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COMPARISON OF SYSTEMS AND SINGLE-MEDIUM APPROACHES IN ENVIRONMENTAL RISK-BASED DECISION MAKING: A CASE STUDY OF A SLUDGE MANAGEMENT PROBLEM

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ABSTRACT

The traditional single-medium approach to environmental management mitigates problems in one environmental medium at a time without considering interactions between different media. The management strategies selected from the single-medium approach may, therefore, simply shift problems between media. Alternatively, a systems approach advocates focusing on the environmental system as a source of risk, and selecting risk management strategies based on minimization of the composite risk from all pathways. However, entrenched interests and organizational structures associated with the current regulatory system, and the computational complexity of a systems approach, present obstacles for the adoption of a systems approach. These difficulties raise the question as to whether, or under what conditions, a systems approach is needed for improving decisions significantly. This study combines multimedia risk analysis and an optimization framework to develop a methodology for comparing the merits of the two approaches. We then apply the methodology to a sludge management decision problem and demonstrate that there are many cases in which the systems approach leads to the selection of optimal management strategies that differ from those using a single-medium approach.

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INTRODUCTION

This study examines the suitability of a systems approach as a replacement to the existing single-medium approach to analyzing and reducing risk in an environmental pollution problem. The single-medium approach to environmental management has become traditional and dominates current environmental decisions. This approach analyzes exposures through one environmental medium at a time (the primary exposure pathway) without formally considering the interrelationships between different media. The resulting environmental regulations seek to control pollutants as if they remain in the same medium—the air, water, or soil—into which they are initially released. Environmental solutions using such an approach where it is not appropriate have created new problems [1, 2].

By contrast, a systems approach advocates focusing on the entire environmental system as a source of risk. When looked at as a system, the important components within the environment and the interrelationships between the components need to be considered in estimating risk. A systems approach is designed to optimize the effectiveness of a management strategy in controlling risks from all exposure pathways, rather than from any isolated pathway [3-5].

Interest in the multimedia perspective is growing [6, 7]. However, the traditional single-medium approach remains dominant because political, legal, institutional, and technical barriers stand in the way of adoption of a systems approach to environmental management [8, 9]. In addition to the organizational features of the regulatory arena which mitigate against a systems approach, the technical difficulty in handling the complexity of a systems approach represents a challenge. These obstacles to applying a systems approach to environmental management raise the question as to whether, or under what conditions, a systems approach is needed for improving decisions. From a policy standpoint, the central question is whether the extent and seriousness of the cross-media problems are large enough to justify a change, and whether the inaccuracies in analyzing risk and the inefficiencies in reducing risk caused by the single-medium approach justify moving to a more complex systems approach.

This study develops a methodology for comparing a systems approach and a single-medium approach to environmental management. The central analytical issue is: Does use of a systems approach lead to selection of an optimal mitigation strategy which differs significantly from that which would have been selected using a single-medium analysis? This issue then is analyzed through a case study that applies the methodology to a sludge management decision problem in Wilson County, North Carolina.

A SLUDGE PROBLEM

This case study focuses on examining a representative waste management system of sludge. The decision problem is to choose an appropriate sludge management strategy to minimize cancer and non-cancer risk and the degree of inequitable distribution of risk between white and non-white populations. There is a large number of sludge management alternatives represented by combinations of disposal methods, air pollution control devices and wastewater treatment processes. Two major disposal methods, incineration and land application, are chosen here as the base of analysis.

Figure 1 shows the waste management system of sludge as represented by a decision influence diagram that connects the sludge source to a human receptor. A fraction of the sludge may be incinerated and another fraction applied to land. Air pollution control devices (APCDs) typically are installed to control air emissions by the incinerator. The end products of incineration include air emissions escaping from APCDs, and collected bottom and fly ash. The ash may then be released onto the land. If the APCDs use wet processes to capture air emissions, wastewater can be generated and typically is treated before being released into a water body. A wastewater treatment process may also release volatile pollutants into the air or concentrate pollutants into solid form, which then are put onto the land. Some pollutants may also enter the water body through effluent discharge. These sludge disposal and pollution control measures lead to pollutant discharge into the various environmental media—air, water, and land. The pollutants subsequently redistribute among the environmental media through natural processes, and contact people through multiple exposure pathways.

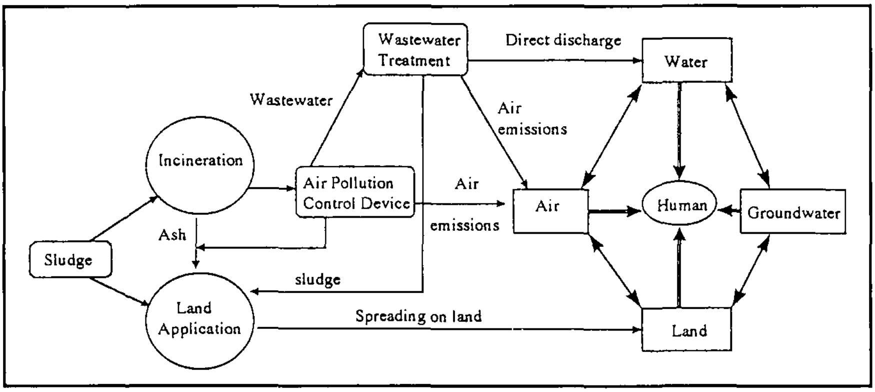

Figure 1. A sludge disposal decision influence diagram. Beginning from a given sludge, various disposal methods (incineration and land application) and air and water control processes will lead to different releases of pollutant into the environment. The pollutants then may contact the same receptor through multiple media and pathways.

THE DECISION METHODOLOGY

Different analytic approaches (single-medium or multimedia analyses) may lead to the selection of different optimal sludge management strategies and thus produce different degrees of risk. A multimedia risk analysis is combined in this study with an optimization framework to develop a methodology for comparing a systems analysis with a single-medium analysis of the sludge management problem described above. The comparison proceeds as follows:

(1) Based on the optimization framework utilizing the systems approach, find an optimal management strategy and the resulting risk. In this framework, a multimedia risk analysis is conducted to take into account multiple exposure pathways and multiple pollutants.
(2) Modify the optimization framework to simulate a single-medium approach.
(3) Find the optimal management strategy for the modified single-medium decision problem and characterize the resulting risk.
(4) Compare the two optimal strategies (one from the single-medium and one from the multi-pathway analyses) and their associated risks against each other and against a baseline case consisting of application of all sludge onto the land (typically the default management strategy). If the optimal strategies from (1) and (3) are different, then:
(5) Compare the risk from the optimal strategy in (1) against the risk from the baseline case to obtain the increment of total risk and inequity for the optimal solution selected by the systems approach, relative to the baseline case.
(6) Compare the risk from the optimal strategy in (3) against the risk from the baseline case to obtain the increment of total risk and inequity for the optimal solution selected by the single-medium approach, relative to the baseline case.
(7) Compare (5) and (6) to determine the improvement in risk reduction offered by the systems approach, relative to the single-medium approach.

Since it may be the case that improvements in risk reduction offered by the systems approach are context dependent, a systematic analysis is performed of the improvements under a variety of environmental conditions and analytic/decision criteria. In particular, the following six conditions and criteria were considered and separate analyses performed using all permutations of these:

- Different chemicals and combinations of chemicals were considered. The combinations were TCE only; BEHP only; TCE and BEHP and TCDD; Cd only; Cr(VI) only; Cd and Cr(VI); and all five of the chemicals as a mixture.

- The location of a farm was selected to be either a real site in the region around the proposed Wilson County facility or a site receiving the highest air deposition (the site of maximal exposure in regulatory analyses).
- The fraction of food consumed from local contaminated sources rather than from more remote and uncontaminated farms. These two fractions were those for a typical non-farming resident and for a typical farmer.
- The percentage of the exposed population allowed to exceed some regulatory limit on risk, and the certainty levels with which this percentage is estimated (i.e., a decision criterion that the optimal solution must protect at least x% of the population with at least y% confidence).
- The method of incorporating population risk and risk equity into the utility function used for locating optimal solutions. Four possibilities are considered here:
  1. E1: The objective is to minimize total numbers of cancers subject to constraint that the cancer risk is less than 10^{-6} for individuals in both populations (white and non-white). In addition, the hazard quotient should not exceed 1.0 for non-carcinogens.
  2. E2: The objective is to minimize total numbers of cancers subject to the constraint that the mean cancer risk in the two populations not differ by more than a factor of 2 (a consideration of risk equity or environmental justice). In addition, the hazard quotient should not exceed 1.0 for non-carcinogens.
  3. E3: The objective is to minimize the total number of cancers in the non-white population only (for purposes of redressing past instances of environmental injustice). In addition, the hazard quotient should not exceed 1.0 for non-carcinogens.
  4. E4: The objective is to minimize the total number of cancers in the exposed population, weighted by the ratio between the two population's individual cancer risk. In this case, the total number of cancers is multiplied by the ratio of the mean individual cancer risk in the non-white population over the mean cancer risk in the white population; higher values of this ratio would result in a less desirable strategy. In addition, the hazard quotient should not exceed 1.0 for non-carcinogens.
- The manner in which the single-medium approach was formulated as a decision problem. The two possibilities were (i) to establish maximal allowed concentrations (concentration-based environmental standards) in each medium, and to reject a strategy if these were exceeded; (ii) to minimize the risk for one of the following primary exposure pathways: inhalation only; ingestion only; air only; surface water only; soil only; and groundwater only (risk-based standard).

The above listing of possible environmental conditions and decision criteria leads to 8,064 combinations of these which might be considered by a decision-maker as illustrated in Figure 2. The analysis which follows addresses the question of whether differences in optimal management strategies selected under the single-medium and multi-pathway approaches depend critically on which of these 8,064 combinations of criteria form the basis for decisions.

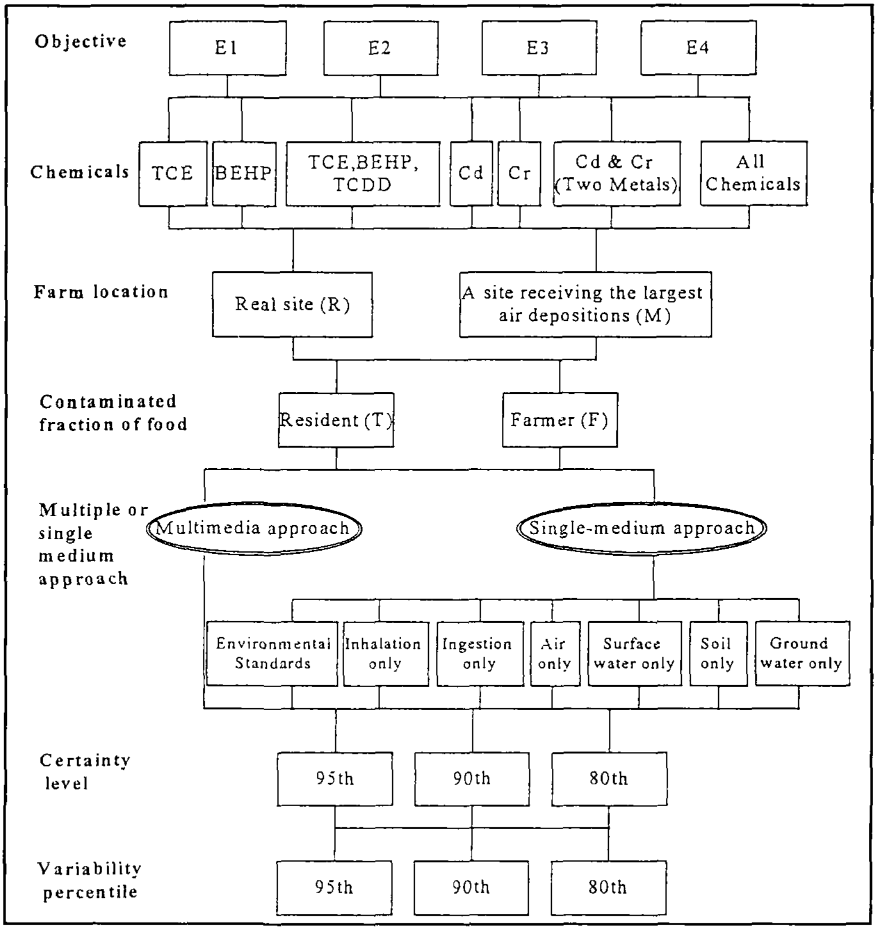

Figure 2. Illustration of the combinations of conditions. The figure shows the combinations of analytic and decision conditions under which an optimal sludge management strategy is determined in this study. The conditions consist of seven categories, with a total of 8,064 (= 4 × 7 × 2 × 2 × 8 × 3 × 3) combinations of considerations.

THE MULTIMEDIA RISK ANALYSIS METHODOLOGY

Embedded in the optimization framework is a multimedia risk analysis, which establishes the quantitative relationship between the release of risk agents from alternative management options into the various environmental media, transport through the environmental system, exposure to defined populations, and risk. It consists of four interrelated steps: release assessment, exposure assessment, consequence assessment; and risk characterization [10].

Release Assessment

Release assessment characterizes the pollutant source terms associated with each management alternative. As an example, this study examines four of the most common constituents of sludge: (chromium or Cr VI; cadmium or Cd, Bis(2-ethylhexyl)phthalate or BEHP, and trichloroethylene or TCE); and the combustion product of most concern (2,3,7,8-TCDD dioxin) as the risk agents to be analyzed. The concentration of each of these constituents in the original sludge was selected to be representative of those found nationally in typical sludge streams [11, 12]. The waste-feed rate, the destruction rates of incineration, and the removal efficiencies of APCDs and wastewater treatment systems then determines the initial release of the pollutants into the air, surface water, and soil of the land application unit. Figure 3 illustrates the methodology of assessing the initial releases.

Exposure Assessment

Exposure assessment is used to translate contaminant source terms into estimates of the amount of contaminant that comes into contact with a specified population. The assessment process can be divided into two connected parts: multimedia transport and transformation modeling, and multiple-pathway exposure modeling [13, 14].

Multimedia transport and transformation modeling predicts the temporal and spatial distribution of pollutant concentrations in the environment. In this study, the multimedia model was constructed by linking single-medium models so the output files of one model are used as the input files of the next. The single-medium models were based on uniformly mixed compartments and transfer between compartments by first-order processes [15, 16]. The exception is the air compartment, where spatial inhomogeneity of concentrations are calculated through the Industrial Source Complex-Short Term version 3 (ISCST3) air dispersion model. The algorithms for soil and water transport used in two models, the Multi-Pathway Risk Assessment Model (MPRAM) developed at Research Triangle Institute and the Multimedia Environmental Pollutant Assessment System (MEPAS) developed at Battelle, were combined to model multimedia transport and exposure associated with land application and incineration of

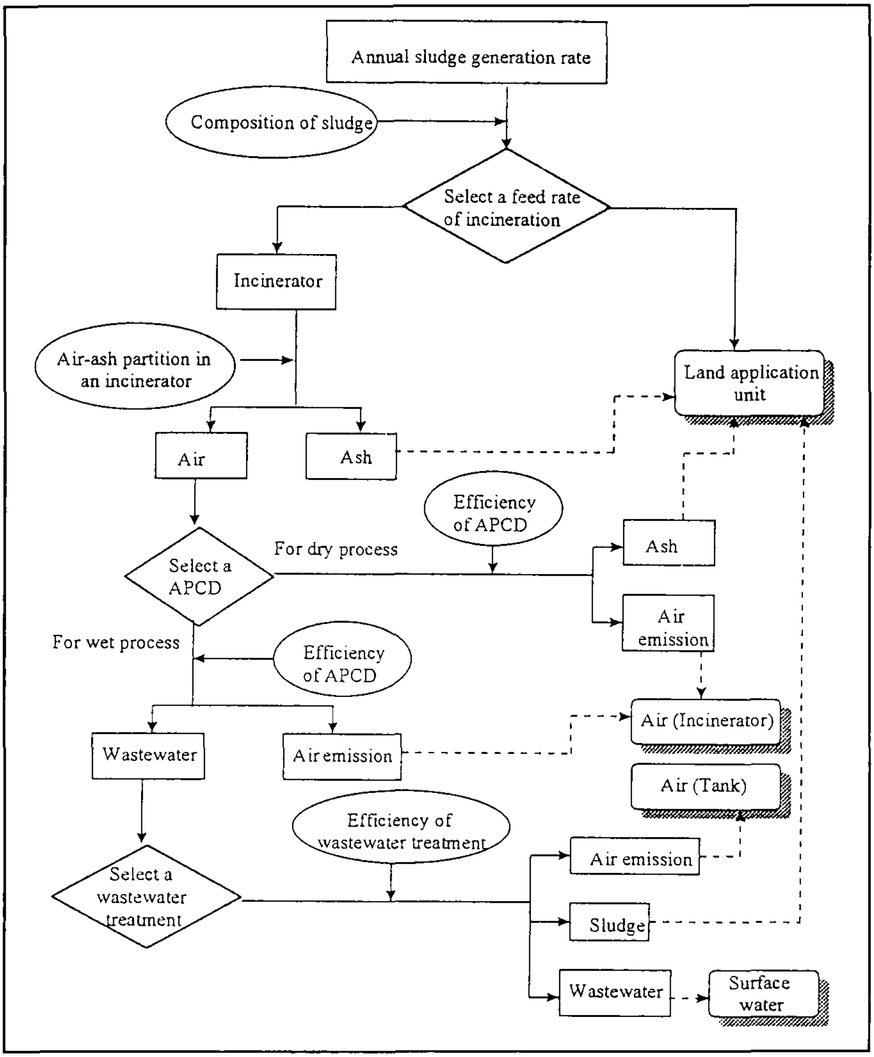

Figure 3. The methodology for assessing initial release from a combination of sludge disposal and pollution control and treatment processes. The rhombi represent the selections of disposal or treatment methods. The ellipses represent the information inputs. With available typical sludge compositions, destruction rates and release factors of incineration, and the removal efficiencies of APCDs and wastewater treatment systems, the initial release of pollutants into the air, surface water, and the soil of the land application unit respectively is a function of the fraction of sludge incinerated (or the fraction of sludge put on the land) and the selected APCD and wastewater treatment level.

sludge [7-20]. The various exposure pathways then correspond to specific linkings of these models, with each combination of linkings being referred to as a transport scenario.

The outputs of the models are (i) annual average concentrations of air and soil in each grid-zone surrounding the modeled sludge management facility over the exposure period; (ii) annual concentrations in the surface waterbodies identified as drinking water and fish sources; and (iii) steady-state groundwater concentrations under the area of each zone. The methodology of modeling environmental transport and subsequent exposure as a result of the initial release of pollutants into an environmental medium is summarized in Figure 4.

After estimating the pollutant concentrations in each environmental medium in each grid block surrounding the site, exposure scenarios that link an environmental medium and an exposure route were used to estimate multiple-pathway exposure. Exposure routes included inhalation, ingestion, and dermal uptake. The exposure scenarios examined in this study, grouped by the environmental medium with which an exposure scenario begins, are listed below:

- Releases to air
  - → direct inhalation → Inhalation exposure[a]
  - → deposition onto produce → Ingestion exposure[b]
  - → deposition onto plants → forage by beef and cattle → Ingestion exposure[b]
  - → any of the above → breast milk → Ingestion exposure[b]
- Releases to soil
  - → volatilization and resuspension into air → Inhalation exposure[a]
  - → direct ingestion of soil → Ingestion exposure[b]
  - → root uptake → aboveground produce and root vegetables → Ingestion exposure[b]
  - → root uptake → forage by beef and cattle → Ingestion exposure[b]
  - → root uptake → silage and/or grain → use to feed beef, dairy, and pork → Ingestion exposure[b]
  - → ingestion of soil by cattle, pigs and chickens → Ingestion exposure[b]
  - → Dermal exposure
  - → any of the above → breast milk → Ingestion exposure
- Releases to surface water
  - → drinking water supply → Ingestion exposure[b]
  - → fish → Ingestion exposure[b]
  - → bathing → volatilization → Inhalation exposure[a]
  - → bathing → Dermal exposure
  - → any of the above → breast milk → Ingestion exposure[b]
- Releases to groundwater
  - → drinking water supply → Ingestion exposure[b]

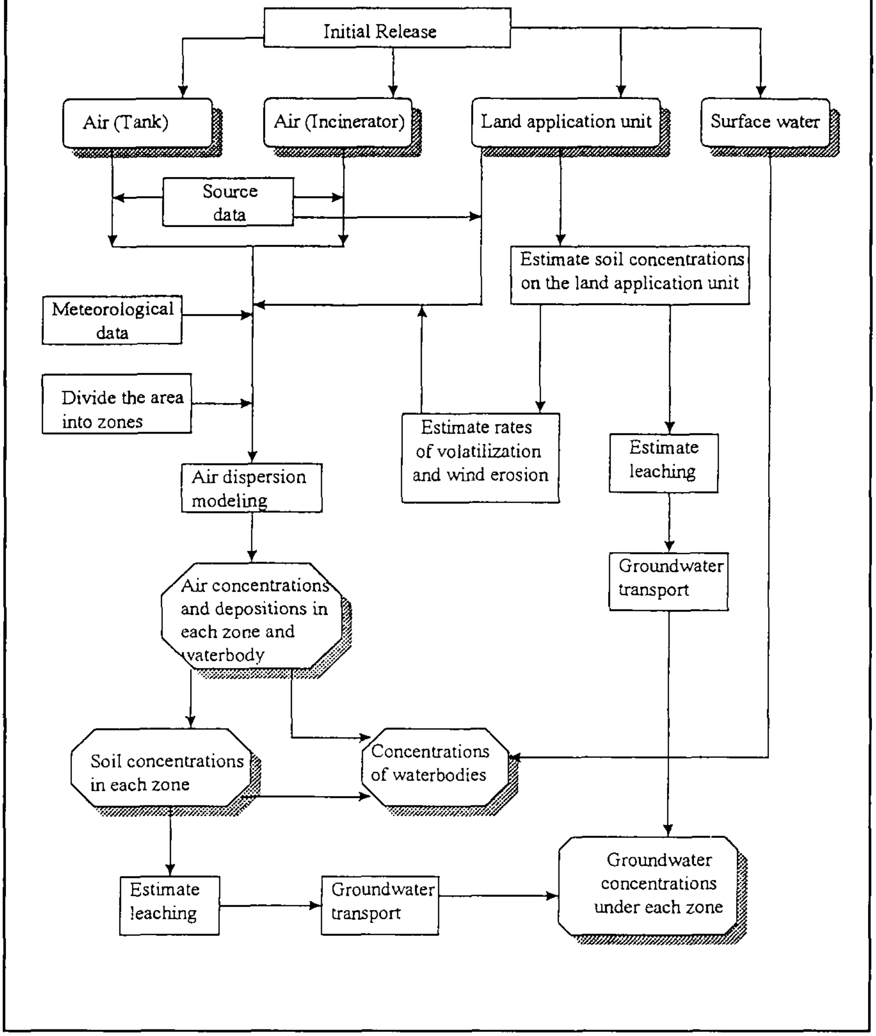

Figure 4. Methodology for assessing environmental transport. The area around the waste management facility is divided into zones by a grid. ISCST3 is used with the air emissions from the incinerator, the tank, and the land application unit to model air concentrations and ground depositions in each zone. The concentrations of soil and waterbodies are then estimated based on the identified loss and transport mechanisms. The groundwater concentrations are calculated by estimating the leaching rates from soil and the transport in the aquifer.

→ bathing → volatilization → Inhalation exposure[a]
→ bathing → Dermal exposure
→ any of the above → breast milk → Ingestion exposure[b]

In the above list, "Inhalation only" is the sum of those pathways with superscript a; and "Ingestion only" is the sum of those pathways with superscript b.

Age-dependent exposure factors (rates of inhalation, ingestion of food and water, and soil contact) were used to determine the exposure through each of these pathways. Separate calculations were performed for each grid block surrounding the site, and the population size in each grid block determined from census track data. The variability of risk in each separate grid block was generated, then a composite variability distribution generated for the entire population. It is this latter variability distribution which must display the property of having at least x percent of the population at or below the acceptable limit on risk, as described in the previous section on decision criteria.

Consequence Assessment

The linear, non-threshold model of carcinogenesis using potency factors (or slope factors) was used to calculate individual lifetime risk of cancer resulting from these exposures. The non-cancer effects were expressed as a hazard index, which is the ratio of the concentration in an environmental medium divided by the concentration allowed by the regulator (here, the EPA). All numerical values of slope factors and reference doses (used to calculate the hazard index) were taken directly from the EPA IRIS database [21].

Risk Characterization

The input parameters into risk estimates developed in this study include environmental parameters, chemical-specific parameters, and exposure and biological parameters. The exposure and biological parameters are age-dependent [22, 23] and were made such in the study. Both inter-subject variability of these exposure and biological parameters, and uncertainty in the characteristics of the variability distributions, were incorporated into the analysis. The mean of each parameter (but not the variance) was characterized as uncertain, reflected as a probability density function on this mean. A Monte Carlo technique was used to combine uncertainty and variability probability distributions associated with individual model parameters to produce uncertainty and variability distributions for the risk estimates [24]. The result for each analysis of a mitigation strategy, therefore, was a variability distribution for the risk in the exposed population, and an uncertainty distribution for the prediction of risk associated with the x*th* percentile of the variability distribution (x is either 80, 90, or 95% as shown in Figure 2). The need for both the uncertainty and variability distributions arises from the decision criterion that an acceptable strategy must protect at least x percent of the population (derived from the variability distribution) with at least y percent confidence (derived from the uncertainty distribution).

THE OPTIMIZATION FRAMEWORK

The decision problem was constructed within an optimization framework in which all necessary mitigation goals (described previously) are combined in an objective function. The optimization framework can be formulated as the following:

Objective: one of the four objectives identified previously (the E1, E2, E3, or E4 in Figure 2). **Alternatives**: combinations of sludge disposal and pollution control measures. **Subject to**: the relationship between alternatives and resulting risk, which is given by the various models, and subject to the constraint that there must be at least y percent confidence that at least x percent of the population satisfies the risk criterion of 10^{-6} for cancer risk and a hazard index of 1.0 for non-cancer health endpoints.

The defining equations and constraints are then:

$$R_{ijk} = f_{ijk}\,(I,\, X_{Wk},\, X_{Ak'})$$

$$\begin{array}{lll} X_{Wk} & = 1 \text{ for all } k & \text{, if wastewater treatment technology } Wk \text{ used} \\ & \quad 0 & \text{, otherwise} \\ X_{Ak'} & = 1 \text{ for all } k' & \text{, if air pollution control technology } Ak' \text{ is used} \\ & \quad 0 & \text{, otherwise} \end{array}$$

and

$$0 \leq I \leq 1$$

where R_{ijk} is the risk from environmental medium i and exposure route j for population k, predicted the transport, exposure and risk models and I is the fraction of sludge that is incinerated.

Two optimization methods were used to select the optimal sludge management strategies. One uses a branch-and-bound algorithm for the mixed integer programming problem. The second used the data filter and search functions in Microsoft Excel. The constraints of the optimization formulation served as a filter to filter out the outputs of mitigation strategies that do not meet those constraints, and the best solutions then were searched for from the filtered data.

RESULTS

The results of this study are the determinations of optimal waste management strategies under each of the 8,064 combinations of considerations. A discussion concerning whether the optimal strategies from a multimedia approach and from a single-medium approach are different (under a given combination of considerations) is described below, grouped into sections according to the regulatory goals (E1, E2, E3, and E4 as defined previously).

The number of optimal solutions produced by the single-medium approach which differ from the corresponding optimal solution under the multimedia approach for different combinations of conditions is shown in the cells of Tables 1 through 4. Note that because there are 9 (= 3 × 3) combinations of certainty levels (Y% confidence) and variability percentiles (X% of the population) which a decision-maker might use, there is a total of nine optimal solutions in each cell of Tables 1 through 4, which is reflected in the denominator in each cell. In each cell, the number of these nine cases in which the multimedia and single-medium optimal solutions differ is shown in the numerator. Therefore, the ratio is the fraction of the analyses in which the optimal solutions differ between the multimedia and single-medium analyses.

For about 73 percent of the conditions under objective E1, no optimal solution was found from the multimedia analysis because all sludge management strategies under those conditions result in the individual risk of white and non-white populations being above 10^{-6}, which is not acceptable by the decision criterion E1. But for those conditions where solutions were found, the optimal strategies from the multimedia and single-medium approaches are the same. Only when "all chemicals" are considered (i.e., risk is aggregated over all chemicals) do many single-medium approaches produce different optimal strategies than the multimedia approach. This was true when the single-medium approach was based on "inhalation only," "soil only," "groundwater only," and "air only." The other three single-medium approaches ("environmental standards," "ingestion only," and "surface water only") produce the same optimal solutions as the systems approach. That the "ingestion only" and "surface water only" approaches do not generate differences indicates that ingestion and surface water are the dominant exposure pathways even under multimedia analyses. When chemicals other than "all chemicals" are considered, almost all conditions produce the same optimal solutions from the two approaches. This indicates that the problem with the single-medium approach appears most readily when small errors introduced by the analysis of any one chemical are compounded by consideration of multiple chemicals.

For about 50 percent of the conditions under objective E2, no optimal solution was found from the multimedia analysis because all sludge management strategies under those conditions result in the individual risk ratio between white and non-white populations being above 2, which is not acceptable by this decision criterion. For chemicals other than metals, the single-medium approach often produced different optimal solutions than the multimedium approach; the exception is when the former was based on an "environmental standards" approach. When "all chemicals" were considered, all single-medium approaches produced different optimal solutions under almost all conditions. That the

Table 1. The Number of Different Optimal Solutions for Objective E1[a,b,c]

Chemicals	Farm Location & Contaminated Fraction	Single-Medium Approach						
		Environmental Standards	Exposure Route		Environmental Medium			
			Inhalation	Ingestion	Air	Water	Soil	GW
TCE	RT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
BEHP	RT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT*	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF*	0/9	0/9	0/9	0/9	0/9	0/9	0/9
Three Organics	RT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT*	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF*	0/9	0/9	0/9	0/9	0/9	0/9	0/9
Cd	RT*	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF*	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT*	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF*	0/9	0/9	0/9	0/9	0/9	0/9	1/9

Cr(VI)	RT*	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF*	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT*	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF*	0/9	0/9	0/9	0/9	0/9	0/9	0/9
Two Metals	RT*	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF*	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT*	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF*	0/9	0/9	0/9	0/9	0/9	0/9	1/9
All Chemicals	RT*	0/9	9/9	0/9	9/9	0/9	9/9	9/9
	RF*	0/9	9/9	0/9	9/9	0/9	9/9	9/9
	MT*	0/9	9/9	0/9	0/9	0/9	9/9	9/9
	MF*	0/9	9/9	0/9	0/9	0/9	9/9	8/9

[a] Each cell of the table shows the number of different optimal strategy produced by a particular single-medium approach than a corresponding multimedia approach under a combination of chemicals considered, a farm location, and a contaminated fraction of food. Because 9 combinations of conditions (3 percentiles in the uncertainty distribution and 3 percentiles in the variability distribution) are included in each cell, the denominator, 9, represents there is a total of 9 optimal strategies in each cell. The numerator represents the number of different optimal solutions in those 9 conditions.

[b] R denotes the real location of the farm; M denotes the location that receives the largest air depositions; T denotes the set of contaminated fraction of food for a typical resident; and F denotes the one for a typical farmer.

[c]* represents the condition where an optimal solution from the multimedia approach cannot be found when the amounts of pollutants are not decreased by half and thus the number of different optimal solutions cannot be determined.

Table 2. The Number of Different Optimal Solutions for Objective E2^{a,b,c}

Chemicals	Farm Location & Contaminated Fraction	Single-Medium Approach						
		Environmental Standards	Exposure Route		Environmental Medium			
			Inhalation	Ingestion	Air	Water	Soil	GW
TCE	RT	0/9	0/9	9/9	9/9	9/9	0/9	9/9
	RF	0/9	0/9	9/9	0/9	9/9	0/9	9/9
	MT	0/9	0/9	9/9	6/9	9/9	0/9	9/9
	MF	0/9	1/9	9/9	6/9	9/9	1/9	9/9
BEHP	RT	0/9	9/9	1/9	9/9	1/9	1/9	4/9
	RF	0/9	9/9	1/9	9/9	1/9	1/9	8/9
	MT*							
	MF*							
Three Organics	RT	0/9	9/9	1/9	9/9	1/9	1/9	9/9
	RF	0/9	9/9	1/9	9/9	1/9	1/9	9/9
	MT*							
	MF*							
Cd	RT*							
	RF*							
	MT	0/9	9/9	0/9	0/9	0/9	0/9	9/9
	MF	0/9	9/9	0/9	0/9	0/9	0/9	9/9

Cr(VI)	RT*							
	RF*							
	MT*							
	MF*							
Two Metals	RT*							
	RF*							
	MT*	0/9	9/9	0/9	9/9	0/9	0/9	9/9
	MF*	7/9	9/9	0/9	0/9	0/9	0/9	9/9
All Chemicals	RT*	9/9	9/9	9/9	9/9	8/9	9/9	9/9
	RF*	9/9	9/9	9/9	9/9	8/9	9/9	9/9
	MT*							
	MF*							

[a] Each cell of the table shows the number of different optimal strategy produced by a particular single-medium approach than a corresponding multimedia approach under a combination of chemicals considered, a farm location, and a contaminated fraction of food. Because 9 combinations of conditions (3 percentiles in the uncertainty distribution and 3 percentiles in the variability distribution) are included in each cell, the denominator, 9, represents there is a total of 9 optimal strategies in each cell. The numerator represents the number of different optimal solutions in those 9 conditions.

[b] R denotes the real location of the farm; M denotes the location that receives the largest air depositions; T denotes the set of contaminated fraction of food for a typical resident; and F denotes the one for a typical farmer.

[c] * represents the condition where an optimal solution from the multimedia approach cannot be found when the amounts of pollutants are not decreased by half and thus the number of different optimal solutions cannot be determined.

Table 3. The Number of Different Optimal Solutions for Objective $E3^{a,b}$

Chemicals	Farm Location & Contaminated Fraction	Single-Medium Approach						
		Environmental Standards	Exposure Route		Environmental Medium			
			Inhalation	Ingestion	Air	Water	Soil	GW
TCE	RT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
BEHP	RT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
Three Organics	RT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
Cd	RT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF	0/9	0/9	0/9	0/9	0/9	0/9	1/9

Cr(VI)	RT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
Two Metals	RT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF	0/9	0/9	0/9	0/9	0/9	0/9	1/9
All Chemicals	RT	9/9	9/9	0/9	9/9	0/9	9/9	9/9
	RF	9/9	9/9	0/9	9/9	0/9	9/9	9/9
	MT	9/9	9/9	0/9	0/9	0/9	9/9	9/9
	MF	9/9	9/9	0/9	0/9	0/9	9/9	8/9

[a] Each cell of the table shows the number of different optimal strategy produced by a particular single-medium approach than a corresponding multimedia approach under a combination of chemicals considered, a farm location, and a contaminated fraction of food. Because 9 combinations of conditions (3 percentiles in the uncertainty distribution and 3 percentiles in the variability distribution) are included in each cell, the denominator, 9, represents there is a total of 9 optimal strategies in each cell. The numerator represents the number of different optimal solutions in those 9 conditions.

[b] R denotes the real location of the farm; M denotes the location that receives the largest air depositions; T denotes the set of contaminated fraction of food for a typical resident; and F denotes the one for a typical farmer.

Table 4. The Number of Different Optimal Solutions for Objective E4[a,b]

Chemicals	Farm Location & Contaminated Fraction	Single-Medium Approach						
		Environmental Standards	Exposure Route		Environmental Medium			
			Inhalation	Ingestion	Air	Water	Soil	GW
TCE	RT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
BEHP	RT	0/9	6/9	1/9	8/9	1/9	1/9	1/9
	RF	0/9	4/9	1/9	8/9	1/9	1/9	1/9
	MT	0/9	9/9	1/9	7/9	7/9	5/9	7/9
	MF	1/9	8/9	1/9	7/9	6/9	4/9	6/9
Three Organics	RT	0/9	9/9	1/9	8/9	1/9	1/9	1/9
	RF	0/9	9/9	1/9	8/9	1/9	1/9	1/9
	MT	0/9	9/9	1/9	7/9	7/9	7/9	7/9
	MF	0/9	9/9	1/9	7/9	7/9	7/9	7/9
Cd	RT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF	0/9	0/9	0/9	0/9	0/9	0/9	0/9

Cr(VI)	RT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
Two Metals	RT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	RF	0/9	0/9	0/9	0/9	0/9	1/9	0/9
	MT	0/9	0/9	0/9	0/9	0/9	0/9	0/9
	MF	0/9	0/9	0/9	0/9	0/9	0/9	0/9
All Chemicals	RT	5/9	5/9	7/9	8/9	8/9	5/9	5/9
	RF	8/9	8/9	5/9	5/9	5/9	8/9	8/9
	MT	9/9	9/9	0/9	0/9	0/9	9/9	9/9
	MF	9/9	9/9	0/9	0/9	0/9	9/9	9/9

[a] Each cell of the table shows the number of different optimal strategy produced by a particular single-medium approach than a corresponding multimedia approach under a combination of chemicals considered, a farm location, and a contaminated fraction of food. Because 9 combinations of conditions (3 percentiles in the uncertainty distribution and 3 percentiles in the variability distribution) are included in each cell, the denominator, 9, represents there is a total of 9 optimal strategies in each cell. The numerator represents the number of different optimal solutions in those 9 conditions.

[b] R denotes the real location of the farm; M denotes the location that receives the largest air depositions; T denotes the set of contaminated fraction of food for a typical resident; and F denotes the one for a typical farmer.

"inhalation only" and "soil only" approaches do not generate a difference indicates that inhalation and soil are the dominant exposure pathways for TCE in this case study.

The outcomes under objective E3 are similar to those described under objective E1. The only difference is that under objective E3, unlike under objective E1, the single-medium analyses based on "environmental standards" approaches produced different optimal solutions when "all chemicals" are considered. With respect to objective E4, considering TCE only, Cd only, Cr(VI) only, and "two metals," produced optimal solutions for the single-medium and multimedia approaches that are the same under almost all conditions. For BEHP only, "three organics," and "all chemicals," many of the optimal solutions differ.

In addition to the qualitative comparison above, a quantitative comparison of the single-medium and systems approaches in terms of their effects on the utility of the optimal solution are shown in Tables 5 through 8. The improvement of the systems approach over the baseline management strategy is represented by the improved objective value (utility) compared to the objective value from the baseline management strategy. This is calculated from the relation:

$$I_M = \frac{B - M}{B}$$

where B is the baseline utility and M is the utility of the strategy selected as optimal under the multimedia analysis. The difference between the optimal objective values from the single-medium and systems approaches represents the magnitude of deterioration in utility of the optimal solution when a single-medium approach is used rather than a systems approach. This difference is calculated from the relation:

$$D_S = \frac{S - M}{B}$$

where S is the utility of the optimal solution when the single-medium analysis is used, and M and B are as defined above. In both of the above equations, the measure of utility is the total number of individuals developing the health endpoint, weighted in the case of objective E4 by the ratio of risks in the white and non-white population.

The results show that compared to the baseline sludge management strategy, the resultant optimal management strategy from the systems approach may improve the utility value by as much as 77 percent. Compared to the systems approach, the single-medium approaches may deteriorate the utility by as much as almost forty times the baseline utility, or even lead to an "optimal" strategy that actually produces an unacceptable risk from the systems perspective.

DISCUSSION AND RECOMMENDATION

This study provides a methodology for comparing the merits of the multimedia and single-medium approaches, and applies that methodology to assessing these merits in a specific case study. With site-specific conditions and realistic policy goals specified, the methodology combines multimedia risk analysis with an optimization framework to determine whether the multimedia waste management approach leads to the same or different management decisions compared to the single-medium approach. It also estimates the magnitude of the improvement in the utility associated with the optimal strategy selected by a multimedia waste management approach over that selected by the single-medium approach. The information is useful for the policy-maker to assess whether or not different medium-specific programs and regulations need to be integrated to manage an environmental pollution problem. The results of the sludge management case study, and their implications for the utility of the methodology, lead to the following conclusions:

- The comparison of single-medium and multimedia wastes management approaches is affected by the environmental modeling and decision conditions considered. The policy goals and site-specific information influence the comparison, although no consistent pattern in the influence of those conditions is found by the present analysis.
- Excluding those conditions where there were feasible solutions from the multimedia approaches, almost one-third of the analyses produced different optimal solutions for single-medium and multimedia approaches.
- Under objective E1, which is equivalent to neglecting the equity issue, about 7 percent of the considerations produced different optimal solutions. When focus is only on the non-white population (objective E3), about 9 percent of the considerations produced different optimal solutions. When equity was incorporated by weighting population risk by the individual risk ratio between the two populations (objective E4), about 21 percent of the considerations produced different optimal solutions. When equity was represented by limiting the ratio of risk between the two populations below 2 (objective E2), about 52 percent of the considerations produced different solutions. The way in which risk equity is represented in the utility function, therefore, significantly influences whether the single and multimedium approaches yield different optimal strategies.
- When only metals are considered, the optimal solutions usually were the same in the two approaches (0 to 5% difference). Analyzing only organics produced different optimal strategies in 13 percent of the cases for "TCE only" and to 20 percent for the mixture of TCE, BEHP, and TCDD. When all chemicals are considered as a mixture, 64 percent of the cases show different optimal solutions.

Table 5. The Improvement of Systems Approaches and Deterioration of Single-Medium Approaches for Objective E1[a]

Chemicals	Farm Location & Contaminated Fraction	I_M	D_S						
		Systems Approach	Environmental Standards	Exposure Route		Environmental Medium			
				Inhalation	Ingestion	Air	Water	Soil	GW
TCE	RT	0	0	0	0	0	0	0	0
	RF	0	0	0	0	0	0	0	0
	MT	0	0	0	0	0	0	0	0
	MF	0	0	0	0	0	0	0	0
BEHP	RT	0	0	0	0	0	0	0	0
	RF	0	0	0	0	0	0	0	0
	MT	0*	0*	0	0*	0*	0	0	0
	MF	0*	0*	0	0*	0*	0	0	0
Three Organics	RT	0	0	0	0	0	0	0	0
	RF	0	0	0	0	0	0	0	0
	MT	0*	0*	0	0*	0*	0	0	0
	MF	0*	0*	0	0*	0*	0	0	0
Cd	RT	36-50%	0*	0	0*	0	0	0	0*
	RF	8-35%	0*	0	0*	0	0	0	0*
	MT	51-57%*	0*	0	0*	0	0	0	0*
	MF	48-64%	0*	0	0*	0	0	0*	0-64%*

Cr(VI)	RT	15-16%*	0*	0*	0	0*	0	0	0
	RF	15-16%*	0*	0*	0	0*	0	0	0
	MT	15-16%*	0*	0*	0	0*	0	0	0
	MF	15-16%*	0*	0*	0	0*	0	0	0
Two Metals	RT	27-40%*	0*	0*	0*	0*	0	0	0*
	RF	11-27%*	0*	0*	0*	0*	0	0	0*
	MT	42-48%*	0*	0*	0*	0*	0	0	0*
	MF	49-59%*	0*	0*	0*	0*	0	0	0-59%*
All Chemicals	RT	0*	0*	3-54%*	0*	3-54%*	0	3-54%	3-54%*
	RF	0*	0*	30-76%*	0*	30-76%*	0	30-76%	30-76%*
	MT	0*	0*	99-139%*	0*	0*	0	99-139%	99-139%*
	MF	0*	0*	19-180%*	0*	0*	0	19-180%	0-139%*

[a]* Represents the condition where an optimal solution cannot be found when the amounts of pollutants are not decreased.

Table 6. The Improvement of Systems Approaches and Deterioration of Single-Medium Approaches for Objective E2[a]

Chemicals	Farm Location & Contaminated Fraction	I_M	D_S						
		Systems Approach	Environmental Standards	Exposure Route		Environmental Medium			
				Inhalation	Ingestion	Air	Water	Soil	GW
TCE	RT	N→A	0	0	N	224-652%	N	0	N
	RF	N→A	0	0	N	0	N	0	N
	MT	N→A	0	0	N	0-1281%	N	0	N
	MF	N→A	0	0, N	N	0	N	0, N	N
BEHP	RT	0	0	–	0-138%	–	0-138%	0-138%	0-469%
	RF	0	0	–	0, N	–	0, N	0, N	481-3256%
	MT	x	x, –	x, –	x, –	x, –	x	x	x
	MF	x	x, –	x, –	x, –	x, –	x	x	x
Three Organics	RT	0	0	–	0, N	–	0, N	0, N	329-2713%
	RF	0	0	–	0, N	–	0, N	0, N	329-2713%
	MT	x	x, –	x, –	x, –	x, –	x	x	x
	MF	x	x, –	x, –	x, –	x, –	x	x	x
Cd	RT	x	x, –	x, –	x, –	x	x	x	x, –
	RF	x	x, –	x, –	x, –	x	x	x	x, –
	MT	51-57%	0	–	0	0	0	0	–
	MF	48-64%	0	–	0	0	0	0	–

Cr(VI)	RT	x	x, –	x, –	x	x	x	x, –	x
	RF	x	x, –	x, –	x	x	x	x, –	x
	MT	x	x, –	x, –	x	x	x	x, –	x
	MF	x	x, –	x, –	x	x	x	x, –	x
Two Metals	RT	x	x, –	x, –	x, –	x, –	x	x	x, –
	RF	x	x, –	x, –	x, –	x, –	x	x	x, –
	MT	42-48%	0	–	0	17-46%	0	0	–
	MF	49-59%	0-23%	–	0	0	0	0	–
All Chemicals	RT	N→A	14-59%	–	N	–	0, N	33-68%	–
	RF	N→A	36-74%	36-74%	N	–	0, N	44-74%	–
	MT	x	x, –	x, –	x, –	x, –	x	x	x, –
	MF	x	x, –	x, –	x, –	x, –	x	x	x, –

[a] "N→A" means systems approach improves the decision from unacceptable to acceptable. "N" means single-medium approach solution is unacceptable. "–" means optimal solution from single-medium approach not found. "x" means that optimal solution from systems approach not found.

Table 7. The Improvement of Systems Approaches and Deterioration of Single-Medium Approaches for Objective E3[a]

Chemicals	Farm Location & Contaminated Fraction	I_M	D_S						
		Systems Approach	Environmental Standards	Exposure Route		Environmental Medium			
				Inhalation	Ingestion	Air	Water	Soil	GW
TCE	RT	0	0	0	0	0	0	0	0
	RF	0	0	0	0	0	0	0	0
	MT	0	0	0	0	0	0	0	0
	MF	0	0	0	0	0	0	0	0
BEHP	RT	0	0	0	0	0	0	0	0
	RF	0	0	0	0	0	0	0	0
	MT	0	0	0	0	0	0	0	0
	MF	0	0	0	0	0	0	0	0
Three Organics	RT	0	0	0	0	0	0	0	0
	RF	0	0	0	0	0	0	0	0
	MT	0	0	0	0	0	0	0	0
	MF	0	0	0	0	0	0	0	0
Cd	RT	38-51%	0	0	0	0	0	0	0
	RF	8-36%	0	0	0	0	0	0	0
	MT	47-54%	0	0	0	0	0	0	0
	MF	51-60%	0	0	0	0	0	0	0-60%

Cr(VI)	RT	15-16%	0	0	0	0	0	0	0
	RF	15-16%	0	0	0	0	0	0	0
	MT	15-16%	0	0	0	0	0	0	0
	MF	15-16%	0	0	0	0	0	0	0
Two Metals	RT	29-40%	0	0	0	0	0	0	0
	RF	12-27%	0	0	0	0	0	0	0
	MT	39-43%	0	0	0	0	0	0	0
	MF	43-52%	0	0	0	0	0	0	0-52%
All Chemicals	RT	0	3-54%	3-54%	0	3-54%	0	3-54%	3-54%
	RF	0	30-76%	30-76%	0	30-76%	0	30-76%	30-76%
	MT	0	78-125%	99-139%	0	0	0	99-139%	99-139%
	MF	0	85-139%	19-180%	0	0	0	19-180%	0-139%

[a]The largest improvement in utility from the systems approach relative to the baseline is about 60% of the baseline objective value (utility); the largest deterioration in utility from a single-medium approach compared to the systems approach is about 1.8 times the baseline utility ("inhalation only" and "soil only" approaches).

Table 8. The Improvement of Systems Approaches and Deterioration of Single-Medium Approaches for Objective E4[a]

Chemicals	Farm Location & Contaminated Fraction	I_M	D_S						
		Systems Approach	Environmental Standards	Exposure Route		Environmental Medium			
				Inhalation	Ingestion	Air	Water	Soil	GW
TCE	RT	0	0	0	0	0	0	0	0
	RF	0	0	0	0	0	0	0	0
	MT	0	0	0	0	0	0	0	0
	MF	0	0	0	0	0	0	0	0
BEHP	RT	0-67%	0	21-2817%	0-67%	0-2817%	0-67%	0-67%	0-67%
	RF	0-69%	0	19-3983%	0-69%	0-496%	0-69%	0-69%	0-69%
	MT	0-77%	0	54-227%	0-94%	0-1%	54-227%	0-0.3%	54-227%
	MF	0-77%	0-54%	0-551%	0-120%	0-53%	0-551%	0-0.04%	0-551%
Three Organics	RT	0-67%	0	21-2818%	0-67%	0-279%	0-67%	0-67%	0-67%
	RF	0-69%	0	19-3983%	0-69%	0-496%	0-69%	0-69%	0-69%
	MT	0-77%	0	23-226%	0-93%	0-0.8%	0-77%	0-77%	0-77%
	MF	0-77%	0	15-364%	0-108%	0-1%	0-74%	0-64%	0-74%
Cd	RT	41-51%	0	0	0	0	0	0	0
	RF	9-37%	0	0	0	0	0	0	0
	MT	43-50%	0	0	0	0	0	0	0
	MF	48-59%	0	0	0	0	0	0	0

Cr(VI)	RT	16-17%	0	0	0	0	0	0	0
	RF	15-16%	0	0	0	0	0	0	0
	MT	15-17%	0	0	0	0	0	0	0
	MF	15-16%	0	0	0	0	0	0	0
Two Metals	RT	28%	0	0	0	0	0	0	0
	RF	28%	0	0	0	0	0	0-55%	0
	MT	28%	0	0	0	0	0	0	0
	MF	28%	0	0	0	0	0	0	0
All Chemicals	RT	0-21%	0-14%	0-14%	0-3%	0-123%	0-21%	0-14%	0-14%
	RF	0-14%	0-36%	0-36%	0-14%	0-2%	0-2%	0-36%	0-36%
	MT	0	74-132%	340-510%	0	0	0	340-510%	340-510%
	MF	0	122-196%	73-882%	0	0	0	73-882%	73-882%

[a] The largest improvement in utility from the systems approach relative to the baseline is about 77% of the baseline objective value (utility); the largest deterioration in utility from a single-medium approach compared to the systems approach is about 40 times the baseline utility (the "inhalation only" approach).

- For those cases where there is a difference in the optimal strategy selected under the two approaches, the deterioration in utility due to use of a single-medium approach rather than the systems range from 0.04 percent (which is an insignificant deterioration) to almost forty times the baseline objective value (which is a significant deterioration). In some cases, a single-medium approach may lead to selection of an optimal strategy that would not be acceptable if the risk were analyzed from the systems perspective.

In summary, the lack of a clear pattern in the conditions under which different optimal solutions are obtained, and the fact that there can be significant deterioration in utility of the optimal solution under the single medium approach, indicates that the multimedium risk analysis approach should become the norm for risk-based decision-making.

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