptors (census data, drinking water intakes, land use); (iv) response resources (police, fire, HAZMAT teams, hospitals); and (v) reference layers (political boundaries, roadways). This locational data was derived primarily from existing GIS datasets available through various government agencies (e.g., waterway area, boat ramps, docks, and gauging stations were derived from existing USACE datasets; waterway network was derived from a U.S. Environmental Protection Agency dataset, and railroad, streets, highways, land use metrics, census data were derived from existing datasets of other government agencies). Additional data sets were developed through address matching and geocoding protocols (e.g., locations of fire stations, hospitals, police stations), and sensitive information datasets, including rare species and water intakes, were developed through georeferenced data available to USACE. The majority of this data (land use, census data, etc.) requires effort (i.e., merging, cropping of raw data sets) for fit to the target area. The inclusion of sensitive data (i.e., water intakes) is at the discretion of the developer, but information security and the intended audience should be evaluated prior to insertion of these layers.

SMIS is constructed as an ArcView-based system and does not offer additional metadata functionality beyond standard tools for creating and managing metadata. If metadata does not already exist for each GIS dataset, it is automatically created. Once created, metadata becomes a part of the dataset. It is automatically moved, copied, and deleted along with the dataset. Metadata was created for all GIS datasets used by SMIS. This metadata can be retrieved and viewed with ArcView's standard tools or SMIS online help files (HMTL format).

Regarding the waterbody of interest, through dynamic segmentation, a logical structure can be superimposed on a physical topology [10] allowing a waterbody to be discretized into discrete segments traceable within GIS. As elucidated by Marsili-Libelli et al. [5], the ArcView element corresponding to the river reach is the route, representing a linear element to which attributes can be associated through a coordinate system starting from the route origin. Using this approach, the river reach is partitioned into elements (or cells), where the initial water quality parameters are assumed to be homogeneous. A route is created in ArcInfo and imported into ArcView where it becomes a theme. Thus, an item is created where the water quality data may be stored. This is accomplished by associating a table with initial (FROM) and final (TO) cell coordinates to the route, generating a new attribute for each water quality parameter.

3. Surface water contaminant transport model

Numerous contaminant transport models are available for evaluating contaminant transport in surface water bodies [11]. The selection of the appropriate model is normally based on the hydrodynamics of the water body of interest (i.e., river, estuary, lake, or reservoir), the need for accuracy (e.g., a 1-D model may suffice in many instances, greatly reducing the data input requirements compared to a 2-D or 3-D model), and the required level of detail for contaminant behavior, including biotic and abiotic decay rates, and interaction with sediments and other water body constituents [1]. In the case of Version 1.0 of SMIS, desirable qualities include the ability to: (i) transform the contaminant plume through regulating devices such as dam spillways; (ii) track plume migration through multiple, interconnected reservoir and/or river sections; (iii) include the influence of wind on contaminant transport; and (iv) accept variable density effects on the flow field associated with intermittent releases from upstream and downstream control structures.

Many USACE waterbodies are highly regulated flow systems for navigation and flood control [1]. USCG and USEPA do not maintain consistent access to USACE and U.S. Geological Survey (USGS) streamflow information. As such, responding agencies look to USACE to provide flow and bathymetry information while attempting to initialize and run their spill models, consuming valuable time. Additionally, it is not possible for the 1-D contaminant transport models commonly employed by USEPA or USCG for spill management to adequately model the complex hydrodynamics of regulated reservoir systems [1]. To note, the General NOAA Oil Modeling Environment (GNOME) provides predictive capabilities on how wind, currents, and other processes may move oil spills, this application is designed for open water harbors, bays, and coasts, not riverine segments [12].

Efforts by McKee [13] and Adams et al. [14,15] chronicle their approaches to model selection and validation of CE-QUAL-W2 (W2) for application to the Cheatham Reach. While W2 is not the only model suitable for this target area, alternate models such as the Water Quality for River–Reservoir Systems (WQRRS) model [16], the Hydraulic Engineering Center Fifth (HEC-5) model [17], and the Hydrologic Simulation Program – Fortran (HSPF) model [18] developed for river basin modeling are noted to have serious limitations [19]. As elucidated by Wells [19,20], HEC-5 (similar to WQRSS) and HSPF models incorporate a one-dimensional (1-D), longitudinal river model with a 1-D, vertical reservoir model (1-D for temperature and water quality and zero-dimensional for hydrodynamics). The modeler is required to identify the location of the transition from 1-D longitudinal to 1-D vertical. In addition to excluding the solution for the velocity field in a stratified reservoir system, a point source input to a reservoir section is distributed over the entire longitudinal distribution of the reservoir layer [20].

Alternate hydraulic and water quality applications capable of modeling unsteady flow include the 1-D dynamic USEPA model Dynamic Hydraulics (DYNHYD) model, used in conjunction with the multidimensional Water Analysis Simulation Program (WASP) [21]. WASP relies on DYNHYD output for 1-D hydrodynamic predictions. If WASP is employed for multidimensional schematization, the modeler must specify dispersion coefficients to allow transport in the vertical and/or lateral directions or use an alternate hydrodynamic model that explicitly includes these effects [19]. Examination of WASP data requirements and digesting the comments of McKee [13] illustrate the potential complexities in working within the WASP framework. WASP was initially developed for water quality analysis and resultantly, employs extensive and detailed water quality algorithms requiring ample background data and numerous variables [21]. In addition to the above mentioned model applications, the USACE model CE-QUAL-RIV1 [22], is a 1-D dynamic flow and water quality model developed for 1-D river or stream sections. None of the aforementioned models satisfy the required criteria and adequately characterize the water quality hydraulics with the relative simplicity of CE-QUAL-W2.

Applicability of CE-QUAL-W2 is further emphasized by the favorable results experienced by Adams et al. [15] using CE-QUAL-W2 to model the impact of combined sewer overflows (CSO) within the study area of interest. While CE-QUAL-W2 is certainly not the only model available for SMIS, the choice of a USACE 'in-house' model for this application was preferred to that of externally developed software. However, by design, the modular nature of SMIS allows for substitution of alternative surface water quality and air quality models, ensuring a high level of future transferability.

CE-QUAL-W2 (W2) is a 2-D model that predicts vertical and longitudinal variations in hydrodynamics, temperature, and constituents in a waterbody through time [23]. Recognized as a state-of-the-art reservoir hydrodynamic and water quality model, W2 has been successfully applied to over 200 different systems within the United States and the world [23]. It is the reservoir model of choice for the Tennessee Valley Authority (TVA), U.S. Bureau of Reclamation (USBR), U.S. Geological Survey (USGS), U.S. Army Corps of Engineers (USACE), and the U.S. Environmental Protection Agency (USEPA) [24]. Mathematically, CE-QUAL-W2 is based on a finite-difference solution of the laterally averaged equations of fluid motion including: (1) free water surface; (2) hydrostatic pressure; (3) longitudinal momentum; (4) continuity; and (5) equation of state relating density with temperature and also dissolved and suspended solids. Hydrodynamics are influenced by variable water density resulting from variations in temperature, total dissolved solids, and suspended solids. Traditional hydrodynamics equations are used in the model's flow formulations, incorporating a finite difference solution of the free-surface frictionally and internally damped long-wave equation. The finite differences are mapped onto a computational grid which allows the user to add or subtract surface layers as the water level changes [23]. The model is based upon the Generalized Longitudinal-Vertical Hydrodynamics and Transport model developed by Buchak and Edinger [25]. The inclusion of water quality algorithms resulted in CE-QUAL-W2 Version 1. Subsequent modifications to improve the model's computational efficiency, numerical accuracy, and prototype physical description resulted in Version 2 [26]. Numerous new capabilities were introduced in Version 2.0, including an algorithm to calculate the maximum allowable timestep and adjust the timestep to ensure hydrodynamic stability requirements are not violated (auto-stepping), volume and mass balances to machine accuracy, and sediment/water heat exchange [27].

The version used for this project is Version 3.1. Versions 3.0 and 3.1 resulted from additional improvements to the numerical solution scheme and water quality algorithms, as well as extension of the utility of the model to provide state-of-the-art capabilities for modeling entire waterbasins in two-dimensions. As noted by Cole and Wells [23], in addition to the general channel sloping feature, new capabilities of Version 3.1 over 2.0 include: (1) an implicit solution for the effects of vertical eddy viscosity in the horizontal momentum equation; (2) addition of Leonard's ULTIMATE algorithm [28] that eliminates over/undershoots in the numerical solution scheme; (3) inclusion of momentum transfer between branches; (4) the ability to model multiple waterbodies in the same computational grid including multiple reservoirs, steeply sloping riverine sections between reservoirs, and estuaries; (5) additional vertical turbulence algorithms more appropriate for rivers; (6) additional re-aeration algorithms more appropriate for rivers; (7) effects of hydraulic structures on gas transfer and total dissolved gas transport; (8) multiple user-defined organic matter groups; and (9) a graphical pre-processor. These upgraded model features further enhance the attractiveness of this application to the Cheatham Reach by permitting the addition of multiple reaches and advanced water quality analysis capabilities. These capabilities are idyllic for ensuring transferability of this technology to similar USACE waterbodies.

Table 1
CE-QUAL-W2 Version 3.1 water quality state variables

No.	Variable	No.	Variable
1	Conservative tracer	10	Ammonia nitrogen
2	Coliform bacteria	11	Total dissolved solids (TDS) or salinity
3	Inorganic suspended solids	12	Labile dissolved organic matter (LDOM)
4	Refractory dissolved organic matter (RDOM)	13	Detritus
5	Phytoplankton	14	Phosphate phosphorous
6	Nitrate + nitrite nitrogen	15	Dissolved oxygen (DO)
7	Organic sediments	16	Total inorganic carbon (TOC)
8	Alkalinity	17	Total iron
9	Biochemical oxygen demand (BOD)		

Seventeen water quality state variables and their kinetic interactions are included in the W2 water quality module and are listed in Table 1. Each constituent, such as temperature, suspended solids, or dissolved oxygen (DO), has a constituent transport equation, specific sources and sinks, or flux terms to compute concentration changes [23]:

$$\frac{\partial BC}{\partial t}+\frac{\partial UBC}{\partial x}+\frac{\partial WBC}{dz} - \partial\left(\frac{BD_x\,\partial C}{\partial z}\right)\partial x-\partial\left(\frac{BD_z\,\partial C}{\partial z}\right)\partial z = CqB+SB \qquad (1)$$

where B is time and spatially varying layer width; C is laterally averaged constituent concentration (mg/L); U is x-direction (horizontal), laterally averaged velocity (m/s); W is z-direction (vertical), laterally averaged velocity (m/s); D_x is x-direction temperature and constituent dispersion coefficient (m^2/s); D_z is z-direction temperature and constituent dispersion coefficient (m^2/s); Cq is lateral inflow or outflow mass flow rate of constituent per volume; and S is source/sink term for constituent concentration.

Execution of CE-QUAL-W2 requires inputs describing reservoir bathymetry, initial conditions, inflow quantity and quality, outflow quantity, and outlet description. The model also requires time series of inflow rates and water quality, meteorological data, water surface elevations, and appropriate kinetic rate coefficients. Calibration is dependent on the availability of observed in-pool water quality constituent concentrations at several locations within the reservoir and accurate descriptions of the loadings. Observed release water quality data may also be used to evaluate predicted release conditions. Any combination of the above state variables (Table 1) may be included in a simulation, but caution must be exercised to ensure that all relevant variables are included. The state variables of particular interest for the SMIS application to the Cheatham Reach included conservative tracer and dissolved oxygen. In association with temperature, these variables were matched with adequate field data from which to evaluate the success of the model application and calibration.

CE-QUAL-W2 requires the reservoir be discretized into longitudinal segments and vertical layers that may vary in length and height. An average width must also be defined for each active cell where an active cell is defined as one which may potentially contain water. Additionally, every branch has inactive cells at the upstream and downstream segments, top layer, and below the bottom active cell in each segment. Segment layer heights and lengths may vary, but were held constant for the study area examined in Version 1.0 of SMIS.

As seeming ideal for application to the Cheatham Reach and future versions of SMIS software, CE-QUAL-W2 does have notable limitations. A primary limitation of the model stems from the lateral averaging of plume migration across the width of the river or reservoir. As such, the model overpredicts lateral plume migration should the source of contamination originate on a lateral bank [29]. Future CE-QUAL-W2 development phases indicate the construction of a quasi 3-D mode [23] that may effectively provide the ability to track the lateral migration of a spill plume. In addition, using Version 3.1 of CE-QUAL-W2, a contaminant is best modeled as a conservative tracer within CE-QUAL-W2 model routines. Currently, limited physical and reactive chemical data is capable of being introduced to CE-QUAL-W2 modeling routines. An Arhennius temperature rate multiplier, settling rate, and zero and first order decay rates are the only descriptors utilized for generic constituents (spill contaminants). Future phases of the SMIS project are aimed at effectively addressing these limitations or developing customized modeling frameworks for GIS applications [29].

4. Air contaminant transport model

Contaminant transport modeling for air is accomplished through the use of the CAMEO database and information management software. Although there exists numerous transport models for air similar to the number of transport models for surface water, CAMEO was specifically designed to plan for and respond to chemical emergencies [30].

The CAMEO system integrates three separate program modules (chemical database, air dispersion model, and mapping capability) into a single information management system [31]. The chemical database comprises chemical-specific information on fire and explosive hazards, health hazards, firefighting techniques, cleanup procedures, and protective clothing for over 6000 hazardous chemicals. Areal Locations of Hazardous Atmospheres (ALOHA) provides contaminant transport information for CAMEO. Originating as an emergency response tool, ALOHA is an air dispersion model used to predict the movement and dispersion of gases [32]. This software allows the user to estimate the downwind dispersion of a chemical cloud based on the toxicological/physical characteristics of the released chemical, atmospheric conditions, and specific circumstances of the release. However, multiple air dispersion models exist, ranging from simple equations capable of being solved by hand to complex models requiring massive amounts of input data and powerful computing power [32]. The type of model suitable for a particular application is dependent upon the scale of the application, the level of detail available for input and required for output, the experience of the user, and the time available for completion of model computations.

Designed for first responders to a spill incident, ALOHA is intended to be used for predicting the extent of the area downwind of a short-term duration chemical accident where people may be at risk of exposure to hazardous concentrations of a toxic gas. The model is not designed for use with accidents involving radioactive chemicals, for permitting of stack gas, or modeling chronic, low-level (fugitive) emissions [32]. In addition, as elucidated in CAMEO [30] and ALOHA [32] guidebooks, ALOHA model outputs may be unreliable when one or more of the following conditions persist: (i) very low windspeeds; (ii) very stable atmospheric conditions, (iii) wind shifts and terrain steering effects; (iv) concentration patchiness; (v) presence of fire/chemical reactions; (vi) presence of particulate matter; and (vii) presence of complex topography. As noted by Turner [33], alternate models are designed to address larger scale and/or air quality issues. Since most first responders do not have extensive dispersion modeling backgrounds, ALOHA is designed to require input data that are either easily obtained or estimated at the scene of an accident [32].

Input parameters for ALOHA include spill location, chemical type, volume and rate of spill, and weather conditions (temperature, air stability, wind speed/direction). Spatial outputs include a 'cloud footprint' that can be imported to the GIS-based information management system. To obtain a footprint plot, a threshold concentration of an airborne pollutant, usually the concentration above which the gas may pose a hazard to people, must be identified. This value is deemed the 'Level of Concern' (LOC). The footprint represents the area within which the ground-level concentration of a pollutant gas is predicted to exceed the established LOC at 1 hour after a release commences [32]. On the footprint plot, a shaded area represents the footprint itself. Dashed lines along both sides of the footprint, the 'wind direction confidence lines', indicate 95% confidence limits in which the gas cloud is likely to remain, given an expected amount of fluctuation in wind direction (Fig. 2). Lower wind speeds are accompanied by greater variation in wind direction, which generate broader confidence limits. Confidence limits may form a circle when the wind speed is very low [32]. Ultimately, use of CAMEO in conjunction with ALOHA footprints represent 'best guess' estimates of what will happen downwind of a chemical release. These estimates are utilized within SMIS as guidelines for abatement and response procedures rather than serving as definitive impact assessments.

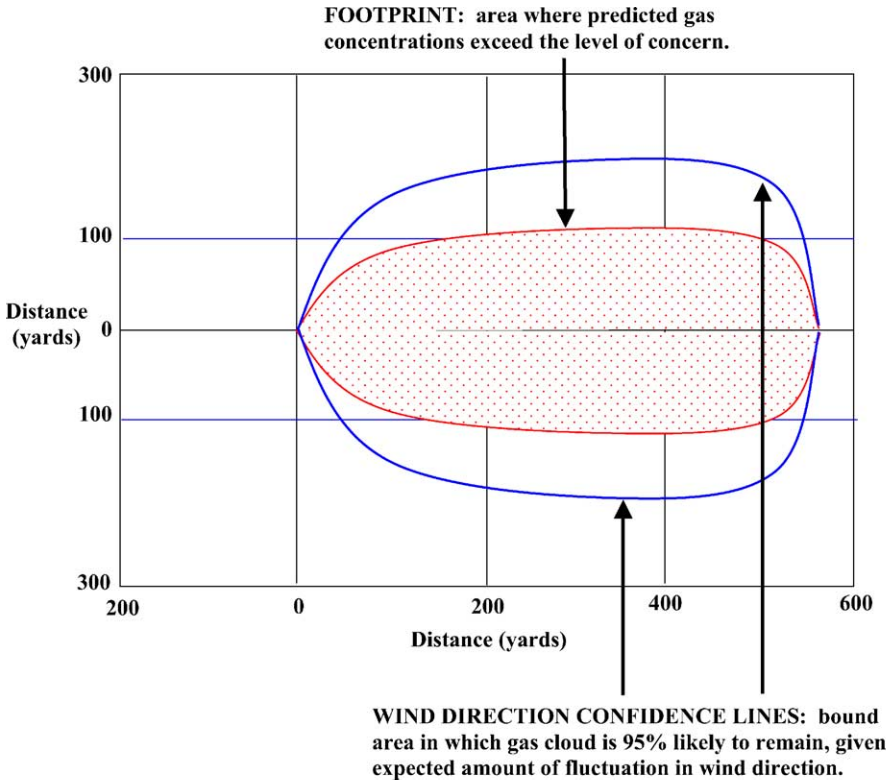


Fig. 2. ALOHA footprint.

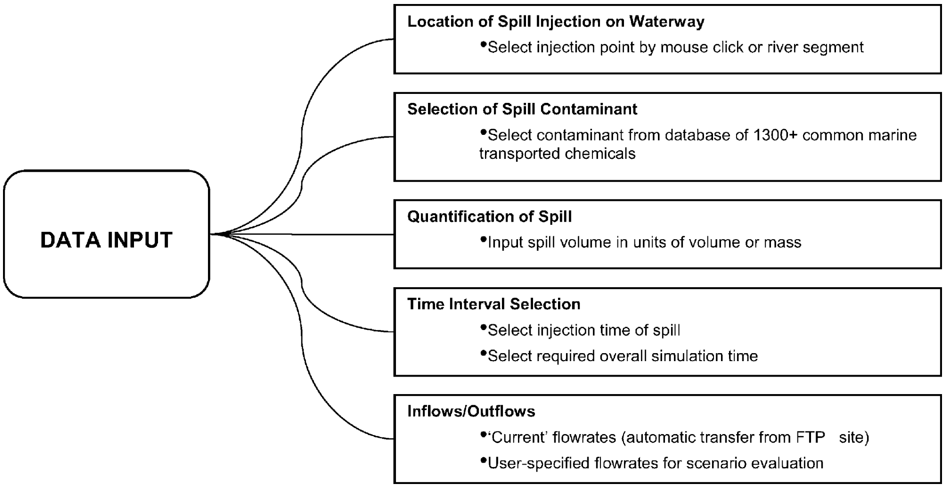


Fig. 3. SMIS input requirements.

5. Data input and pre-processing functions

Following development, calibration, and validation of suitable models for the target region, SMIS requires limited and straightforward data for spill response simulations. Data input requirements for SMIS include contaminant identification, volume or mass of injected spill, location of the spill on the waterway, spill duration, overall simulation duration, inflow and outflow release rates, and meteorological conditions (Fig. 3).

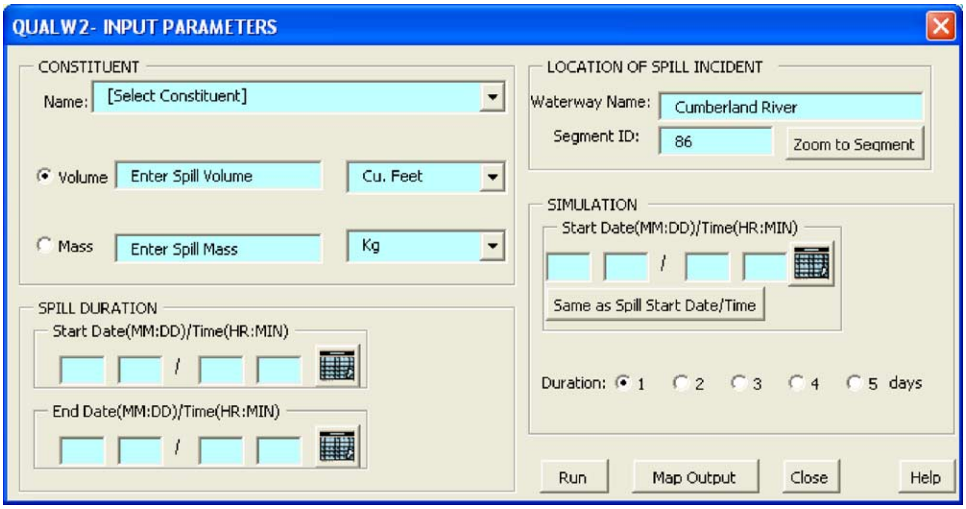
Users may select the injected contaminant from a database of over 1300 common waterway transport chemicals generated from the Chemical Hazard Response Information System (CHRIS) developed by the USCG [34], North American Emergency Response Guidebook (NAERG) [35], and the chemical database of the CAMEO modeling system [30]. Proper identification of the injected chemical ensures the transfer of appropriate physical parameters (e.g., density and/or specific gravity) into the CE-QUAL-W2 modeling system for simulation. Additional information is available for each chemical in the database through the provision of access to a detailed Portable Document Format (PDF) information sheet which includes physical/chemical characteristics and potential acute and chronic health hazards. After selecting the contaminant, users must identify the volume or mass of the injected material. Commonly utilized measurement units are provided to minimize conversion requirements.

Location of the origin of the spill may be selected by river segment number that corresponds to river mile (RM) or by selecting the inflow location on the video display terminal using a mouse click. Location of the injection site is transferred into the CE-QUAL-W2 model for simulation using a VB routine. Spill duration and overall simulation duration are distinct inputs within the SMIS GUI. Spill duration refers to the elapsed time of the spill injection and is assumed constant. Instantaneous injection or a time-averaged input rate are each capable of being modeled. Overall simulation duration refers to the cumulative time modeled by CE-QUAL-W2. Since SMIS is designed for short-term acute impact studies, overall simulation time was designed to bracket short-term simulation periods – a minimum of one day and a maximum of five days (Fig. 4) in the case of Version 1.0.

Primary inflows and outflows of the riverine system may be user-specified or current values relayed from a file transfer protocol (FTP) site for model use (Fig. 5). VB programming bridges enable the user to acquire hourly updated flowrates from remote USACE file transfer protocol (FTP) sites. Meteorologic data is also maintained externally and is accessed for current weather conditions for use in the predictive modeling environment.

6. SMIS parameters and execution

The SMIS interface may be interpreted as a 'black-box' application, as the neophyte user has limited control over the coefficients and parameters used within the CE-QUAL-W2 model. However, SMIS functionality relies on the assumption that validated simulation models are employed for spill analysis. The open coding structure of CE-QUAL-W2 allows advanced users access to the source code and coefficients in order to make desired modifications. Hence, SMIS reliability requires the careful calibration and validation of the employed predictive modeling routines. Within the CE-QUAL-W2 model, spill injections are modeled conservatively in order to develop a 'worst-case' scenario for short-term spill response. This feature introduces a factor of safety to the simulation and provides a mitigation and response 'time-buffer' in the event of a spill. By limiting the amount of information required to run a simulation and having dispersion models calibrated to the waterbody of interest, little modeling



Name: [Select Constituent]

● Volume Enter Spill Volume Cu. Feet

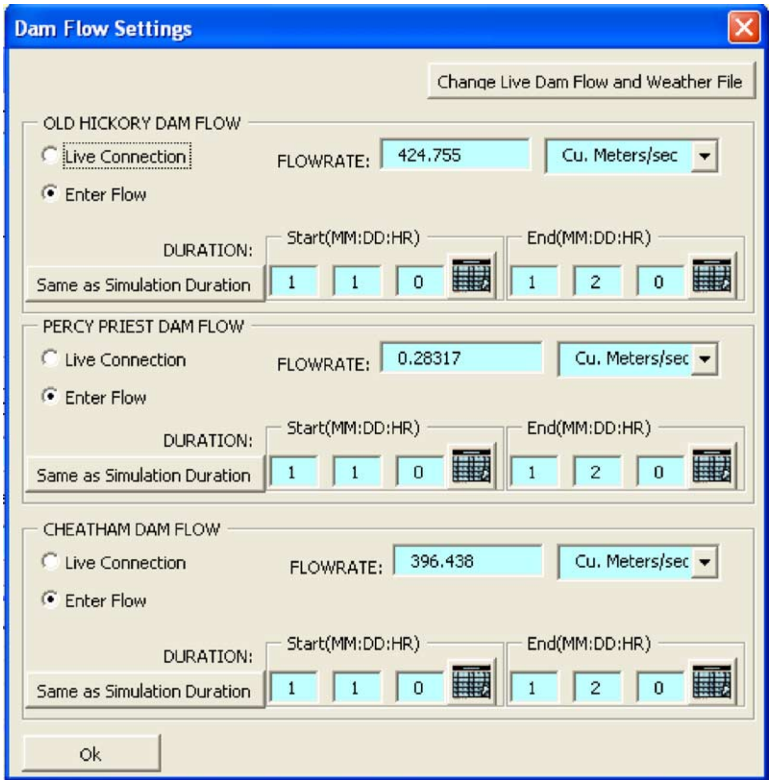
○ Mass Enter Spill Mass Kg

Waterway Name: Cumberland River

Segment ID: 86

Duration: ● 1 ○ 2 ○ 3 ○ 4 ○ 5 days

Fig. 4. SMIS spill data input graphical user interface (GUI).



OLD HICKORY DAM FLOW
○ Live Connection
● Enter Flow
FLOWRATE: 424.755 Cu. Meters/sec
Start(MM:DD:HR): 1 1 0
End(MM:DD:HR): 1 2 0

PERCY PRIEST DAM FLOW
○ Live Connection
● Enter Flow
FLOWRATE: 0.28317 Cu. Meters/sec
Start(MM:DD:HR): 1 1 0
End(MM:DD:HR): 1 2 0

CHEATHAM DAM FLOW
○ Live Connection
● Enter Flow
FLOWRATE: 396.438 Cu. Meters/sec
Start(MM:DD:HR): 1 1 0
End(MM:DD:HR): 1 2 0

Fig. 5. SMIS inflow/outflow GUI.

experience is required by the user to execute SMIS simulations.

Having entered the input data and model parameters, the user is able to execute the simulation (Fig. 6). VB subroutines are initiated to develop model input and output transactions that remain transparent to the user. As illustrated in Fig. 4, cumulative simulation time is restricted to a maximum period of five days. This restriction reinforces the short-term predictive power of SMIS and minimizes the time required to simulate a spill event. During the CE-QUAL-W2 hydrologic simulation, program status and stability measures are displayed to the user for observation and monitoring.

7. Data output and results interpretation

Upon completion of predictive model simulations, a series of GIS layers are imported into GIS. These layers include: (i) concentration levels within the reservoir systems at the surface, 1 m, 2 m, 3 m, and bottom depths; and (ii)

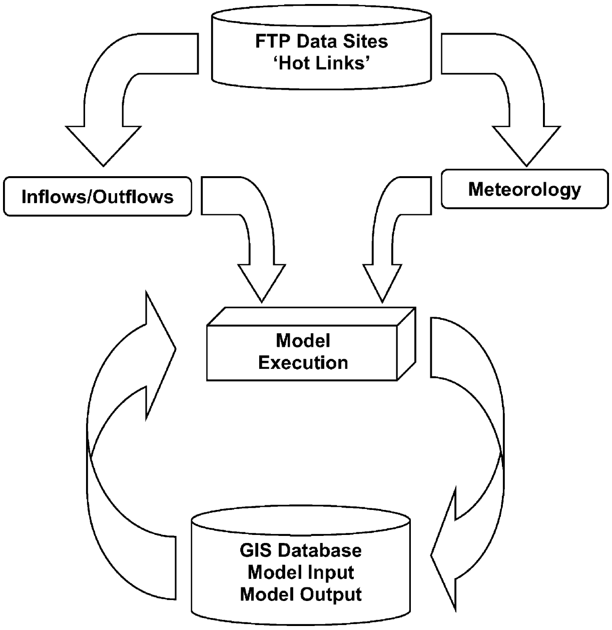


Fig. 6. Model parameters and execution.

the areal contaminant plume calculated 1 hour after spill injection. GIS functions to merge the tabular data together with discrete and/or continuous representations of the study area. Once modeling results are incorporated into this format, logical selection may be initiated to highlight data sets of interest. Using color graphics for model output, the major impact areas may be identified, improving the understanding of the basic patterns and relationships within the study area. GIS breaks away from traditional databases in its ability to stage not only logical selections based on attribute data but also selection based on spatial location and proximity. Additional interpretive tools within SMIS include: spill animation, spill concentration versus depth layers, and the risk analysis routines inherit to GIS (Fig. 7). The DBMS is employed to maintain a singular source of information for SMIS applications. Chemical characteristics and airborne and surface water dispersion datasets are combined in a single database, eliminating redundancy and improving the user's ability to update and retrieve pertinent attributes describing hazardous chemicals. DBMS also serves as a data output repository from CE-QUAL-W2 model runs and acts as the source from which to construct GIS layers of spill diffusion.

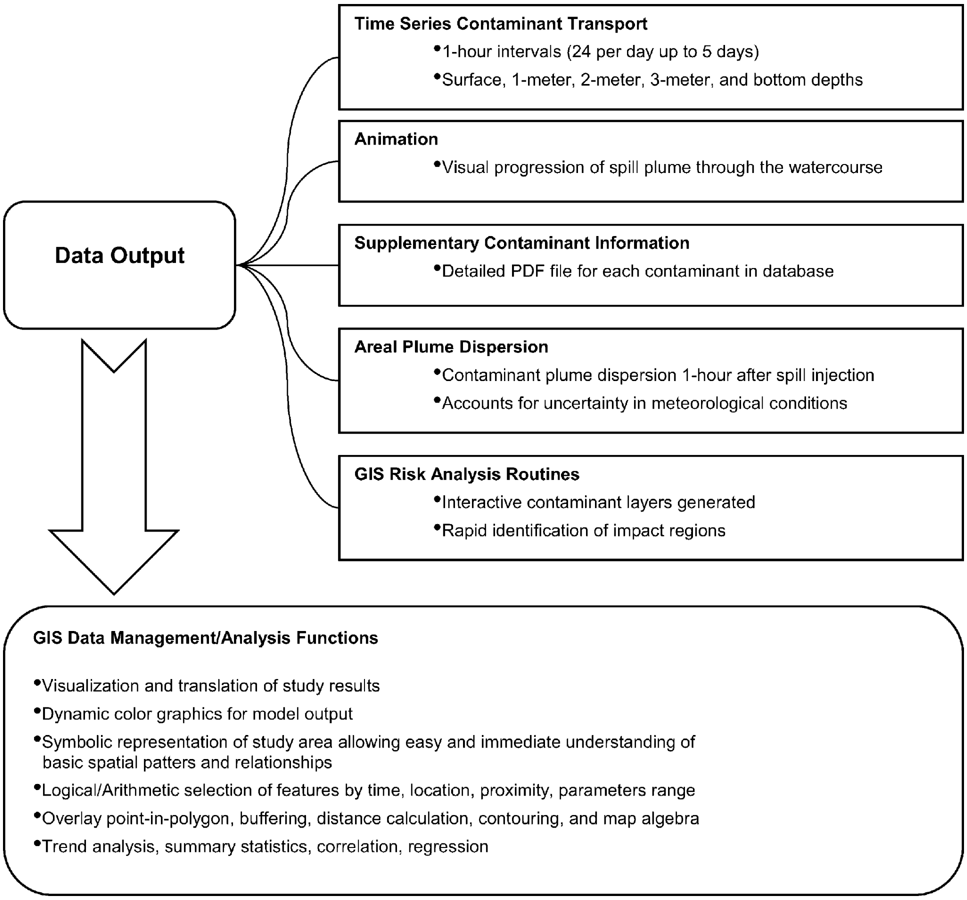


Fig. 7. SMIS data output.

8. Case study

Illustration of the functionality of SMIS is provided through its application to the Cheatham Reach of the Cumberland River near Nashville, TN. Selected because of its proximity to a large population center (Nashville, TN), the Cheatham Reach is a 67 mile (108 km) pool of the Cumberland River located in Middle Tennessee, bounded upstream by Old Hickory Dam (RM 216) and downstream by Cheatham Dam (RM 148) (Fig. 8). The only regulated inflows are from the Cumberland River at Old Hickory Dam and from the Stones River out of J. Percy Priest Dam (RM 206). Major tributaries include the Stones River (RM 206) and the Harpeth River (RM 152.9). Minor tributaries include Johnson Creek, Dry Creek, Mill Creek, Richland Creek, Pond Creek, Sam's Creek, Brush Creek, Big Marrowbone Creek, and Sycamore Creek. Cheatham is a long, narrow, run-of-the-river reservoir that is not designed for flood control [36]. The reach is fairly dynamic as water elevation changes of 1.5–3 m (5–10 ft) are frequent during extreme wet weather events or dam releases. The USACE reservoir is operated for recreation, navigation, and peaking power generation. Summer flows from Old Hickory are intermittent in nature, with typically little or no flow during the morning hours and 75–150% of the daily average flow in the late afternoon. The upper reaches of the Cheatham Reach are typified by the urban and developed areas of Nashville, whereas the lower reaches are relatively rural in nature. Along the length of the reach, there are a series of water and wastewater treatment facilities. Nashville operates three wastewater treatment plants (WWTPs) – Dry Creek, Central, and Whites Creek. Typical dry weather flows are approximately 530,000 m^3/day (140 mgd). At its normal summer pool elevation of 117 m (385 ft) above mean sea level, the Cheatham Reach has a surface area of 3070 ha (7450 acres) and a total volume of 128,000,000 m^3 (104,000 acre-ft).

As elucidated by Cole and Tillman [3], successful model application requires calibrating the model to observed in-pool water quality. If possible, two or more years should be modeled with widely varying hydrology and/or water quality data. For the Cheatham Reach, the years 1999, 2000, and 2001 were utilized for calibration. Calibration data was provided by USACE and included daily flowrates (m^3/s), DO values (mg/L), and temperature (°C) for Old Hickory Dam, flowrates (m^3/s), DO values (mg/L), and temperature (°C) for Cheatham Dam and flowrates (m^3/s) only for Percy Priest Dam. To evaluate model performance, graphical and statistical comparisons of computed versus observed data were made. While interpreting temperature and water quality predictions for CE-QUAL-W2, several points need to be noted. First, temperature and water quality predictions are averaged over the length, height, and width of a cell, whereas observed data represent values at

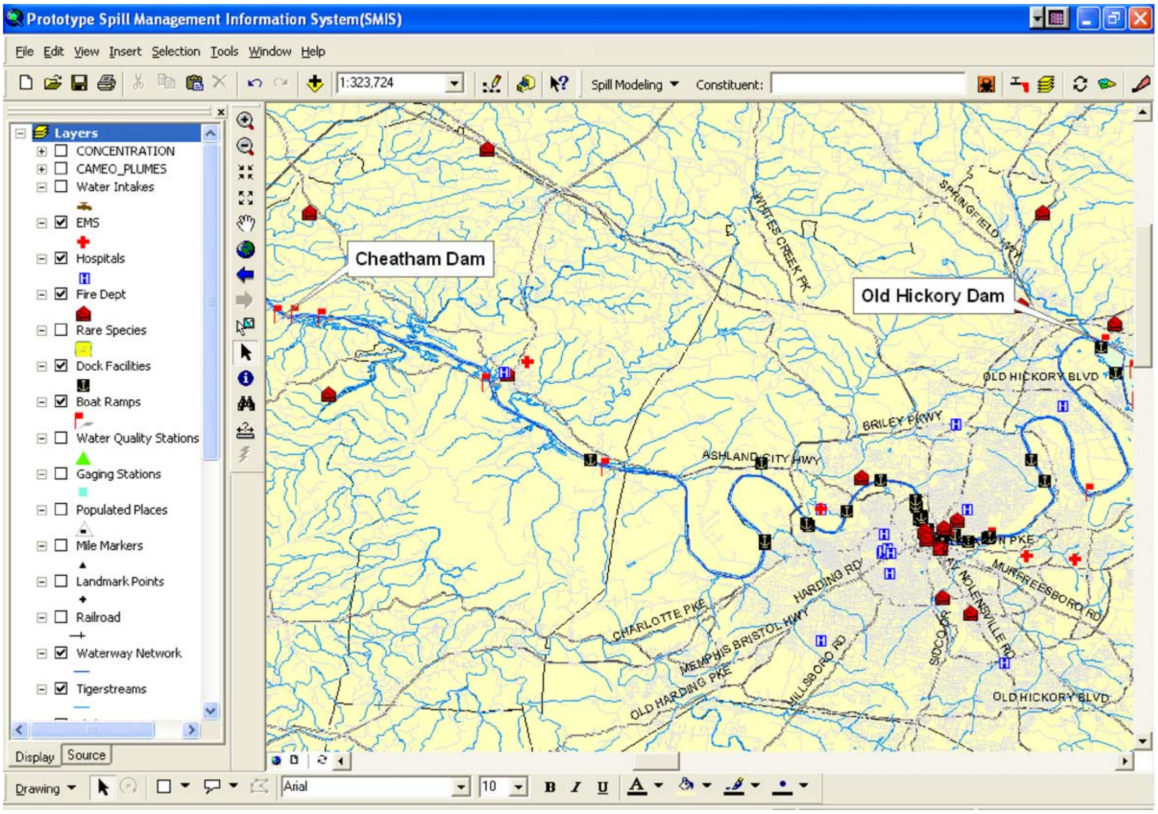


Fig. 8. GIS perspective of the Cheatham Reach.

a specific point in the reservoir. Second, limitations on the availability of weather data and streamlining of the simulation process to minimize simulation execution times will affect the calibration results.

Statistical comparison between observed and computed values was utilized to gauge model performance. As elucidated by Cole and Tillman [24], the absolute mean error (AME) indicates how far, on average, computed values are from observed values. An AME of 0.5 indicates that the predicted data are, on the average, within ±0.5 of the observed values. The root mean square error (RMS) indicates the spread of how far the computed values deviate from the observed. An RMS error of 0.5 indicates that 67% of the predicted data are within ±0.5 of the observed value. For the Cheatham Reach calibration, dissolved oxygen AME values (RMS error) ranged from 1.04 to 1.23 (1.42–1.67) while temperature AME values (RMS error) ranged from 1.06 to 1.25 (1.33–1.59). These data indicate that, on average, predicted versus observed temperature (°C) and DO (mg/L) values are within ±1.1, indicating good agreement with the model.

As noted by Cole and Tillman [24], point to point comparisons of model predictions with observed data is the most rigorous means of evaluating model output. Modelers will compare computed versus observed contour plots or average model output and observed data over space and/or time in order to determine if the model is capturing general trends in the observed data. While appropriate for determining the proper temporal and spatial scales of resolution suitable for a given model, these methods of presentation also obscure a model's shortcomings [24]. As such, the chosen technique of presenting model results in this paper is intended to identify the model's shortcomings as well as strengths in order to provide more information as to the model's capabilities and limitations when used in conjunction with a DSS.

Fig. 8 provides an overview of the project area from the perspective of the GIS interface. The bathymetry grid for the CE-QUAL-W2 model was developed from USACE cross-sections of the Cheatham Reach [37]. The 67-mile reach was discretized into 264 lateral segments of 400 m length with a maximum of 18 vertical 1-m segments. Flowrates of the major and minor tributaries and WWTP facilities are derived from gauged streamflow data furnished by the USCG, USACE, and Nashville Metro Water Services (Metro) [37]. Base layers of GIS data for the target region are developed from public access Internet sites. Sensitive information (i.e., water intakes, endangered species) was added as required by USACE.

For illustrative purposes, a 50,000 L spill of benzene, spilt over 1 hour is simulated at RM 207 of the Cheatham Reach on November 14, 2003 at 2.00 p.m. Meteorological conditions at the time of spill included a 5 mph wind from the east and an ambient temperature of 65 °F. USACE flowrates for Old Hickory, Percy Priest, and Cheatham Dam, current for

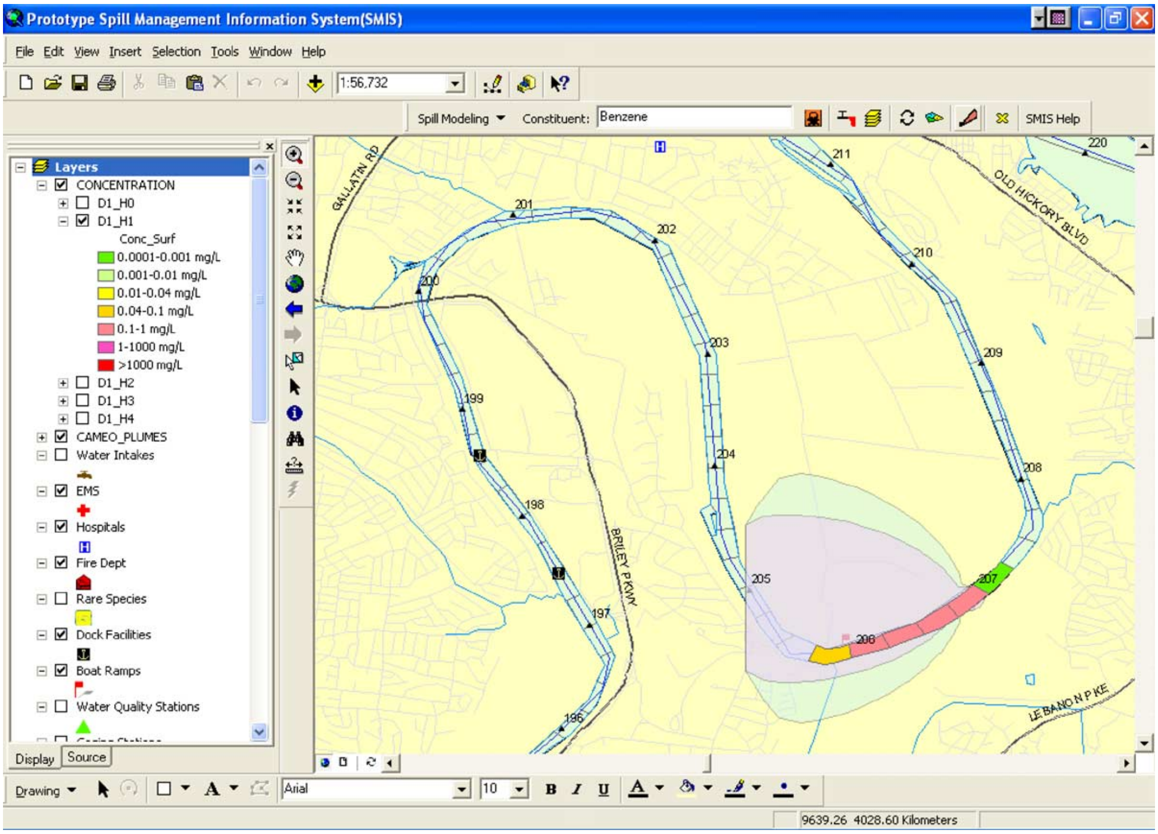


Fig. 9. Spill contamination levels (surface) and air dispersion prediction 1 hour after spill injection.

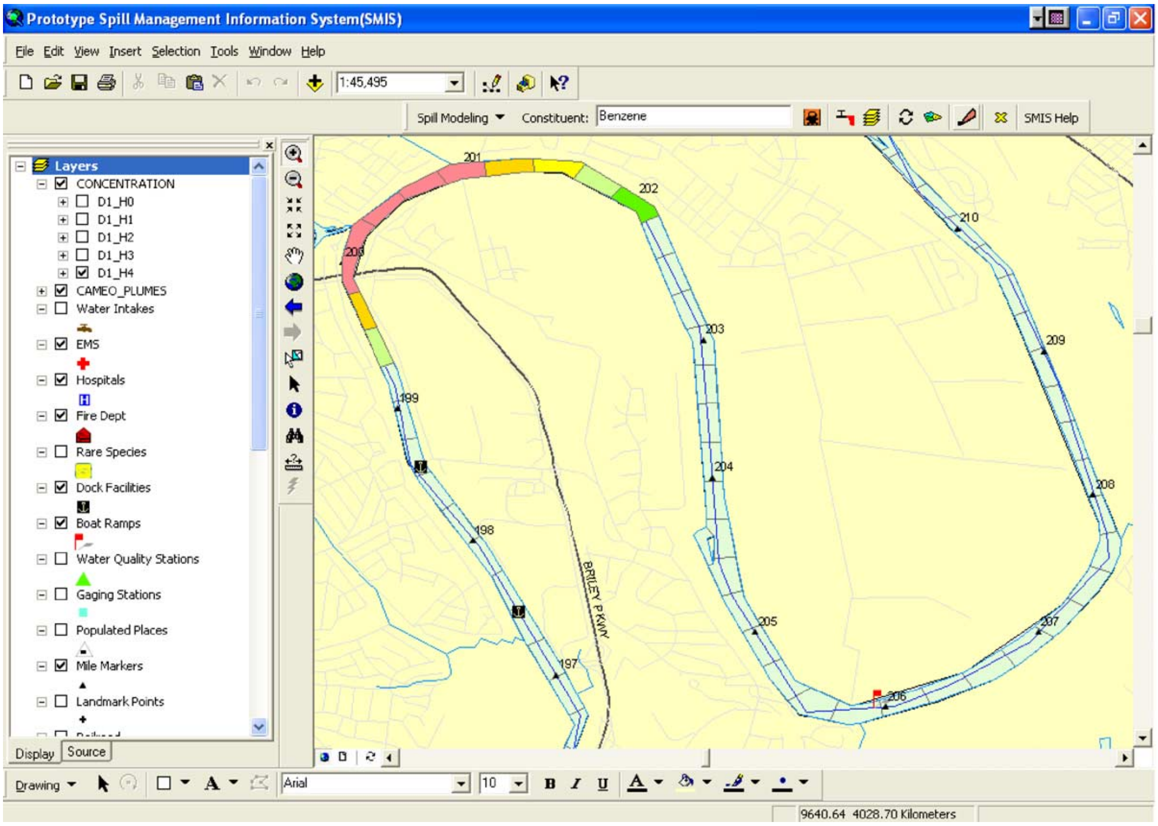


Fig. 10. Spill contamination levels (surface) 4 hours after spill injection.

the time of spill injection, are utilized in the simulation. The overall simulation time is set for one day. Fig. 9 illustrates the spill contamination levels at the surface in the Cheatham Reach and the projected air dispersion plume at 1 hour after spill injection. Fig. 10 depicts the spill contamination levels in the Cheatham Reach at 4 hours after spill injection. Once the spill contaminant layers have been updated within GIS, risk analysis routines may commence.

An animation routine, developed through VB coding, is included within the SMIS GIS interface. This function performs rapid toggling between generated GIS spill layers, resulting in an animated display of spill progression through the waterway. Any time interval of interest (1 hour, 2 hour, etc.) may be uploaded into the animation routine for analysis. This feature provides responders a dynamic view of spill diffusion and progression, allowing for increased awareness and enhancing the interpretive capability of the system. Efficiency of spill response units deployment increases as personnel may be directed to the nearest boat launch/access point after comparing travel time of the spill to the predicted response time of abatement personnel.

A combining approach [38] to GIS and model interfacing maintains the interactivity of the GIS spill layers. Functional mechanisms offered by GIS packages: macro languages, interface programs written in standard program languages, and libraries of user callable routines are maintained [39]. As such, risk analysis routines may be utilized to identify sensitive receptors after a spill incident by querying GIS layers generated by the spill dispersion models (CAMEO and W2). Locations of populations, water intakes, endangered species, and water access sites may be rapidly identified using inherit GIS analysis routines. Resultantly, SMIS provides real-time planning and analysis capabilities for first-responders, facility operators, and emergency response organizations.

9. Potential applications and developmental options for SMIS

Future enhancement of SMIS may follow three pathways: (i) enhancements to the existing Cheatham Reach; (ii) transfer of Cheatham Reach SMIS to similar waterway systems; and (iii) model enhancements for dissimilar waterway systems.

While SMIS Version 1.0 employs a number of important spill information management functions, additional enhancements will enable SMIS to be an even more valuable asset for first responders to spills within the Cheatham Reach. Such enhancements may include: (a) threat zone analysis queries to evaluate spill impacts on sensitive areas; (b) web-based SMIS for field portability; (c) resource analysis to estimate the level of response (i.e., equipment deployment) required for particular spills; and (d) application of enhanced or alternate water and air dispersion models. Additionally, the GIS framework and modular structure of SMIS may provide an outstanding platform to evaluate additional water quality information applications. For example, Department of Defense's (DoD) Watershed Management System (WMS) may be used in conjunction with CE-QUAL-W2 to establish a watershed-surface water interface capable of modeling the effects of watershed modifications (e.g., land use changes) on surface water quality, all within a GIS-based environment. Such applications can be particularly useful in evaluating total maximum daily load (TMDL) requirements for nonpoint sources of pollution.

For application to similar waterways, SMIS Version 1.0 provides the proof-of-principle for interfacing state-of-the-art water quality and air dispersion models with a database management system within a GIS framework. As such, SMIS may be readily adapted to other effectively modeled waterways with CE-QUAL-W2. Prioritization of work may include other major population centers and/or large volume transportation sectors possessing similar water hydrodynamics to the Cheatham Reach of the Cumberland River. Required data for SMIS application to such systems includes acquiring or developing GIS layers representative of the geographic area of interest and developing a CE-QUAL-W2 model to the waterway of interest. Techniques behind establishing links to meteorological or flow data have been established and only require changes in their respective digital addresses.

As SMIS Version 1.0 employs a modular framework, additional water quality models may be employed to more appropriately model water bodies possessing hydrodynamics that are dissimilar to those capable of being modeled by CE-QUAL-W2. Such systems may include Resource Management Associates 2 (RMA2) and Resource Management Associates 4 (RMA4). RMA2 is a 2-D, depth-averaged, hydrodynamic modeling code that supports subcritical flow analysis, including wetting and drying and marsh porosity models. It is part of the TABS Numerical Modeling System written by the U.S. Army Corps of Engineers Waterways Experiment Station (USACE-WES). RMA4 is also a part of the TABS Numerical Modeling System and is used for tracking constituent flow in RMA2. RMA4 can be applied to represent the transport of a contaminant, salinity intrusion, or tracking other water quality constituents, including dissolved oxygen and biochemical oxygen demand. When combined with RMA2, RMA4 is particularly well-suited for wide water bodies where lateral dispersion is an important consideration. Other water quality models of interest include the USEPA Water Analysis Simulation Program (WASP), and DoD's WMS and Surface Water Modeling System (SMS). Required enhancements to such systems include the acquisition of required GIS layers and redefining data transfer patterns for the selected water quality model.

10. Conclusions

A closely coupled hydrodynamic/pollutant transport GIS model provides functionality for data capture, data editing, pre-processing, embedded artificial intelligence and result interpretation. The use of SMIS can improve and enhance the rapid identification of receptor sites and fate of pollutants, improving response time and mitigation strategies in the event of a discharge. Keeping SMIS 'hot' by dynamically linking the model to real-time streamflow and meteorologic information can reduce the time required to provide predictive model capability. SMIS also provides each incident responder with access to the same maps and contaminant spill information that other responders possess. Updates to chemical spill activity and its location relative to critical infrastructure items such as water intakes or water access points can be provided to all responders simultaneously.

Overall, SMIS capabilities serve to enhance preparedness, response time, information access, and the employment of suitable contaminant transport modules. Establishment of SMIS as part of an organization's environmental response program can assist environmental response teams by improving their ability to coordinate with other agencies to ensure an appropriate and adequate response to a chemical spill emergency. In addition, SMIS can provide invaluable training opportunities through execution of spill response exercises, as well as enhanced decision support through implementation of "what-if" scenarios both during exercises and actual spill incidents. In essence, SMIS is a software tool designed to help answer the crucial question in any Area Contingency Plan: How do I develop a plan that protects my area against likely spills?

The use of this GIS-based interface module can improve first responders' understanding and fate of pollutants, potentially improving response time and mitigation efforts in the event of a deliberate or intentional spill. At the same time, this analysis tool can assist in the implementation and preparation of abatement tactics. This system promotes the successful and accurate application of sophisticated hydrodynamic/pollutant transport and air dispersion simulation through a simple GUI. The use of this tool can improve the communication of the basic patterns associated with hydrodynamic/pollutant and air dispersion transport. This merger possesses the ability to assist responders in better defining spill mitigation approaches, promote a shared view of intended response activities, and ultimately permit better communication of these problems to stakeholders. In this age of vast information availability, decision makers must work to develop improved tools to disseminate and interpret the increasing amount of available data. Predictive models coupled with GIS technology will enhance model performance, as demonstrated in this paper, and ultimately improve decision making capability.

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