

INTERIM REPORT I

Advanced Capabilities in the Underwater Munitions Expert System

SERDP Project MR19-1126

MAY 2020

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REPORT DOCUMENTATION PAGE					<i>Form Approved</i> OMB No. 0704-0188											
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.																
1. REPORT DATE (DD-MM-YYYY) 07/31/2020		2. REPORT TYPE SERDP Interim Report I			3. DATES COVERED (From - To) 4/9/2019 - 4/8/2022											
4. TITLE AND SUBTITLE Advanced Capabilities in the Underwater Munitions Expert System - Community Feedback and Design of Visualization Output for the Underwater Munitions Expert System				5a. CONTRACT NUMBER 19-C-0015												
				5b. GRANT NUMBER												
				5c. PROGRAM ELEMENT NUMBER												
6. AUTHOR(S) Sarah E. Rennie Alan Brandt				5d. PROJECT NUMBER MR19-1126												
				5e. TASK NUMBER												
				5f. WORK UNIT NUMBER												
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Johns Hopkins University Applied Physics Laboratory 11100 Johns Hopkins Road Laurel, MD 20723					8. PERFORMING ORGANIZATION REPORT NUMBER FPS-R-20-0281											
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Strategic Environmental Research and Development Program 4800 Mark Center Drive, Suite 17D03 Alexandria, VA 22350-3605					10. SPONSOR/MONITOR'S ACRONYM(S) SERDP											
					11. SPONSOR/MONITOR'S REPORT NUMBER(S) MR19-1126											
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.																
13. SUPPLEMENTARY NOTES																
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15. SUBJECT TERMS Visualization Output, Underwater Munitions, Expert System																
16. SECURITY CLASSIFICATION OF: <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 33%; padding: 2px;">a. REPORT</td> <td style="width: 33%; padding: 2px;">b. ABSTRACT</td> <td style="width: 33%; padding: 2px;">c. THIS PAGE</td> </tr> <tr> <td style="text-align: center; padding: 2px;">UNCLASS</td> <td style="text-align: center; padding: 2px;">UNCLASS</td> <td style="text-align: center; padding: 2px;">UNCLASS</td> </tr> </table>			a. REPORT	b. ABSTRACT	c. THIS PAGE	UNCLASS	UNCLASS	UNCLASS	17. LIMITATION OF ABSTRACT UNCLASS		<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 50%; padding: 2px;">18. NUMBER OF PAGES 45</td> <td style="width: 50%; padding: 2px;">19a. NAME OF RESPONSIBLE PERSON Sarah Rennie</td> </tr> <tr> <td colspan="2" style="padding: 2px;">19b. TELEPHONE NUMBER (Include area code) 443-778-8178</td> </tr> </table>		18. NUMBER OF PAGES 45	19a. NAME OF RESPONSIBLE PERSON Sarah Rennie	19b. TELEPHONE NUMBER (Include area code) 443-778-8178	
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Community Feedback and Design of Visualization Output for the Underwater Munitions Expert System

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July 2020

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Community Feedback and Design of Visualization Output for the Underwater Munitions Expert System

Acronyms

API	Application Programmer Interface
BN	Bayesian Network
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CPT	Conditional Probability Table
CSM	Conceptual Site Model
DAIMON	Decision Aid for Marine Munitions
DERP	Defense Environmental Restoration Program
DGM	Digital Geophysical Mapping
DMM	Discarded military munitions
DoD	Department of Defense
DSS	Decision Support System
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FS	Feasibility Study
GIS	Geographic Information System
GUI	Graphical Users Interface
HA	Hazard Assessment
HDF5	Hierarchical Data Format version 5
IDQTF	Intergovernmental Data Quality Task Force
IPCC	Intergovernmental Panel on Climate Change
JHU/APL	Johns Hopkins University / Applied Physics Laboratory
LUC	Land Use controls
MC	Munitions constituents
MEC	munitions and explosives of concern
MEC HA	MEC Hazard Assessment
MR	Munitions Response
MRP	Munitions Response Program
MRS	Munitions Response Site
MRSP	Munitions Response Site Prioritization Protocol
NATB	Naval Amphibious Training Base
NAVFAC	Naval Facilities Engineering Command
NAVSEA	Naval Sea Systems Command
NFA	No Further Action
NFS	Naval Support Facility
OET	OpenEarth Toolbox (Deltares)
ORM	Operational Risk Management

Acronyms (continued)

PA	Preliminary Assessment
PDF	Probability Distribution Function
PDT	Probability Distribution Table
PNNL	Pacific Northwest National Laboratory
QA	Quality Assurance
QA/QC	Quality Assurance/Quality Control
QAPP	Quality Assurance Project Plan
RA	Remedial Action
RAC	Risk Assessment Code
RAO	Remedial Action Objective
RD	Remedial Design
RI	Remedial Investigation
ROD	Record of Decision
RPM	Remedial project manager
SERDP	Strategic Environmental Research and Development Program
SI	Site Inspection
UnMES	Underwater Munitions Expert System
UFP-QAPP	Uniform Federal Policy for Quality Assurance Project Plan
USACE	United States Army Corps of Engineers
UXO	unexploded ordnance
VSP	Visual Sample Plan
WS	Worksheet

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Community Feedback and Design of Visualization Output for the Underwater Munitions Expert System

Summary

This document presents guidance for designing a user interface for the Underwater Munitions Expert System (UnMES) as determined through engagement with the remediation management community. As a synthesis of SERDP underwater Munitions Response research projects, UnMES has been developed to provide probabilistic predictions of the burial and migration behavior of underwater munitions. A review of existing decision support tools in common use by project managers shows a wide variety of implementation approaches ranging from simple spreadsheets to sophisticated statistical systems integrated with a geoscience data management scheme.

This report documents preliminary software design goals to enable UnMES to become a module within an operational Decision Support System. The innovative probabilistic form of guidance provided by UnMES might be incorporated within an existing framework with established legal precedence and governmental approval, to facilitate consideration of the expert system's capabilities. Incorporation of results from UnMES into extant risk management software could provide the optimal way forward for adoption by the user community of the expert systems' predictive capabilities. Presentation of UnMES probabilistic predictions calls for thoughtful and creative visualization techniques to ensure appropriate interpretation of the multidimensional results. Various software approaches for visualization, as well as incorporation of UnMES into geospatial information systems, are reviewed.

1. Introduction

As a legacy of years of military activities, including training and testing, there are numerous current and former Department of Defense aquatic sites contaminated with munitions and explosives of concern (MEC). At many of these inland water and coastal areas the risk of human interaction with unexploded ordnance (UXO) is of grave concern, so that efforts have been mandated to manage and clean up these contaminated sites. The Munitions Response program of the Strategic Environmental Research and Development Program (SERDP) is tasked with developing innovative methods to remediate and sustainably administer areas contaminated by unexploded test firings and discarded munitions. Towards this end, a probabilistic expert system has been developed to predict underwater migration potential and possible depth of burial of munitions in the seabed. UnMES is a computer model based on the best science available from research projects supported by the SERDP Munitions Response program, along with relevant studies from the scientific literature, specifically designed to help guide remediation management of underwater sites contaminated with abandoned munitions.

1.1 Objective

The ultimate goal will be to transition this expert system as part of a Decision Support System (DSS) which can assist planning and decision-making by managers of Munitions Response Sites (MRS). To this end, feedback was solicited from managers of active sites, to understand how they can best receive and make use of the probabilistic predictions that UnMES will provide. To ensure buy-in by the community, it is important that a tool be accessible, easy to use, and clearly address problems that the Remedial Project Manager (RPM) face.

MRS managers are responsible to multiple stakeholders, many of whom are not trained in the interpretation of statistically complex geospatial presentations and the evaluation of uncertainty. Research into optimal presentation methods, designed with the maximum allowable simplicity for clarity, will help overcome barriers to adoption of this unfamiliar modeling approach, and provide value in assuring continuing usage of UnMES as a support tool. As discussed in Section 2.3, specialized expertise required to interpret and manage geospatial statistics is often obtained by subcontracting with industry consultants. In designing a future interface for UnMES, it is also important to consider their role in the management process.

In order to achieve accurate and well-resolved understanding of UXO burial and migration behavior, UnMES requires a significant amount of input data to clearly define both the site environment and the types of munitions that are present. UnMES is designed to operate with varying levels of input information, however it must be clearly understood that if the MRS environment and/or the UXO deployment history are poorly known, the predictions will necessarily have a high degree of uncertainty.

For successful transition to a useful tool, UnMES input structure and format should conform with existing standards for environmental surveys, geophysical investigations and munitions characterization. Therefore, a review of current Munitions Response Program (MRP) templates and protocols was undertaken, with aspects relevant to UnMES discussed in this report.

1.2 Background

SERDP has sponsored many years of research into developing methods for effective cleanup of munitions at terrestrial sites, which were successfully transitioned to real-world application through the Environmental Security Technology Certification Program (ESTCP). Upon subsequently tackling contaminated aquatic sites, it became clear that established terrestrial geophysical surveying techniques would be difficult in an underwater environment, due to the challenges both of deployment technologies and sensor performance. Navigation accuracy required for re-acquisition of previously identified anomalies is difficult to achieve underwater,

and burial of ordnance under sediment reduces detectability. In addition, strong waves and currents have the potential to cause munitions to migrate significant distances (e.g., up to 100 m in a storm). As a result, SERDP has funded a number of Munitions Response projects aimed at understanding underwater UXO burial and migration behavior in different storm conditions, and in various environments. The first environment studied was a sandy, wave-dominated coastline, and the prototype Underwater Munitions Expert System was a synthesis of that research applied to the shoaling and surf zones. Further projects are studying UXO behavior in the swash zone on sandy beaches, and on muddy sediments in estuarine environments. Results from these projects will be incorporated in future versions of UnMES.

1.3 Technical Approach

The expert system is built as a Bayesian network, a popular tool for modeling complex systems, especially in the presence of uncertain input, data gaps, or subsystems of dissimilar resolution. The Bayesian network (BN) framework represents all variables (nodes) in the BN as probability distributions, and influences are shown by connecting arcs [Pearl, 1988]. Because a node's distribution is represented by a finite number of discrete values (bins, or states), probabilities are formed as a table (PDT) rather than a probability distribution function (PDF). The network nodes that have dependent relationships are connected, and the relationship is characterized by a conditional probability table (CPT). Bayesian networks supply probabilistic inferences for an outcome of interest based on the propagation of evidence through computation of the CPTs for each node [Spiegelhalter *et al.*, 1993].

A common approach to building a BN network is to train the CPT using a dataset of example cases. However, because field and laboratory data applicable to UXO burial and mobility is extremely limited, the approach used for UnMES development has been to establish deterministic models that capture first-order physics of the processes of interest [Rennie *et al.*, 2019]. Then Monte Carlo simulations of these models are run over relevant combinations of the input variables in order to populate the CPTs in UnMES. For some nodes in the prototype versions of UnMES, where a validated deterministic model has not yet been developed, the CPT is formed using expert opinion, or rules-of-thumb, as in Jäger *et al.*, [2017]. Bayesian networks are especially suitable for modeling in an evolving field of research such as in the SERDP MR program. The modular architecture of a BN, and ability to easily update the CPTs, make it a very adaptable method for knowledge integration.

All parameters that might have predictive capacity for the output nodes (representing hazards) are possible candidates for use in the BN, however, due to the high levels of uncertainty in both the environment and the physics that control burial and migration, only first-order processes are included. If the cases used to train UnMES represent a regional climatology, and there is no

additional input provided to shape the input PDT (i.e., the BN is unconditioned), then the marginal distributions represent prior predictions. By updating and constraining the network with specific input data ("findings"), a forward prediction (posterior distribution) is obtained. The BN propagates the uncertainty, both that of inputs and contributions from the imperfectly known controlling physics, resulting in a probabilistic prediction that is a truer representation of the current state of knowledge.

The UnMES Bayesian network has been implemented in the software product Netica™ [Norsys, 2020], which provides a GUI that allows the causal structure to be easily visualized, as shown in the schematic representation of the prototype version of UnMES in Figure 1.1. This graphical interface is particularly valuable during research and development when important factors and interrelationships are being explored. Managers are likely familiar with this style of presentation because a number of environmental restoration project management tools commonly use similar flow charts to describe pathways between potential sources and receptors (e.g., USEPA, [2010]). However, especially as UnMES grows more comprehensive, this Netica GUI interface becomes increasingly complex and requires a steep learning curve for interpretation, which may present a difficulty for MRS managers with numerous other obligations.

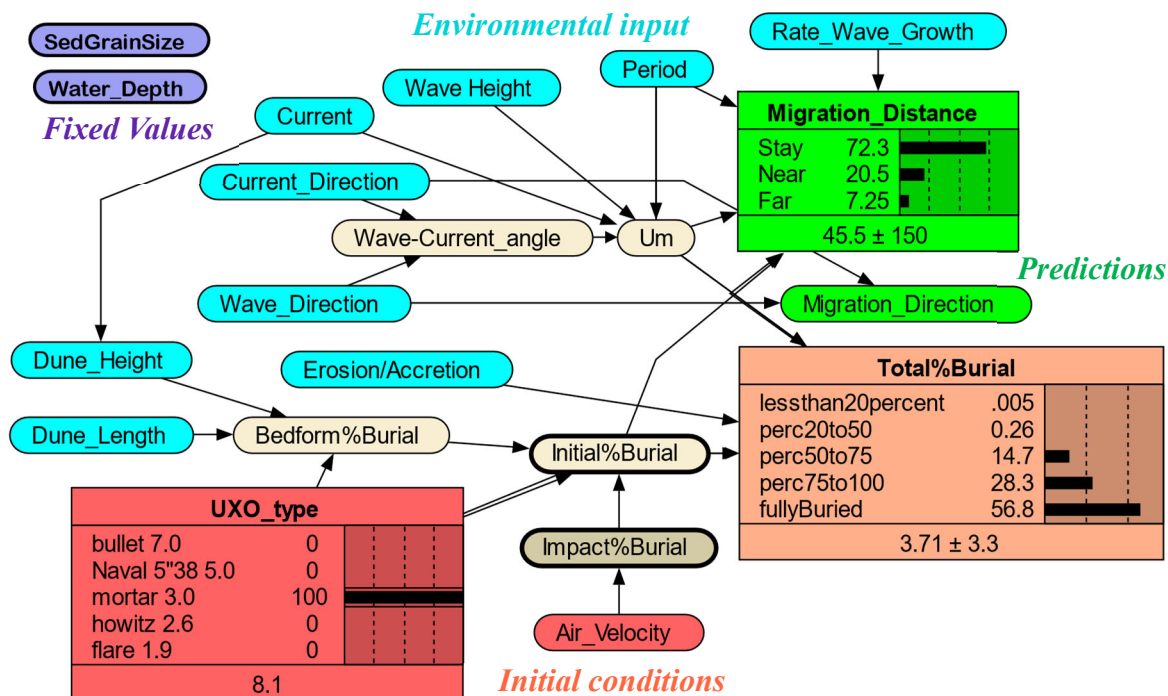


Figure 1.1 Bayesian Network Diagram for Prototype version of UnMES [Rennie *et al.*, 2019]

In Figure 1.1, the hydrologic energy driving burial and migration is shown by the variables (nodes) in blue. This environmental input also includes morphologic information about temporal variation in the seabed: erosion or accretion, and migrating dunes. Intermediate variables are shown in beige. Output nodes (predictions) describe Total%Burial (orange) and Migration (green). Parameters that are unchanging within this UnMES instantiation are shown in purple. The red nodes indicate input variables describing what is known about the munitions present at the site of interest: caliber, density, mode of deposition. Often this information is not well known, especially during early stages of the remediation project before in-situ surveys, in which case the uncertainty would be represented by broad probability distributions. This usually results in increased uncertainty in the output distributions (predictions). When the input distributions are more precisely known, the predictions are correspondingly more certain (narrow distributions).

The node display styles in Netica are either simple labeled boxes, or, as shown for the three nodes in Figure 1.1 that are expanded to reveal all the states for the variables, along with the probability for that state plotted as horizontal bars (termed "belief bars"). Continuous nodes, such as Total%Burial (units are % of diameter), or Migration Distance (measured in meters) are discretized into states that cover contiguous ranges of the variable's domain. Some nodes are inherently discrete, such as UXO Type. Further consideration of possible display options for visualizing Bayesian networks is discussed in Section 3.

The core UnMES BN represents UXO behavior at a single location, characterized by the local water depth, geomorphic setting and environmental forcing. It is expected that conditions will vary spatially across most underwater sites, so that a comprehensive mobility and burial assessment will need to be displayed in a map format, encompassing the results from a range of locations. One approach to modeling cross-site variation is investigated in SERDP project MR-2733 where the CFD coastal ocean model DELFT3D is implemented to compute the hydrologic and morphologic response to time-varying offshore boundary conditions [Palmsten & Penko, 2018]. The initial set up of DELFT3D with UnMES was applied to the Duck, NC location where several SERDP MR field experiments have been completed [Jenkins *et al.*, 2015, Calantoni, 2017].

Wrapper software manipulating multiple core BNs has been written to connect DELFT3D output with a spatially-explicit implementation of UnMES (see Section 3.3). An interface suitable to the MRS management community needs to be designed to provide this functionality in an application that is simple to install, easy to use and in a familiar format. This report documents preliminary software design goals for UnMES as a decision support tool. The design is guided by initial feedback from RPMs about the types of decisions they make, kind of guidance they are seeking, and the format of existing management software currently in use.

2. Engagement with Remediation Community

In order to build a genuinely useful tool for site managers, the research community needs to understand the operational setting of remediation efforts. A review of Munitions Response projects modeled on the cleanup process developed under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) legislation was undertaken in order to pinpoint steps where UnMES could contribute. Varied approaches were pursued to better understand how a remediation project team determines that MEC in underwater areas under their purview poses an environmental liability, and then what types of risk-based decisions are made to manage that identified liability. A questionnaire was sent to multiple contacts in the user community, both within the Naval Facilities Engineering Command (NAVFAC) and in the US Army Corps of Engineers (USACE), asking about their most common concerns and procedures. This initial engagement was made with the hope that some of the managers, or their technical staff, would be interested in working in a closer relationship with the UnMES development team in the future. Several reports from underwater MRS managed by these contacts were examined for familiarity with real world practice. A review of existing software support tools currently in use by RPMs provided detailed information about the type of environmental information generally used to characterize a site, as well as insight into the regulations that guide the projects' tasking.

2.1 Review of the Underwater Munitions Response Process

The Navy's Munitions Response Program (MRP) is part of the Defense Environmental Restoration Program (DERP) designed to perform environmental cleanup at former Naval ranges or munitions disposal sites in compliance with CERCLA [U.S. Navy, 2018]. Best management practices call for the development and continual updating of a Conceptual Site Model (CSM), the detailed interpretation of site data that serves as a systematic planning instrument. The CSM is a concise combination of text, diagrams, plots, maps, and other visualization products that document all the site information in a manner that can be clearly conveyed to all the stakeholders and contractors. With conditions varying spatially across most sites, use of a Geographic Information System (GIS) to organize the map-based data within the CSM is standard. The CSM itself can be considered an iterative decision support tool, and it will evolve as additional data becomes available.

A preliminary CSM starts as a comprehensive overview of the site, including information about past and current usage (based on historical archives both from the military and from the surrounding local government), the environmental setting (geologic/hydrologic information from regional databases), and any proposed future usage for the site. A top priority is to define potential situations in which humans could come into contact with MEC (receptor pathways). Using information from the preliminary CSM, input to UnMES about UXO characteristics and the

environment will necessarily be uncertain, however the expert system could still provide generalized prediction of the burial and mobility potential for guidance. As further information about the site is obtained during the remediation steps, and the CSM is updated, the UnMES prediction can become more certain, and of greater use in guiding management decisions. Standard remediation steps for Munitions Response are discussed in the following sections.

2.1.1 Assessment Phase

Site assessment is accomplished by the Preliminary Assessment (PA) phase, followed by a Site Inspection (SI). These are not intended as full-scale studies of the extent of UXO hazards on site, but rather to identify the site and determine the nature of the threat. The PA extends the preliminary CSM's collection and review of historical information about the MRS, and aims to delineate boundaries, collect broad information, and perform an initial assessment of the risk. On terrestrial sites, the PA might include a visual survey to see if there is physical evidence of the presence of MEC, and then the SI would include a visual and detector-aided field inspection focused on identifying surface evidence of MEC. After either step, if the evidence supports an assessment that there is insignificant MEC threat, a decision of No Further Action (NFA) can be made. If performed correctly, the SI should eliminate sites that pose no significant threat. At the other extreme, if dangerous UXO accessible in current activities is found during the assessment, an Interim Remedial Action would be recommended before proceeding. After the assessment steps are complete, the preliminary CSM would be updated to the Baseline CSM.

For underwater sites, inspection surveys are substantially more complicated and expensive, usually requiring bathymetric and side-scan sonar surveys for seabed characterization, followed by towed digital geophysical mapping (DGM) surveys using electromagnetic induction sensors to locate anomalies. Project teams at Navy MRS are explicitly instructed to take cost into account in managing a MR projects. With that in mind, the Naval Support Facility (NFS) Indian Head, a large base on the Potomac River in Maryland with a dozen different UXO sites, used an assessment procedure for their underwater MRS which followed a modified set of steps: first, a "Water Area Munitions Study" was commissioned from an environmental contractor specializing in water management. Following this study, it was still uncertain whether underwater MEC were present in three of the sites, so an "Expanded PA" was assigned to a second contractor to gather supplemental historic records about site operations, and conduct a literature review on local water and sediment dynamics [CH2MHill, 2010], prior to investing in a Site Inspection. Generalized conclusions about munitions mobility and burial were based on this review. An equivalent exercise applying UnMES could model the mobility and burial with improved fidelity; discriminating varying behavior for different UXO types and revealing spatial variation across the sites. The Indian Head Expanded PA also included risk analyses that will be discussed in Section 2.3 as an

example of current management decision procedures.

2.1.2 Investigation Phase

The second phase to meet CERCLA requirements is usually separated in to a Remedial Investigation (RI) and a Feasibility Study (FS). The RI phase involves the most extensive data collection. Its primary objective is to evaluate the potential explosive hazard at site. Sufficient site-specific data must be collected to characterize conditions, determine the type and extent of MEC present along with potential exposure scenarios, and to form a basis for the risk assessment [NAVFAC, 2019]. There is an accepted protocol established by the Environmental Protection Agency (EPA) to complete a MEC Hazard Assessment (MEC HA) for terrestrial sites [US EPA, 2010]. Several responses to the questionnaire lamented the lack of an official (approved or accepted) MEC HA for underwater remediation. Possible modifications and additions to the existing protocol needed to make it applicable to aquatic sites, and the role that UnMES could play in this extended hazard assessment, are discussed in Section 2.3.3.

The primary technique for RI is to perform a detailed geophysical investigation with follow-on intrusive investigations of target anomalies. This is an expensive and time-consuming task. Analysis of the RI phase will result in an updated Characterization CSM, and should reach a stage where alternative remediation plans can be compared. In the Feasibility Study, response objectives are defined and various threat-reduction remedies evaluated using CERCLA criteria [US EPA, 2010]. The other important goal of the FS is consensus among all the stakeholders, including EPA, state, local, and Navy (or USACE) authorities. An important part of achieving consensus is the systematic work plan required in the form of a Uniform Federal Policy for Quality Assurance Project Plan (UFP-QAPP). The UFP-QAPP enforces structured planning and documentation, ensuring that the type and quality of environmental data needed to make a specific decision will be obtained [U.S. EPA, 2018]. UFP-QAPP consists of a sequence of worksheets. In Section 2.3.1 the specific worksheets are identified where UnMES results are relevant.

2.1.3 Remediation Phase

After the site investigation phases, the CSM (a crucial part of the UFP-QAPP) is updated with the RI/FS findings, passing through the Design stage to the Mitigation stage. During the FS, some number of Remedial Action Objectives (RAOs) can be recommended, based on the specific circumstances at the MRS, including the type, extent and depth of the MEC, and the cleanup goals. The Remedial Design (RD) step selects the most appropriate and effective detection technologies to achieve those RAOs. The choice and operation of the optimal detection sensors can be strongly influenced by the thickness of sediment which may be overlying the target munitions, so that

UnMES predictions of burial is an important input to the Remedial Design.

2.2 Questionnaire to Experienced Munitions Response Site Managers

A preliminary questionnaire was written in collaboration with Bryan Harre at NAVFAC Engineering Service Center, a Munitions Response expert with long familiarity with Navy remediation activities. A selected set of RPMs who have experience working on underwater munitions at NAVFAC sites was contacted, with the aim of eliciting information about their chief management challenges. In addition, a similar version of the questionnaire was sent to several project team leaders at the USACE coastal remediation sites. A summary of the responses received are listed in Table 2.1 and discussed below, with the NVFAC sites highlighted in blue and the USACE sites highlighted in beige. These give insight into the real-world application of the designated procedures outlined in Section 2.1, and helps the JHU/APL development team understand how to optimally present UnMES for use by site managers.

Table 2.1 Summary of Questionnaire Responses from Site Managers

Underwater Site Identification	Environment	Description / Comments	Current Remediation Phase
Indian Head, Potomac River, VA	Riverine	Large (12,000 acres) impact area from firing range	Extended PA and SI completed (2010)
MCRD Parris Island, SC	Estuarine	shallow tidal waterways very difficult to access	in planning for RI Phase II
Tinian Mortar Range, Marianas	Coral Reef	both shallow and deep: fringe reef with sudden drop-off into channel	planning initial survey
Vieques, Puerto Rico	Coral Reef	Many UXO sites w/ varied history / Need update post Hurricane Maria	Extensive, long-term w/ multiple removal actions
Bogue Sound, NC	Estuarine	Eroding island: land --> underwater / 6600 acres w/ >10K potential targets	PA and SI completed plus underwater survey
MCAS New River (Camp LeJeune), NC	Riverine	incomplete questionnaire response	PA/SI
Governors Island, NY	Sandy Coastal / Riverine	Small (< 200 acres). Piers, Seawalls. Busy vessel traffic and construction	in RI Phase II w/ Diver investigation planned
Ft. Pierce NATB, FL	Estuarine / Sandy Coastal	Medium (~ 4,000 acres) High value property = high visibility	RI/FS after several previous removal actions
Passage Key Range, FL	Sandy Coastal	Large (13,000 acres) former gunnery range; Popular boating location	Extended PA and SI completed (2010)
Camp Gordon Johnston, FL	Sandy Coastal	Medium (3,500 acres) amphibious training beaches, gunnery range	RI/FS after multiple delays
Fort Pickens, FL	Sandy Coastal / Barrier Island	Very Large (>100,000 acres) rifle and bombing range	Completed SI, recommended RI/FS
Ft Monroe (Buckroe Beach), VA	Sandy Coastal	Contamination occurred during unscreened beach replenishment project	Completed RI/FS following removal action

One issue of note for the sites covered by the questionnaire is that out of the twelve locations, less than half have sandy coastal, wave-driven characteristics (all at the USACE sites). The NAVFAC

sites are largely riverine/estuarine, with two locations composed of coral reefs. For UnMES to be relevant to sites of these types it must be extended to cover the geomorphic setting, dominant physics, and UXO behavior in these environments.

An interesting finding from the questionnaire responses was the very long timeframes over which many of the remediation efforts extended. Often the assessment phases had been on-going for several years, and only a few underwater sites had completed a large-scale underwater RI including anomaly identification. Many projects contained both terrestrial and underwater areas, and the focus has been largely on the former. The managers expressed concern about proceeding with aquatic area cleanup while underwater geophysical mapping technologies were not as advanced as on land. In addition, the options for remedial action in an underwater setting are not as mature, usually involving divers, and therefore hazardous, slow and extremely expensive.

By far the most common management practice reported by the questionnaire was monitoring in place with Land Use Controls (LUC) including access restrictions, warning signs, and markings on navigational charts. Research suggests that leaving munitions undisturbed is often a safer option than attempting to recover and destroy [e.g. Beddington and Kinloch, 2005]. This fact, along with the enormous cost of underwater removal actions, encourages the management choice to monitor in place.

In the cases where rapid progress to remedial action had been taken, they were either at high-value coastlines near affluent beachfront communities (e.g. USACE project at Ft. Pierce Naval Amphibious Training Base (NATB), or at the specially funded NAVFAC project at Atlantic Fleet Weapons Training Area Vieques, PR. In general, the USACE sites were further along in the remediation process than the NAVFAC sites, with the exception of Vieques, PR.

Another interesting characteristic of the responses was the pervasive lack of knowledge about the type of munitions to be found in the underwater sites. Because many projects had not yet undertaken the RI study that would clearly identify the ordnance type present at the contaminated sites, the project team relied on historical records of base activity that were often incomplete. Responses also noted that MEC fragments, and extensive corrosion, were common. This feedback is an important process to incorporate into UnMES where currently munitions types are modeled as discrete states of specific munitions (caliber, density) without regard to their condition. A more appropriate probabilistic representation in the face of this uncertainty would be states encompassing some more continuous range of values.

Managers expressed a need for guidance on best practices for underwater monitoring. Because of the reliance on LUC, it makes sense that the main management concern expressed was the potential for mobility and migration: the possibility that MEC move outside the boundaries of the controls.

To inspire confidence in the ability of UnMES to accurately predict migration, sufficient validation of the expert system by field observations is crucial. Up to this time, although models for the onset of mobility have been validated, the total distance migrated during any given forcing event is not yet well established [Rennie *et al.*, 2019]. Depth of MEC burial was of secondary interest to managers, however burial depth was acknowledged to be important in that it plays a role in determining mobility potential, and also influences the detection success of survey sensors. In addition, deeply buried UXO reside in anoxic conditions which decreases corrosion, resulting in fewer broken casings with leaked contents. This is an essential piece of information for management of Munitions Constituents.

Both CERCLA and Navy criteria require the consideration of cost when designing a site management plan. Current geophysical sensors suitable of underwater surveys that are commercially available have difficulty distinguishing metallic clutter from MEC due to limited detection capability and the challenge of controlling the sensor to bottom standoff distance [NAVFAC, 2019]. Clutter composed of numerous manmade items on the seabed (anchors, pipes, general metallic debris) is common, especially near highly-trafficked harbors and ports.

A challenge for UnMES proposed by the manager at NFS Indian Head is to provide predictions that convince stakeholders that a given level of investigation suffices to safeguard human life and property, within the context that no matter how much work is performed during RI/FS, the large underwater site at Indian Head will in all likelihood end up with Land Use Controls. To convey probabilistic statistics to assure this audience, a thoughtful and effective presentation method will be required (Sections 3.2 and 3.3).

2.3. Existing Remediation Management Support Tools

The presentation of UnMES results should anticipate requirements of the remediation community with an understanding of how they use software tools to aid in decision making. An examination was made of the existing computer-based decision tools to understand the approach and style with which managers are already familiar. A number of software tools were mentioned in the RPM questionnaire responses. The complexity and approach of these management aids range from simple EXCEL spreadsheets to a sophisticated statistical package, or a Visual Sample Plan (VSP). The former are accessible by all users, while VSP requires extensive training to use.

2.3.1 UFP-QAPP and NAVFAC MRP-QA-Spreadsheet

The Uniform Federal Policy for Quality Assurance Project Plan (UFP-QAPP) is a collection of templates and worksheets required to be completed by the remediation project team in an effort to enforce quality standards [U.S. EPA, 2018]. DoD MR projects must use UFP-QAPP to

systemically plan and document environmental data collection. UFP-QAPP is a type of software tool with many of the 37 required worksheets formatted in a familiar Excel spreadsheet form. Reference to UFP-QAPP worksheets are pervasive throughout all remediation project planning efforts. A useful exercise for relating the unfamiliar probabilistic expert system to common MRP procedures is to identify those worksheets where UnMES predictions make a clear contribution. The expert system requires environmental input; if that input is defined with reference to the UFP-QAPP data collection plan, it will be in a form familiar to the RPM. This formatting requirement should be considered when designing the UnMES wrapper code discussed in Section 3.

The documentation organized and detailed within the UFP-QAPP is a crucial part of eventually receiving a cleanup Record of Decision (ROD) at a remediation site; a component so important that NAVFAC provides a meta-tool, the NAVFAC-MRP-QA-Spreadsheet. This consists of Excel-format check-sheets to ensure that all the Quality Assurance Project Plans in UFP-QAPP have been filled out fully and correctly. The NAVFAC MEC QAPP check-sheet focuses on the main QAPP of concern where UnMES functionality is relevant. The most important is Worksheet (WS) #10 that specifies the *Problem Definition* at the MRS, for which the horizontal and vertical distribution of the MEC must be described. UnMES provides this information in more detail, along with scientific backing than was previously unavailable. WS#10 is given in narrative format and can encompass figures and maps as output by the expert system. The NAVFAC MEC QAPP expects WS#10 to specify the anticipated depth clearance requirements to render the site safe for future use. UnMES burial predictions can provide this information as partitioned probabilities suitable for quantitative risk analysis tools (Section 2.3.2).

Another UFP-QAPP worksheet where UnMES results are useful is WS#12, the *Measurement Performance Criteria*. Measurement criteria are based on estimates of field sensor detection thresholds, which are strongly affected by burial probability, provided by UnMES. Burial prediction also can be an important input to WS#17, *Sampling Design and Rationale*, where the design of detection surveys is given a statistical basis. UnMES results also enter into the ultimate worksheet, WS#37, *Usability Assessment*, where overall measurement error is documented. The design of UnMES output should allow transparent connections to these worksheets to encourage consistent use of the expert system by remediation project teams.

In existing protocols for evaluating site cleanup, RPMs are already familiar with two sources of commonly acknowledged uncertainty: sampling and analytical. The former refers to statistics of spatial heterogeneity considered either during soil sampling for the presence of Munitions Constituents (MC), or when designing investigative surveys to search for MEC, the focus of tools discussed in Section 2.3.4. Analytical uncertainty is the recognized inaccuracy of analyte testing required for MC analysis. There are long-established quality assurance/quality control (QA/QC)

standards imposed by the EPA on analytical measurement uncertainty, so that the concept of data error is well established with remediation managers. Multiple UFP-QAPP worksheets are specifically focused on quality control of analytical measurements. Extension of this concept to encompass input and prediction uncertainty organized as probability distributions in UnMES could best be couched in terms familiar to these established in Quality Assurance plans.

2.3.2 Risk Analysis Tools

Examples of several simple risk assessment tools can be seen among the PA and SI performed at the various MR sites represented by the questionnaire responses. There have been several risk analysis procedures developed to provide simple, defensible methods to make, justify and record remediation decisions. A generic assessment conceptualizes risk as accumulating through a Source - Action - Receptor pathway. In the case of munitions as the source, explosive hazard is the action of concern, and risk is focused primarily on human receptors. An older, generic Operational Risk Management (ORM) matrix [U.S Navy, 2004] was performed to defend and document several recommendations of the Indian Head Expanded PA [CH2MHill, 2010]. The commonly cited Munitions Response Site Prioritization Protocol (MRSP) [U.S. DoD, 2007], and the Munitions and Explosives of Concern Hazard Assessment (MEC HA) [U.S. EPA, 2010] provide semi-quantitative risk assessments. The MEC HA is particularly useful, being able to quantify relative improvement provided by various remedial actions under consideration. The current MEC HA Protocol is approved for terrestrial use only, although extensions required to handle underwater conditions are fairly easily defined. In the returned questionnaires, several RPMs complained that lack of an official risk management methodology for underwater sites hampered their ability to justify planning decisions and move forward. Further discussion of the MEC HA and recommendations for an underwater extension are found in Section 2.3.3.

The older ORM approach, illustrated here by an example from the Indian Head Expanded PA [CH2MHill, 2010], is typical of the recommended structured process where several hazard factors are coarsely discretized to form an analysis matrix. Based on the CH2MHill literature review of water and sediment dynamics, it was concluded that the riverine sites of interest are generally depositional, so that old UXO would be fully buried. At one location at a bend in the river, the eastern bank was determined to be eroding; nevertheless, it was concluded that UXO burial was still likely. Because UXO burial was assumed everywhere across the MRS, it was decided both that sidescan sonar surface surveys would be ineffective, and that there was no risk for human exposure (i.e. receptor pathways were incomplete) for any water activities. Only activities that intrude below the surface of the seabed, such as dredging or anchoring, were considered risky. To organize and document the decisions based on the Expanded PA recommendations, a hazard

analysis matrix was tabulated based on 2 standard ORM factors:

- 1) Mishap Probability - the likelihood that an accident will happen, given exposure, ranging in 4 states from "Likely to Occur Immediately (A)" to "Unlikely to Occur (D)"
- 2) Hazard Severity - assessment of the expected consequence, grouped in 4 states from "May Cause Death (I)" to "Presents a Minimal Threat (IV)"

At all of the Indian Head underwater UXO sites, the Mishap Probability "Probably Will Occur in Time (B)" was assigned, with anchoring or dredging activity considered a hazardous event triggered by shock or movement of the subsurface MEC. The Hazard Severity "May cause Severe Injury (II)" was the second assigned factor. The combined expression of risk, the Risk Assessment Code (RAC) was then determined by the ORM matrix to be "Serious (Level 2)" for all sites.

The RAC, ranging from "Critical (1)" to "Negligible (5)" provides a ranked expression of risk, that managers have used to compare hazard abatement priorities and to defend remediation decisions [U.S. Navy, 2004]. The simple matrix formulation is similar to the long-standing method to estimate the detectability of sea mines employed in the Navy's Mine Warfare and Environmental Decision Aids Library (MEDAL), where 4 factors describing the seabed and bottom clutter, each with 3 states, are combined into a value that indicates the "mine-hunting environment", i.e., the fraction of undetectable mines [U.S. Navy, NWP 3-15.41]. These uncomplicated tabular formulations are easy for decision-makers to apply, and, after they become official protocol, are difficult to supplant, even when a new procedure is clearly superior in risk analysis accuracy.

These ordinal combinations of explanatory variables, or risk factors, are a kind of simple rule-based expert system, which defines a sequence of logical rules. This straightforward method is easy to understand, but is not able to account for any uncertainty in the knowledge of the factors. The probabilistic form of UnMES extends the rule-based concept, incorporating physics-based knowledge that can be quantified, more accurately compared, and better able to distinguish UXO hazard levels between different sites. The transition from a coarsely delineated ordinal ranking of risk to a more refined quantitative measure by necessity requires the investment of additional resources.

UnMES is capable of increased resolution in risk assessment; especially if a larger investment is made in measurements of the local environment and dynamics. The levels of investment required to take advantage of UnMES capabilities is analogous to that required for the *UXO Mobility Model* developed at Scripps Institute of Oceanography also under the auspices of SERDP-ESTCP [Jenkins *et al.*, 2015]. The *UXO Mobility Model*, described as a hazard assessment tool in the recent NAVFAC RI/FS guidance manual [NAVFAC, 2019], can be run at several levels of resolution, with the data requirements (and, therefore, costs) increasing for each level or "mode." The regional

study performed for the Expanded PA at Indian Head corresponds most closely to a "Mode 1" situation, where only the general setting and basic history is known about a MRS. The corresponding "Mode 1" data applied to UnMES will result in predictions of broad probability distributions, whereas a "Mode 3" level investment in extensive site-specific, high resolution measurements will allow those predicted distributions to be more narrowly distributed. NAVFAC guidance cites concerns about setup costs and predictive uncertainties for the *UXO Mobility Model*; these are addressed by within the current SERDP funding of UnMES development.

2.3.3 Munitions and Explosives of Concern Hazard Assessment (MEC HA)

When designing an end-user interface for UnMES, attention should be paid to existing risk assessment tools that are commonly used, such as the MEC HA [U.S. EPA, 2010]. The MEC HA, which was frequently cited in the questionnaire responses, was developed to assist in evaluation of explosive safety hazards at an MRS in a manner consistent with CERCLA requirements. The MEC HA extends the RAC hazard matrix discussed in the previous section to consider several additional factors and sub-factors. The MEC HA encompasses more information about the accessibility and frequency of MEC encounters at the site, as well as additional details on the explosive potential of the munitions. The major risk variables are categorized as "Severity", "Accessibility", and "Sensitivity"; each of these three being composed of several sub-variables, for a total of nine input factors. Both Severity and Sensitivity provide information about the explosive hazard action (consequence), while Accessibility describes the part of the pathway between the action and the human receptor. The risk Source is conceptualized as the aggregate of munitions present at the site; information about the former site usage estimates an "Amount" factor representing the relative abundance of explosive items. If multiple MEC types are present, the maximum factor is chosen.

A multiagency workgroup carefully assigned a system of weights to these factors, essentially creating an expert system. This weighting scheme was then refined based on feedback from use in the field, resulting in a semi-quantitative hazard score which managers find useful in evaluating the relative effectiveness of various remediation actions under consideration. The nine input factors have between two to eight pre-defined possible state assignments, and there are almost 200K possible combinations of weighted scores. This hazard analysis was designed to be thorough, and thus is necessarily complex, requiring a software tool to superintend data input and calculations.

The MEC HA approach combining multiple variables into aggregate scores has been published for the remediation community in automated Excel workbooks. The user is guided through a sequence of detailed, self-documenting worksheets in which macros compute the cumulative

hazard level. Some entries in the MEC HA Excel worksheets are free-form, but many are managed by drop-down lists allowing selection of pre-defined states, from which the required input factors are determined (examples in Figure 2.1a). The MEC HA structure is easily visualized as a directed graph where, in the same manner as for UnMES, the variables are represented as discretized nodes and influences are shown by connecting arcs (arrows). Figure 2.1b illustrates a Netica implementation of the MEC HA in which nodes are treated as deterministic, with the inputs each set to only one state (100% in a single bin) which represents the assigned MEC HA weight (shown in bottom row of the belief bars displays).

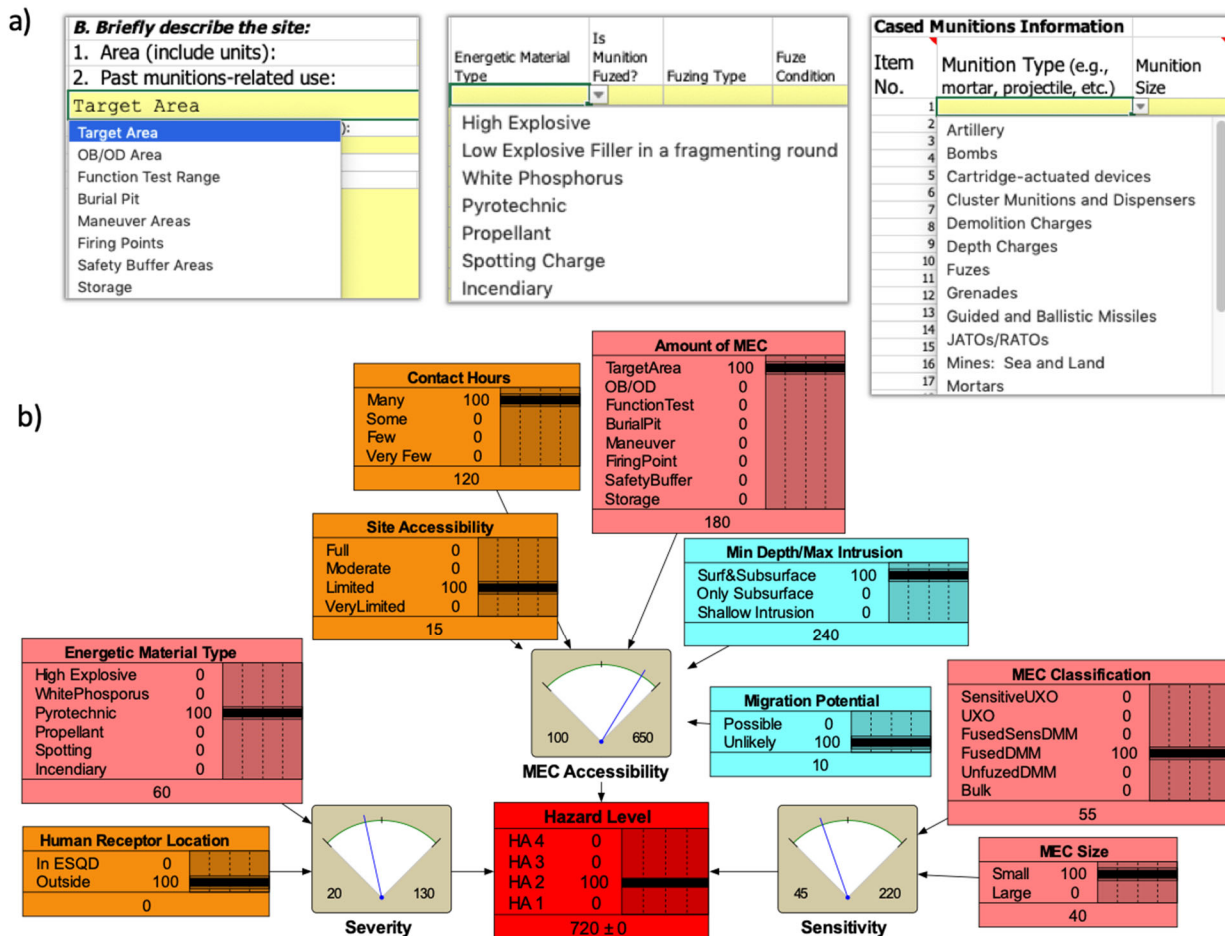


Figure 2.1 a) Example categories (states) in MEC HA Excel worksheets. b) Bayesian Network MEC HA with all input represented with no uncertainty (only state allowed, set to 100% probability).

The three major risk variables, Severity, Accessibility and Sensitivity, are displayed with their aggregate scores in analog "meter" style, which shows the possible range as well as the current setting. These three scores are combined into a final Hazard Level, which is categorized into four states, where Hazard Level 1 (combined score between 840 to 1000) identifies MRS with the highest potential explosive hazard conditions, and Hazard Level 4 (score between 125 to 525)

exhibits low hazard potential. For the example shown in Figure 2.1b, Severity and Sensitivity are fairly low, however the Accessibility score is high, resulting in a final Hazard Level "2" indicating high explosive potential (score between 725 to 835). CERCLA procedures require the evaluation of possible removal and remedial actions, and these four Hazard Levels have become a standard method to compare, contrast and justify remedial alternatives.

In order to clarify the collection of required information, the input factor nodes are color-coded in the Netica graph, with red representing MEC characterization, and orange denoting human activity at the MRS. The blue nodes highlight factors informed by UnMES predictions: the potential for migration, as well as the burial depth of the munitions, are factors in the Accessibility risk, which is the dominant contributor to the total Hazard Level. The input "Minimum MEC Depth Relative to the Maximum Intrusive Depth" was assigned the largest weight of all MEC HA factors, where intrusive depth refers to activities that could disturb MEC lying below the sediment surface. The strong weighting for this factor was doubtlessly driven by the desire to distinguish a remediation alternative that performs subsurface cleanup (a very expensive response action). For underwater sites with current technology, subsurface cleanup may be considered prohibitively costly.

A number of modifications need to be made to the existing terrestrial MEC HA before it could be officially adopted for application to underwater sites, as requested by several questionnaire responses. A possible Underwater MEC HA which incorporates UnMES capabilities is considered here. While the three main categories remain the same, several inputs, including the anthropogenic factors, will change. Recreation and commercial usage of aquatic sites are clearly different than land-based activities. In general, Site Accessibility might always be considered "Limited" (defined as "requiring special transportation") or lower, and the ranges for Contact Hours (stated as receptors-hours/year) will need to be reformulated downward.

Of particular consideration for the role of UnMES, the Migration Potential factor needs to be redefined and assigned heavier weights. For the terrestrial application, "migration" was envisioned as vertical, with driving mechanisms limited to erosion and frost-heaving, and therefore related to the "Min Depth/Max Intrusion" factor. For underwater conditions, change in subsurface depth can be affected by deposition as well as erosion, along with scour and liquefaction burial. In addition, the potential for significant horizontal migration introduces a new risk factor given that previously established site boundaries may be violated by MEC movement driven by waves and currents during strong storms. With the addition of UnMES with the ability to resolve gradation in burial depth and horizontal translation distance, Migration Potential would not be classified only by "Possible" and "Unlikely", but could be categorized into multiple quantitative states for improved discrimination of Accessibility hazard.

As a new underwater version of the MEC HA is considered, it is an interesting exercise to

formulate the updated tool using a BN approach. This would serve several purposes. Site managers would become accustomed to a Netica-style implementation of a risk analysis tool in a familiar context. In addition, a probabilistic implementation allows uncertain input that is more representative of the actual extent of site knowledge. Many of the input factors could be quantified as probability distributions, so that scores indicate the degree of uncertainty present at a given stage of the site investigation. A notional extension of an underwater site MEC HA encompassing probabilistic capability is illustrated in Figure 2.2. Several of the factors are specified to be the same as in Figure 2.1b, but in this example Contact Hours and Site Accessibility are set lower. However, knowledge about access and site usage is considered uncertain, and therefore designated by PDTs with findings spread over the lowest states. The MEC Classification at this example site is known to be Discarded Military Munitions (DMM), however the fuzing type is unknown, so the findings are spread among those MEC Classification states. The aggregate scores are displayed again in "meter" style. Now the needle shows the expected value of the node and shaded bands to either sides show the spread of the distribution (standard deviation). For the nodes displayed as belief bars, the bottom numbers show the expected value $\pm$ standard deviation.

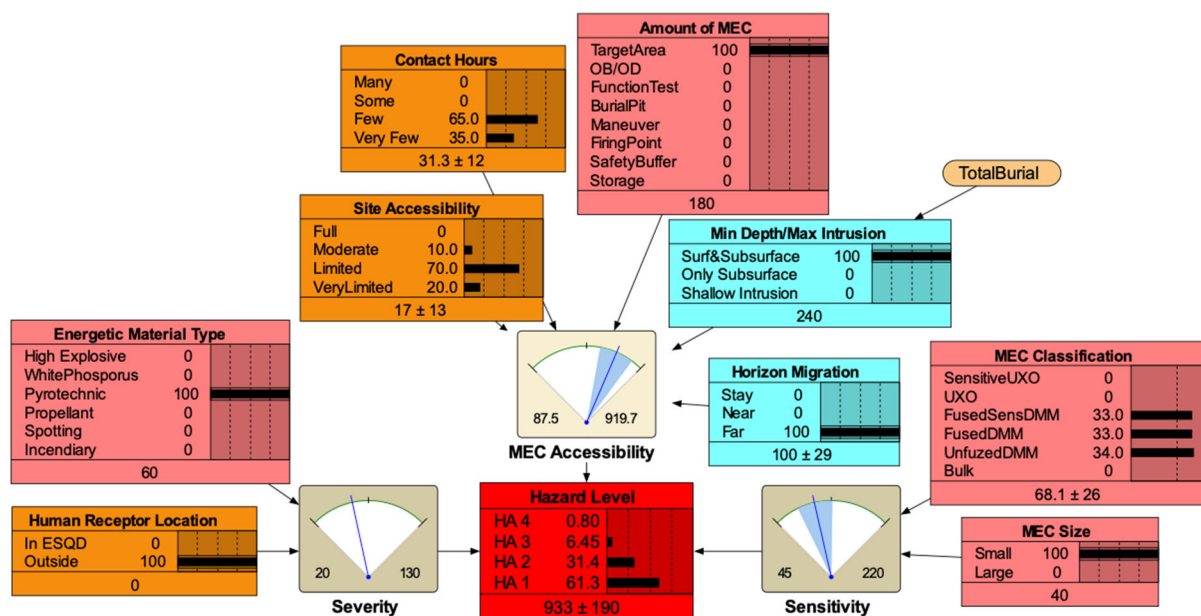


Figure 2.2 Notional underwater version of MEC HA as a Bayesian Network with example input allowed to represent uncertainty, resulting in probabilistic estimation of Accessibility, Sensitivity and Hazard Level.

Examples of the modifications needed to represent underwater conditions are shown in Figure 2.2. The TotalBurial node as computed by UnMES would express the combined potential of erosion

(accretion), plus local and far-field burial processes to modify MEC depth. The Migration Potential node shown in Figure 2.1b is replaced by an input variable derived from UnMES prediction of Horizontal Migration, similar to the Migration Distance node in Figure 1.1. In this case Horizontal Migration is shown with a strong probability of large movement (100% in state "Far"). This finding makes the Accessibility score quite high, and drives the total score so that the highest probability (>61%) lies in Hazard Level 1. The spread within the PDT in the Hazard Level node reveals the hazard uncertainty given current lack of knowledge about the input factors. While uncertain Hazard Level results are more complex, they provide a risk assessment more representative of the true status of the site investigation.

2.3.4 Statistical Survey Design Tools

Another set of software products that are commonly used by MRS project teams fall in the category of geospatial statistical tools that justify survey design, especially during the Remedial Investigation phase. A number of software products have been developed as the results of SERDP/ESTCP sponsored research, and are now standard references accepted as part of MEC QAPP documentation. Visual Sampling Plan (VSP), developed by Pacific Northwest National Laboratory (PNNL), is a statistical sampling design and analysis tool that has been successfully adopted, and is in common usage for DGM survey design by remediation management. VSP has modules specifically designed to determine RI requirements, document defensible sampling plans, and verify success criteria when planning UXO remediation.

VSP software was ostensibly developed to be used by project managers and users without expertise in statistics; however, a significant investment in learning is expected before VSP functionality can be fully exercised. PNNL maintains an active training schedule of 3 to 5-day courses, now largely administered online. Often an MRS project team will hire subcontractors with experience in VSP or similar software products, such as those proprietary to industry consulting companies, e.g. Black Tusk Geophysics' Detection Modeler [Beran *et al.*, 2016], or OASIS Montaj [Geosoft, 2020]. In fact, USACE Technical Guidance for MR projects requires that any GIS manager must have at least three years of experience with the chosen geospatial data system [USACE, 2015], essentially guaranteeing that specialist subcontractors must be employed.

Personnel with VSP or similar expertise have become familiar with many of the concepts required to interpret the probabilistic results provided by the Underwater Munitions Expert System, including Bayesian statistics and confidence metrics. One possible method to incorporate UnMES capability within a familiar decision tool would be to implement the expert system as a module within software like VSP or OASIS Montaj, within which the geospatial database characterizing the MRS has already been populated.

3. Design Considerations for UnMES Interface

While Section 2 reviewed software tools in common usage by the MR community, similar approaches developed within the academic community for the related field of environmental decision support are examined here, especially with regard to presentation formats for the dissemination of risk information. Environmental policy researchers concerned with risk management of coastal areas face many of the same problems as found in MR. The concerned parties of vulnerable coastal systems encompass numerous disciplines, including oceanography, geology, socio-economics and political concerns, similar to the stakeholders at munitions response sites. Risk is assessed using the Source - Action - Receptor pathway in environmental coastal management, considering storms as the source, while hazards (consequences) are due to wave action and flooding/erosion. There are multiple receptors considered including property damage and environmental degradation, as well as human safety. Formulation of the risk pathway for coastal storm hazards is very similar to the high-level risk evaluation framework for the CERCLA-driven MR protocols.

Bayesian networks are a popular academic method of modelling uncertain and complex environmental management domains. Several examples of the application of coastal risk BNs in combination with GIS are examined to see if useful guidance can be obtained from the methods used to present these complex probabilistic results to their diverse audience of multiple stakeholders. In considering the design for incorporating UnMES into a future Decision Support System (DSS), the exact software environment need not be specified at this time, given rapidly evolving software capabilities, especially in open-source supported products. However, specific BN and GIS packages will be discussed to compare capabilities, and provide guidance for the software choices available at the time of future DSS implementation.

3.1 Graphical Representation of Bayesian Networks

Information conveyed about the Bayesian Network belongs to two categories: understanding the network structure (how the input nodes relate to the output nodes), and how the predicted probabilities are distributed. Much of the literature on BNs display the network structure in a manner similar to Figure 1.1, with most of the nodes as labeled boxes, sometimes showing a few nodes expanded into bar chart format, or belief bars, to present the probabilities. It is important to make the node names intuitively clear and precise; many figures have the node name include the units so that the bar labels are comprehensible. Showing all the arcs (sometimes called edges) illustrates the operative causal connections and assumed independence between the variables. However, when the number of arcs exceed more than a dozen, the complexity will likely exceed what a non-specialist audience can comfortably comprehend. It is preferable to illustrate the structural framework of the BN showing a simplified network, possibly with sub-networks denoted

by a single meta-node for clarity, as seen in several papers on *RISC-KIT*, the European Union coastal risk reduction project coordinated by Deltares [van Dongeren *et al.*, 2018]. Note that Deltares is the institute responsible for DELFT3D, the numerical hydrographic model being used in coordination with UnMES [Palmsten *et al.*, 2019], discussed in Section 3.3.

Early work within the *RISC-KIT* partnership was developed in Netica software [e.g. Poelhekke *et al.*, 2016], while more recent BN development frequently uses the GeNie graphical modeling system from BayesFusion [2020]. For enhanced information expression, the GeNie presentation allows color-coding, not only of the nodes, as done in Netica (Figure 1.1), but also of the arcs to indicate classes of relationships. In addition, the width of the arcs is made thicker or thinner to display the strength of influence between two nodes. GeNie also color-codes different states of the belief bar charts, and, by substantial use of pop-ups, allows an intuitive exploration of the BN by the user.

The *RISC-KIT* example BN [Jäger *et al.*, 2018], estimating coastal storm damage to people, infrastructure and the environment, is displayed with nodes involving hazards and consequences grouped by receptors, but the source nodes (water level and wave height) are shown individually. An analogous presentation of UnMES could look like Figure 3.1, where multiple burial processes, shown individually in Figure 1.1, are grouped into a single label box. If details about the individual components are needed, the burial sub-network can be expanded to the level shown in Figure 1.1. For clarity, the waves and currents are grouped as hydrodynamic forcing in Figure 3.1, while the component characteristics (magnitude, direction, acceleration) are available as pop-ups when queried by the user.

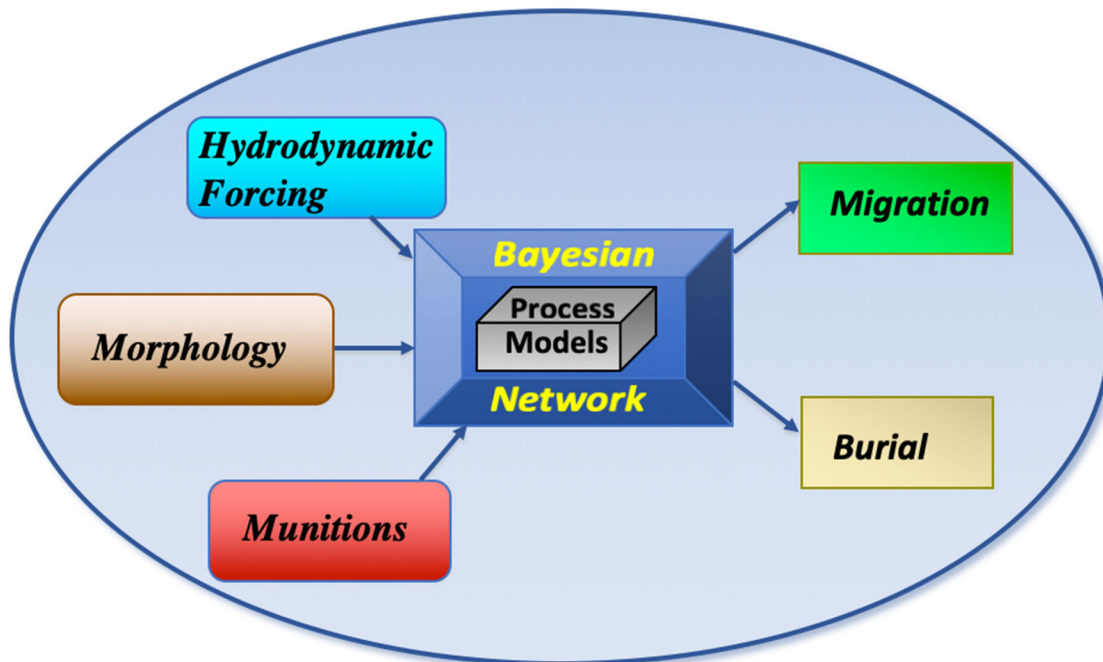


Figure 3.1. UnMES components displayed as functional sub-models for clarity.

Rather than distributing stand-alone software, adoption of a web-based approach has many advantages, especially the wide-spread familiarity with browser access. Maintenance and upgrades can be overseen at the centralized development institute, along with the improvement of on-line tutorials in response to user feedback. There are existing web-based modular training packages that provide a good illustration of a number of best practices in visualization and user-interaction techniques. For example, the USACE Report on Risk Management Strategies for Coastal Communities [USACE, 2020], uses a variety of vivid interactive and animated graphics to convey information. The online report allows the viewer to click to see more complexity and detail, so that learning is driven based on the user's questions and concerns. There is extensive use of hypertext popups with definitions and examples, along with links to resources. Although this USACE report is a training document, and not a working decision tool, the presentation provides excellent guidance for a format that is friendly, clear, and easy to use for a variety of stakeholders.

There are online examples of functional Bayesian networks that can be explored on the demonstration website of HUGIN Expert [2020], a Danish company specializing in Bayesian network software. HUGIN maintains examples of many European BN projects which have been adapted to web-based form using their Web Service Application Programmer Interface (API) [Madsen *et al.*, 2013]. One relevant BN example, <http://demo.hugin.com/example/Coastal>, [Uusitalo *et al.*, 2011] is from the University of Helsinki who have pioneered a number of maritime BN applications. While these online BNs are interactive and functional, the presentation is rudimentary and not suitable for easy operation by a nonacademic end-user. A more practicable

and informative format needs to be developed before such a web-based tool would be readily adopted.

The Decision Aid for Marine Munitions (DAIMON) is an example of an online web-based decision support system relevant to MR site management. DAIMON is a European project for risk categorization of underwater munitions in the Baltic developed by partners in the EU INTERREG Baltic Sea Region, led by the Technical University of Clausthal, Germany [Reuter and Bohlmann, 2019]. The software was demonstrated at the SERDP/ESTCP 2019 Symposium by Claus Böttcher from the Schleswig-Holstein Ministry of Environment. Initial access, encompassing tutorials and demonstration of functionality, is public, which allows project managers to determine if the tool is worth their investment of time. Further use is password-protected with multilevel security to control access to potentially sensitive information. The target users include maritime and military authorities, in addition to environmental protection agencies. Such a project requires committed partners to ensure long-term operability and durable support for users.

3.2 Graphical Representation of Probabilistic Results

An early demonstration of BN modeling of coastal prediction was presented by Plant and Holland [2011]. Rather than display the nodes' probability distributions in Netica's horizontal belief bar style, the PDTs were plotted as vertical bar charts, as being a more familiar format. Bar charts are better for conveying magnitude, and making quantitative comparisons, than pie charts [Spiegelhalter *et al.*, 2011], or the analog meter style introduced in Figure 2.1. However, BN literature frequently display probabilistic results as connected belief bars (e.g. several *RISC-KIT* papers, Gutierrez *et al.*, [2015]). This format fully presents both the network structure and the probability predictions, but requires significant commitment on the reader's part to comprehend. To reduce the barriers to understanding, simpler visualization methods should be developed for UnMES output, even if that requires an iterative presentation with an increased number of graphics.

Plant and Holland [2011] also employed innovative methods of graphically presenting probabilistic predictions (e.g. Figure 3.2a). Related work was extended to consider the BN as a bridge between numerical coastal physics modeling and a decision support application [Fienen *et al.* 2013, Pearson *et al.* 2017]. These papers make use of similar graphical formats, illustrated in Figure 3.2. These BN emulate a physics-based process model after being trained using deterministic model output, in the manner of UnMES, and then provides quantified uncertainty information required for decision making.

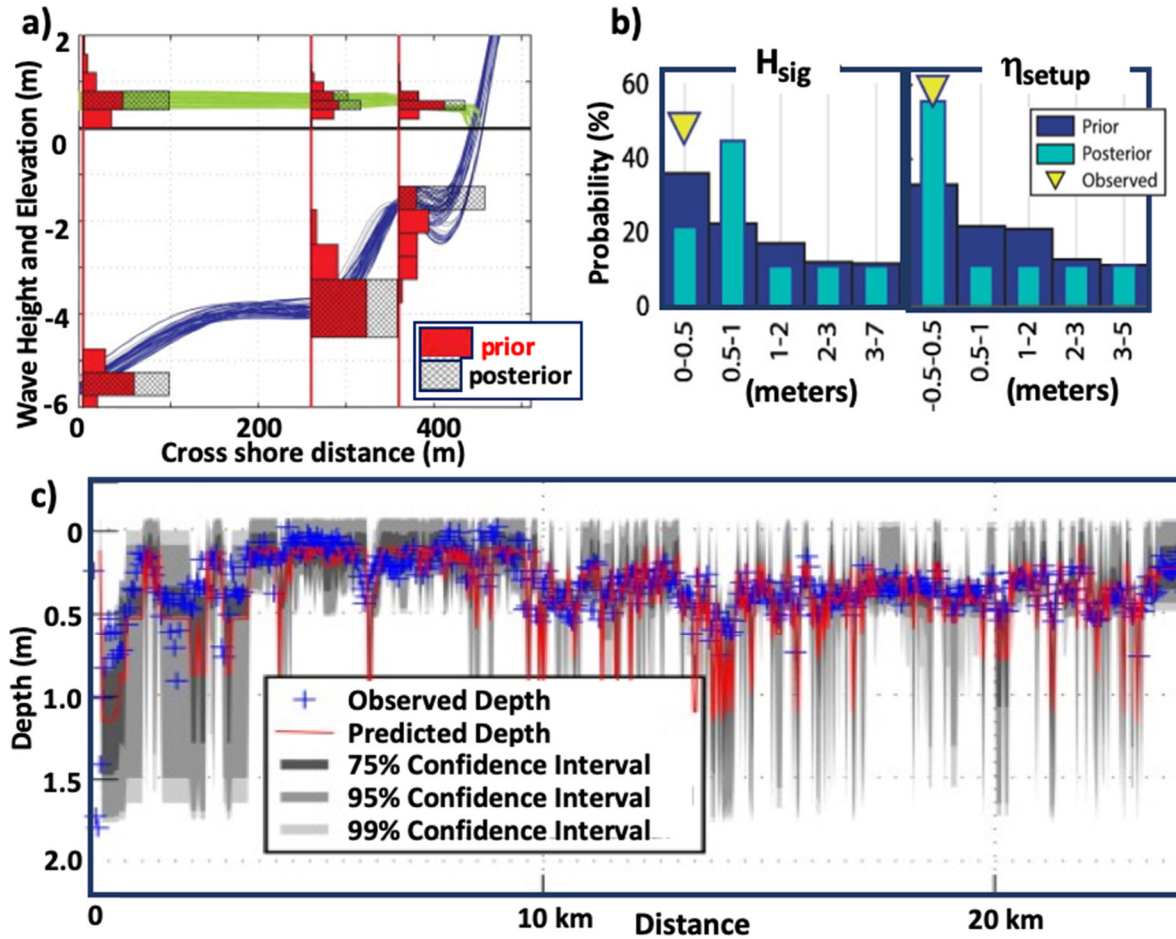


Figure 3.2. Probabilistic graphics from Bayesian Network literature: a) prior (red) and posterior (cross-hatched) belief bars overlaid on bathymetry (blue) and deterministic wave predictions (green), adapted from Plant and Holland [2011]; b) prior (blue) and posterior (cyan) belief bars overlaid with observation (yellow), Pearson *et al.* [2017]; c) spatial series of observations (+), process model prediction (red line), and grey-shaded confidence intervals from emulation BN probabilities, adapted from Fienen *et al.* [2013].

Before project managers will adopt a BN as part of their risk assessment toolkit, they must be convinced that the Bayesian model accurately represents the situation of concern. To accomplish this, the example plots in Figure 3.2 are designed to convey validation information, showing both observations and predictions. This increases the complexity of the display, requiring additional investment on the end-user's part. For the operational user, it is recommended that validation presentations be available in separate graphics from those meant to convey decision guidance.

Figure 3.2 panels a) and b) show both the prior probability distributions (interpreted as representing the climatological, or characteristic, conditions) along with posterior distributions which are

computed after particular findings are entered in the input nodes, defining a specific scenario of interest. In these static plots, as found in published literature, the prior and posterior distributions are overlaid. However, an interactive interface would allow the user to toggle back and forth between various scenarios. Studies find that active engagement between the user and the software display increases comprehension [MacEachren *et al.*, 2005], allowing the user to explore predictions while following their own line of questioning. The presentation format used in Figure 3.2c is frequently used for time-series. The shaded areas, utilizing darker greys for lower confidence, convey the width of the predicted probability distributions, and provide an intuitive representation of regions of larger or smaller uncertainty. Shaded areas are easier to read than the whisker format of many percentile graphics, especially for plots of series.

Academic graphics such as Figure 3.2 convey an abundance of quantitative information. However, many end-users in the operational world prefer risk analysis to be presented as simply as possible, even boiled down to a 3-level stoplight chart (Figure 3.3a). There is no exact quantifiable interpretation of High versus Low, or Red versus Green in a stoplight chart. However, the ability to assess relative risk levels is considered very useful, as was demonstrated in the MEC HA tool (Section 2.3.3).

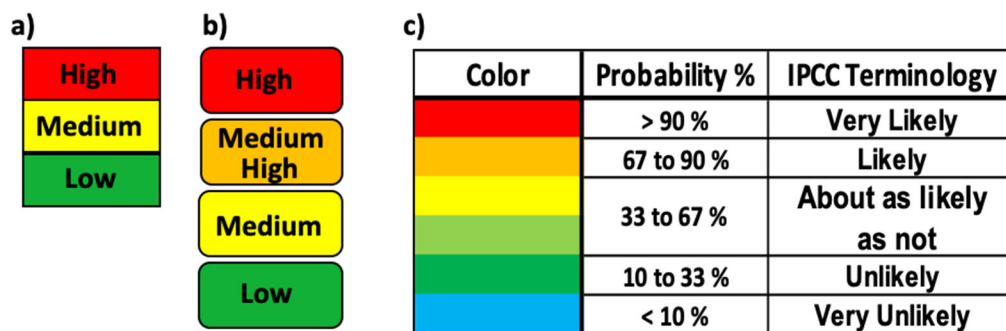


Figure 3.3 Categorical probability charts: a) standard stoplight chart, b) 4 colors used for DAIMON risk analysis results, c) IPCC recommended terminology for expressing risk categories.

The DAIMON DSS provides a web-based view of an extensive compilation of munitions databases collected by partners in the Baltic region. The spatial display and data visualization of DAIMON are fairly sophisticated (see next section); however, risk analysis results are presented only as one of set of 4 colors, inserting a category describing "Medium High" risk (Figure 3.3b). Again, there is no measurable way to compare these 4 risk levels between different objects of concern, but they do provide a relative evaluation for differing environmental and human activity scenarios involving the same object.

A more informative set of risk levels has been proposed for decision making based on guidance from the Intergovernmental Panel on Climate Change (IPCC), which uses a logarithmic

discretization of probabilities, shown in Figure 3.3c [Cubasch *et al.*, 2013]. This evaluation is possible when using quantified probabilities provided by the UnMES prediction of burial or mobility. The accompanying phrasing expresses perceptive acknowledgement of the uncertainty, while each level is specifically related to a numeric probability level, rather than being merely a relative level. This set builds on the familiar stoplight approach, but with 5 levels provides more discrimination among scenarios. An example MR risk scenario might examine the concern that a designated site still contains ordnance even after surface clearance is completed. This risk is equivalent to the UnMES probability of full burial, such that no UXO surface evidence is detected in post-clearance surveys. In this case, the risk of residual subsurface ordnance can be intuitively conveyed to managers using the natural language terminology from Figure 3.3c. For future implementation of UnMES with sufficient validation to support further discretization of the probability ranges, IPCC terminology can be extended to include two end categories: "Exceptionally unlikely" for probability < 1% and "Virtually Certain" for probability > 99%, as presented in Gutierrez *et al.*, [2015].

3.3 Spatial Representation of Probabilistic Models

As described in Section 2.1, many munitions response sites cover a range of environmental conditions that vary spatially within the site, so that a detailed GIS representation of a Munitions Response Site is usually created early in the CSM process. Often, the RPM requires information that will distinguish between different regions within the MRS, and help prioritize remedial actions among those regions. UnMES is envisioned as a module within a data-driven DSS, and given the inherent spatial structure of the problem, there are obvious advantages to implementing the DSS within a GIS framework. ESRI's ArcGIS is the prevailing GIS package, and Geosoft OASIS Montaj software [Seequent, 2020], cited by some of questionnaire respondents discussed in Section 2, is developed in partnership with ArcGIS, including some modules specific to UXO management. The VSL software commonly used for DGM survey design is not exclusively coupled with any specific GIS package, but accommodates ArcGIS formats, as the industry standard. In keeping with a web-based approach, web-GIS architecture would be ideal for integration of UnMES with existing geospatial databases. Visualization of geospatial information in a Google Earth overlay, or as a Google Hybrid map, is another standard being adopted, with the Google Earth web browser providing a familiar interface, and increasing interconnectivity with web-GIS that is readily available.

Methods for connecting Bayesian Networks with existing geographic information systems have been increasingly utilized [Johnson *et al.*, 2011, Chen and Pollino, 2012]. Methods to integrate the BN and GIS range from simple one-way connections to complex coupling, illustrated schematically in Figure 3.4. A simple example, where the GIS provides input data to the BN, and

then receives output from the BN for spatial visualization (illustrated in Figure 3.4a), was the HUGIN Visual Basic API used to link with ArcGIS [Johnson *et al.*, 2011]. A recent implementation, detailed in Zeigler *et al.*, [2019], relied on the ArcMap component in ArcGIS with the associated Python programming language environment to connect with a Netica BN assessing coastal habitats for bird populations. A GIS database was created with layers describing the coastal geology, vegetation, topography, etc. A layer in the GIS was populated with data for each input node in the BN. As in many environmental applications, all the layers are held in raster format. Then GIS layers for each of the input nodes were combined into one layer using the ‘intersect’ operation, and the combined GIS layer exported to be entered into the Netica BN as findings in a case file. The updated probabilities for output nodes (i.e. nodes without findings) as imported back to the GIS into a new layer from which habitat probability maps are displayed.

This approach, where gridded data is passed through the BN as case files, is used in the current integration scheme between UnMES and DELFT3D presented by Palmsten and Penko, [2019]. Gridded model output for waves and currents computed by DELFT3D is processed into case files with one line for each grid cell, which are then entered as findings into UnMES via Python API wrapper code. Input for UXO input nodes can be held fixed across the grid. The wrapper then queries the Total Burial and Migration node PDTs, and plots various representations of the probabilities as overlays on Google Earth maps. Figure 3.4c shows an example map of the probability that a UXO of type "bullet" will be fully buried, presented in the IPCC risk categories discussed in Section 3.2. The example is formed from the Duck, NC implementation of DELFT3D [Palmsten *et al.*, 2019] combined with UnMES. At present, the DELFT3D and UXO input are not integrated into a site GIS, but accessed from data files exported into some standard machine-independent format. However, inclusion into an existing GIS is easily accomplished.

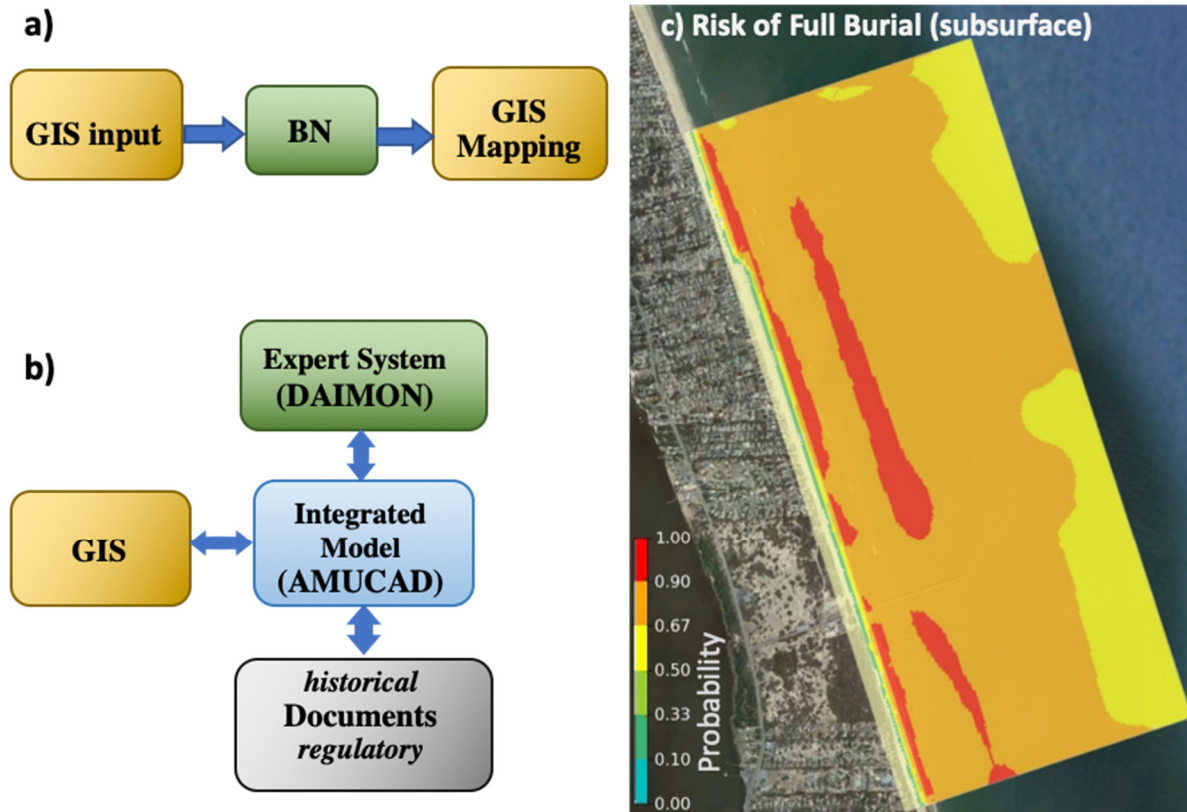


Figure 3.4 Integration of Bayesian Networks (or other expert systems) with GIS: a) simple pass-through connection, b) DSS with coupled connections, c) GIS map overlay presenting risk of complete burial from UnMES-DELFT3D combination. a) and b) adapted from Johnson *et al.* [2011].

Alternate open-source geospatial system software includes PostGIS [2020], built on the PostgreSQL database software. PostGIS is incorporated into Deltares OpenEarth Toolbox (OET) which provides open source infrastructure for data and model management tailored to coastal applications [Deltares, 2020], along with extensions to Google Earth mapping services. A number of the coastal management applications in the *RISC-KIT* project make use of Deltares OET, which is being considered for enhancement of the UnMES - DELFT3D integration and visualization architecture. Another architecture investigated by Landuyt *et al.*, [2015] adopted the open-source QGIS spatial data management software, and integrated Netica BN models using a QGIS plug-in written in Python [QGIS, 2020]. Again, the QGIS data is held in raster format, and the BN applied at each pixel.

The DAIMON project [Reuter and Bohlmann, 2019] makes use of spatial datahub and visualization software developed by EGEOS GmbH, a German visual analytics company. A large database of military detritus in the Baltic and North Sea has been collected by the EGEOS project Ammunition Cadastre Sea

(AMUCAD) into a GIS with a focus on data fusion capabilities, consolidating spatial and non-spatial data, along with visualization, management and analysis functionality [EGEOS, 2020]. While not BN-based, DAIMON is a module providing the risk assessment expertise, tightly coupled with AMUCAD as diagrammed in Figure 3.4b, and provides an integration architecture example for UnMES within a complete DSS.

AMUCAD provides the user interface for management investigation of Baltic UXO; DAIMON analysis does the risk assessment, with AMUCAD software visualizing risk and connecting to metadata bases for further information. Custom interface formats were developed within AMUCAD for the specialized requirements of each receptor, based on several rounds of user feedback. The risk presentation at present is largely text-based, with only a few interpretive graphics [Wendt, 2019]. For UnMES implementation, improvements to provide more immediate and vivid information to the site manager would be preferred. AMUCAD does administer impressive automated report generation capability to support the risk analysis, accessing and organizing geo-referenced historic documents and relevant regulatory guidance, which makes a valuable contribution for meeting requirements to justify and record management decisions.

3.4 Communication of Predictive Uncertainty in Geospatial Applications

Remediation managers routinely make decisions based on imperfect, uncertain information. Methods for visually representing and interacting with uncertainty are an area of active research; several are reviewed here for application to UnMES. Uncertainty is difficult to successfully communicate to a non-scientific audience. When combined with spatially-varying displays, the difficulty increases. The probabilistic predictions from UnMES result in a multi-state PDT, while pseudo-color presentations in map format can only summarize the PDT into one scalar value in the display. In Figure 3.4c the probability of one particular state of concern (full burial) was chosen. From this map, a manager can discern what is the risk level of the UXO being completely hidden under the sediment surface; an alternate interpretation would be that the map represents the percentage of UXO expected to be totally buried. However, no information is communicated about the spread, or uncertainty, of the burial PDT, including details about the possibility of partial burial.

Investigations into uncertainty visualization techniques have proposed the use of additional visual cues including texture, scaling, transparency, and glyphs to convey the multidimensional information on a map [e.g. MacEachren *et al.*, 2005]. However, geospatial presentations are already complex; and are themselves just one input into a complex DSS. Depending on the target audience, so much information in a crowded visualization can be difficult to assimilate. Instead, several studies have found that the optimal presentation requires a sequence of realizations [Landuyt *et al.*, 2015, Laskey *et al.*, 2010]. Ideally, the user would interact with these alternate displays through a self-driven investigation. Rather than static images, the visualization software

design for UnMES must support exploration in a manner that encourages comprehension and guides the user to answer management questions.

At a minimum, two maps are needed to represent probability: the first displays a univariate quantity of interest summarized from the probability distribution, while the second map represents the uncertainty associated with that quantity. There are several options for the summary scalar metric chosen for these displays. Traditional academic metrics are Expected Value (mean of the PDT) for the quantity, and Standard Deviation for the uncertainty, while a map of Most Probable State (mode of the PDT), along with the probability of that the mode, may be a more intuitive dual presentation for management purposes (Figure 3.5). Some common choices for the quantity and uncertainty metrics are shown in Table 3.1, where the top four lines represents choices for quantity, and the bottom three are measures describing uncertainty. Displaying the mode is especially effective for nodes that are qualitative (e.g. Hazard Level in Figure 2.2). For a BN with discretized nodes like UnMES, rather than a continuous color mapping, it is helpful to divide the color map into color bands that align with the discrete States, as illustrated in Figure 3.5a.

Table 3.1 Choices for Quantity and Uncertainty Display Metrics

Metric	Equation
Expected Value (mean)	$E[X] = \sum_{x \in Set} P(x) * x$
Probability of State of Interest (SoI)	$P(SoI) = P(x \in SoI)$
Most Probable State (Mode)	$Mode = State \left[\frac{\max}{x \in Set} P(x) \right]$
Probability of Most Probable State	$P(Mode) = \frac{\max}{x \in Set} P(x)$
Standard Deviation	$\sqrt{\sum_{x \in Set} (E[X] - x)^2 * P(x)}$
Cumulative Probability ABOVE BELOW Threshold of interest	$P(X \lessgtr Threshold) = \sum_{x \lessgtr Threshold} P(x)$
Cumulative Risk with risk threshold (1 - α)	$State \left\{ \left[\sum_{x \in Set} P(x) \right] > \alpha \right\}$

As can be seen in the belief bars of Figure 1.1, Burial and Migration PDTs often have strongly skewed, rather than normal, distributions, so the usual intuitive interpretation of mean as the center, and standard deviation as the width, of the distribution do not convey the correct understanding. Discretization for several nodes in UnMES is irregular, with the final State encompassing a much larger range than the upper States, which distorts the calculation of standard deviation. In strongly modal cases, displaying Most Probable State in the quantity map is very informative. However, for making management decisions, the ability to display a specific State of Interest (SoI) or a Probability Threshold can be the most useful. For the example quantity map shown in Figure 3.4c, the focus was on UXO that were fully buried, therefore the quantity map plots the probability of that SoI. In some situations, especially where extreme responses are paid most attention, users have found that four maps presenting Most Probable State, and Probability of Most Probable, side by side with maps of the analogous Least Probable and Probability of Least Probable State, decisively convey the desired information.

Another frequent management concern expressed in the MRS questionnaires (Section 2) was the potential for migration over distances such that UXO would extend beyond established Land Use Controls. For the Migration Distance node in UnMES, the State "Stay" indicates minimal horizontal change in location (on the order of reacquisition accuracy), while the State "Near" could denote a length some fraction of the distance to the LUC boundaries. Then, for a location in the central region of the MRS, the cumulative probability BELOW the State "Far" indicates the percentage of UXO likely to remain with the LUC, ($P(X < \text{"Far"})$) equals 92.8 for the example shown in Figure 1.1. Alternatively, a revealing metric might be formed as Cumulative Risk, where the manager sets a risk criterion, e.g. $\alpha = 90\%$, and determine the State that cumulatively meets that risk. For the same Migration Distance PDT as in Figure 1.1, the cumulative State "Near" encompasses 90% of the Migration risk.

Given multiple display choices, and the inherent difficulties in visualizing uncertainty in map-based data, the best presentation achieves a sensible balance between portraying the spatial big picture, and the details about uncertainty. One possible approach uses hue to denote quantity and saturation to indicate certainty, with uncertain predictions shown with paler colors. In this case, a threshold can be set so that data is displayed only in locations where the predictions are above some level of certainty. Visualization software for the UnMES-DSS integration should provide multiple available formats, as it is clear that no one approach is suitable for all users and situations [Spiegelhalter *et al.*, 2011]. The optimal design process would iterate through several feedback cycles to assess if the users' needs are met.

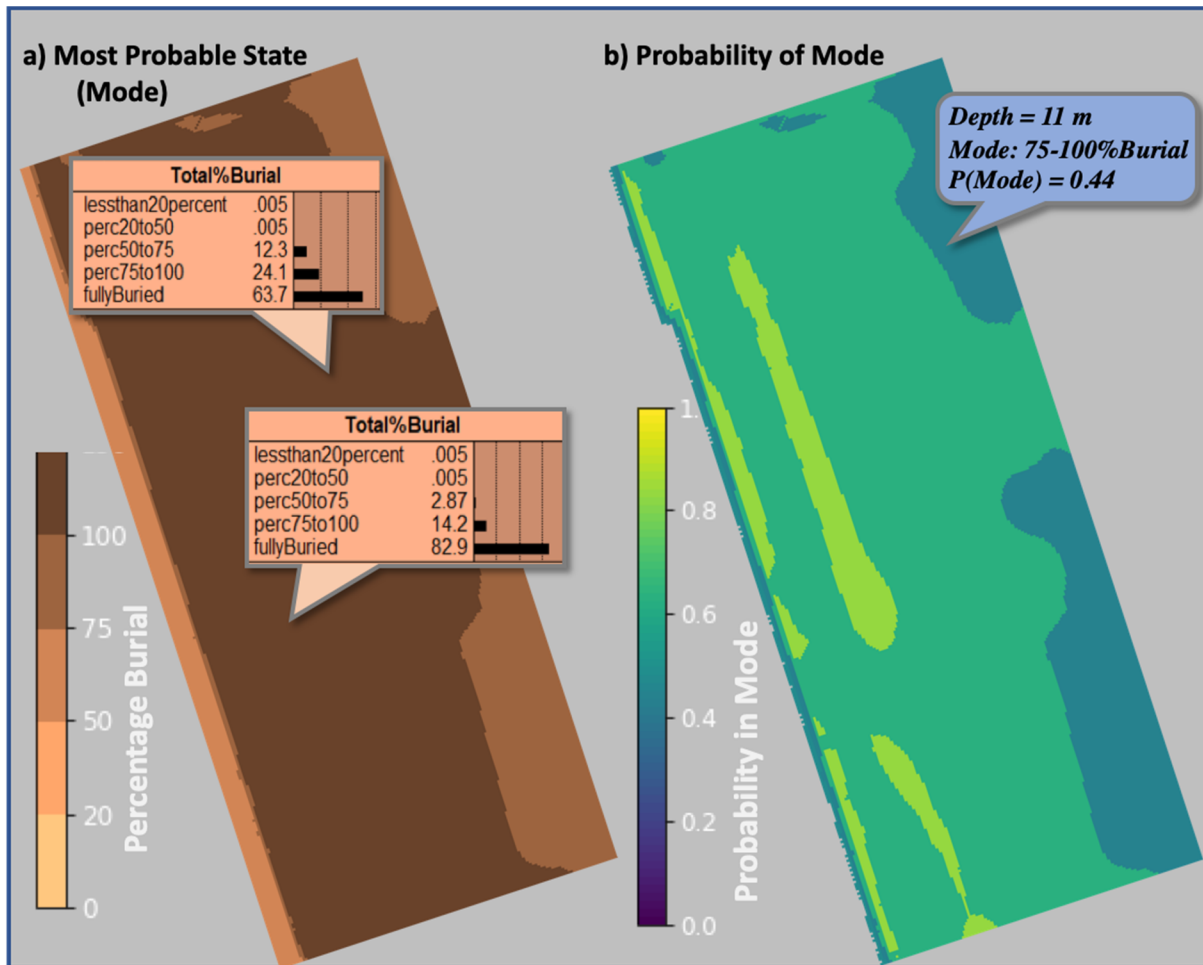


Figure 3.5 Examples of geospatial presentation options from UnMES-DELFT3D implementation at Duck, NC, for Total%Burial predictions for UXO Type of Mortar: a) %Burial quantity expressed as mode, b) %Burial uncertainty expressed as probability of modal state.

Another effective solution for helping decision makers cope with display complexity is to promote effortless interactivity [MacEachren *et al.*, 2005]. A familiar enhancement is to explicate the graphics with pop-up numbers or explanatory text that appear temporarily where the cursor hovers within the display (Figure 3.5b upper right). Well-designed DSS graphics must allow users to dynamically view or suppress uncertainty as they explore the results, controlling how uncertainty is depicted and manipulating the graphics to adjust the visual dominance of uncertainty depiction, to increase their understanding of the probability structure. In particular, permitting control over the probability threshold levels (Table 3.1) encourages the user to customize the investigation to address their specific management issues.

A straightforward method for exploratory interaction with a geovisualization display allows the

user to click on a location to produce pop-ups with additional information about the local probability distribution, as illustrated in Figure 3.5a where all states of the Total%Burial PDF are displayed for two locations of the UnMES-DELFT3D example from Duck, NC. While the Most Probable State is the same across the region (modal state = *fully Buried*), that state is much more probable in a narrow offshore strip located along a bathymetric gradient. This area is revealed more clearly by including the second plot which shows the probability of the mode in Figure 3.5b. Another useful form of interaction is the ability to toggle between alternate information layers on a map. If the maps in Figure 3.5 are toggled with a concordant map of the regional bathymetry, it becomes clear that the narrow area of enhanced burial occurs where shoaling depths cause the waves to steepen and break.

It was clear in Section 2 that MRS managers direct their project based on a comparison of remedial alternatives. Therefore, when designing the software, a strong focus should be on providing the ability to perform quantitative alternative testing. One reason for the popularity of BN frameworks is that they permit rapid feedback to queries into proposed scenarios [Gutierrez *et al.*, 2015]. For UnMES, varying storm scenarios can be evaluated, as well as remedial alternatives that might modify the burial or migration potential. Again, the interactive use of visual toggling can help gain insight into differences between scenarios.

At this stage, following initial community feedback from a group of representative RPMs, a set of requirements for the software to integrate UnMES within a DSS have been discussed. Specifying the exact details of the software architecture and environment, with explicit choices of GIS, BN and graphics packages, would be premature, given the rapid evolution in these fields. Following the verification and statistical validation of the Underwater Munitions Expert System [Calantoni, 2018], UnMES developers should work with visualization software experts to design and build the user interface needed to promote adoption of the UnMES with an approved operational DSS.

4. Conclusions

The Underwater Munitions Expert System (UnMES) has been developed to predict the probability of burial or mobilization of munitions on the seabed. For this information to be successfully transition to site managers UnMES must be incorporated as part of a Decision Support System designed for ease of use by MR management. To understand the needs of MR management and provide a basis for future incorporation of UnMES within a DSS, initial contacts with experienced remediation project managers were made through a questionnaire sent to managers at both NAVFAC and USACE sites. The questionnaire asked about the types of decisions that RPM make, the guidance sought, and the top issues or concerns. While the development of an approved DSS incorporating UnMES, along with its appropriate interfaces, is beyond the scope of the

present project, preliminary considerations of these goals will inform and guide the current continuing effort to develop and improve UnMES.

It is clear that barriers to adoption of UnMES include unfamiliarity with Bayesian Networks and probabilistic models in general. In addition, justifying and documenting management decisions is a high priority, for which decision aids with an established history of acceptance are required. Therefore, integration of UnMES into an existing MR decision tool will likely provide the best transition path. Several tools commonly in use by the MR community were reviewed, with an eye to where UnMES predictions could be best incorporated.

Building a custom user-centered interface for UnMES along with optimized integration with GIS capabilities is best performed by software professionals in consultation with the UnMES developers and the remediation community. Because probabilistic predictions may not be familiar to some users, it is important to design clear, thoughtful display formatting so that information is easily accessible. A recommended path forward would establish a cooperative relationship with several experienced and interested RPMs, who could provide feedback on the effectiveness of the graphics displays and interface. Before UnMES is adopted as a DSS module, satisfactory validation must be presented to the MR community to promote confidence in the value of the expert system results. The exact degree of statistical confidence required is not clear at this time; the general guidance is to validate UnMES "to the regulator's satisfaction." Again, achieving this level of regulatory acceptance will require a close working relationship with the remediation community, toward which the present effort is an initial step.

In order to establish preliminary software design goals for UnMES integration into a DSS, a number of similar projects were analyzed where Bayesian Networks contribute management guidance. A variety of available software packages for Bayesian Networks, GIS and geospatial display have been reviewed with the goal of better understanding the optimal approach for incorporation on UnMES into an eventual MR DSS. At this time, it is premature to specify the exact choice of software environment for the eventual DSS, given the rapid evolution of available packages. However, the use of an open-source software environment, with the aim of a web-based user option is recommended. Substantial commitment will be required to build through the SERDP/ESTCP process a successful, durable UnMES-DSS with sufficient community acceptance and support to secure long-term operability.

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