1.0 Introduction

While there is a high potential for exposure of humans and ecosystems to chemicals and metals released from hazardous waste sites, the degree to which this potential is realized is often uncertain. Conceptually divided among parameter, model, and modeler uncertainties realized during model simulation, inaccuracy in model predictions result principally from lack of knowledge and data. Uncertainty can be imparted through purely subjective judgment or empirical description, and, in the latter case, can be examined along lines of variability and empirical uncertainty. In comparison, sensitivity analysis can lead to a better understanding of how models respond to variation in their inputs, which in turn can be used to better focus laboratory and field-based data collection efforts on processes and parameters that contribute most to uncertainty in outputs.

In resolving uncertainty in model predictions about a target population or subpopulations of interest, separation of variability from uncertainty in empirical parameters, along with identification of associated input sensitivities, leads to a better understanding of how models respond to variation in their inputs. Knowledge of output sensitivity to various model inputs, in turn, can be used to better focus laboratory and field-based data collection efforts on processes and parameters that contribute most to uncertainty in outputs. In integrating risk assessment and risk management, clear communication of risk assessment attributes of the target population and subpopulations are crucial. The NRC (1994) points to the critical need to concurrently engage both in model development and risk assessment stages. In the case of developing empirical representations of model inputs and outputs, subjectivity plays a strong role. In the end, good judgment and Bayesian inference (Box and Tiao, 1973) are relied upon to provide a useful interpretation of risk assessment results based on any modeling exercise.

Elucidating variability, uncertainty, and sensitivity in environmental models can be a difficult task, even for low-order, single-medium constructs driven by a unique set of site-specific data. Quantitative analysis of integrated, multimedia models that simulate hundreds of sites, spanning multiple geographical and ecological regions, will ultimately require a comparative model evaluation approach using several algorithmic techniques, coupled with sufficient computational power.

In practice, knowledge gained through uncertainty, variability, and sensitivity assessment, together with performance validation and prediction auditing represents incremental learning steps in the evaluation process for a given model, in the context of its application. In turn, these endeavors increase our confidence in a model's use over the time. Employed by the scientist, model developer, model user, and decision-maker before and after decision-making, these steps are critical in defining new modeling designs, and updating simulation strategies to further expose details and relationships between key inputs and outputs of the model.

1.1. Report Objectives

This report presents the following aspects of uncertainty and sensitivity analyses, both completed to date and planned for evaluating 3MRA Version 1.0 and Version 1.x. Figure 1-1 describes differences in various 3MRA software versions and terminology (i.e., 3MRA Versions 1.0, 1.x, and 2.0) that will be referenced to in this document.

This document, Volume IV, of the four-volume set describing 3MRA Version 1.0/1.x:

- Describes the underlying principles of probabilistic risk assessment, uncertainty analysis, sensitivity analysis, and holistic model evaluation practices that will provide the context for 3MRA model implementation for a specific purpose,
- Presents an overview of the risk assessment strategy and the conceptual approach that frame the 3MRA modeling system,
- Briefly reviews the dimensions and science modules that make-up the 3MRA model, including chemicals and metals, sources, exposure pathways, receptors, health and ecological benchmarks, and risk metrics,
- Describes a computational and software framework for conducting model evaluation strategies for 3MRA Version 1.0 based on use of 3MRA Version 1.x,
- Provides example outputs of this computational software framework,
- Delineates and summarizes 3MRA model inputs and model outputs, and
- Finally, provides a detailed model evaluation plan with elements of uncertainty analysis, sensitivity analysis, and sensitivity-analysis-based performance validation that complements the efforts to date to assert compositional and performance validity of the 3MRA modeling system

1.2 3MRA Risk Assessment Problem Statement

A modeling-based methodology entitled Framework for Multimedia, Multipathway, and Multireceptor Risk Assessment (3MRA) (Marin *et al.*, 1999, 2003) was originally developed with the goal of facilitating the establishment of national regulatory limits related to "safe" constituent concentration levels in waste streams entering land-based solid waste management units. The 3MRA methodology is a conceptual approach to "site-based" regulatory risk assessment problems. Site-based regulatory problems and assessments, in this context, refer to national scale regulatory decisions that are based on risk assessments conducted at individual sites that are statistically determined to be representative of the set of actual sites that occur, or may occur, across the nation. The original draft 1999 methodology document (Marin *et al.*, 1999) is presented in Appendix A.

Currently there exist three technologies related to 3MRA.

3MRA Version 1.0: This technology represents the modeling system designed to execute national site-based risk assessments. This technology is the primary subject of this document set and is fully available to the public.

3MRA Version 1.x: This technology is an extension of 3MRA Version 1.0 that includes software specifically designed to facilitate (1) the execution of 3MRA Version 1.0 on a network of 176 Personal Computers linked together to form a supercomputing capability, and (2) the execution of uncertainty analysis and sensitivity analysis studies using 3MRA Version 1.0.

This technology is currently operational in a research context. It is described in Volume IV and is being applied to assess the uncertainties and sensitivities in the national exemption level application of 3MRA Version 1.0.

3MRA Version 2.0: This technology represents an extension of 3MRA Version 1.0 to facilitate the execution of site-specific risk assessments and to advance the design of the underlying software infrastructure. The science-based goal of this technology is to contain the science models and databases needed to conduct both national and site-specific assessments within the same modeling system. It further seeks to integrate a robust suite of UA/SA model evaluation technologies for developers, stakeholders, and decision-makers.

This technology is coming online, in Beta release form, during the summer of 2003.

Finally, the infrastructure for each of the 3MRA technologies is based on the **F**ramework for **R**isk **A**nalysis in **M**ultimedia **E**nvironmental **S**ystems (FRAMES). FRAMES represents a collaborative effort among four Federal Agencies (EPA, DoE, DoD, and NRC) to establish a common modeling infrastructure for conducting human and ecological risk assessments. The goal of the FRAMES effort is to facilitate scientific collaboration among the Agencies and to maximize community access to the collective set of models, databases, and data analysis tools developed and applied by the Agencies. Thus, the reader may see references to the following technologies that are synonymous with those listed above.

FRAMES 3MRA Version 1.0
FRAMES 3MRA Version 1.x
FRAMES 3MRA Version 2.0

Figure 1-1. FRAMES 3MRA Software Versions - Naming Conventions.

The 3MRA Version 1.x modeling system, as developed to date and with planned post-processing enhancements discussed in Section 6, embodies and extends in several ways the original 3MRA Framework Methodology (Marin *et al.*, 1999, 2003). The result is a useful, flexible application paradigm for conducting site-specific, regional, and national risk assessments of land-based hazardous waste disposal. 3MRA, among many capabilities, can determine constituent-specific waste stream concentrations that represent a threshold below which RCRA (1976) Subtitle C disposal will not be required, allowing a waste stream to safely "exit" the hazardous waste management system and be managed in a RCRA Subtitle D (nonhazardous) waste management facility. It was to accomplish this task that EPA developed the state-of-the-science, multimedia, multiple exposure pathway, multiple receptor risk assessment (3MRA) modeling system. 3MRA essentially represents a site-based, screening-level, risk assessment approach.

1.2.1 National Risk Assessment Problem Statement Formulation

As originally captured by Marin *et al.*, (1999) in the 3MRA Framework Methodology, the general problem statement was defined as follows:

Problem Statement: To determine constituent-specific wastestream concentrations that represent a threshold below which Subtitle C disposal will not be required and thus the wastestream may "exit" the hazardous waste management system and can be managed in a Subtitle D (non-hazardous) waste management system.

The fundamental question that the 3MRA assessment methodology is designed to answer, for a given organic chemical or metal waste constituent, was also restated by the Office of Solid Waste in the following way:

Problem Restatement: If a "receptor of concern" is defined as all receptors of a given type that currently reside within a specified radius of all currently existing Subtitle D waste management facilities in the continental U.S., then what percent of the total number of current receptors of concern would be exposed to risk/hazard quotient levels above specified target levels if each facility were to manage the chemical/metal at the same wastestream concentration at all facilities?

Rephrasing this latter question into one that 3MRA is directly capable of answering, the problem may be stated as follows: At what waste stream concentration (C_w) will wastes, when placed in a nonhazardous waste management unit over the unit's life, result in:

- Fewer than A% of the people living within B distance of the facility with a risk/hazard of C or less, and
- Fewer than D% of the habitats within E distance of the facility with an ecological hazard less than F,
- At G% of facilities nationwide?

3MRA Version 1.0 represents a site-based risk assessment approach with post-processing capabilities for "rolling-up" or aggregating model output to construct regional and national population-based risk assessments.

1.2.2 Validity of the National Risk Assessment Implementation

Taken directly from the 3MRA Framework Methodology of Marin *et al.*, (1999) context for the validity of the national assessment strategy is outlined by the following statements:

The validity of any implementation of the 3MRA national assessment methodology depends ultimately on the amount, type, and quality of the data available to estimate the probability distributions of the modeling system inputs, and the quality of the underlying modeling system. It also requires a thorough repetitive application of the model across many scenarios to quantify prediction uncertainty and the sensitivity of model outputs to its inputs.

Clearly, any attempt to determine nationwide risks is a challenge. Performing a risk assessment at a site-specific level is difficult enough. Extending the site-specific effort to a nationwide scale introduces an additional, and significant, layer of difficulty. Ideally, the nationwide risk assessment would be performed in four steps. First, identify all current waste management facilities in the continental U.S. Second, collect all of the site-specific data necessary to characterize each facility and associated site/receptor characteristics, and relevant waste constituent fate and transport processes. Third, develop a site-specific mathematical model to predict the impacts at each site; and fourth, run the site-specific model at each of the sites and aggregate the predicted risks to assess the nationwide impacts on the "receptors of concern".

Under ideal conditions, the 3MRA approach would be based on the following database:

- *A statistically designed sample of waste management units from the target population of WMUs in the U.S.*
- *Direct measurement of the facility/site characteristics (e.g., unit area and volume; depth to groundwater; aquifer thickness; hydraulic conductivity; hydraulic gradient; distance to nearest well; number, location and physiological/behavioral characteristics of receptors) at each sampled site; and*
- *Availability of calibration/validation data sets to estimate data measurement and component model prediction error structures.*

In reality, data limitations, constraints on time and computational resources, and the limits of our scientific knowledge impose a number of departures from the ideal conditions.

Given the inherent limitations in achieving validated "futures" of the 3MRA application to national scale risk assessments, the EPA formulated, and executed, a formal research plan to establish peer acceptance of the process-based science, its integration into a modeling methodology, and, to the extent possible, quantitative measures of the uncertainty and sensitivity of 3MRA risk estimates. The elements of this plan included the following:

- Demonstrate that the individual modules that make up 3MRA include well accepted and peer reviewed, science-based descriptions of each element of a risk assessment.
- Demonstrate that the integrated risk assessment modeling system produces results consistent with field observations and other models designed for similar applications.
- Characterize the uncertainty associated with model estimates for a particular national regulation, and
- Conduct a systematic and comprehensive sensitivity analysis.

At this time, the final steps of uncertainty and sensitivity analysis related to the above stated problem-solution formulation for model evaluation are underway at the Office of Research and Development. This report documents activities conducted to date and final elements of the plan for those efforts, and describes the intended outcome of those efforts.

1.3 Overview of Uncertainty and Sensitivity Analyses Concepts

The formal analysis of 3MRA predictive uncertainty will initially focus on empirical uncertainty derived from: (1) the use of *variable and certain* national and regional-based random input variables describing national and regional variability of various model inputs, where uncertainty is imparted in their use to describe individual site-based assessments that make-up the national assessment strategy; and (2) the use of *constant and uncertain* national, regional, and site-based random input variables, for example, that characterize wastestream properties or various chemical properties. The approach undertaken here allows for separation of these empirical-based uncertainties from inter-site variability derived from *constant and certain* inputs measured at individual sites, as represented in the sampled-site database in 3MRA.

The meaning, implied assumptions, and limitations in use of terms *variable and certain*, *constant and uncertain*, and *constant and certain*, as well as *variable and uncertain,* are described in detail in Section 2. The predictive uncertainty analysis planned for 3MRA (Section 9) will be constructed using a "pseudo" 2^{nd}-order analysis, which is essentially a 2-stage Monte Carlo technique (Marin *et al.*, 1999; Cullen and Frey, 1999). The probabilistic risk analysis approach embodied by 3MRA represents an investigation of uncertainty in describing population and subpopulation receptor risk variability due to land-based disposal of contaminated solid wastes, on a national scale. The uncertainty analysis will also deal with what we will refer to as output sampling error (OSE) associated with simulation-based approaches to modeling system equation solution, such as imposed by use of Monte Carlo simulation techniques.

While some uncertainties in the national scale assessment cannot be explicitly dealt with at this time, their impact may be evaluated to degree through use of various sensitivity analysis techniques that will also be investigated for 3MRA. For example, input sampling error (ISE), or how uncertain we are in describing the existing probability distribution functions parameterized in 3MRA databases, would require additional data and the use of a more generalized 2nd-order Monte Carlo technique dealing with *variable and uncertain* model inputs. In the existing description of national, regional, and site-based databases, this is not currently accounted-for empirically, lacking quantified descriptions of uncertainty in the actual distribution parameters for 3MRA (for example, how "true" are the mean and variance of a given random input variable X). Under this constraint, an initial analysis of 2nd-order predictive uncertainty is highly subjective, and instead is best prefaced by an investigation of sensitivity to the model inputs themselves to determine their individual importance. As will be shown, depending on the approach taken, a sensitivity analysis can also be extended to contribute to establishing a quantitative, performance-based measure (i.e., essentially a prior validation), at the modeling system level, for a specific use or problem statement as noted in Section 1.2.

Detailed discussion on these topical areas of model evaluation is pursued in Section 2. Background is first provided in the following materials to familiarize the reader with the topics of uncertainty and sensitivity as applied to evaluation of the 3MRA modeling system. Initial conceptualizations of sensitivity analysis (SA), uncertainty analysis (UA), and related concepts are compiled here from the works of Jon Helton, Freddie Davis, Andrea Saltelli and others (Saltelli *et al.*, 2000). These concepts are subsequently built upon from the works of many additional researchers in the UA/SA plan formulation for 3MRA laid-out in Section 9, especially those of Beck *et al.* (1997), Morgan and Henrion (1990), Cullen and Frey (1999), and Young, Hornberger, and Spear (Young *et al.*, 1978; Hornberger and Spear, 1980; and Spear and Hornberger, 1980).

1.3.1 Notation and Terminology of Uncertainty and Sensitivity Analyses

The 3MRA model results can be represented by an output vector function $\mathbf{y} = [y_1, y_2, \ldots, y_{n_y}]$ for an associated input vector $\mathbf{x} = [x_1, x_2, \ldots, x_{n_x}]$, where n_x and n_y represent the total number of elements of **x** and **y**, respectively, and there is uncertainty in both **x** and $\mathbf{y}(\mathbf{x})$. Uncertainty analysis (or UA) is the process of evaluating the uncertainty in $\mathbf{y}(\mathbf{x})$ given the total uncertainty in **x.** In characterizing total uncertainty, we can extend separate recognition to variability, and empirical uncertainty in variability (Cullen and Frey, 1999; Marin *et al.*, 1999, 2003), to the degree we can distinguish variability from empirical uncertainty in model inputs.

To evaluate sensitivity of 3MRA, several regression-correlation based global analysis techniques will be evaluated. Global techniques to be investigated early on will be based on standard statistical sampling strategies and will rely on assumptions of near-linearity and near-monotonicity in describing relations between input and output vectors. Following the terminology above (Helton and Davis, 2000, 2002, 2003), we are interested in developing a statistically appropriate sample $\mathbf{x}_k = [x_{k_1}, x_{k_2}, \ldots, x_{k_{n_x}}]$ for k = 1 , 2, …, n_S and output vector $\mathbf{y}(\mathbf{x}_k) = [y_1(\mathbf{x}_k), y_2(\mathbf{x}_k), \ldots, y_{n_y}(\mathbf{x}_k)]$. Described by Helton and Davis, these techniques involve five major components:

1) Definition of uncertainty distributions $D_1, D_2, \ldots, D_{n_x}$ that describe the total uncertainty in input factors, if any;

2) Generation of $\mathbf{x}_k$ from the input distributions;

3) Generation of $\mathbf{y}(\mathbf{x}_k)$;

4) Displays of the uncertainty in **y** from the analysis outcomes of $\mathbf{y}(\mathbf{x}_k)$ (i.e., uncertainty analysis; e.g., using CDF's); and

5) Exploration of the mapping $[\mathbf{x}_k, \mathbf{y}(\mathbf{x}_k)]$ to determine the effects of elements [or groups of elements] of **x** on **y** (i.e., sensitivity analysis).

Uncertainty analysis (UA) can be evaluated, for example, by determining the expected value and variance of **y**. Sensitivity analysis (SA), as used here, is the process of determining how important the elements of **x** are with respect to the uncertainty in $\mathbf{y}(\mathbf{x})$. The vector **x** is comprised of n_x elemental factors x_i that represent input variables (measured factors) and parameters (unmeasured factors or inherent model variables set during calibration). In forming groups of elements of interest, for example, one may wish to segregate inputs by underlying mechanistic process (e.g., streambed sedimentation), or associated groups of processes defining larger portions of the conceptual model (e.g., surface water).

Henceforth, we will generally refer to input variables as model inputs. From a practical perspective, the two concepts, uncertainty analysis (UA) and sensitivity analysis (SA), can be functionally related, and investigation of their structure is a requisite for proper model evaluation. Section 8.1 provides more explicit detail regarding terminology and notation used throughout this document in referring to 3MRA model inputs and outputs, as well as overall dimensionality of the national-scale assessment problem statement.

1.4 Quality Assurance in Modeling

As stated, elucidating uncertainty and sensitivity structures in environmental models can be a difficult task, even for low-order, single-medium constructs driven by a unique set of site-specific data. The challenge of examining ever more complex, integrated, higher-order models is a formidable one. This is particularly true in regulatory settings applied on national scales that must ensure the continued protection of humans and ecology, while preserving the economic viability of industry. Ultimately, we seek to provide enhanced confidence and technical basis for a regulatory decision through integrated, "full-service" modeling (i.e., bringing science and communicating its uncertainties directly into regulation). In essence, a statement of the quality assurance in 3MRA's use for its intended purpose is sought. This is increasingly accomplished in practice today through systematic characterization of model input variability and uncertainty, and the assessment of their overall sensitivity expressed in model outputs.

Achieving adequate quality assurance in modeling, in essence, requires a battery of tests designed to establish the model's validity, trustworthiness, and relevance in performing a prospective task of prediction (Chen and Beck, 1999). To this end, model evaluation is seen as an increasingly critical step in the process of establishing confidence in a model's use, and providing a requisite level of confidence that decision-makers may more objectively rely upon. Together with peer review and repetitive application, this process derives qualitative and quantitative information on various aspects of simulation science and model verification, validation, assessment of variability and uncertainty in inputs and model structure, and the identification of the sensitivity of model output to selected inputs.

1.4.1 Qualitative and Quantitative Model Evaluation Approaches

Assessment of the effects of uncertainty and variability in model inputs upon model output, derived from their explicit representations in model inputs, generally first involves the propagation of both through the model. It is then desired to apportion variance in inputs to variance in outputs.

Aspects of sensitivity for a given model may be evaluated through a wide array of computational techniques, for example, screening methods, local differential-based methods, and global methods (Saltelli *et al.*, 2000). In addition to the variance-based global sensitivity methods outlined by Saltelli *et al.* (2000), which provide the ability to quantitatively relate variance in input to variance in output, there are equally provocative schemes (Funtowicz and Ravetz, 1990) to be investigated that more fully characterize elements of uncertainty, reaching well beyond the quantifiable, commonly applied Monte Carlo-based probabilistic assessments (Cullen and Frey, 1999; Robert and Casella, 1999). In the NUSAP (Numeral, Unit, Spread, Assessment, and Pedigree) scheme of Funtowicz and Ravetz (1990), for example, uncertainty is constructed along a continuum of familiar, quantitative information, as well as less familiar, qualitative information that asserts a level of confidence in the former. Together, the NUSAP entities impart a deep structure of quality assurance in the information system otherwise historically represented by a model's prediction and the best of intentions.

Though done outside the direct guidance of the NUSAP methodology as a model evaluation and quality assurance guidance tool, in retrospect, the 3MRA modeling system development, documentation, and peer-review process has undertaken these major steps along similar lines to NUSAP. Value of information analysis aside (Dakins *et al.*, 1994), to sustain our current course of evaluating ever more complex questions through use of increasingly complex models, variability, uncertainty, and sensitivity analyses will likely continue to rely on application of Monte Carlo-based techniques. However, the future will continue to see advances in methodological approach, and modelers will desire to apply all of these computationally demanding model evaluation procedures in a timely fashion (Beck, 1999).

This report provides an overview of the UA and SA activities completed to date, and planned, for the 3MRA modeling system. It proceeds through a description of a set of hardware and software supercomputing tools that have been created to facilitate model evaluation, summarizes 3MRA runtime costs associated with Windows-based, PC-based simulation, and provides illustrative, conceptual approaches for the implementation of a systematic study of 3MRA uncertainty and sensitivity. Regarding this report's focus on issues of model evaluation and uncertainty analysis of high order models, we are and continue to be greatly indebted to the large collection of researchers in this field and the expertise and advances they have provided.