3MRA Uncertainty and Sensitivity Analysis

SAB Review 3MRA Version 1.0

Panel Meeting: August 26, 2003

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Presentation Outline

- Modeling System Overview; 3MRA Versions
- 3MRA Version 1.0
- National-scale Assessment Dimensionality
- SuperMUSE: Windows-based Supercomputer
- 3MRA Ver1.x – UA/SA Software Tools
- Model Evaluation Approaches
- 3MRA Version 1.0 UA/SA Plan
- Example Model Output Using Version 1.x

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Modeling System Version Overview:

FRAMES and 3MRA

Definition and Relationship between FRAMES and 3MRA

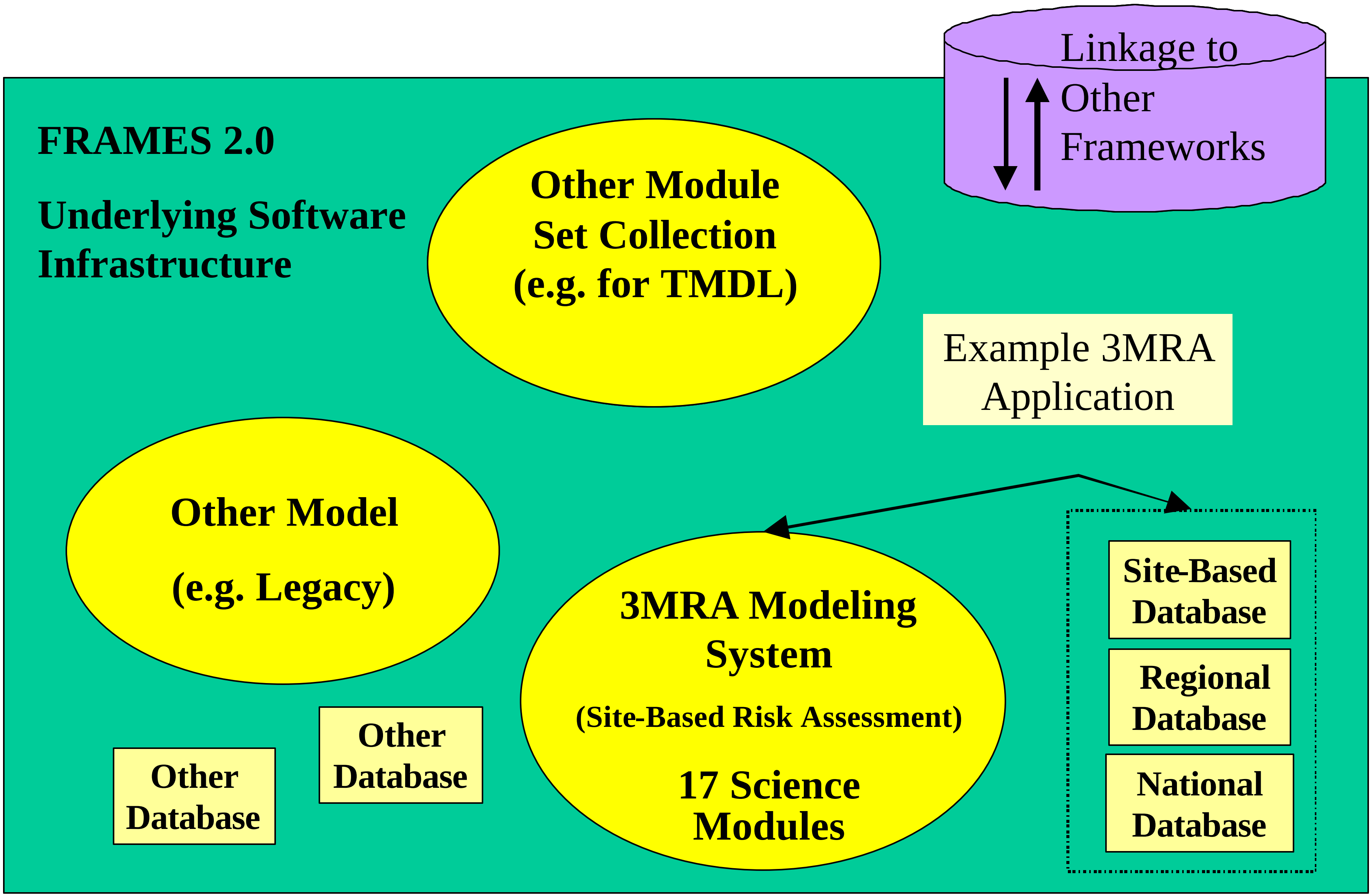
FRAMES — **F**ramework for **R**isk **A**nalysis in **M**ultimedia **E**nvironmental **S**ystems

Underlying software infrastructure for 3MRA and other models and modeling systems

3MRA — **M**ultimedia, **M**ultipathway, **M**ultireceptor, **R**isk **A**ssessment

A specific set of models for conducting site-specific or site-based risk assessments, and "rolled-up" studies on regional and national scales.

Conceptual Relationship Between Framework Technology, Models and Modeling System, and Applications



FRAMES 3MRA Versions

3MRA Version 1.0: National site-based risk assessments

3MRA Version 1.x: A tool set extension to facilitate:
(1) Parallel processing of 3MRA model runs
(2) Uncertainty and sensitivity analyses studies

3MRA Version 2.0 Beta: Same science and data with an extension to facilitate site-specific risk assessments. Significantly advances the design of the underlying FRAMES infrastructure.

FRAMES 2.0 joint, multi-agency development

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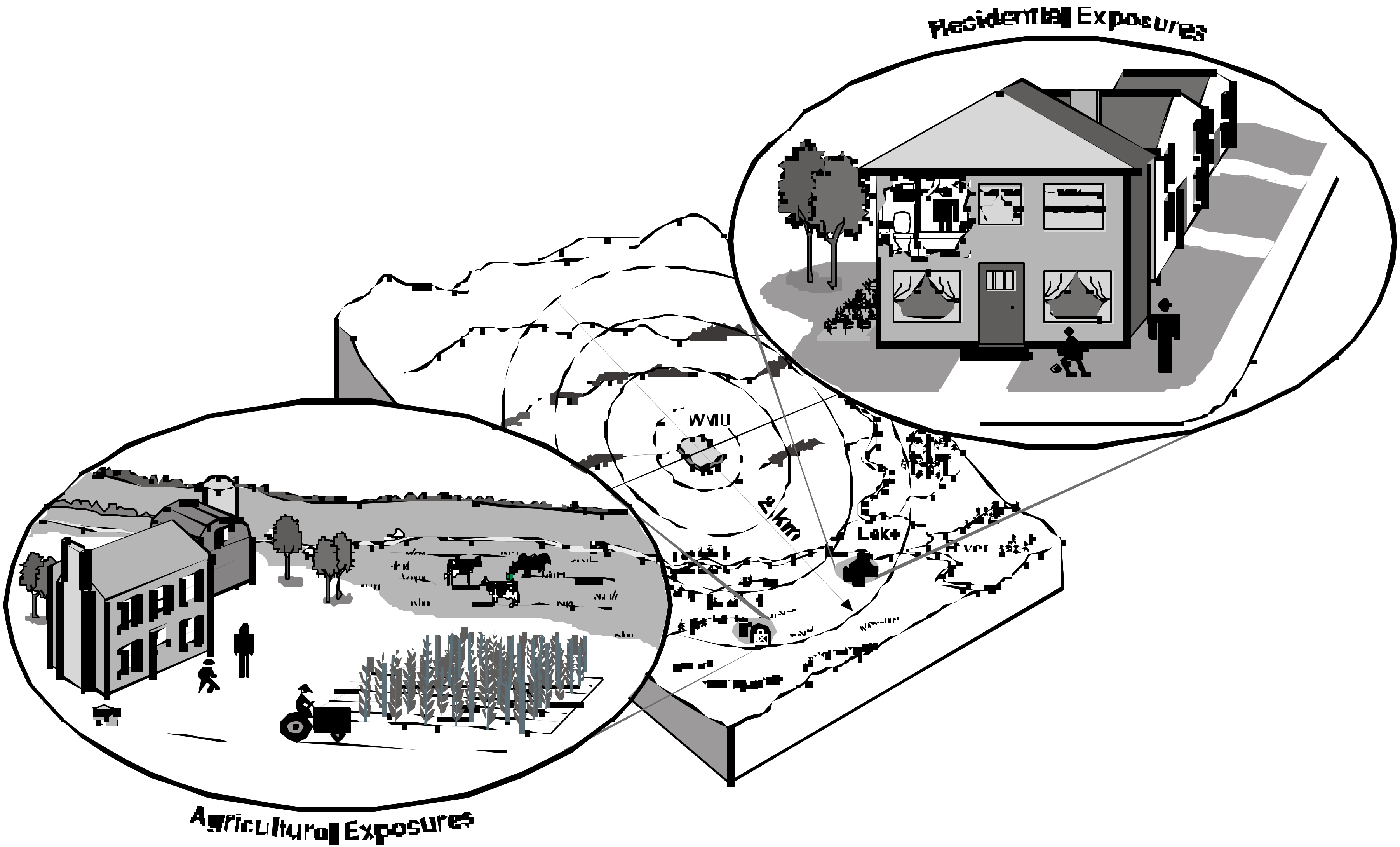
3MRA Version 1.0

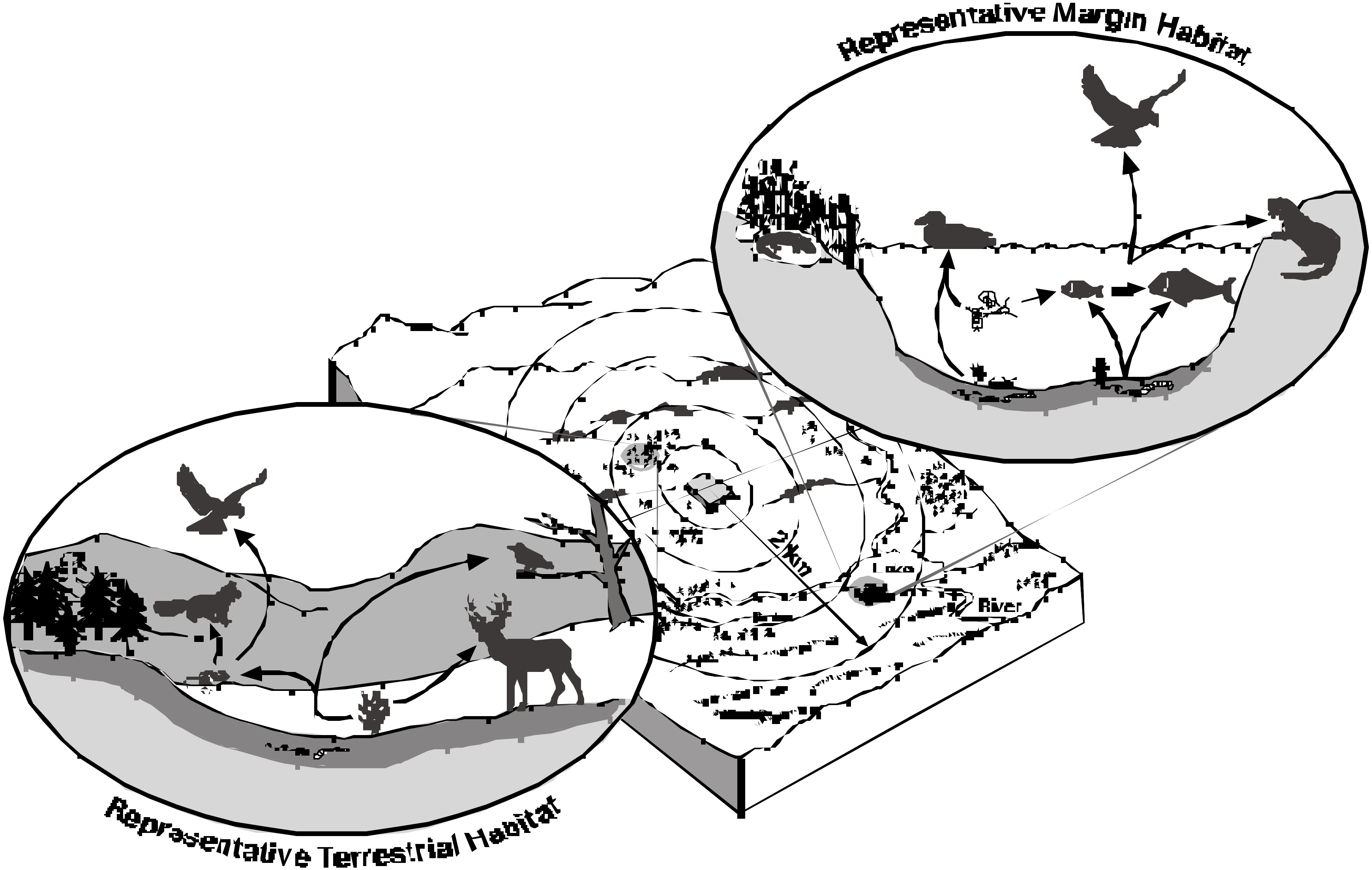
Multimedia, **M**ultipathway, **M**ultireceptor,
Risk **A**ssessment

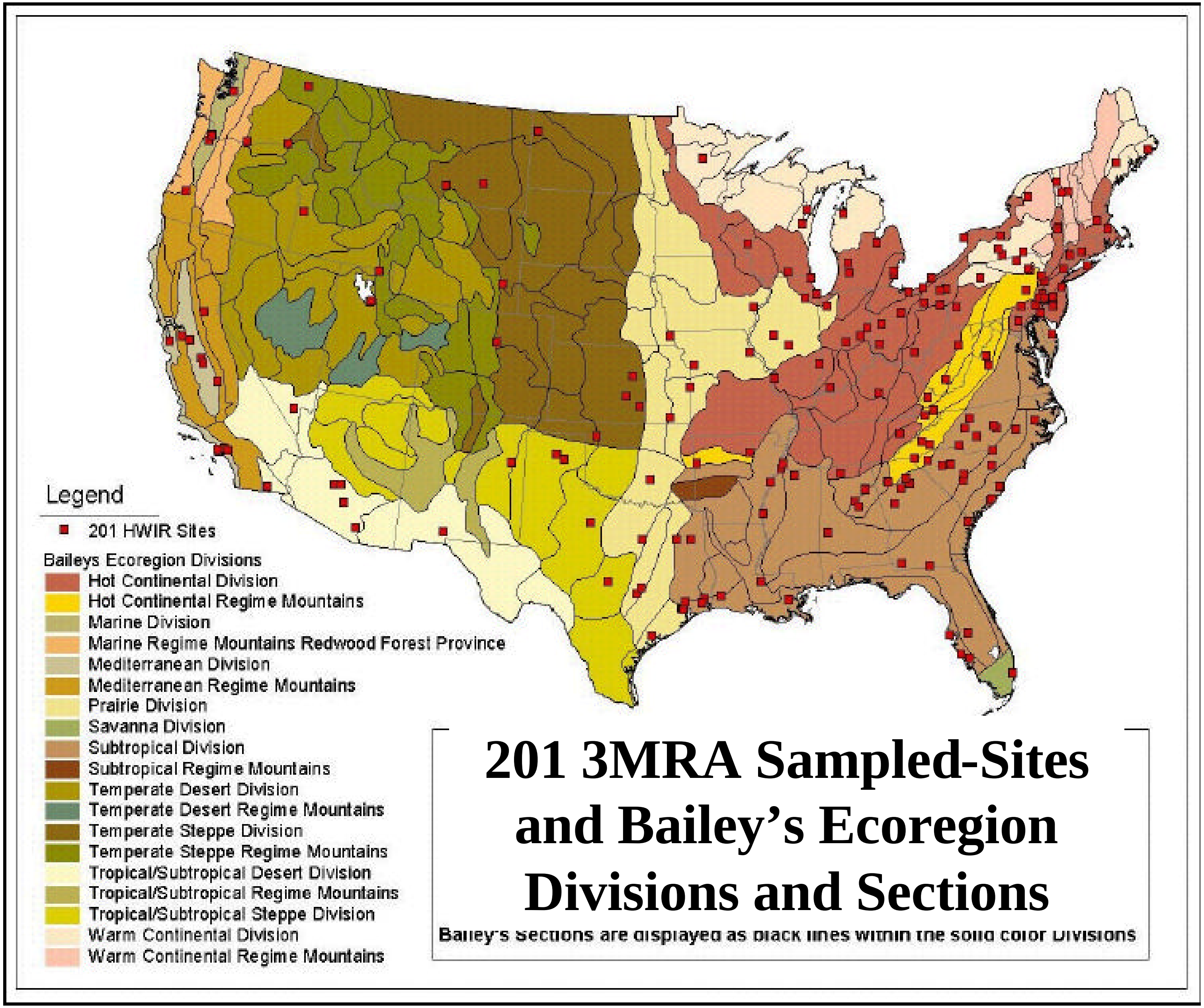
…A screening-level, site-based modeling approach for national-scale assessment of land-based hazardous waste disposal .

Conceptual Framework For Human Receptors



Conceptual Framework For Ecological Receptors





…419 Site-WMU Combinations in 3MRA databases

Overview of 3MRA National Study

Source Types (WMUs)

- Surface Impoundment
- Aerated Tank
- Landfill
- Waste Pile
- Land Application Unit

Problem Statement

Conceptual Model

Modeling System

Input Data

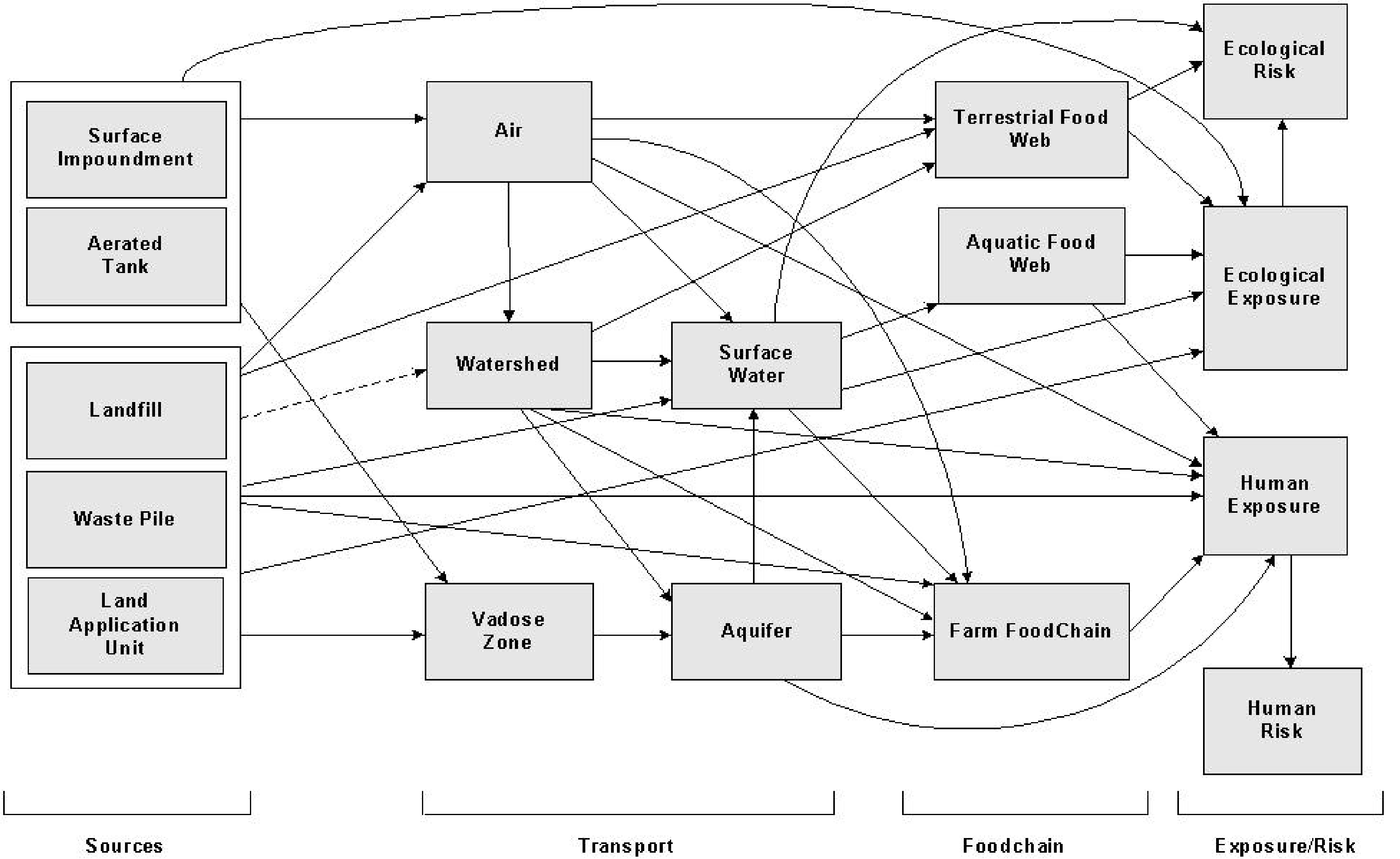
Sampling-Based Simulation

Output Data

"Exit Level" Post-Processing

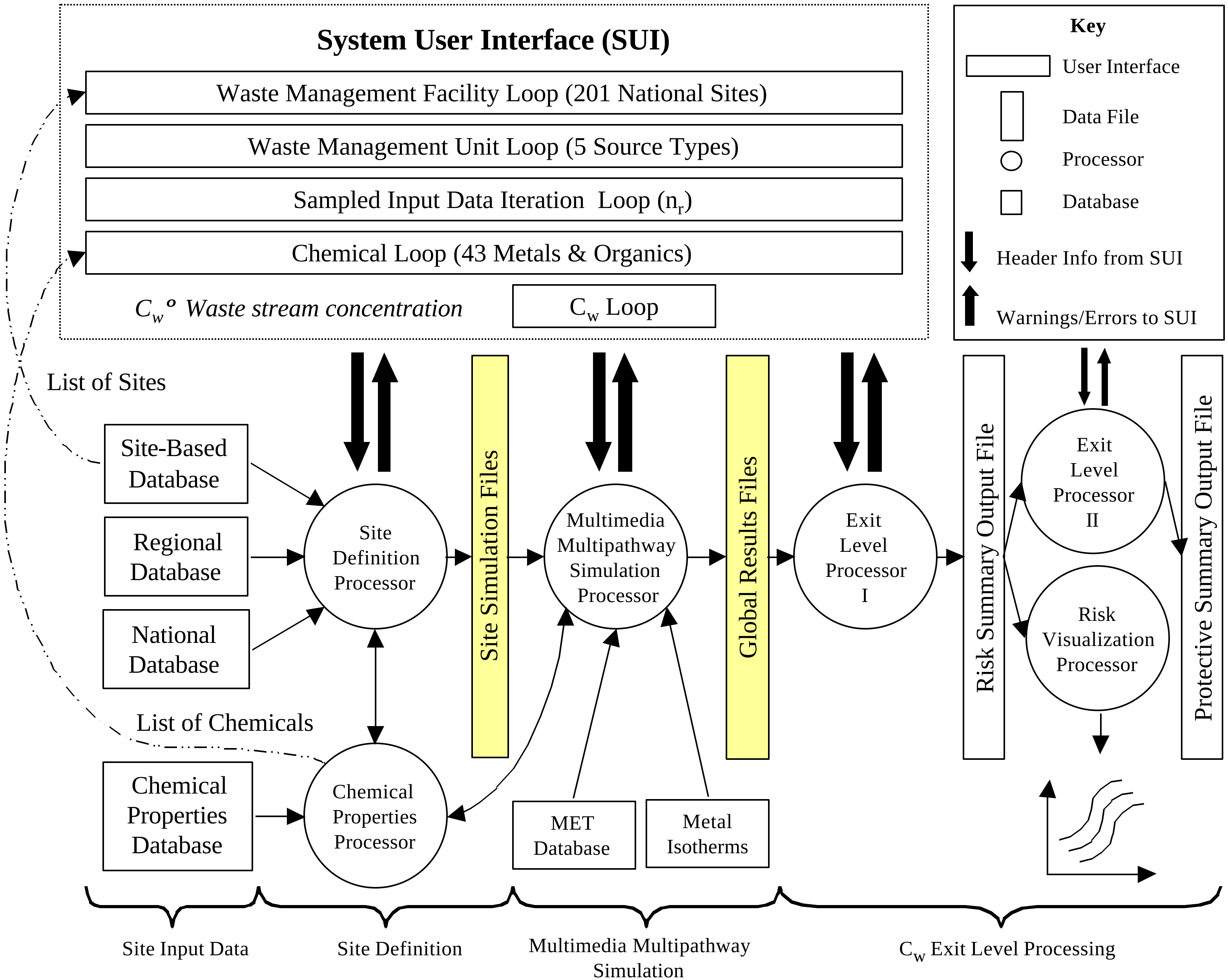
- Variability, Uncertainty and Sensitivity
- Cancer (risk probability)
- Noncancer (hazard quotient)
- Population weighted risk distribution
- Multiple protection measures

3MRA Science Modules and Connectivity



17 science-based models

3MRA Stand-Alone Design: Input-Output



3MRA Model Input Variables (966)

SystemGroup	3MRA10	
DictCode	ssf	
Number of Inputs		
ModGroup	Dictionary Description	Total
af	aquatic foodweb	21
aq	saturated zone	14
ar	air	23
at	AT	24
cp	chemical properties	142
ee	ecoexposure	14
er	ecorisk	4
ff	farm foodchain	45
hd	header	63
he	human exposure	105
hr	human risk	7
lau	LAU	51
lf	LF	44
si	SI	25
sl	site layout	208
sw	surface water	24
tf	terrestrial foodweb	31
vz	vadose zone	3
wp	WP	50
ws	watershed	23
Grand Total		921

Broken down by 20 iconic input dictionaries

Each input - up to 3 dimensions...

3MRA Model **Output** Variables (372)

SystemGroup	3MRA10	
DictCode	grf	
Number of Inputs		
ModGroup	Dictionary Description	Total
af	aquatic foodweb	18
aq	saturated zone	11
ar	air	17
ee	ecoexposure	3
er	ecorisk	27
ff	farm foodchain	39
he	human exposure	78
hr	human risk	39
sl	site layout	4
sr	source	38
sw	surface water	19
tf	terrestrial foodweb	60
vz	vadose zone	5
ws	watershed	14
Grand Total		372

Each output up to 5 dimensions...

These are further post-processed into more useful risk endpoints….

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3MRA
National Assessment Strategy

… screening-level, site-based modeling approach for national-scale assessment of land-based hazardous waste disposal .

National-Scale Problem Statement

At what waste stream concentration (C_w) will wastes, when placed in a non-hazardous waste management unit over the unit's life, result in:

1. **(Human)** Greater than **A%** of the people living within **B** distance of the facility with a risk/hazard of **C** or less, and

2. **(Ecological)** Greater than **D%** of the habitats within **E** distance of the facility with an ecological hazard less than **F**,

3. **(National)** At **G%** of facilities nationwide,

4. **(Uncertainty)** With confidence **H%** accounting for subjective input uncertainty, and confidence **I%** accounting for output sampling error.

$C_{w_{exit}}$ ° exit level

Monte Carlo Simulations Needed for 3MRA National Assessment

Individual 3MRA Modeling System Simulations Needed

Deterministic Model Runs

- **Source (WMU) Types (5)**
- **Site (201)**
- **Waste Level (5)**
- **Chemical (43)**

MC Iterations (1000)

UA/SA

Total Simulations

90,000,000+

2,000,000 +/chemical

One national iteration for 1 chemical, 1 WMU = 2095 model runs (i.e., for exit levels: 5 C_w * 419 site-WMUs = one output sample)

Wastestream (C_w) Exit Levels Possible in 3MRA

Human Roll-ups

- Distances (3)
- Pathways (13)
- Receptor Type (5)
- Cohort (4)
- Cancer Risk Bins (7)
- Hazard Risk Bins (4)

Subtotal (21,840)

Ecological Roll-ups

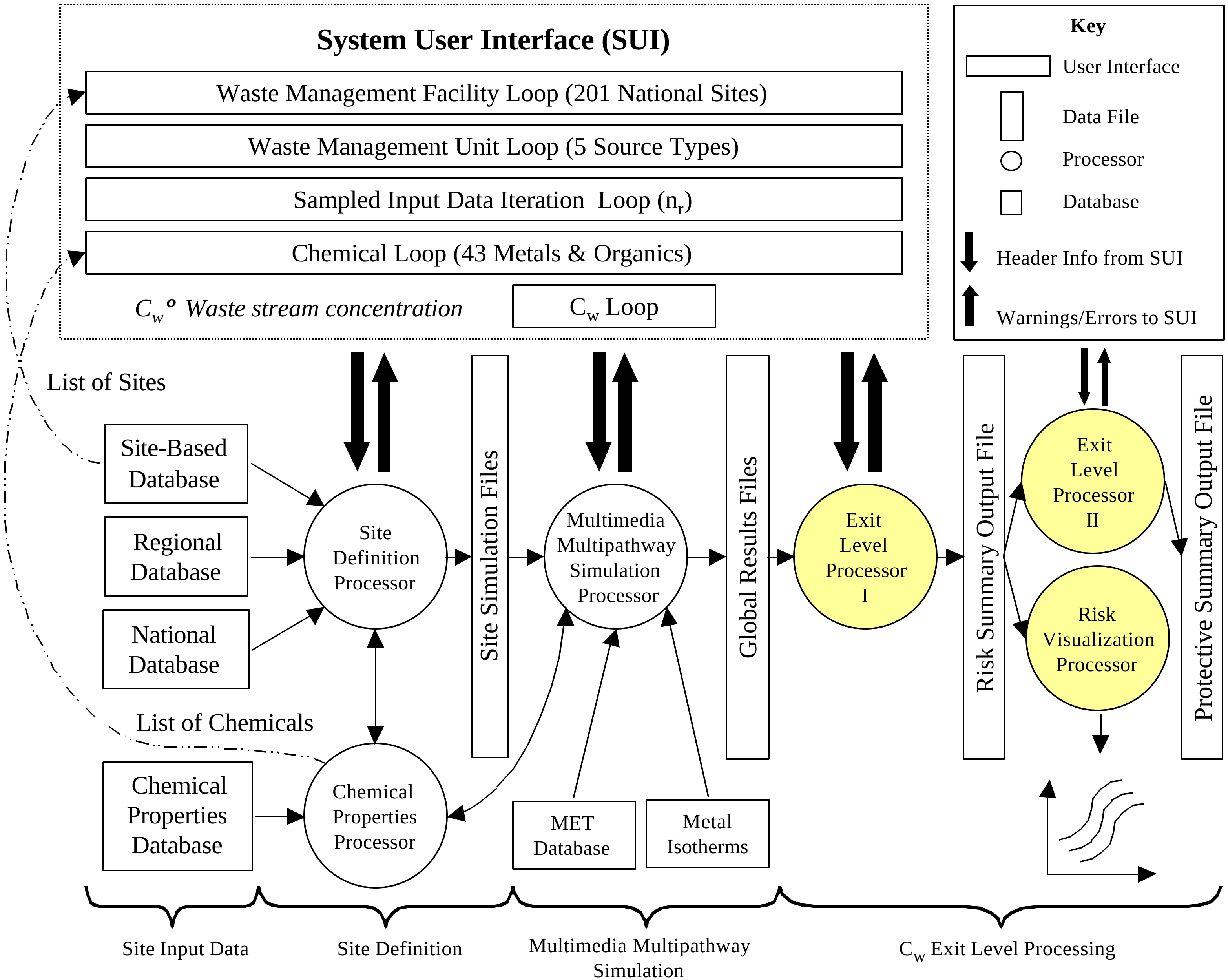
- Ring Distances (3)
- Roll-up Options (6)
- Habitat Group (3)
- Habitat Type (12)
- Receptor Group (9)
- Trophic Level (5)

- Ring and Habitat Group (9)
- Ring and Habitat Type (36)
- Ring and Receptor Group (27)
- Ring and Trophic Level (15)
- Habitat and Rec. Groups (27)
- Hab. Grp. and Trop. Lev. (15)
- Hazard Risk Bins (5)

Subtotal (645)

Total (22,485) X [Population % (10) / Risk Measures (2)] X [Chemical (43) / Source Type (5)] $< 10^8$

Importance of the "Exit Level" Processors……



Problem Statement Revisited

In determining a single exit level waste stream concentration ($C_{w_{exit}}$):

Output Profile Scenario Description

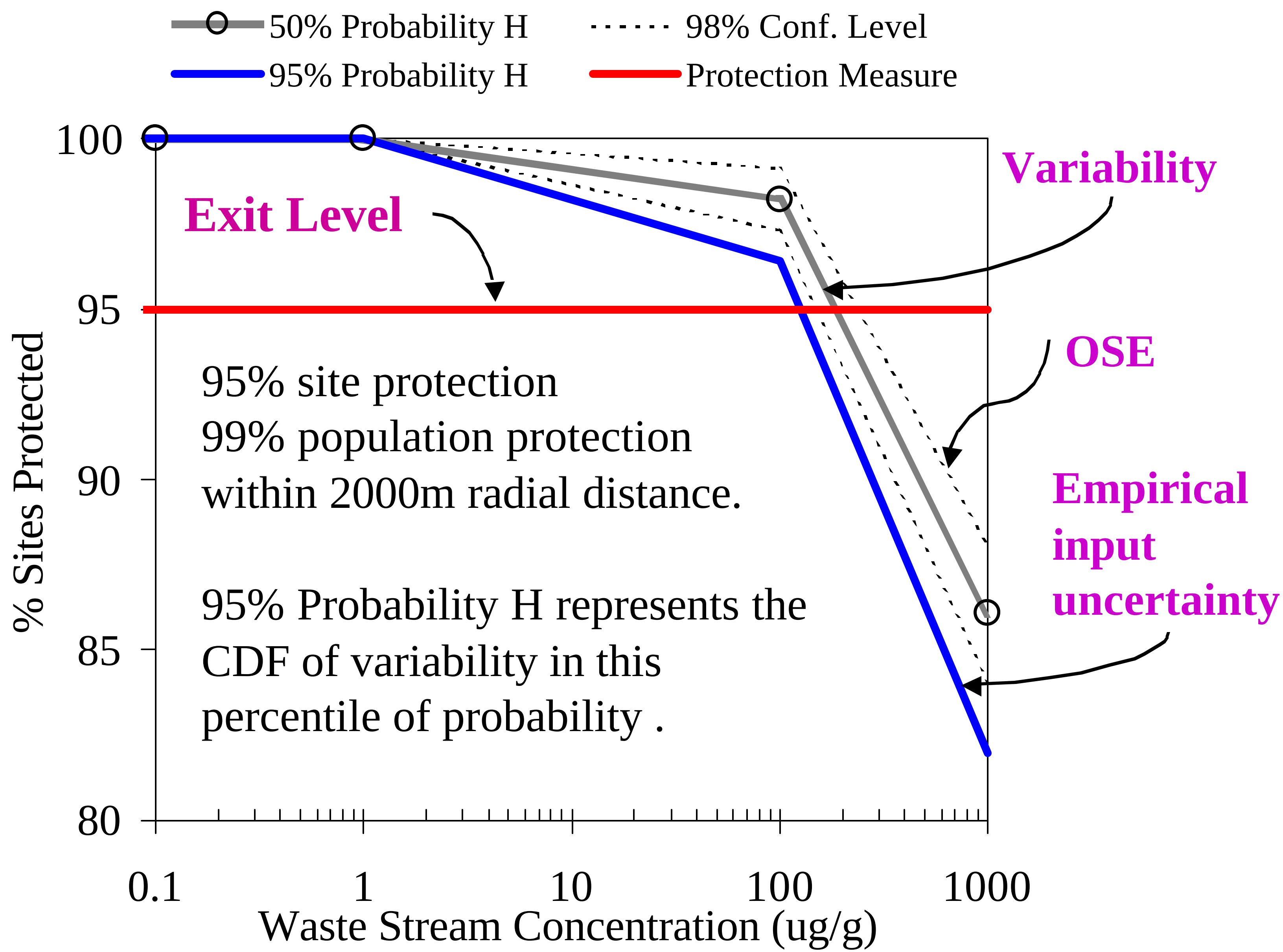
a. Chemical

b. Source Type (i.e., WMU)

c. 9-tuple Risk Profile:

A% human pop.	D% ecol. pop.	G% sites
B distance	E ring distance	H% uncertainty
C risk level	F risk level	I% precision

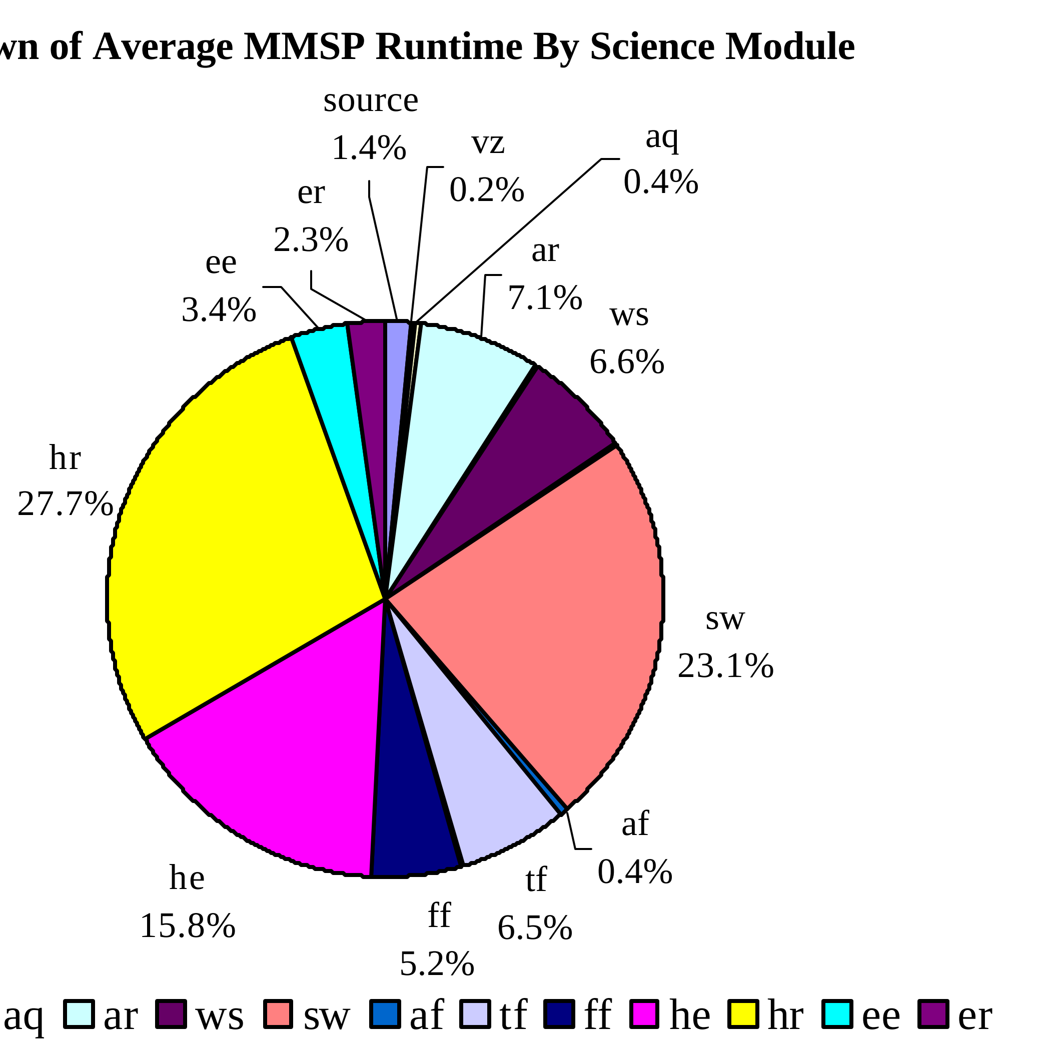
Example 3MRA Exit Level Calculation for Benzene



Summary of Dimensionality for National-Scale Problem Statement

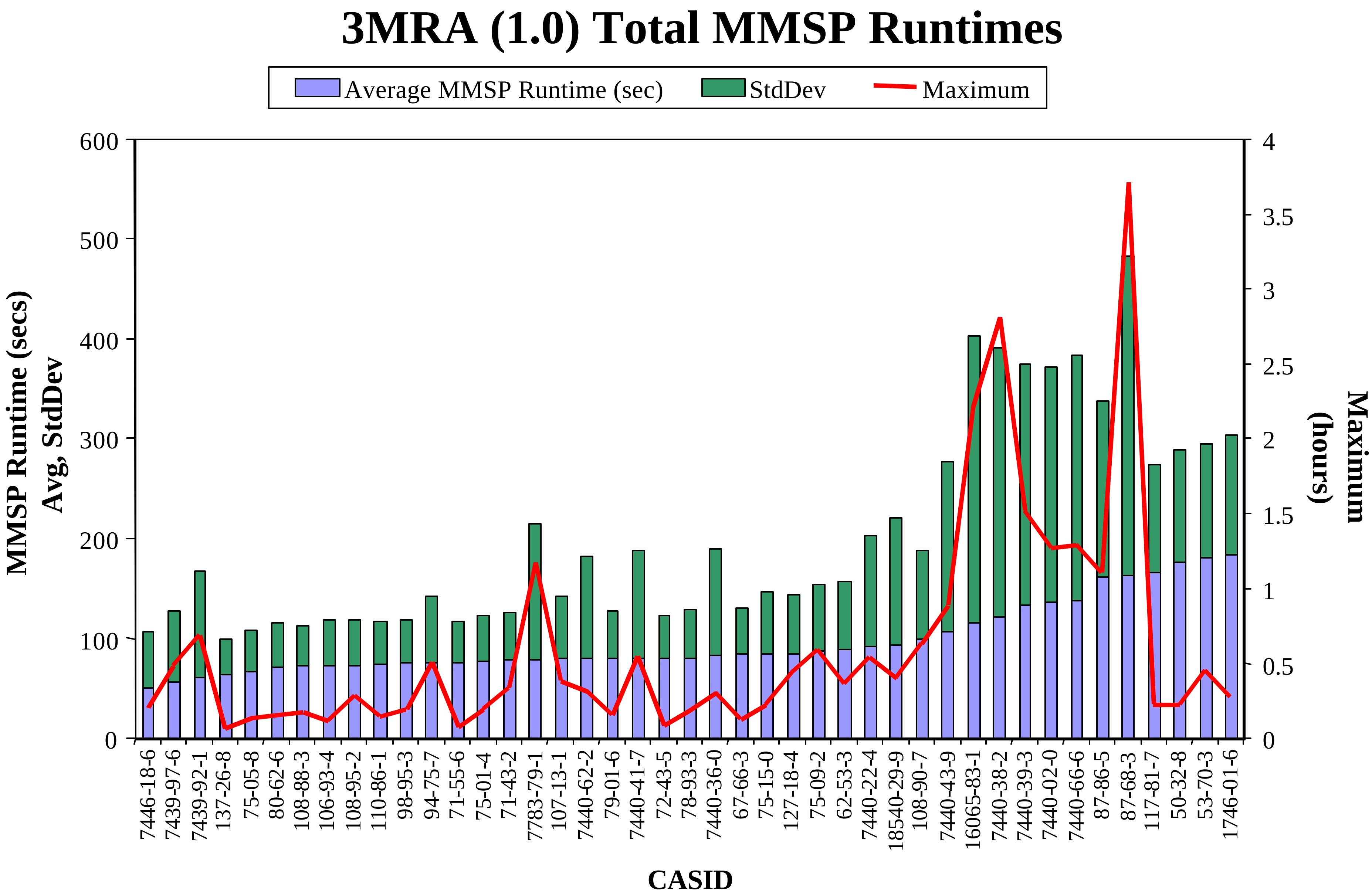
- **# Module/Processor Inputs = 966 per model run** ($\leq$3D)
- **# Module/Processor Outputs = 372 per model run** ($\leq$5D)
- **Model runs needed for probabilistic national risk assessment per chemical (i.e., UA_p): ~ 2,000,000 (+)**
- **Post-processed exit levels (C_w) possible for a 3MRA national assessment: ~ 10^8 accounting for:**
  - **Multiple decision variables in risk context**
  - **Population and subpopulation analysis**
  - **43^+ chemicals, 5 waste management unit types**

3MRA Modeling System Runtimes



66% of runtime: sw, he, hr

Average individual site scenario run ~ 2 min.



3MRA (1.0) Total MMSP Runtimes
Average MMSP Runtime (sec)
StdDev
Maximum
MMSP Runtime (secs) Avg, StdDev
Maximum (hours)
CASID
600
500
400
300
200
100
0
4
3.5
3
2.5
2
1.5
1
0.5
0
7446-18-6
7439-97-6
7439-92-1
137-26-8
75-05-8
80-62-6
108-88-3
106-93-4
108-95-2
110-86-1
98-95-3
94-75-7
71-55-6
75-01-4
71-43-2
7783-79-1
107-13-1
7440-62-2
79-01-6
7440-41-7
72-43-5
78-93-3
7440-36-0
67-66-3
75-15-0
127-18-4
75-09-2
62-53-3
7440-22-4
18540-29-9
108-90-7
7440-43-9
16065-83-1
7440-38-2
7440-39-3
7440-02-0
7440-66-6
87-86-5
87-68-3
117-81-7
50-32-8
53-70-3
1746-01-6

3MRA Run Time for National-Scale Problem Statement

1. All chemicals: average model run time ~2 minutes
2. On SuperMUSE: ~ 2 days per 100 national realizations of model runs needed for probabilistic national risk assessment per chemical (i.e., UA_p)
3. Single PC: ~ 10 months per chemical per 100 realizations
4. Single PC: ~ 8 years per chemical per 1000 realizations
5. Single PC: ~ 344 years, 43 chemicals, 1000 realizations

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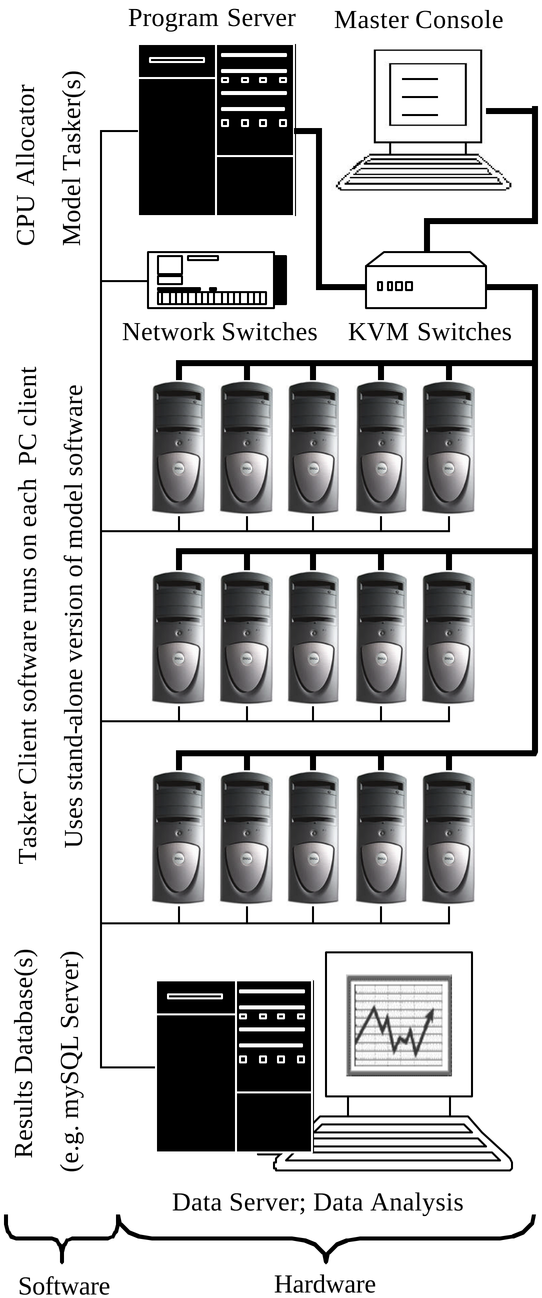
SuperMUSE:

Supercomputer for Model Uncertainty and Sensitivity Evaluation

… 180-client nodes,

215 GHz, PC-Based - Windows and Linux both supported

Hardware



SuperMUSE

Supercomputer for Model Uncertainty & Sensitivity Evaluation

Major Components:

- Front-end program server,
- Back-end data server,
- Currently 180 client PCs
- 16-port Raritan KVM switches,
- 24-port Linksys (10/100) switches
- Master CISCO 3550-24/2 switch.
- Network protocol TCP/IP.
- GigE channel (1000 megabits/sec) data flow to and from servers.

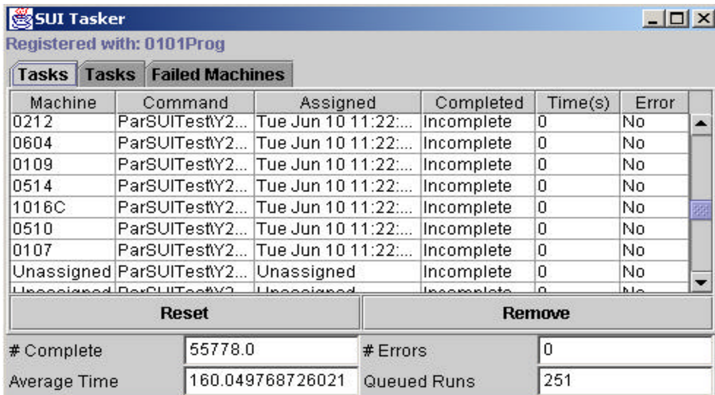
Windows & Linux OS supported

SuperMUSE Parallel Computing Cluster at ORD/NERL/ERD, Athens, Georgia

Software

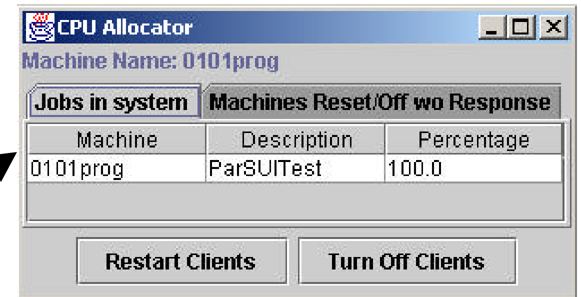
Model Tasker (MT)

Model dependent



CPU Allocator

Model independent



Register

1. Announces availability.

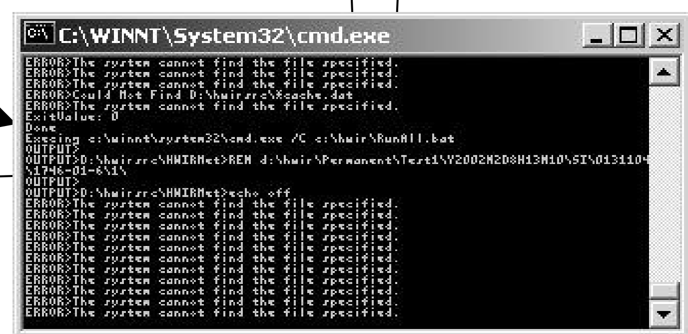
2. If no MT active, then idles

3. Requests job

6. Says Done

4. Do job X; a single task line in the MT.

5. Report job X Results



Tasker Client

Model independent

Executes OS-based commands delivered by MT

MiniMUSE Parallel Computing Cluster

Beneficial Impacts of PC-Based SuperMUSE*ing*

- ✓ SuperMUSE is scalable from 2 to 1000^{+} PCs.
- ✓ Supports Windows or Linux based modeling systems.
- ✓ Solves "**embarrassingly parallel**" computing problems.
- ✓ A local solution → empowers model developers and users.
- ✓ Simple, inexpensive, can be built/operated by PC novices.
- ✓ Ideal for debugging models and performing UA/SA.
- ✓ For an average model runtime of 2 minutes, ERD's SuperMUSE can run over 3 million simulations/month.

3MRA Version 1.x
Tools to Support UA/SA

…includes both model dependent and model independent tools

Supercomputing Software System Needs

Facilitating Distribution of Workloads Among PCs

- CPU Allocator ✔
- Model Tasker ✔
- Tasker Client ✔
- Client Monitor ✔

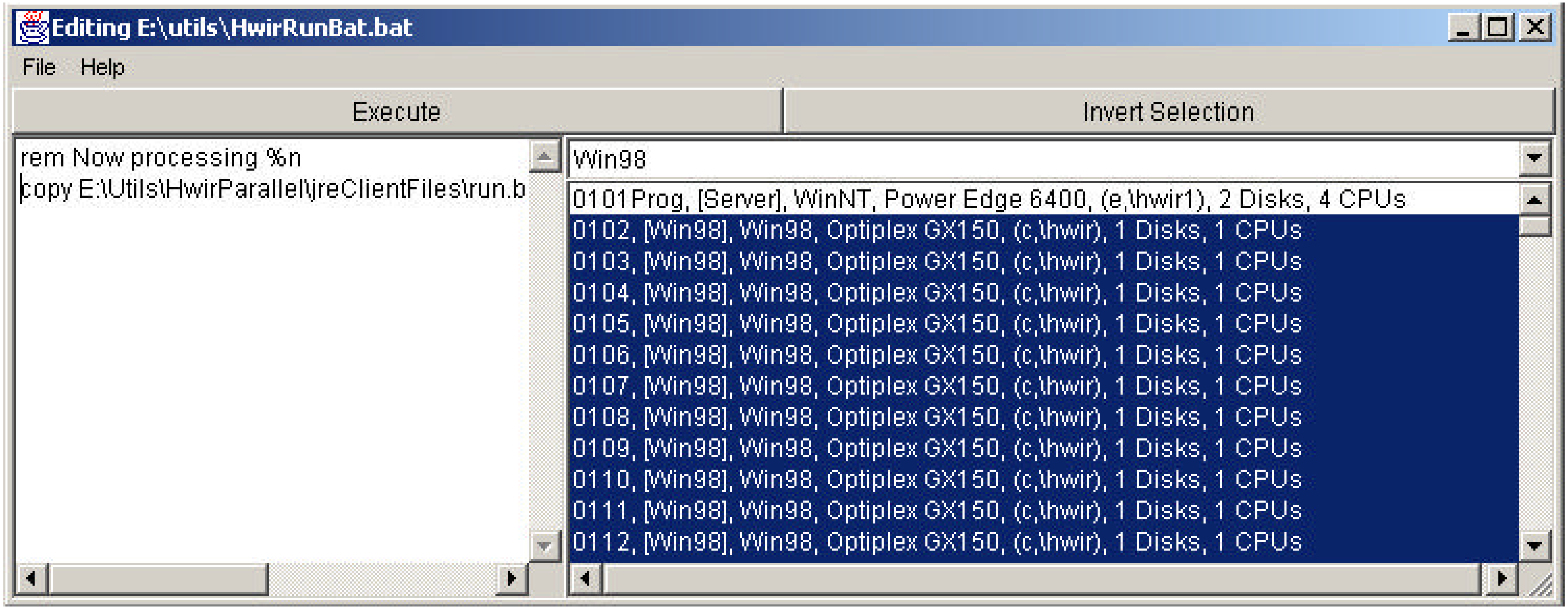
Managing files and Data Across PCs

- Update Client ✔
- Command Tasker ✔
- Process Messages ✔
- ELP1 Client Collectors
  - *Aggregated* ✔
  - *Disaggregated*

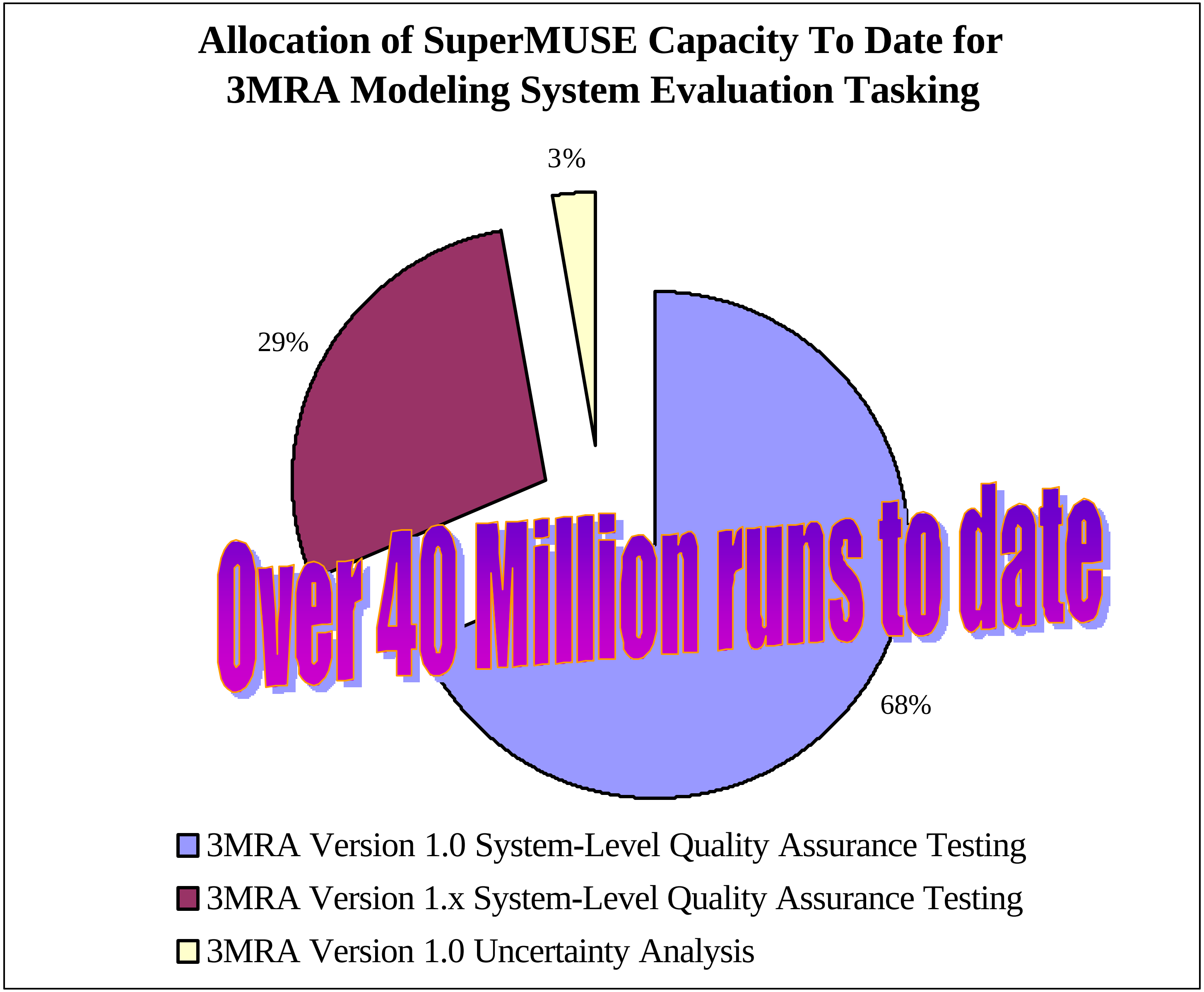
Facilitating 3MRA-Specific Data Analysis

- Site Visualization ✔
- Site Summary ✔
- Aggr. MySQL ELP1 ✔
- Aggr. MySQL ELP1 ✔
- Aggr. ELP2Vis ✔
- Automated UA/SA Tools
- Disaggregated ELP1
- Disaggregated ELP2
- Enhanced SUI

Example: Server–Side Update Client Tool User Interface



Use of SuperMUSE and 3MRA Version 1.x



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Model Evaluation Approaches

…leading to an overall statement of quality assurance in design for a specific intended purpose

(Beck et al, 1997)

Classes and Types of Uncertainty

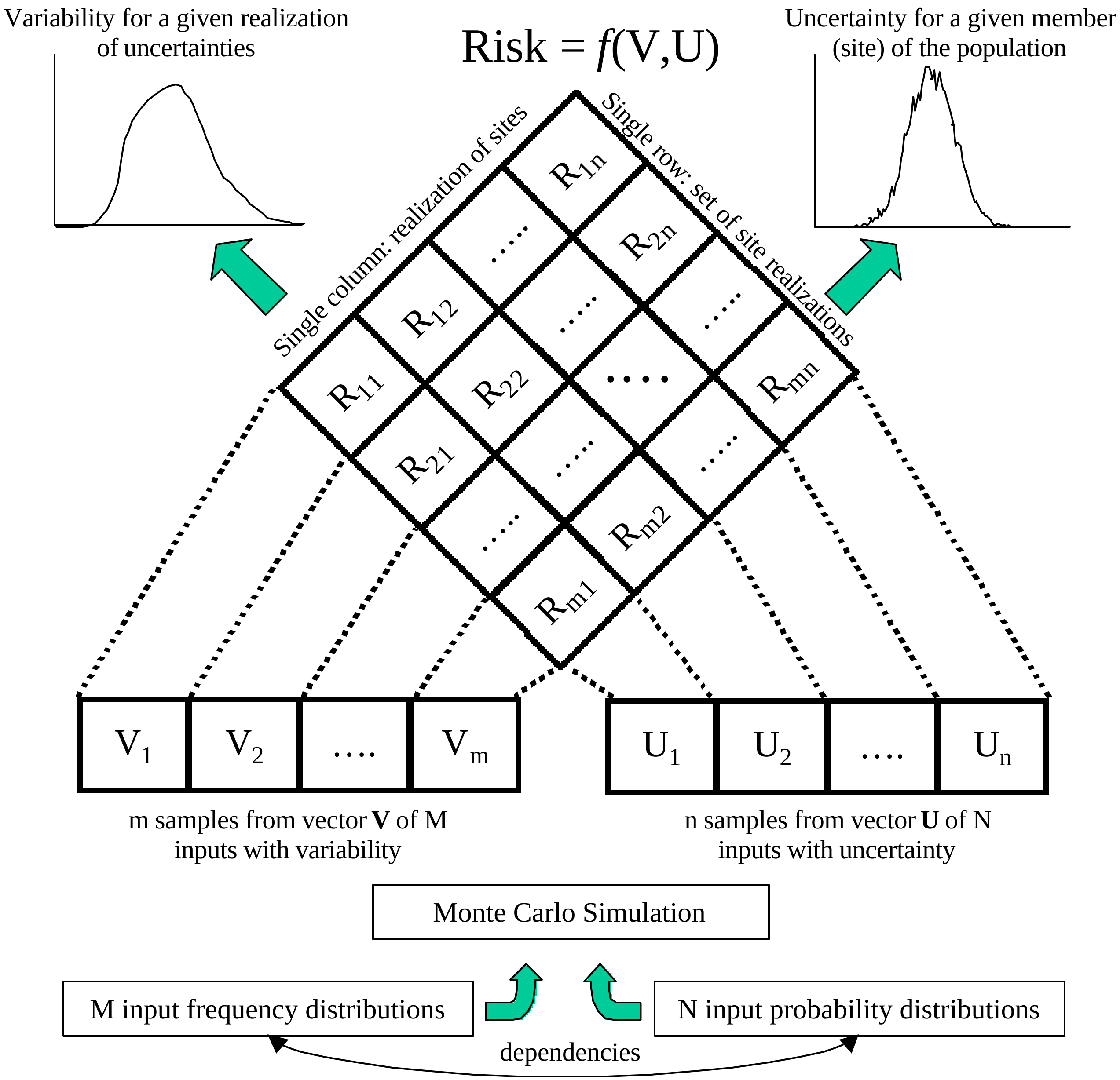
General Classes of Uncertainty
Variability (V)
Empirical Uncertainty (U)
Model Error (ME)
Types of Empirical Uncertainty
Random Error (RE)
Systematic Error (SE)
Sample Measurement Error (SME; see RE, SE)
Input Sampling Error (ISE; see RE)
Output Sampling Error (OSE; see RE)
Inherent randomness
Correlation
Disagreement

Performance Uncertainty Analysis (UA_p)

…describing potential differences between model predictions and nature.

Uncertainty due to lack of knowledge and data…..

Analysis Approach → ***given uncertainty in both models and their inputs, quantify/qualify uncertainty in model output(s).***

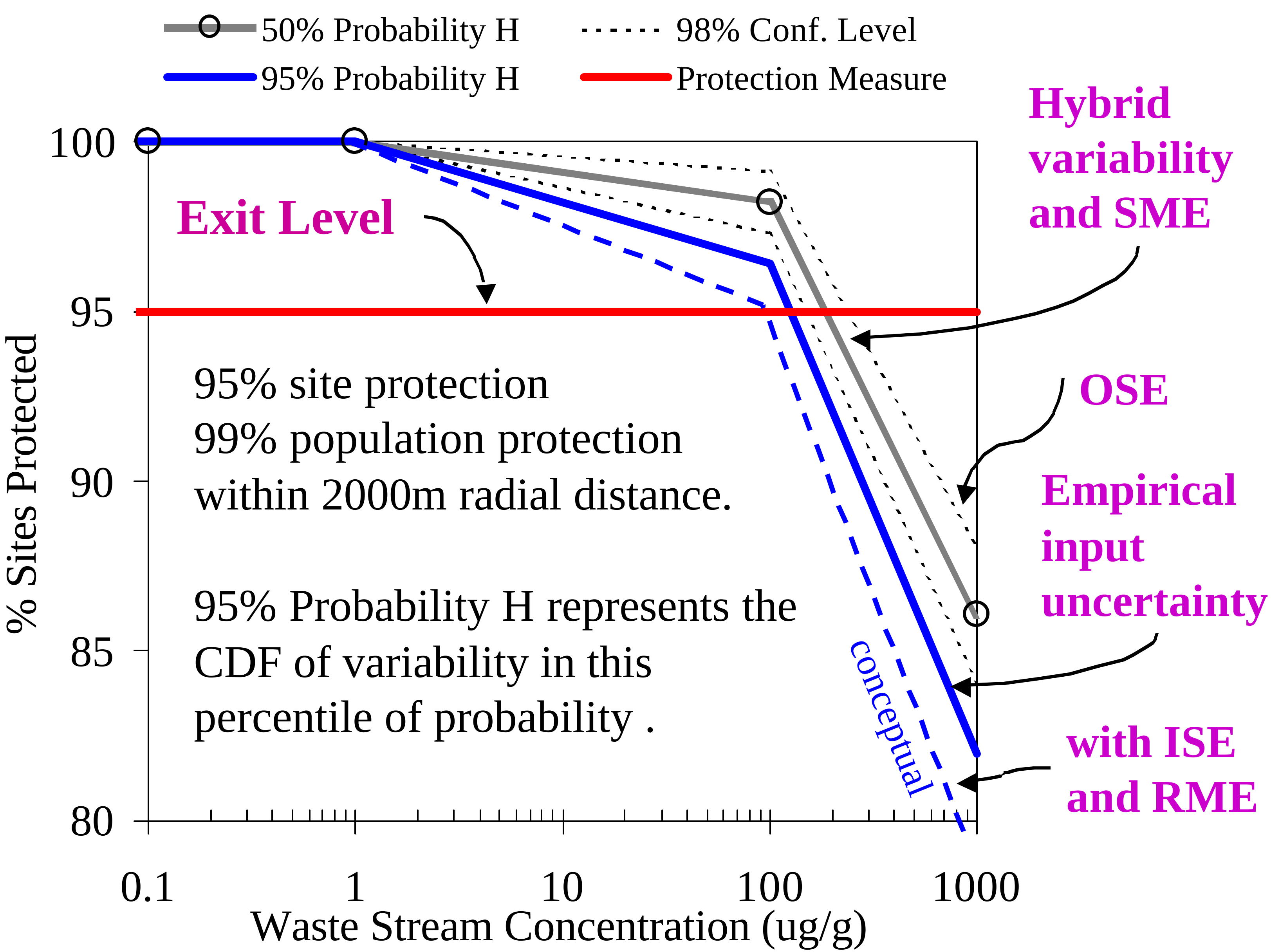


2-Stage Monte Carlo….

Separating <u>uncertainty</u> and <u>variability</u> in output predictions.

(adapted from Rhodes and Frey, 1996)

3MRA Exit Level Uncertainty

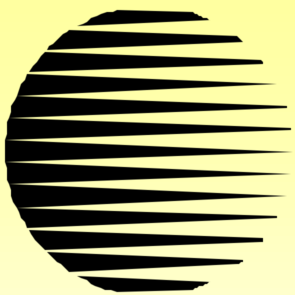


Sensitivity Analysis (SA):

….a study of how the uncertainty in output of an analytical or numerical model can be apportioned to different sources of uncertainty in the model input.

A. Saltelli

Input Space Assessment Techniques



Local

works intensely around a specific set of input values (i.e., the local condition)

Screening

quick and simplistic, ranks input variables and ignores interactions between variables

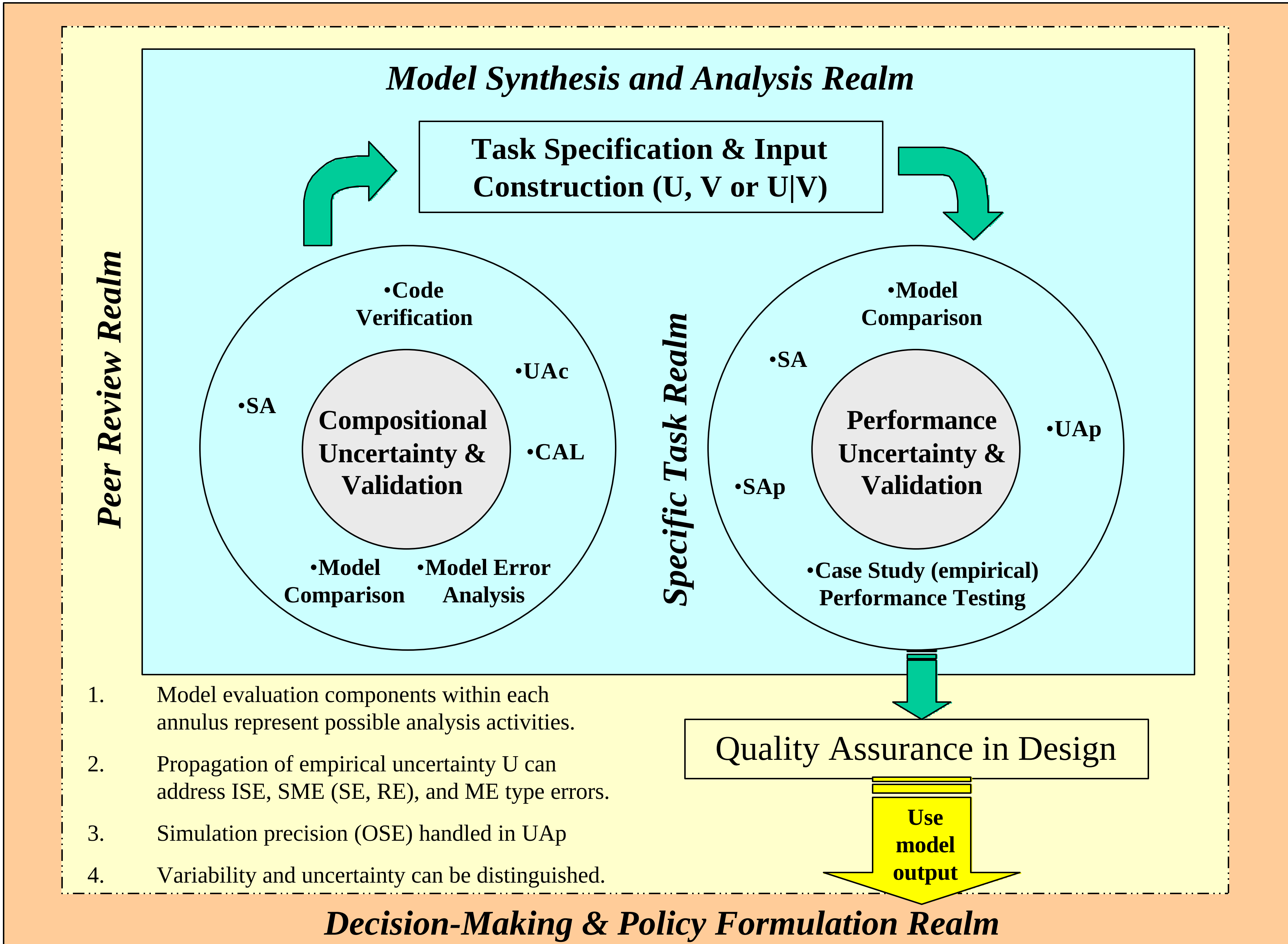
Global

quantifies scale & shape of the I/O relationship; all input ranges; assesses parameter interaction

Components of Model Evaluation.

(a.k.a., Verification, Validation, and Predictive Uncertainty Analysis)

Components of Model Evaluation
Uncertainty (U)
Variability (V)
Total Uncertainty (TU)
Compositional Uncertainty Analysis (UA_c)
Performance Uncertainty Analysis (UA_p = UA)
Sensitivity Analysis (SA)
Calibration (CAL)
Code Verification (CodVer)
Model Comparison (ModComp)
Compositional Validity (CompVal)
Performance Validity (PerfVal)
Model Validation (ModVal)
Peer review


Model Synthesis and Analysis Realm
Task Specification & Input Construction (U, V or U|V)
Peer Review Realm
•Code Verification
•UAc
•SA
•CAL
Compositional Uncertainty & Validation
•Model Comparison
•Model Error Analysis
Specific Task Realm
•Model Comparison
•SA
•UAp
•SAp
Performance Uncertainty & Validation
•Case Study (empirical) Performance Testing
1. Model evaluation components within each annulus represent possible analysis activities.
2. Propagation of empirical uncertainty U can address ISE, SME (SE, RE), and ME type errors.
3. Simulation precision (OSE) handled in UAp
4. Variability and uncertainty can be distinguished.
Quality Assurance in Design
Use model output
Decision-Making & Policy Formulation Realm

Sensitivity-Analysis-Based Performance Validation (SA_p)

…assessing and describing the behavioral and non-behavioral characteristics of the modeling system.

A specific construction of performance validation as a reflection, by way of sensitivity analysis, of the evaluation of the external definition of the current task back onto the internal composition of the model.

Model Evaluation: Summary Perspective

Model evaluation is seen as a statement of quality assurance in design (i.e., tool or technology):

…..a result of the model synthesis and analysis effort,

…..viewed as the outcome of the overall model validation effort for the specific task defined.

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3MRA Version 1.0
UA/SA Plan

……..…for the national-scale assessment problem statement

3MRA UA/SA Plan

- **Performance uncertainty analysis (UA_p)**
- **Sensitivity analysis (SA)**
- **Sensitivity-based Performance Validation (SA_p)**
- **7 Chemicals:**
  - **Benzene,**
  - **PCE,**
  - **2,3,7,8-TCDD,**
  - **Benzo(a)pyrene,**
  - **Arsenic,**
  - **Nickel, and**
  - **Divalent Mercury.**

3MRA UA/SA Plan (UA_p)

Performance Uncertainty Analysis:

- Entails propagation of input uncertainty through the modeling system, while also addressing output sampling error (OSE) associated with computational limitations of the sampling-based MCS strategy.

- Uses a pseudo 2nd-order analysis to separate variability and empirical input uncertainty, while quantifying OSE.

3MRA UA/SA Plan (SA)

Sensitivity Analysis:

- A balanced, tiered formulation of SA is planned for identifying key, important, and redundant model inputs. The basic approach to be undertaken is global input space assessment via sampling-based methods.

- SA to be conducted for this purpose will enhance both compositional and performance validation aspects for the modeling system.

- Will include global based SA techniques:

  Correlation /Regression

  Regional Sensitivity Analysis (RSA)

  Tree Structured Density Estimation (TSDE)

3MRA UA/SA Plan (SA_p)

SA-based Performance Validation:

- **Basically an assessment of a “prior” validity through the execution of a regional sensitivity analysis (RSA) procedure, realized as an assessment of the model’s maximum relevancy in predicting model behavior for various population percentiles.**

- **Will investigate higher order interactions via TSDE.**

Example 3MRA Version 1.x Output:
79 National Realizations

Risk Endpoint Description	Scenario	
Scenario ID	**1**	**2**
% Population Protected	99%	95%
% Sites Protected	95%	95%
Protective?	More	Less
Human		
Distance (m)	500	2000
Cancer Risk	10^{-6}	10^{-5}
Hazard Risk	0.1	1
Pathway	Sum Ing. & Inh.	
Receptor Group	All	
Cohort Group	All	
Ecological		
Ring Distance (m)	2000	2000
Hazard Risk	1	1
By Ring and Habitat Group	Terr., Aq., Wetland	
Simulation		
Sources/Chemicals/Cws	5/7/5	
Sites/sources	419	
# National Realizations	79	
# Modeling System Runs	1,158,535	

Example Simulation Experiment

Simulated 7 Chemicals & Metals

CASID	Chemical Name	Human				Ecological
		Carcinogenic		Non- Carcinogenic		
		Inhalation	Ingestion	Inhalation	Ingestion	
127-18-4	PCE	✓ ⊕	✓		✓	✓
71-43-2	Benzene	✓ ⊕	✓			✓
1746-01-6	2,3,7,8-TCDD	✓ ⊕	✓		✓	✓
50-32-8	Benzo(a)pyrene		✓			✓
7440-38-2	Arsenic	✓	✓		✓	✓
7440-02-0	Nickel	✓			✓	✓
7439-97-6	Dival. Mecury			✓	✓	✓

⊕ Additive Risk

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Back Forward Stop Refresh Home Search Favorites Media History Mail Print Edit Discuss Dell Home

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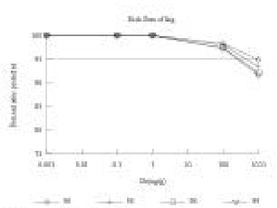
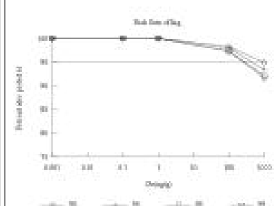
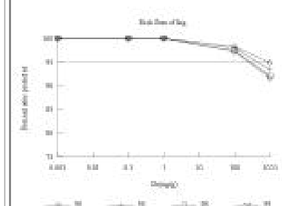
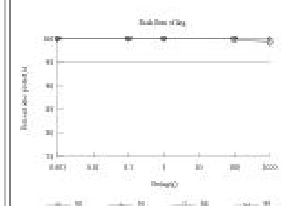
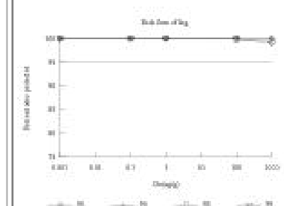
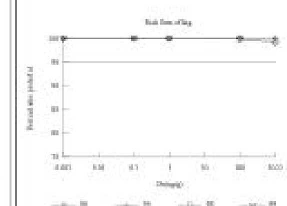
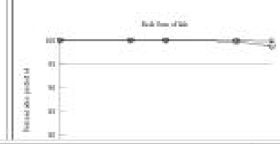
ELP2VIS Output

Benzene(71-43-2) in Landfill

SCENARIO 1	SCENARIO 1b	SCENARIO 1c	SCENARIO 2a	SCENARIO 2b	SCENARIO 2c
Human Health **Distance**: 500.0 **Exposure Pathway**: Sum of Ing. and Inh. **Receptor Type**: All Receptors **Cohort**: All Cohorts **Risk Trigger Level**: 1.0E-6 **Risk Pop. Prot. %**: 99 **Risk Prot. % of Sites in US**: 95 **Ecological Health** **Ecological Measure**: By Ring and Habitat Group **For**: <2000m **And** : terrestrial **Eco. Trigger Level**: 1.0 **Eco. Pop. Prot. %**: 99 **Eco. Prot. % of Sites in US**: 95	**Human Health** **Distance**: 500.0 **Exposure Pathway**: Sum of Ing. and Inh. **Receptor Type**: All Receptors **Cohort**: All Cohorts **Risk Trigger Level**: 1.0E-6 **Risk Pop. Prot. %**: 99 **Risk Prot. % of Sites in US**: 95 **Ecological Health** **Ecological Measure**: By Ring and Habitat Group **For**: <2000m **And** : aquatic **Eco. Trigger Level**: 1.0 **Eco. Pop. Prot. %**: 99 **Eco. Prot. % of Sites in US**: 95	**Human Health** **Distance**: 500.0 **Exposure Pathway**: Sum of Ing. and Inh. **Receptor Type**: All Receptors **Cohort**: All Cohorts **Risk Trigger Level**: 1.0E-6 **Risk Pop. Prot. %**: 99 **Risk Prot. % of Sites in US**: 95 **Ecological Health** **Ecological Measure**: By Ring and Habitat Group **For**: <2000m **And** : wetland **Eco. Trigger Level**: 1.0 **Eco. Pop. Prot. %**: 99 **Eco. Prot. % of Sites in US**: 95	**Human Health** **Distance**: 2000.0 **Exposure Pathway**: Sum of Ing. and Inh. **Receptor Type**: All Receptors **Cohort**: All Cohorts **Risk Trigger Level**: 1.0E-5 **Risk Pop. Prot. %**: 95 **Risk Prot. % of Sites in US**: 95 **Ecological Health** **Ecological Measure**: By Ring and Habitat Group **For**: <2000m **And** : terrestrial **Eco. Trigger Level**: 1.0 **Eco. Pop. Prot. %**: 95 **Eco. Prot. % of Sites in US**: 95	**Human Health** **Distance**: 2000.0 **Exposure Pathway**: Sum of Ing. and Inh. **Receptor Type**: All Receptors **Cohort**: All Cohorts **Risk Trigger Level**: 1.0E-5 **Risk Pop. Prot. %**: 95 **Risk Prot. % of Sites in US**: 95 **Ecological Health** **Ecological Measure**: By Ring and Habitat Group **For**: <2000m **And** : aquatic **Eco. Trigger Level**: 1.0 **Eco. Pop. Prot. %**: 95 **Eco. Prot. % of Sites in US**: 95	**Human Health** **Distance**: 2000.0 **Exposure Pathway**: Sum of Ing. and Inh. **Receptor Type**: All Receptors **Cohort**: All Cohorts **Risk Trigger Level**: 1.0E-5 **Risk Pop. Prot. %**: 95 **Risk Prot. % of Sites in US**: 95 **Ecological Health** **Ecological Measure**: By Ring and Habitat Group **For**: <2000m **And** : wetland **Eco. Trigger Level**: 1.0 **Eco. Pop. Prot. %**: 95 **Eco. Prot. % of Sites in US**: 95
Cw: 252.3 Risk Sum of Ing. 	Cw: 252.3 Risk Sum of Ing. 	Cw: 252.3 Risk Sum of Ing. 	Cw: 1000. Risk Sum of Ing. 	Cw: 1000. Risk Sum of Ing. 	Cw: 1000. Risk Sum of Ing. 
Cw: 133.8 Risk Sum of Inh. 	Cw: 133.8 Risk Sum of Inh. 	Cw: 133.8 Risk Sum of Inh. 	Cw: 1000. Risk Sum of Inh. 	Cw: 1000. Risk Sum of Inh. 	Cw: 1000. Risk Sum of Inh. 

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Example Exit Level Results

2 Scenarios - 7 Chemicals

(Example, Preliminary Summary)

Source Type	Surface Impoundment		Aerated Tank		Land Application Unit		Waste Pile		Landfill	
# Sites Evaluated	137		137		28		61		56	
Total Simulations	378,805		378,805		77,420		168,665		154,840	
	50th Percentile (Average) Exit Level (ppm)									
Chemical/Scenario	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
PCE	0.36	100*	6.5	100*	3.2	5000*	453	5000*	778	5000*
Benzene	0.13	100*	1.5	100*	2.1	1000*	8.1	1000*	109	1000*
Benzo(a)pyrene	0.001*	0.001*	0.001*	0.001*	1.0*	1.0*	1.0*	1.0*	1.0*	1.0*
2,3,7,8-TCDD	2.2E-7	1E-4*	1E-4*	1E-4*	1.4E-6	1.6E-5	2.5E-4	0.001	0.001	0.004
Arsenic	0.095	2.1	50*	50*	0.004	0.59	3.0	18	1.8	298
Nickel	11	1000*	1000*	1000*	6.7	127	352	10000*	446	10000*
Divalent Mercury	0.1*	0.1*	0.1*	0.1*	0.49	2.2	10	10*	10*	10*

*** Shows max Cw analyzed in experiment**

Scenario 1 = more protective

Scenario 2 = less protective

Dominant Human Pathways, Human Receptors, and Ecological Habitats

(Example, Preliminary Summary)

Chemical	Dominant Risk/Route	Surface Impoundment		Aerated Tank		Land Application Unit		Waste Pile		Landfill	
Scenario		1	2	1	2	1	2	1	2	1	2
PCE	**H^{Cancer}**	**Cr,Wa**	**Crop**	**Crop**	**Crop**	**Water**	**Crop**	**Crop**	**Crop**	**Crop**	**Crop**
	Ing.	Fa,G,Fi	Fa,G,Fi	G,Fi	G,Fa,Fi	G,R,Fi	G,Fi	G,Fi,R	G,Fi,Fa	Fa,G,Fi	Fa,G,Fi
Benzene	**H^{Cancer}**	**Air,Cr**	**Air,Cr**	**Air,Cr**	**Air,Cr**	**Air, Sh.**	**Air**	**Show.**	**Air**	**Show.**	**Air**
	Inh., Ing	G,Fi,R	G,Fi,R	G,Fi,R	G,Fi,R	G,Fi,R	G,Fi,R	Fi,R,G	Fi,R,G	G,Fi,R	All
Benzo(a)pyrene	**Low Risk**	**Cr, Beef**	--	--	--	**Crop**	--	**Crop**	--	**Bf,Cr**	--
	--	--	--	--	--	--	--	--	--	--	--
2,3,7,8-TCDD	**H^{Cancer}, Eco**	**Air**	**Air**	**Air**	--	**Air**	**Eco**	**Fi,Cr,Air**	**Eco**	**Eco**	**Eco**
	Inh.	Bf, Oth.	--	Bf,Oth.	--	All	Ter,Aq	Fi,G,R	Wet.	Ter,Aq	Ter,Aq
Arsenic	**H^{Cancer}, Eco**	**Water**	**Eco**	--	--	**Wa,Cr**	**Eco**	**Wa,Cr**	**Eco**	**Water**	**Eco**
	Ing.	Fi	Ter.			G,Fi,R	Aq.,Ter	G,Fi,R	Wet.	All	Aq.
Nickel	**H^{Hazard}, Eco**	**Water**	--	--	--	**Water**	**Eco**	**Water**	**Eco**	**Water**	**Eco**
	Ing.	Fisher				R,G,Fi	Ter,Aq	R,G,Fi	Wet.	Fa,Fi	Aq,Ter
Hg^{+2}	**H^{Hazard}**	--	--	--	--	**Fish**	**Fish**	**Fish**	**Fish**	**Eco**	**Eco**
	Ing.					Fisher	Fisher	Fisher	Fisher	Ter,Aq	Ter,Aq