A Remote Sensing and GIS-assisted Spatial Decision Support System for Hazardous Waste Site Monitoring

John R. Jensen, Michael E. Hodgson, Maria Garcia-Quijano, Jungho Im, and Jason A. Tullis

Abstract

Humans produce large amounts of waste that must be processed or stored so that it does not contaminate the environment. When hazardous wastes are stored, waste site monitoring is typically conducted in situ *which can lead to a serious time lag between the onset of a problem and detection. A* Remote Sensing and GIS-assisted Spatial Decision Support System for Hazardous Waste Site Monitoring *was developed to improve hazardous waste site management. The system was designed to be* recursive, flexible, *and* integrative. *It is* recursive *because the system is implemented iteratively until the risk assessment subsystem determines that an event is no longer a problem to the surrounding human population or to the environment. It is* flexible *in that it can be adapted to monitor a variety of hazardous waste sites. The system is* integrative *because it incorporates a number of different data types and sources (e.g., multispectral and lidar remote sensor data, numerous type of thematic information, and production rules), modules, and human expert knowledge of the hazardous waste sites. The system was developed for monitoring hazardous wastes on the Savannah River National Laboratory near Aiken, South Carolina.*

Introduction

Hazardous waste site management is a major environmental problem in the world today. For example, the United States generated 40 million tons of hazardous waste in 2001 (USEPA, 2003). The majority of the total volume produced annually is stored in landfills because of the tremendous costs and/or technical limitations of other management approaches (USEPA, 1999). Once a landfill reaches its maximum storage capacity it often undergoes "closure" (referred to as "capping") where surface and subsurface barriers (such as interleaved layers of soil and polyethylene sheeting) are installed to isolate the material, prevent its dispersal off-site, and limit water infiltration into the waste site (USEPA, 1998).

John R. Jensen and Michael E. Hodgson are with the Department of Geography, University of South Carolina (jrjensen@sc.edu; hodgsonm@sc.edu).

Maria Garcia-Quijano is with the Department of Geosciences, Florida Atlantic University (mgarci97@fau.edu).

Jungho Im is with the Department of Environmental Resources and Forest Engineering, State University of New York College of Environmental Science and Forestry (imj@esf.edu).

Jason A. Tullis is with the Department of Geosciences, University of Arkansas.

Materials classified as "hazardous" are typically grouped into a toxic or radioactive category. Radioactive materials are typically classified as low level (e.g., animal carcasses used in research, hospital materials) or high level (e.g., spent nuclear fuel, large quantities of heavy elements). High level radioactive wastes are often confined to specially prepared reservations and capped.

Unfortunately, as capped landfills exceed their planned design life, they may undergo changes that can compromise the integrity of the cap materials. While some of these changes are foreseen by planners and engineers, other changes may not be anticipated. Therefore, *in situ* inspection must constantly be performed to identify problems such as subsidence, desiccation cracking, frost damage, and biointrusion (i.e., the introduction of unwanted vegetation such as shrubs). In addition, monitoring wells are often installed to assess changes in hydraulic head and measure water and soil characteristics. This kind of *in situ* monitoring is expensive, labor-intensive, and often undersampled (Jensen *et al.*, 2003; Serrato, 2007). In the aftermath of the 9/11 terrorist attack, there is also a need to safeguard potentially sensitive or vulnerable facilities, such as hazardous waste sites.

Numerous scientists and agencies have warned that there must be significant improvement in our ability to monitor hazardous waste sites so that anomalies can be detected and corrected rapidly to safeguard humans and the environment (USEPA, 1998). On-site inspection will always be important, but must be coupled with more advanced methods of monitoring hazardous waste sites. What is needed are spatial decision support systems (SDSS) that monitor the entire site yet function in harmony with information obtained from *in situ* investigation.

This paper summarizes the development of a *Remote Sensing and GIS-assisted Spatial Decision Support System for Hazardous Waste Site Monitoring*. The conceptual and practical development of the system was based on real-world hazardous and low-level radiological waste sites on the Savannah River National Laboratory (SRNL) located near Aiken, South Carolina.

Spatial Decision Support Systems and Emergency Management

Spatial decision support systems (SDSSs) are defined as computer systems that provide decision-makers with an

Photogrammetric Engineering & Remote Sensing
Vol. 75, No. 2, February 2009, pp. 169–177.

0099-1112/09/7502–0169/$3.00/0

opportunity to assess and solve ill-structured problems with spatial information. SDSS lie at the interface between Geographic Information Systems (GIS) and aspatial Decision Support Systems (DSS) (Armstrong and Densham, 1990). SDSS are characterized by powerful graphical display capabilities and by improved handling of spatial data when compared to general purpose aspatial DSS. Additionally, SDSS provide specific analytical and modeling capabilities that are commonly lacking in a conventional GIS (Ehler *et al*., 1995).

SDSSs have sparked great interest in the emergency management community as a possible way to address the spatial component of natural and technological hazards (Fedra, 1997). As a result, several specialized SDSS have been developed that assist decision-makers with both cumulative or *slow-onset* hazards like droughts and agricultural pestilence (MacLean *et al*., 2000; Agatsiva and Oroda, 2002), and with *fast-onset* catastrophic hazards, such as floods, hurricanes, wildfires, and earthquakes (Fulcher *et al*., 1995; Radke, 1995; Sanders and Tabuchi, 2000; Jaber *et al*., 2001 Hodgson and Cutter, 2002; Jensen and Hodgson, 2006).

Existing waste management SDSS applications have focused mainly on the development of Multi-Criteria Decision Support Systems (MCDSS) for municipal solid waste. These MCDSS have been used to address siting problems for new facilities (Haastrup *et al*., 1998) and to optimize waste allocation among recycling, disposal, and incineration management alternatives (Costi *et al*., 2004; Morrissey and Browne, 2004).

An extensive literature review identified just a few functional decision support systems and one academic demonstration dealing specifically with hazardous waste sites. FEMA's *Consequences Assessment Tool Set* (CATS) developed in collaboration with the U.S. Defense Threat Reduction Agency and Science Applications International, Inc. provides users with natural hazard simulation of hurricanes, hurricane storm surge, earthquakes, and floods; and technological hazard simulation such as chemical spills/releases, releases of biological agents, nuclear reactor releases; and the simulation of effects from nuclear, biological, and chemical weapons of mass destruction (Swiatek, 1999). Note the emphasis on simulation, not monitoring. The *Field Analysis System for Emergency Response* was developed by Edgerton, Germeshausen, and Grier (EG&G), Inc. to provide the United States Department of Energy (DOE) emergency response officials with a spatial data analysis toolbox based on off-the-shelf GIS and image analysis software (Guber *et al*., 1995). It does not incorporate expert systems suggestions about what should be done in the event of an anomaly detection. DOE's *EM50* is an Organization Decision Support System designed to support investment decisions in clean-up technology for DOE's more than 3,700 hazardous waste and substance release sites (Sen *et al*., 2000). *EM50* cannot be considered a SDSS since its decision-making approach lacks an explicit spatial component. Another system was developed by Ehler *et al*. (1995) to assist in the siting of new facilities at SRNL. Finally, the academic demonstration "*Where to Dispose of Britain's Radioactive Waste?*" used a GIS based-SDSS for public participation in establishing new radioactive waste sites in Great Britain. It was developed by Carver *et al*. (1996) to demonstrate the role of the Internet in facilitating public involvement in decision-making. Finally, the Hazard Prediction and Assessment Capability (HPAC) system was developed at DOE's Oak Ridge National Laboratories (ORNL). HPAC includes moderate resolution land-cover and population datasets for the world and air/water environmental transport models, primarily for planning purposes. HPAC has been coupled to some expert system response modules in the Visual Interactive Site Analysis Code (VISAC) for incidents at radioactive and industrial facilities (Peplow *et al*., 2002).

Design of a Remote Sensing and GIS-assisted Spatial Decision Support System for Hazardous Waste Site Monitoring at SRNL

SRNL contains more than 450 hazardous waste sites that store a wide variety of materials, including waste products generated from the processing of plutonium (Pt^{239}) and tritium (H^3) for nuclear weapon production from 1953 to 1988 (Mackey, 1998). SRNL installed claycaps to contain radioactive-related waste products buried in relatively shallow pits. An orthophotograph of several clay-capped hazardous waste sites at the SRNL is shown in Figure 1.

In situ claycap monitoring is a major component of existing emergency management at SRNL. Claycap monitoring is an essential safety measure for identifying compromised areas, so that they can be repaired before any claycap failure takes place. *In situ* visual monitoring, however, is costly and can miss early evidence of claycap compromise such as subsidence or biointrusion, that might go undetected (Serrato, 2007).

Consequently, remote sensing is considered an important technology for monitoring capped hazardous waste sites, since it can provide non-destructive and exhaustive (wall-to-wall) landfill surface reconnaissance (Vincent, 1994). Several very important parameters can be remotely sensed. First, it is possible to use photogrammetric or lidargrammetric techniques to create bare-earth digital terrain models (DTMs) of the hazardous waste sites that can be used to identify subsidence or other direct topographic expressions of claycap change on the order of just a few centimeters (Garcia-Quijano, 2006; Garcia-Quijano *et al*., 2008). In addition, the vegetative cover on a landfill is a valuable surrogate variable that provides an integrative response to changes on the claycap. Heavy metals such as copper or zinc, and variations in water content affect vegetation biophysical parameters (e.g., leaf area index, biomass) and optical spectral reflectance characteristics (Schuerger *et al*., 2003). Vegetation spectral responses have been successfully used for the detection of contaminant leaks at Superfund sites and on landfills (Herman *et al*., 1994; Jensen *et al*., 2003). Remote sensing can therefore be used to survey the spatial and temporal variation of vegetation on landfills as a surrogate measure of changes taking place on the claycap. Any unwanted vegetation on the cap is called biointrusion.

The *Remote Sensing and GIS-assisted Spatial Decision Support System for Hazardous Waste Site* was designed to contribute to strategic planning and response to emergency situations. A simplified flow diagram of the system's architecture and the interaction among its fundamental components is shown in Figure 2. The system contains four subsystems which are described in greater detail in the following sections:

1. The **database management subsystem** (DBMS) includes spatial and aspatial data assembled from a variety of sources that are updated on a systematic basis. Data standardization constitutes a large part of the overall SDSS implementation effort because it is essential that all data be stored in a common format to facilitate rapid data access for decision-making. The DBMS stores, organizes and queries basic metadata for aspatial and spatial data using Microsoft Access® 2003 and Environmental Systems Research Institute (ESRI) ArcGIS® 9.2.
2. The **monitoring subsystem** examines the spatial data within the DBMS and searches for changes and/or anomalies associated with the capped hazardous waste sites based on remotely sensed data, GIS modeling, and inductive reasoning. Changes in vegetation spectral behavior are derived from a time series of multispectral and hyperspectral remote sensing data acquired on near-anniversary dates whenever possible (Jensen, 2005). Changes in elevation are assessed, by comparing DTMs acquired on multiple dates or by analyzing a DTM produced from a single date acquisition.

Figure 1. Orthophotograph of selected hazardous waste sites at the Savannah River National Laboratory (SRNL) near Aiken, South Carolina.

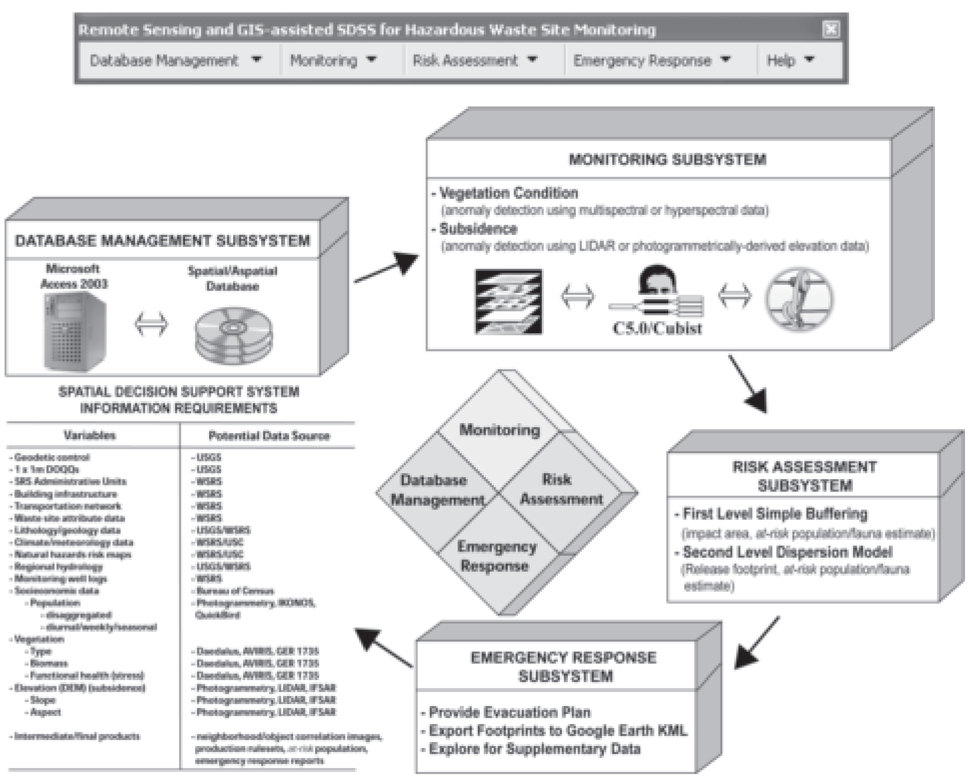

Figure 2. User interface and conceptual diagram of the Remote Sensing and GIS-assisted SDSS for Hazardous Waste Site Monitoring.

3. The **risk assessment subsystem** is triggered when the monitoring subsystem detects changes or anomalies on the claycap. When an anomaly is identified, information about the nature of the failure (e.g., slow-onset versus fast-onset, kind of material and concentration released), its source location, and its estimated intensity is passed to the risk assessment analytical system. The risk assessment subsystem identifies populations at risk.
4. The **emergency response subsystem** focuses on developing and analyzing response alternatives to an emergency event. Responses include the design of evacuation plans for populations deemed *at-risk* by the risk assessment subsystem based on predicted areal extents of exposure to a hazardous material and on population distribution models.

The four subsystems are connected in a cyclic manner (Figure 3). For example, a scientist analyzes new remote sensing data placed in the DBMS to detect any potential anomalies on claycaps such as subsidence or change in vegetation health or condition. Various change detection (monitoring) modules have been specially created for this purpose. If the monitoring subsystem identifies any suspicious surface anomaly, *on-site* experts are immediately dispatched to examine the area. If the expert identifies a release of any hazardous material, additional steps are initiated. If the release goes into the atmosphere, the risk assessment subsystem estimates *at-risk* human population and fauna. The emergency response subsystem provides evacuation plans. The atmospheric release of hazardous materials could occur when on-site experts perform field inspections. If the release is believed to impact subsurface soils or groundwater, then proprietary external subsurface models are triggered and further ground examination is performed by *on-site* experts. Subsurface movement of the hazardous waste may involve excavation and/or well drilling to obtain additional information. Figure 3 illustrates the cyclic process.

Development of the System

All subsystem modules of the system are implemented as a dynamic-linked-library (DLL) using Visual Basic so that they can be closely coupled or, in some cases, embedded with ESRI ArcMap® 9.x. Additional software packages required include C5.0 and/or Cubist by RuleQuest Research for data mining, Leica's ERDAS Imagine® for basic preprocessing of remote sensor data, and *e*Cognition® for image segmentation. Microsoft Access® 2003 is the database management software. The system software architecture is based on the three distinct components found in almost all SDSS (i.e., database management, modelbase management, and user interface) (Figure 4). Through the user interface, users access the database, manage the database, and apply a variety of models (i.e., tools) developed to extract rules (i.e., responses) for effective monitoring of the hazardous waste site.

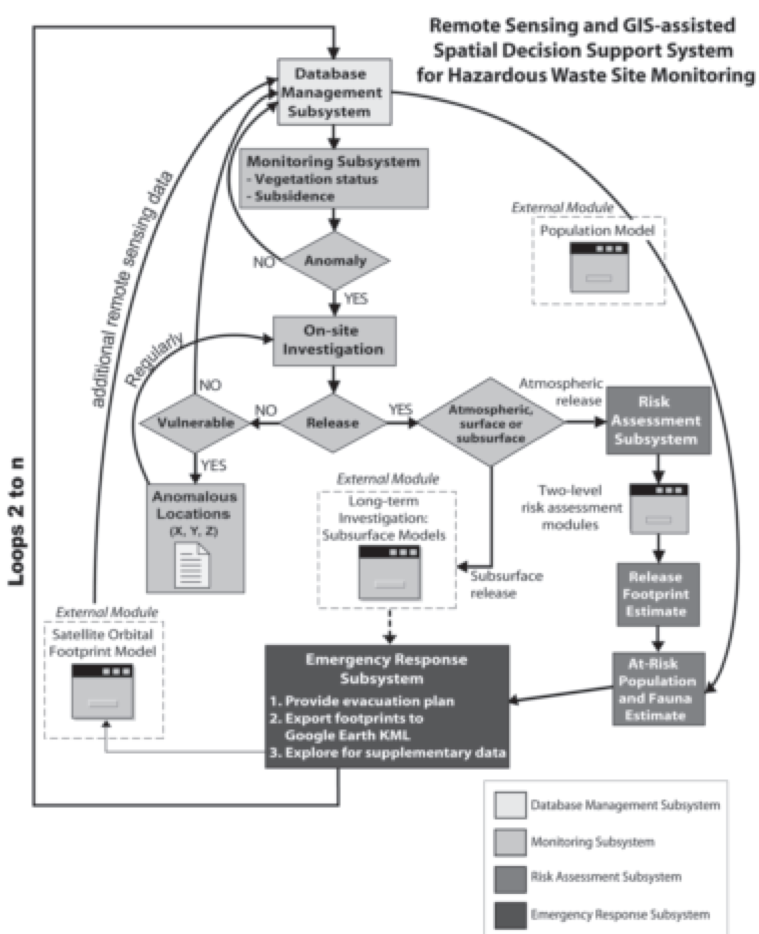

Figure 3. Cyclical work flow of the remote sensing and GIS-assisted SDSS for hazardous waste site monitoring.

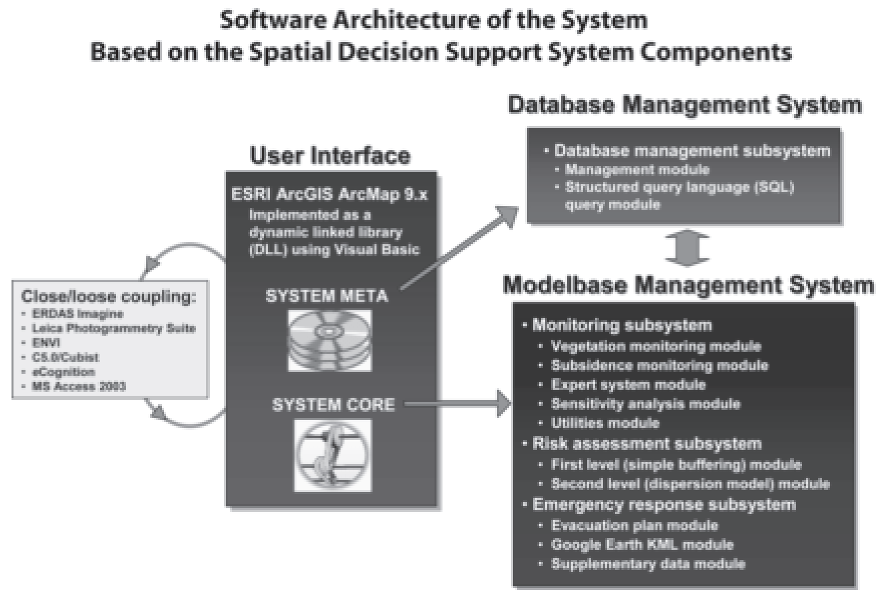

Figure 4. Software architecture of the remote sensing and GIS-assisted SDSS for hazardous waste site monitoring based on the three components of a typical SDSS.

As mentioned earlier, the system consists of four subsystems that function in a cyclic manner (Figures 2 and 3). It is instructive to review the details associated with each of these subsystems.

Database Management Subsystem

The database developed for the system does not store actual remote sensing/GIS data. Instead, the database contains basic metadata of the original, preprocessed data, and intermediate or final products as well as *link* information (i.e., files/folder paths). Users access, manage, and query the database directly in ArcMap®.

Monitoring Subsystem

One of the most critical parts of the SDSS is the monitoring subsystem, where a variety of remotely-sensed data ranging from high-resolution aerial photography, multispectral, hyperspectral, and lidar data are analyzed to identify change on the surface of the hazardous waste sites. The authors developed a variety of new tools for effective anomaly detection, which include neighborhood correlation image analysis, object correlation image analysis, subsidence detection, and change (anomaly) detection using an automated calibration model (Im, 2006; Im *et al.*, 2007). For example, optical correlation image analysis is based on the fact that pairs of brightness values from the same geographic area (e.g., object) between multi-temporal image datasets tend to be highly correlated when little change has occurred, and uncorrelated if the area has changed (Im and Jensen, 2005). Thus, pixels with low correlation values correspond to areas where the spectral behavior of the vegetative cover on the claycap has changed significantly between the dates analyzed. It has been demonstrated that neighborhood/object correlation image analysis is a powerful technique for detecting change between two dates using multiple-date, multispectral imagery (Im and Jensen, 2005; Im *et al.*, 2008).

Photogrammetric and lidargrammetric techniques are used to create a time series of DTMs derived from historical large-scale stereoscopic aerial photography or from airborne lidar data acquired on a regular basis. For example, a lidar-derived DTM of four experimental hazardous waste sites is shown in Figure 5a. The depressions highlighted on the controlled waste sites are only a few centimeters deep (Jensen, 2007). All DTMs in the database are referenced to a common map projection and horizontal/vertical datum and can be compared (i.e., mathematically differenced) to identify if subsidence has taken place. In addition, a subsidence detection module that uses a single-date DTM was developed. It is useful when multiple-date DTMs are not available. The module compares an original DTM and a simulated one using sampled elevation from the original DTM. An example of subsidence detection using this module and the four experimental hazardous waste sites is shown Figure 5b.

Quinlan's C5.0/Cubist inductive machine learning program (RuleQuest Research, 2005), one of the most widely used data mining tools, is used to develop decision trees used by the system. It produces decision trees, but also can automatically simplify the trees by converting them into production rules. Each rule consists of one or more *if-then* statements, which are easy to understand, compared to the trees. C5.0/Cubist was never designed specifically for remote sensing applications. Therefore, it is usually very difficult to apply the generated decision trees (or production rules) to the corresponding imagery due to the lack of an automatic procedure. Consequently, the authors developed a tool to apply decision trees and/or production rules generated to the corresponding imagery in the system (Im, 2006). In addition, several other utilities were developed to facilitate hazardous waste site monitoring, including: *sampling tools*, *accuracy assessment*, *image normalization*, and *spectral reconstruction* which are not described here.

When the monitoring subsystem detects an anomaly on the waste site, *on-site* experts are dispatched to investigate the anomaly and determine if there has been a release. The monitoring subsystem reduces the time and effort associated with field investigation since the *on-site* experts only need to examine potentially anomalous areas identified through the remote sensing-assisted monitoring subsystem.

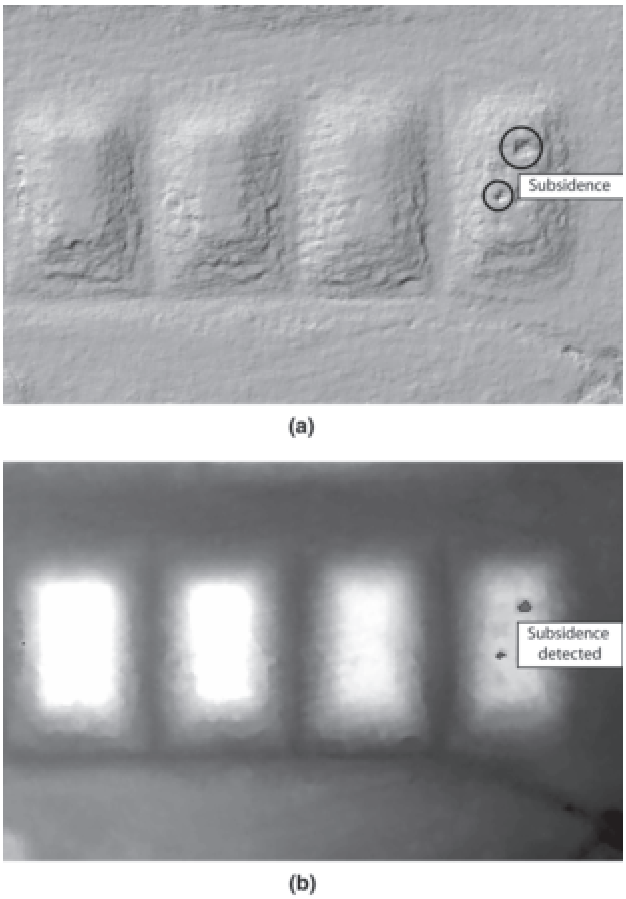

Figure 5. (a) Lidar-derived digital terrain model (DTM) in shaded-relief format of four experimental hazardous waste sites on the SRNL. Two areas experiencing subsidence are identified; and (b) the subsidence detection module successfully identified the two subsidence locations using a single date of lidar data.

Risk Assessment Subsystem
Three types of possible accidental releases may occur on the waste sites: atmospheric, surface, and subsurface (underground). Each release type requires a different response. If the monitoring subsystem reports a potential failure on the clay cap and the *on-site* experts identifies that the failure has created an atmospheric or surface release of the hazardous materials, then a rapid-onset, fast response is required. At the request of SRNL personnel, the SDSS currently concentrates on developing risk assessments for atmospheric releases which can influence the greatest number of people or fauna in the shortest possible time. On the other hand, if the on-site expert determines that a subsurface release has occurred, then a more systematic and relatively long-term investigation (i.e., slow onset) of the groundwater and soil contamination around the failure location is required.

When an atmospheric release occurs, detailed information such as kind of materials and their concentration released at the point source is provided by the *on-site* expert and input to the risk assessment subsystem. The risk assessment subsystem then estimates the potential risk to the human population and fauna. Several analytical modules for the modeling of an atmospheric release of hazardous materials are functional within the risk assessment subsystem.

When a subsurface release of hazardous materials occurs, the system requests that *on-site* experts investigate the release using *external* models to assess risk and report the results to the system.

The modules internally incorporated in the risk assessment subsystem estimate the risk to human population and fauna. The modules operate at two distinct levels (Figure 2). The first level module is based on simple circular buffering which estimates *at-risk* population and/or fauna using a GIS buffering function, e.g., identify the populations at-risk within 1,500 meters of the release. This module is valuable when an event requires a very rapid response and is commensurate with the Department of Transportation's (DOT) concept of protective-action distances (DOT, 2004).

The second level module conducts a more extensive and systematic risk assessment, which provides specific calculations about the direction and dispersion of the hazardous materials released and models its spatial distribution and concentration. Atmospheric dispersion modeling is achieved through an embedded Gaussian Dispersion Model. The dispersion model provides a "footprint" showing the predicted area that is affected by a particular release using three emergency response planning guideline values (ERPG-1 through 3). This information is merged with population and/or fauna distribution data to estimate *at-risk* population and/or fauna.

Disaggregated population models within the impacted area are created using Census Bureau population and socioeconomic data from the 2000 Census at the census block level, as well as population estimates derived from high-spatial resolution remotely sensed data such as 0.6 m $\times$ 0.6 m PAN-sharpened QuickBird imagery. An example of a hypothetical off-site population *at-risk* estimate derived from the automated risk assessment tool developed based on the Gaussian air dispersion model is shown in Plate 1.

Emergency Response Subsystem
The emergency response subsystem uses the risk information (e.g., *at-risk* population, census blocks, risk footprints) provided from the risk assessment subsystem and consists of three modules. The first and most important module provides evacuation plans for population that are deemed *at-risk* (such as those shown in Plate 1). The plans contain specified *if-then* recommendations for evacuating the people such as those shown in Plate 2. Five digit zipcode polygons, not census layers, are used to prepare the evacuation plans so that responders can easily determine populations that may be affected from the particular event. The evacuation plans are provided to local police who have the responsibility for evacuating the populations at risk using the most appropriate evacuation routes suggested by the system.

The second module exports risk buffers and/or footprints in the GoogleEarth™ KML (Keyhole Markup Language) format so that multiple response personnel can quickly identify geographic areas at risk using GoogleEarth™ at home and/or the office if they have access to the Internet. Using this interface, people can also locate additional evacuation routes if they are in at-risk areas using the driving direction function built into GoogleEarth™.

The third module requests the acquisition of more data, such as new remote sensing imagery, to assist in the decision-making process. The third module incorporates an interface to a satellite imagery collection opportunity modeling system (shown in Figure 3) that provides the SDSS with a list of available sensors and the spatial/temporal windows of opportunity for collecting additional remote sensing data. The satellite orbital model is part of the *Remote Sensing Hazard Guidance System*, a separate SDSS developed at the University of South Carolina (Jensen *et al.*, 2002).

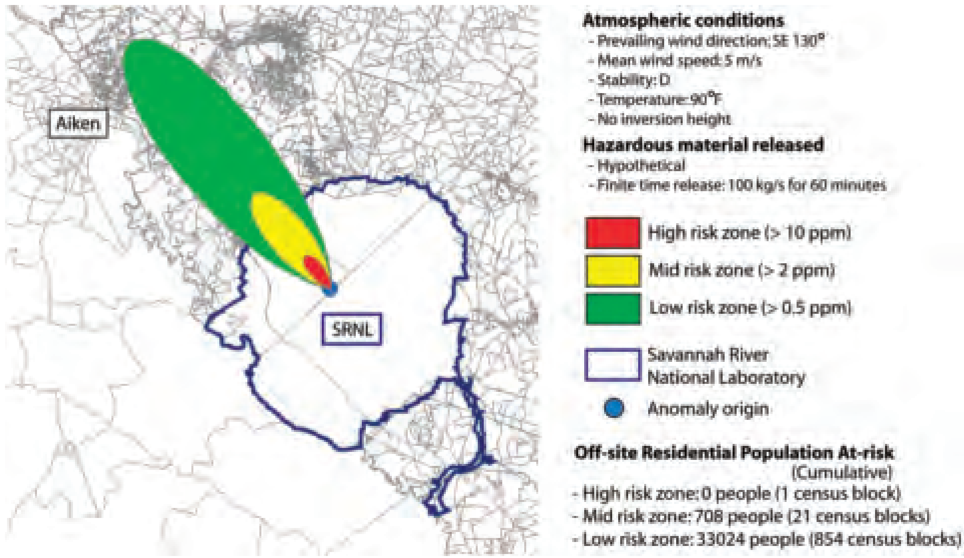

Plate 1. Hypothetical example of off-site population *at-risk* derived from the automated risk assessment tool based on a Gaussian air dispersion model. The origin of the anomaly is on the SRNL.

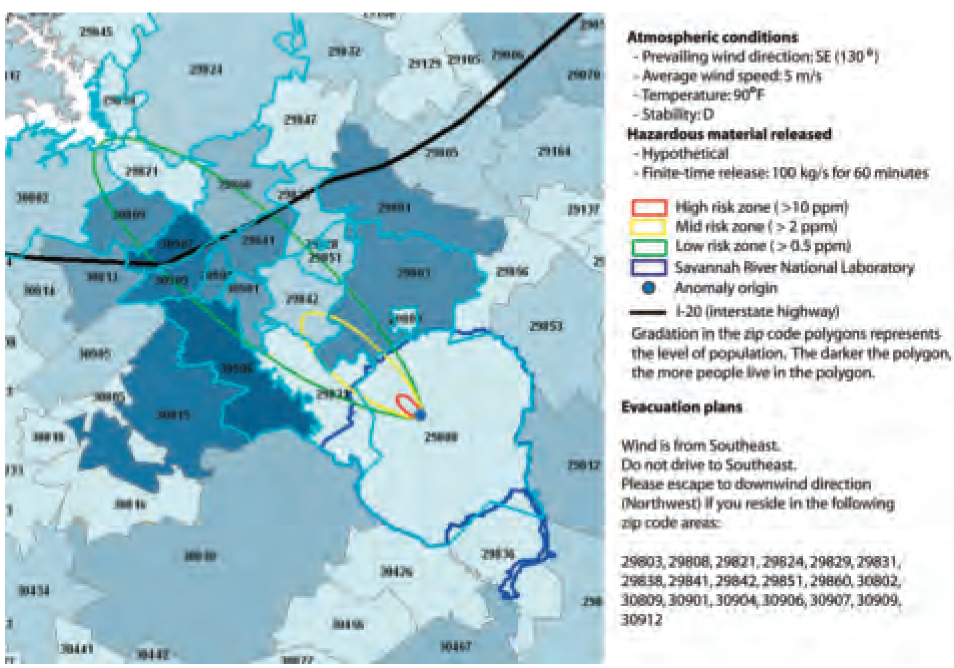

Plate 2. Hypothetical example of evacuation plans based on the footprints extracted from the air dispersion model in Plate 1.

The satellite orbital modeling system is available online (**http://ww2.rshgs.sc.edu/SatModel_PredictCollection.aspx**). A hypothetical request using the satellite orbital model is presented in Table 1. The model also provides the location of the satellite for each available date and maps the potential viewing area and off-nadir angles (Hodgson and Kar, 2008).

The effectiveness of the proposed emergency mitigation plan is evaluated based on a series of recursive passes through the SDSS (Figure 3). The second pass through the system investigates changes to the affected area caused by the recommendations generated by the emergency response subsystem. Risk is re-assessed, which generates a new set of response and mitigation recommendations that target residual impacts. Additional passes through the SDSS are implemented until the risk assessment component indicates that the event is no longer a significant threat to the population or to the environment.

TABLE 1. INPUT PARAMETERS AND SEARCH RESULTS FROM THE EXTERNAL SATELLITE ORBITAL FOOTPRINT MODEL USING QUICKBIRD-2 (SHOWN IN FIGURE 3) FOR A SEARCH ON THE SRNL POINT LOCATION SHOWN IN PLATE 1 FOR 29 MARCH 2007

Input parameters				
Satellite	Start date	Number of days	Location (longitude)	Location (latitude)
QuickBird 2	29 Mar 2007	7	−81.66	33.28

Satellite name	UTC	Local time	Sunlit?	Sub sat longitude	Sub sat latitude	Off-nadir angle	Satellite azimuth	Satellite heading
QuickBird 2	29 Mar 2007 4:37:58 pm	29 Mar 2007 11:37:58 am	Day	−81.81223	33.14127	1.97	281.54	188.69
QuickBird 2	31 Mar 2007 4:00:46 am	31 Mar 2007 11:00:46 pm	Night	−81.97012	33.06307	4.01	258.71	351.57
QuickBird 2	03 Apr 2007 4:42:55 pm	03 Apr 2007 11:42:55 am	Day	−83.00960	33.35218	16.99	282.22	189.38

The emergency management community has long recognized that society's response to disaster events evolve through time. The succession of emergency response stages after a disaster event, known as the Emergency Management Cycle, includes a phase of response/rescue operations, a later phase of recovery/reconstruction, and a stage focused on mitigation and monitoring for future events (Cutter, 1993). This SDSS is innovative in that it addresses the temporal dimension of hazards and the stages involved in emergency response in a cyclical manner as represented in Figure 3.

The implementation of a functional SDSS that encompasses all components of the Emergency Management Cycle represents an important contribution to the management of technological hazards. Additionally, the suite of models and expert knowledge incorporated in the system are specifically targeted for monitoring hazardous waste sites. This addresses the concern expressed by Mondschein (1994) who warned about a lack of actual implementation of SDSS during emergency situations, which he attributed to the complex nature of specific hazards, which might not be adequately addressed by general emergency management SDSS. The procedures developed for this particular application are relevant for other hazardous waste sites around the world.

Summary

The *Remote Sensing and GIS-assisted Spatial Decision Support System for Hazardous Waste Site Monitoring* incorporates a robust module for monitoring hazardous waste sites based on the recursive analysis of spatial data stored in a database management system. Specially developed remote sensing change detection tools in the monitoring subsystem are used to detect anomalies on the hazardous waste sites. A risk assessment subsystem provides timely information about potential risk due to the hazardous materials released to humans and fauna, especially for atmospheric releases. The system helps site managers prepare appropriate emergency responses based on the analytical risk assessment modules. The system can request that additional spatial information be obtained and then analyzed recursively until the problem is deemed to be resolved. The system may be downloaded from the following Internet site at:
http://webra.cas.sc.edu/reason/home.aspx.

References

Agatsiva, J., and A. Oroda, 2002. Remote sensing and GIS in the development of a decision support system for sustainable management of the drylands of eastern Africa: A case of the Kenyan drylands, *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 34:42–49.

Armstrong, M.P., and P.J. Densham, 1990. Database organization strategies for spatial decision support systems, *International Journal of Geographical Information Systems*, 4:3–20.

Carver, S., M. Blake, I. Turton, and O. Duke-Williams, 1996. *Where to dispose of Britain's Nuclear Waste: Open Spatial Decision Making on the Internet*, URL: http://www.ccg.leeds.ac.uk/projects/atomic/ (last date accessed: 04 November 2008).

Costi, P., R. Minciardi, M. Robba, M. Rovatti, and R. Sacile, 2004. An environmentally sustainable decision model for urban solid waste management, *Waste Management*, 24:277–295.

Cutter, S., 1993. *Living with Risk: The Geography of Technological Hazards*, London: Edward Arnold.

Department of Energy, 2001. *High Frequency Electromagnetic Impedance Measurements for Characterization, Monitoring and Verification Efforts*, Washington D.C.: U.S. Department of Energy.

Department of Transportation, 2004. *Emergency Response Guidebook*, Washington D.C.: U.S. Department of Transportation.

Ehler, G., D. Cowen, and H. Mackey, 1995. Design and implementation of a spatial decision support system for site selection, *1995 ESRI International User Conference*, Palm Springs, California, pp. 8.

Fedra, K., 1997. Integrated risk assessment and management: Overview and state-of-the-art, *Journal of Hazardous Materials*, 61:5–22.

Fulcher, C., T. Prato, S. Vance, Y. Zhou, and C. Barnett, 1995. Flood impact decision support system for St. Charles, Missouri, USA, *1995 ESRI International User Conference*, 22–26 May, Palm Springs, California, pp. 11.

Garcia-Quijano, M., J.R. Jensen, M.E. Hodgson, B.C. Hadley, J.B. Gladden, and L.A. Lapine, 2008. Significance of altitude and posting density on lidar-derived elevation accuracy on hazardous waste sites," *Photogrammetric Engineering & Remote Sensing*, 74(9):1137–1146.

Garcia-Quijano, M., 2006. *Claycap Anomaly Detection using Hyperspectral Remote Sensing and Lidargrammetric Techniques*, Ph.D. dissertation, Department of Geography, University of South Carolina, 141 p.

Guber, A.L., R.G. Best, T.A. Chatfield, and K.A. Miller, 1995. A geographic information system for radiologic emergency response, *1995 ESRI International User Conference*, 22–26 May, Palm Springs, California, pp. 6.

Haastrup, P., V. Maniezzo, M. Mattarelli, F. Mazzeo Rinaldi, and I. Mendes, 1998. A decision support system for urban waste management, *European Journal of Operational Research*, 109:330–341.

Herman, J.D., J.E. Waites, R.M. Ponitz, and P. Etzler, 1994. A temporal and spatial-resolution remote-sensing study of a

Michigan superfund site, *Photogrammetric Engineering& Remote Sensing*, 60(9):1007–1017.

Hodgson, M.E., and B. Kar, 2008. Modeling the potential swath coverage of nadir and off-nadir pointing remote sensing satellite-sensor systems, *Cartography and Geographic Information Science*, 35(3):147–156.

Hodgson, M.E., and S.L. Cutter, 2002. Mapping and the spatial analysis of hazardscapes, *American Hazardscapes: The Regionalization of Hazards and Disasters* (S.L. Cutter, editor), Washington D.C.: Joseph Henry Press, pp 37–60.

Im, J., and J.R. Jensen, 2005. A change detection model based on neighborhood correlation image analysis and decision tree classification, *Remote Sensing of Environment*, 99:326–340.

Im, J., 2006. *A Remote Sensing Change Detection System Based on Neighborhood/Object Correlation Image Analysis, Expert Systems, and an Automated Calibration Model*, Ph.D. dissertation, Department of Geography, University of South Carolina, 178 p.

Im, J., J. Rhee, J.R. Jensen, and M.E. Hodgson, 2007. An automated binary change detection model using a calibration approach, *Remote Sensing of Environment*, 106:89–105.

Im, J., J.R. Jensen, and J.A. Tullis, 2008. Object-based change detection using correlation image analysis and image segmentation, *International Journal of Remote Sensing*, 29(2):399–423

Jaber, A., F. Guarnieri, and J.L. Wybo, 2001. Intelligent software agents for forest fire prevention and fighting, *Safety Science*, 39:3–17.

Jensen, J.R., 2005. *Introductory Digital Image Processing*, Third edition, Upper Saddle River, New Jersey: Prentice Hall, 526 p.

Jensen, J.R., 2007. *Remote Sensing of the Environment: An Earth Resource Perspective*, Second edition, Upper Saddle River, New Jersey: Prentice Hall, 592 p.

Jensen, J.R., Y. Cheng, D. Cowen, S.L. Cutter, B. Davis, J. Gladden, M. Hodgson, and E.T. Slonecker, 2002. *Development of Remote Sensing-Assisted Natural and Technological Decision Support Systems*, Response to NASA call for REASoN proposals from the University of South Carolina, 52 p.

Jensen, J.R., and M.E. Hodgson, 2006. Remote sensing of natural and man-made hazards and disasters, *Manual of Remote Sensing, Chapter 8*, American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, pp. 401–429.

Jensen, J.R., B.C. Hadley, J.A. Tullis, J. Gladden, E. Nelson, S. Riley, T. Filippi, and M. Pendergast, 2003. *2002 Hyperspectral Analysis of Hazardous Waste Site on the Savannah River Site*, Technical Report, Department of Geography, University of South Carolina, 92 p.

Mackey, H.E., 1998. *Roles of Historical Photography in Waste Site Characterization, Closure, and Remediation*, WSRC-MS-98-00096, Washington Savannah River Company, 13 p.

MacLean, D.A., W.E. MacKinnon, K.B. Porter, K.P. Beaton, G. Cormier, and S. Morehouse, 2000. Use of forest inventory and monitoring data in the spruce budworm decision support system, *Computers and Electronics in Agriculture*, 28:101–118.

Mondschein, L.G., 1994. The role of spatial information systems in environmental emergency management, *Journal of the American Society for Information Science*, 45:678–685.

Morrissey, A.J., and J. Browne, 2004. Waste management models and their application to sustainable waste management, *Waste Management*, 24:297–308.

Peplow, D.E., and C.D. Sulfredge, R.L. Sanders, R.H. Morris and T.A. Hann, 2002. Calculating nuclear power plant vulnerability using integrated geometry and event/fault tree models, *Transactions of the American Nuclear Society*, 87:559–561.

Radke, J., 1995. A spatial decision support system for urban/wildland interface fire hazards, *1995 ESRI International User Conference*, 22–26 May, Palm Springs, California, pp. 14.

RuleQuest Research, 2005. *C5.0 Release 2.01* (data mining software), RuleQuest Research, St. Ives NSW, Australia.

Sanders, R., and S. Tabuchi, 2000. Decision support system for flood risk analysis for the River Thames, United Kingdom, *Photogrammetric Engineering & Remote Sensing*, 66(11):1185–1193.

Schuerger, A.C., G.A. Capelle, J.A. Di Benedetto, C.Y. Mao, C.N. Thai, M.D. Evans, J.T. Richards, T.A. Blank, and E.C. Stryjewski, 2003. Comparison of two hyperspectral imaging and two laser-induced fluorescence instruments for the detection of zinc stress and chlorophyll concentration in bahia grass (*Paspalum notatum Flugge.*), *Remote Sensing of Environment*, 84:572–588.

Segrera, S., R. Ponce-Hernández, and J. Arcia, 2003. Evolution of decision support system architectures: Applications for land planning and management in Cuba, *JC&T*, 3:40–46.

Serrato, M., 2007, Aiken: Westinghouse Savannah River Laboratory, personal communication, 23 May.

Sen, T.K., L.J. Moore, and T.J. Hess, 2000. An organizational decision support system for managing the DOE hazardous waste cleanup program, *Decision Support Systems*, 29:89–109.

Swiatek, J.A., 1999. *Crisis Prediction Disaster Management*, SAIC, URL: http://www.saic.com/products/simulation/cats/VUPQPV4R.pdf (last date accessed: 04 November 2008).

USEPA, 1998. *Evaluation of Subsurface Engineered Barriers at Waste Sites*, EPA 542-R-98-005, USEPA, 148 p.

USEPA, 2003. *National Biennial RCRA Hazardous Waste Report: Based on 2001 Data*, USEPA, 71 p.

USEPA, E.P.I.C., 1999. *Using Aerial Photographs for Locating and Investigating Hazardous Waste Sites, Fact Sheet*, 090CMB03-FS-ER-Drft, USEPA, Reston, Virginia, 2 p.

Vincent, R.K., 1994. Remote sensing for solid-waste landfills and hazardous-waste sites, *Photogrammetric Engineering & Remote Sensing*, 60(9):979–982.

(Received 13 April 2007; accepted 13 August 2007; revised 07 November 2007)