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Stochastic multimedia risk assessment for a site with contaminated groundwater

H.-W. Ma

Abstract. There exist many sites with contaminated groundwater because of inappropriate handling or disposal of hazardous materials or wastes. Health risk assessment is an important tool to evaluate the potential environmental and health impacts of these contaminated sites. It is also becoming an important basis for determining whether risk reduction is needed and what actions should be initiated. However, in research related to groundwater risk assessment and management, consideration of multimedia risk assessment and the separation of the uncertainty due to lack of knowledge and the variability due to natural heterogeneity are rare. This study presents a multimedia risk assessment framework with the integration of multimedia transfer and multi-pathway exposure of groundwater contaminants, and investigates whether multimedia risk assessment and the separation of uncertainty and variability can provide a better basis for risk management decisions. The results of the case study show that a decision based on multimedia risk assessment may differ from one based on risk resulting from groundwater only. In particular, the transfer from groundwater to air imposes a health threat to some degree. By using a methodology that combines Monte Carlo simulation, a rank correlation coefficient, and an explicit decision criterion to identify information important to the decision, the results obtained when uncertainty and variability are separate differ from the ones without such separation. In particular, when higher percentiles of uncertainty and variability distributions are considered, the method separating uncertainty and variability identifies TCE concentration as the single most important input parameter, while the method that does not distinguish the two identifies four input parameters as the important information that would influence a decision on risk reduction.

Keywords: Multimedia risk assessment, Risk management, Sensitivity, Uncertainty, Monte Carlo methods

1
Introduction

Like air and surface water, groundwater is a valuable natural resource. Unlike air and surface water, however, groundwater contamination is not easily detected and is often discovered only after pollution events have occurred for a long time. This increases the difficulty, and hence cost, of remediation. In the United States, 34 states report serious groundwater contamination problems; more than 80% of the

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H.-W. Ma
Graduate Institute of Environmental Engineering,
National Taiwan University, 71 Chou-Shan Road,
Taipei, Taiwan 106
e-mail: hwma@ccms.ntu.edu.tw

Superfund sites involve groundwater contamination (Maxwell et al., 1998). In Taiwan, many sites with contaminated groundwater have been identified and thus public awareness is increasing. It has been found that 91.4% of the 58 groundwater samples taken from the 38 monitoring wells located in five cities of northern Taiwan were contaminated by chlorinated organics (Tsai and Kuo, 1988). Most of the contamination is due to inappropriate disposal of hazardous materials and wastes and may cause adverse effects on the environment and human health.

Those contaminated sites must be ranked in terms of their need for control or management because limited resources are available. For any contaminated site, whether management measures are necessary and what level of management should be achieved must be determined. Health risk assessment is one of the most important tools for providing the relevant evaluation because of its capability of systematically quantifying the health impacts. For example, Risk-Based Corrective Action (RBCA) has become popular in the US (Barkan et al., 1996). In literature related to groundwater, the body of research quantifying health risks caused by contaminated groundwater, and discussions of associated risk management decisions, is growing (for example, see Andričević and Cvetković, 1996; Jacobs et al., 1996; Pelmulder et al., 1996; Maxwell et al., 1998; Lahkim and Garcia, 1999).

Health risk assessment involves identifying the potential of a risk source to introduce risk agents (e.g., chemical contaminants) into the environment, estimating the amount of risk agents that come into contact with the human-environment boundaries, and quantifying the health consequences of exposure. Since the risk assessment paradigm was established in 1983 (NRC, 1983), the practice of risk assessment has become more sophisticated. There have been three historical stages of development in sophistication for these assessments: the incorporation of site-specific information rather than using generic default assumptions, the performance of multimedia risk assessment, and the introduction of stochastic risk assessment methods. Site-specific risk assessment is desired because the health risk received by a receptor is dependent on the conditions of the environment and the receptor's exposure patterns. Multimedia risk assessment is desired because pollutants distribute to various environmental media after their release from the source and because a receptor may receive multiple exposures from various environmental media (Ma and Crawford-Brown, 1998; Ma, 2000). Finally, stochastic risk assessment is desired because of the natural variability of environmental conditions and exposure patterns at a given site, and the lack of complete knowledge needed to develop estimates of exposure and risk.

However, within the literature on risk assessment and management of contaminated groundwater, research that incorporates techniques of multimedia assessment is rare. Most researchers did not consider multimedia transfer of groundwater contaminants. Some only considered the risk from ingestion of contaminated groundwater (Andričević and Cvetković, 1996); some considered multiple exposure pathways following use of contaminated groundwater, such as the inhalation pathway from showering in addition to ingestion of contaminated groundwater (Maxwell et al., 1998; Lahkim and Garcia, 1999), but the groundwater was still the only contaminated medium. Regarding the incorporation of stochasticity, some assessments did consider the uncertainty involved in risk assessment, but most did not distinguish between uncertainty and spatio-temporal variability (Maxwell and Kastenberg, 1999). Because of different sources, properties, and implications of uncertainty and variability, the importance of their distinction is recognized in risk-based decision-making (Finkel, 1990).

Compared to generic, single-medium, and deterministic risk assessment methods, site-specific, multimedia, and stochastic risk assessment methods require a relatively large amount of information. Therefore a question arises: will stochastic, multimedia risk assessment that separates uncertainty and variability make a difference in decision-making (i.e. is the increased accuracy and detail in predictions of risk worth the increased complexity of assessment)? To address the question, this study seeks to: (1) present a multimedia risk assessment framework integrating multimedia transfer and multi-pathway exposure of groundwater contaminants, (2) investigate whether consideration of multimedia transfer can provide a better basis for risk management decisions, and (3) explore whether stochastic multimedia risk assessment methods separating uncertainty and variability can provide better information in identification of significant parameters. A chlorinated Dense Non-Aqueous Phase Liquid (DNAPL)-contaminated groundwater risk management decision problem serves as the case study to explore this issue, and is described in the next section.

2
The decision problem

The case study used in this paper to examine the issue raised previously is located in Taoyuan City of Taiwan, where it was discovered that soil and groundwater are contaminated by chlorinated hydrocarbons, primarily trichloroethylene (TCE) and tetrachloroethylene (PCE). Although cleanup of the contaminated soil has been completed, it is still under investigation to determine an appropriate course of management of groundwater contamination.

Based on the land use patterns and spatial pattern of contaminant concentrations, the site is divided into four zones, each of which is assessed individually. This paper uses a case of one of the four zones: 80 000 m^2 of farmland with scattered residences and a large fishpond. According to the observations of 15 monitoring wells in this zone, the mean and standard error of the contaminant concentrations are 0.12 and 0.02 mg/l for TCE, respectively, and 0.0005 and 0.0001 mg/l for PCE, respectively (Geomatrix, et al., 1998).

Many resources have been spent in trying to remove the contaminants from the groundwater (19 000 000 gallons of groundwater have been drawn), with little reduction in mean concentrations, due to DNAPL's distinct physical characteristics that increase the difficulty of its removal. Risk managers (here, the government) are faced with a decision as to whether residual contamination requires further remediation. A vital problem is to identify and collect information that is essential in reaching such a decision. Collection of site-specific data, however, will prove costly. Therefore setting information priorities is valuable in facilitating data collection, allowing limited resources to be focused on those data most likely to affect decisions. To help resolve this issue, this paper presents a stochastic, multimedia risk assessment and explores whether separation of components of stochasticity related to uncertainty and variability makes a difference to the identification of important information needed for a site-specific assessment of alternative remediation measures. The following section presents the framework of multimedia risk assessment, followed by a section on assessing the influence of separation of components of stochasticity. The last two sections provide results and discussion, and conclusion, respectively.

3
The framework of multimedia risk assessment for a site with contaminated groundwater

After groundwater contamination has been characterized by the concentration profile of TCE and PCE, several interrelated steps are involved in assessing the risk resulting from the contamination: multimedia transfer and transformation modeling, multiple-pathway exposure modeling, consequence assessment, and risk characterization. These steps are described as follows:

A. Multimedia transfer and transformation modeling

The multimedia transfer and transformation modeling step estimates the average concentration of pollutants in various environmental media (i.e., air, soil, and groundwater in the case study). The multiple-pathway exposure modeling models the processes of transferring contaminants from the various environmental media to exposure media (drinking water, food, etc.) and then to humans. The major transfer processes considered in the study involve the diffusion and deposition between groundwater and soil and between soil and air. The associated major calculations are described below.

Diffusion from groundwater to outdoor air (ASTM, 1995; Johnson and Ettinger, 1991)

The vapor phase of a contaminant in the saturated zone diffuses through the porous medium of soil and into the outdoor air. The equation used to model the process is:

$$C_{\text{outdoor}}(mg/m^3) = C_{\text{gw}} \times \frac{H}{1 + \left(\frac{U_{\text{air}}\delta_{\text{air}}L_T}{WD_{\text{ws}}^{\text{eff}}}\right)}$$

where C_{outdoor} and C_{gw} are the concentration of pollutants in the outdoor air and groundwater, respectively; U_{air} is the surface wind speed; δ_{air} is the mixing height; H is the Henry's Law constant; L_T is the distance between the ground surface and the groundwater; W is the length of contamination of this area along the direction of groundwater flow; and $D_{\text{ws}}^{\text{eff}}$ is the effective porous medium diffusion coefficient between groundwater and ground surface.

Diffusion from groundwater to indoor air (Johnson and Ettinger, 1991)

The vapor phase of a contaminant in the saturated zone may diffuse through the porous medium of soil and the cracks in the foundation, floors, and walls of a building and into the indoor air. The equation used to model the process is:

$$C_{\text{building}}(mg/m^3)$$

$$= C_{gw} \times H \times \frac{\left(\frac{D_{\text{ws}}^{\text{eff}} \times A_{\text{B}}}{Q_{\text{building}} \times L_T}\right) \times \exp\left(\frac{Q_{\text{soil}} \times L_{\text{crack}}}{D^{\text{crack}} \times A_{\text{crack}}}\right)}{\exp\left(\frac{Q_{\text{soil}} \times L_{\text{crack}}}{D^{\text{crack}} \times A_{\text{crack}}}\right) + \left(\frac{D_{\text{ws}}^{\text{eff}} \times A_{\text{B}}}{Q_{\text{building}} \times L_T}\right) + \left(\frac{D_{\text{ws}}^{\text{eff}} \times A_{\text{B}}}{Q_{\text{soil}} \times L_T}\right)\left[\exp\left(\frac{Q_{\text{soil}} \times L_{\text{crack}}}{D^{\text{crack}} \times A_{\text{crack}}}\right) - 1\right]}$$

where C_{buliding} is the concentration of pollutants in indoor air; Q_{soil} is the volumetric flow of soil gas into the building; Q_{building} denotes the building's volumetric ventilation rate; L_{crack} is the thickness of the foundation; A_{crack} is the area of cracks through which contaminant vapors enter the building; D^{crack} is the effective vapor-pressure diffusion coefficient through the cracks; A_{B} is the total basement area (floor and walls); and L_T is the distance from groundwater to foundation.

Soil contamination due to irrigation and air deposition (Strenge and Chamberlain, 1995)

The contaminants in air and irrigation water are deposited onto the soil. The equation used to calculate the average soil concentration over the exposure period is:

$$C_{\mathrm{soil}}(mg/g) = \frac{\int_0^{\mathrm{ED}} C_{\mathrm{aw}} \mathrm{d}t}{\mathrm{ED} \cdot t_{\mathrm{dd}} \cdot \rho_{\mathrm{dd}}}$$

where C_{soil} is the average concentration of pollutants in the soil over the exposure period; C_{aw} is the loading of contaminants onto the soil for each unit of area from irrigation water and air; ED is the exposure duration; t_{dd} is the thickness of soil layer; and ρ_{dd} is the soil density.

B. Multiple-pathway exposure modeling

After contaminant concentrations in each environmental medium are estimated, exposure scenarios that link the environmental media and exposure routes (i.e., inhalation, ingestion, and dermal absorption) are examined to estimate multiple-pathway exposures. The exposure scenarios, grouped by the environmental medium that serves as the starting point of exposure, are listed in Table 1. The multiple-pathway exposure step models the transfer of contaminants between environmental media and exposure media, and then estimates the average daily intake of contaminants by human receptors based on the contact rates of the receptors with the exposure media. The equation was used to calculate average daily intake of each contaminant (California EPA, 1993) :

$$\mathrm{ADI}_{ijk} = C_i \times \left[\frac{C_j}{C_i}\right] \times \left[\frac{\mathrm{CR}_{jk}}{\mathrm{BW}}\right] \times \frac{\mathrm{EF} \times \mathrm{ED}}{\mathrm{AT}}$$

where ADI_{ijk} (mg/kg-d) is the average daily intake from environmental medium i, exposure medium j and exposure route k; C_i is the pollutant concentration in

Table 1. Exposure scenarios grouped by the environmental medium that serves as a starting point of exposure

Environmental medium	Exposure scenario
Air	1. Direct inhalation – inhalation exposure 2. Deposition onto produce – ingestion exposure 3. Deposition onto plants – forage fed to pork – ingestion exposure
Soil	1. Resuspension into air – inhalation exposure 2. Direct ingestion of soil – ingestion exposure 3. Dermal exposure
Groundwater	1. Drinking water supply – ingestion exposure 2. Bathing – accidental ingestion – ingestion exposure 3. Bathing – volatilization – inhalation exposure 4. Bathing – dermal exposure 5. Irrigation – produce – ingestion exposure 6. Irrigation – grain fed to poultry – ingestion exposure 7. Water supply of the fish pond – fish – ingestion exposure

environmental medium i; CR_{jk} is the contact rate of exposure medium j through exposure route k; EF is the exposure frequency; ED is the exposure duration; AT is the averaging time; and BW is the body weights of receptors.

In the above equation, C_i is estimated by the multimedia transfer and transformation modeling step presented previously. C_j/C_i is the ratio of the contaminant concentration in an exposure medium over the associated environmental medium. The following equations were used to calculate the pollutant concentrations in the plant and animal food and personal air, transferred from the contaminated environmental media (Bacci et al., 1990, 1992; Mckone, 1987; Travis and Arms, 1988).

Plant contamination due to root uptake

$$P_\mathrm{r} = C_\mathrm{soil} \cdot B_\mathrm{r}$$

Plant contamination due to air deposition

$$P_\mathrm{d} = \frac{\left[D_\mathrm{ydp} + \left(F_\mathrm{w} \cdot D_\mathrm{ywp}\right)\right] \cdot R_\mathrm{p} \cdot \left[\left(1.0 - \exp\left(-k_\mathrm{p} \cdot T_\mathrm{p}\right)\right)\right]}{Y_\mathrm{p} \cdot k_\mathrm{p}}$$

Plant contamination due to air-to-plant transfer

$$P_\mathrm{v} = \frac{C_\mathrm{av} \cdot B_\mathrm{v}}{\rho_\mathrm{a}}$$

where P_r, $P_\mathrm{d,}$ and P_v are the pollutant concentration in the plant due to root uptake, air deposition, and vapor transfer, respectively; D_{ydp} and D_{ywp} are the yearly air dry and wet, respectively, deposition from particle phase; C_{av} is the vapor phase air concentration; R_p is the interception fraction of edible portion of the plant; T_p is the time of plant exposure to deposition; k_p is the plant surface loss coefficient; F_w is the fraction of wet deposition that adheres to plant; Y_p is the crop yield; B_r is the plant-soil bioconcentration factor; and B_v is the air-plant biotransfer factor; and ρ_a is air density.

Animal contamination due to plant and soil ingestion

$$A_i = \left(\sum F_j Qp_j \cdot P_j + Q_\mathrm{s} \cdot C_\mathrm{soil}\right) \cdot \mathrm{Ba}_i$$

where A_i is the pollutant concentration in the ith animal tissue group; P_{ij} is the pollutant concentration in the jth plant group eaten by the ith animal; QP_{ij} is the quantity of the plant group j eaten by the animal group i; Q_s is the ingestion rate of soil by the animal; F_j is the fraction of plant grown on contaminated soil for plant j; and Ba_i is the biotransfer factor for the ith animal tissue group.

Fish contamination due to contaminated water supply

$$C_\mathrm{fish} = C_\mathrm{wt} \cdot \mathrm{BAF}$$

where C_fish is the pollutant concentration in fish; C_wt is the pollutant concentration in the total water body; and BAF is the bioaccumulation factor for fish.

Personal air concentration due to volatilization of bathing water

$$C'_{\mathrm{a}} = C_{\mathrm{water}} \cdot \frac{W_{\mathrm{bath}} \cdot \Phi(\mathrm{bath})}{\mathrm{VR}_{\mathrm{bath}}} \times 10^3$$

where C'_{a} is the pollutant concentration in personal air as a result of vaporization of the pollutant in bathing water; W_{bath} is the water used in shower; $\mathrm{VR}_{\mathrm{bath}}$ is the ventilation rate of the bathroom; and $\Phi(\mathrm{bath})$ is the mass transfer efficiency from water to air and is calculated by:

$$\Phi(\mathrm{bath}) = 0.6 \times \frac{\left(3 \times 10^{10}\right)^{-2/3}}{\left[\frac{2.5}{D_{\mathrm{w}}^{2/3}} + \frac{RT}{H \times D_{\mathrm{a}}^{2/3}}\right]},$$

where D_{w} is the diffusion coefficient in water and D_{a} is the diffusion coefficient in air.

C. Consequence assessment

Consequence assessment depicts the toxicological responses as a result of exposure. In this study, cancer risk is used as the measure of health impacts. The linear and non-threshold model of carcinogenesis using potency factors (or slope factors) is used to calculate individual lifetime risk of developing cancer (USEPA, 1989).

D. Risk characterization

Risk characterization consists of integrating the results from previous steps to generate quantitative measures of individual lifetime risk of developing cancer. Additionally, in this step, a Monte Carlo technique is used to propagate parameter variance to produce the uncertainty associated with the risk estimate. Each of the input parameters is treated as a random variable with known or estimated probability density function (pdf). For each of the variables, one value is selected at random with respect to the associated pdf. The individual cancer risk is then calculated by using the multimedia risk assessment method described above with the sampled set of input values. The sampling and calculation are repeated many times to produce the pdf of the risk estimate (Iman and Helton, 1988; Ma, 2000).

There are two types of uncertainties considered here: Type A (due to spatio-temporal variability that results in variation of exposures between individuals) and Type B (due to lack of knowledge of the system being modeled). Type A uncertainty reflects natural heterogeneity and cannot be reduced, while Type B uncertainty can be reduced through further research and collection of more information. When the value of a variable is fixed for all exposed individuals but unknown, the uncertainty is of Type B. When a variable is a distribution with known statistical parameters across a population of people, the uncertainty is of Type A. When there is a mixture of the two types of input parameters, the uncertainty associated with the risk estimation is “two dimensional”, characterized by an intersubject variability distribution whose true mean, variance, and shape are uncertain. As risk assessment has become an important basis of policy making, it has been increasingly required to provide both uncertainty and variability information on risk (Hoffman and Hammonds, 1994).

To produce the two-dimensional uncertainty information, a nested Monte Carlo technique is used with uncertainty and variability pdfs of individual parameters. The technique has been detailed in a previous study (Ma, 2000). Parameters on properties of air, soil, and groundwater, and contact rates of drinking water and foods, in addition to physicochemical properties of TCE and PCE are used in this case study. Since only one division of the site is being considered, the environmental parameters are not variable but are uncertain. Exposure parameters are variable but no uncertainty is assumed for the purpose of simplification. The uncertainty and variability distribution information for the major parameters is shown in Table 2.

4

The method for assessing influence of separating uncertainty and variability in identification of important information

Sensitivity analysis methods are often used to identify information whose uncertainty and variability is a driving factor in the overall uncertainty and variability of risk estimates for the population. In this study, a rank correlation coefficient between each input parameter and the associated risk output is computed to measure the importance of each parameter to the overall uncertainty. The rank correlation coefficients are indicators of the degree of monotonic relationship between the sample value of the model prediction and those of the uncertain inputs. For this reason, rank correlation coefficients often work better to rank parameter contributions to uncertainty than other methods that are based on linear relationships only (Morgan, 1990; McKone, 1996).

Although the combination of Monte Carlo simulation with calculation of rank correlation coefficient provides a method for identifying information with major contributions to overall variance, whether the information identified is essential to reliable decision-making should be examined further in the decision context. The methodology for identifying information important to the decision problem of the case study by combining Monte Carlo simulation, rank correlation coefficients, and decision criteria is summarized as follows (Ma, 2002):

1. The Monte Carlo simulation is performed and the rank correlation coefficients calculated. Then the rank correlation coefficients are squared and normalized to calculate the relative percentage of the total variance attributable to each of the parameters.
2. A parameter selected from the set of parameters with major contributions to the total variance is fixed at its plausible minimum value. The Monte Carlo simulation is then preformed to find the risk output. (The selection of the risk value from the output distribution is described in step 6.)
3. A selected parameter is fixed at its plausible maximum and the Monte Carlo simulation is again performed to find the risk output.
4. It is determined whether the target risk level specified in the decision criteria falls between the range of risk output generated in step 2 and 3. If it does, variation of the values of the parameter from the upper to lower limits may lead to different risk reduction decisions; better information about the parameter is therefore important to the decision. If it does not, better characterization of the value of the parameter would not influence the decision.
5. Repeat steps 2 through 4 for all the parameters that have major contributions to the total variance identified in step 1.
6. For comparison, repeat steps 1 through step 5 for different methods of treating uncertainty. There are two ways of treating uncertainty in the present study: keeping Type A and Type B uncertainty combined into a single pdf reflecting overall stochasticity, and separating these two forms of stochasticity. When the

Table 2. Major parameters used in the case problem

Parameter	Definition	Distribution[a]	Reference
D_a	Diffusion coefficient of TCE in air (cm^2/s)	Lognormal (median = 0.08, GSD_B = 1.05)	Yeh and Kastenberg, 1991
D_w	Diffusion coefficient of TCE in water (cm^2/s)	Lognormal (median = 9.1E-6, GSD_B = 1.05)	Yeh and Kastenberg, 1991
H	Henry's Law constant (unitless)	Lognormal (median = 0.42, GSD_B = 1.2)	California EPA, 1993
Ba	Biotransfer factor of TCE for pork (d/kg)	Lognormal (median = 2.57E-5, GSD_B = 2)	Pelmulder et al., 1996
Q_{soil}	Volumetric flow of soil gas into the building (m^3/d)	Lognormal (median = 0.0018, GSD_B = 1.3)	ASTM, 1995
U_{air}	Surface wind speed (cm/s)	Lognormal (median = 520, GSD_B = 1.1)	Taiwan Weather Bureau
IR	Irrigation rate (l/m^2-month)	Lognormal (median = 0.84, GSD_B = 2)	Site survey
R_p	Deposition interception fraction of vegetables (unitless)	Lognormal (median = 0.25, GSD_B = 2)	Whelan et al., 1987
Kp	Plant surface loss coefficient (yr^{-1})	Lognormal (median = 18, GSD_B = 2)	USEPA, 1993
Yp	Crop yield (kg/m^2)	Lognormal (1.98, GSD_B = 2)	Site survey
Dp_a	Deposition rate to soil from irrigation water (mg/m^2-d)	Lognormal (0.5, GSD_B = 2)	Whelan et al., 1987
DP_w	Deposition rate to soil from air (mg/m^2-d)	Lognormal (0.5, GSD_B = 2)	Whelan et al., 1987
U_{dw}	Ingestion rate of drinking water (l/d)	Lognormal (median = 2, GSD_A = 1.7)	Droppo et al., 1989
U_{ff}	Ingestion rate of fish (kg/d)	Lognormal (median = 0.09, GSD_A = 1.3)	Wu et al., 1997
U_v	Ingestion rate of vegetables (kg/d)	Lognormal (median = 0.52, GSD_A = 1.15)	Wu et al., 1997
U_{mp}	Ingestion rate of pork (kg/d)	Lognormal (median = 0.12, GSD_A = 1.15)	Wu et al., 1997
U_{mc}	Ingestion rate of poultry (kg/d)	Lognormal (median = 0.05, GSD_A = 1.15)	Wu et al., 1997
Ir_{in}	Inhalation rate indoors (m^3/d)	Lognormal (median = 20.7, GSD_A = 1.2)	USEPA, 1999
BW	Body weight (kg)	Lognormal (median = 59.9, GSD_A = 10)	Kao et al., 1997

[a] GSD denotes geometric standard deviation. Subscript A (B) denotes that uncertainty is of Type A (B)

two types of stochasticity are combined, the relevant statistical summary from the risk outputs of steps 2 and 3 is the 95th percentile of the resulting distribution of risk. When the two types of stochasticity are separated, the relevant statistical summaries from steps 2 and 3 are the xth percentile ($x = 95$, 90, 85, and 80) of the uncertainty distribution and yth percentile ($y = 95$, 90, 85, and 80) of the variability distribution.

5
Results and discussion

Importance of multimedia risk assessment

The discussion turns first to the issue of whether a fully stochastic multi-media and multi-pathway assessment yields a different decision than would have been reached under a fully stochastic but single (dominant) pathway assessment. Figure 1 shows multiple realizations of the cumulative probability distribution for inter-subject variability of cancer risk received by typical residents in the study area. As described previously, each curve results from a unique random selection of parameter values used to characterize either an environmental parameter used in the model or the mean of a pdf describing inter-subject variability for an exposure factor (ingestion rate of water, etc). A single curve represents a single realization of the inter-subject variability distribution of risk in the exposed population. From such a curve, the 95th percentile of the risk in the population may be estimated; i.e. one may determine the level of risk for which it may be said that 95% of the population is at or below this risk. By considering multiple curves, and summarizing the variation in their individual estimates of the risk at the 95th percentile of the population, one can develop a pdf describing the uncertainty in this risk at the 95th percentile of the population. The result is a risk value for which the decision-maker may state that he or she is 95% confident that 95% of the population has a risk at or below this risk value (a typical stochastic risk-based decision criterion; other criteria might use different combinations of the uncertainty and variability percentiles). The risk values at the 95th certainty level and 95th variability distribution percentile (abbreviated as 95/95 hereafter) for each of the exposure pathways, categorized by environmental medium and exposure medium, are shown in Table 3.

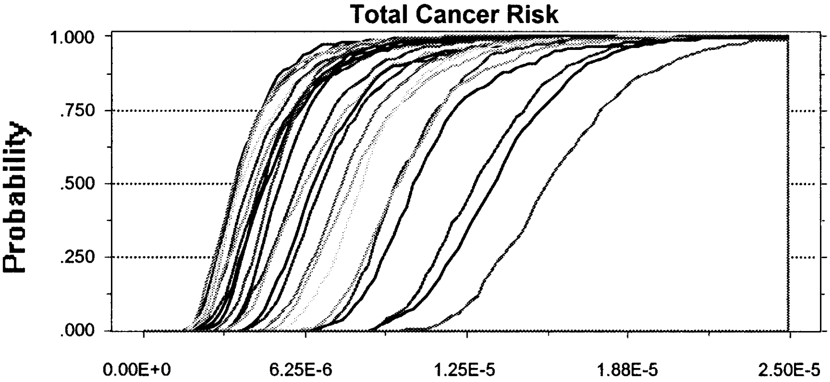

Fig. 1. The cumulative variability and uncertainty distribution of the total risk estimate. A single curve represents a single realization of the inter-subject variability distribution of risk. There are multiple curves because of the uncertainties associated with the variability distribution of risk

Table 3. The Risk value of 95th certainty level and 95th variability percentile for specified pathways. The pathways are characterized by the contact of exposure medium (air, food, etc.) and the environmental medium that directly contaminated the exposure medium

Exposure route	Exposure medium	Environmental medium			Sum
		Air	Groundwater	Soil	
Inhalation	Indoor air	5.35E-07	3.46E-06	–	4.00E-06
	Outdoor air	1.21E-06	–	2.71E-13	1.21E-06
Ingestion	Rice	–	8.06E-08	–	8.06E-08
	Vegetables	6.76E-07	4.93E-06	–	5.61E-06
	Fish	–	6.38E-07	–	6.38E-07
	Pork	8.01E-09	1.69E-07	–	1.77E-07
	Poultry	–	1.88E-09	–	1.88E-09
	Drinking water	–	8.35E-06	–	8.35E-06
	Soil	–	–	5.26E-07	5.26E-07
Dermal	Water	–	1.07E-09	–	1.07E-09
	Soil	–	–	1.29E-16	1.26E-16
Sum		2.43E-06	1.76E-05	5.26E-07	2.06E-5
Contribution		11.8%	85.6%	2.6%	

Among the three contaminated environmental media, it is found that groundwater and air are the major contributors to the total health risk (85.6% and 11.8% of the total risk, respectively), while the risks caused by soil contamination can be ignored. This indicates that in addition to direct ingestion of the contaminated groundwater itself, the transfer of contamination from groundwater to air will impose an health threat to some degree (in this case, the air leads to a cancer risk of 2.43E-6 at the 95/95 cumulative probability distribution level). Among the exposure pathways considered in this study, it is found that ingestion of drinking water (40.5% of the total risk), ingestion of plant food (27.2% of the total risk), inhalation of indoor air (19.4% of the total risk) as a result of using groundwater (such as volatilization during bathing), and inhalation of outdoor air (5.9% of the total risk) are the four major exposure pathways, accounting for 93% of the total risk.

The risk values at different combinations of uncertainty and variability percentiles (i.e., 95/90, 95/85, 95/80, 90/95, 90/90, 90/85, 90/80, 85/95, 85/90, 85/85, 85/80, 80/95, 80/90, 80/85, 80/80) have a similar pattern in terms of relative contributions of various environmental media and exposure pathways. For the purpose of discussion, the risk value at the 95/95 uncertainty and variability combination is used, unless stated otherwise.

From the comparison of the contribution of different environmental media, it can be seen that approximately 15% of the total risk comes from environmental media other than groundwater in this case study. Around 60% of the total risk results from exposure pathways other than direct ingestion of groundwater. Therefore considering the risk from well water only will cause only a 15% underestimation of the total risk, while considering only ingestion of contaminated groundwater (rather than other indirect pathways of exposure) will cause an underestimation by as much as 60% of the total risk. In this case study, the risk resulting from air and soil is around 3E-6.

Whether the increased risk value generated by the multimedia risk assessment will alter the decision is dependent on the decision criteria. For example, in a screening decision to determine whether actions should be initiated, a decision criterion based on the health risk only is often used. If the acceptable risk level is set to be 1E-5, the estimated 95/95 risk resulting from all pathways of exposure to the contaminants residing initially in the groundwater (1.76E-5) already exceeds the acceptable risk level. In this respect, the multimedia risk assessment would not alter the decision (which in this case would be a decision to mitigate). However, when only direct ingestion of groundwater is considered, the resulting risk (8.35E-6) is less than the acceptable level. Under this situation, a decision based on the multimedia risk assessment would be different from the one that considers groundwater ingestion only. In other words, the inclusion of multiple exposure pathways in the screening assessment alters not only the numerical value of the estimated risk, but moves the calculated risk into a new category of decision (from a decision of no mitigation to one of mitigation).

From the comparison of various exposure pathways, it can be seen that the four major exposure pathways mentioned earlier, each of which leads to risk larger than 1E-6, deserve more attention. If it is determined that the total risk is so large that management measures need to be initiated, it is apparent that control on the use of groundwater as a source of irrigation water, drinking water, and bathing water, as well as the avoidance of outdoor inhalation (not a feasible mitigation strategy), should be considered as priority in making risk management plans. In this respect, multimedia risk assessment does provide a better basis for risk management decisions, identifying a wider range of options for risk reduction.

Importance of separating forms of stochasticity in identification of significant parameters for reducing uncertainty

By calculating the rank correlation coefficients of input parameters, it has been found that, in descending order, TCE concentration, ingestion rate of drinking water, yield of vegetables, irrigation rate, fraction of deposition retained on plant surface, plant surface loss constant, and bathroom size are the seven major sources of uncertainty. By following steps 1 to 6 and setting the acceptable risk level at 1E-5, without distinguishing Type A and Type B stochasticity, as described in the methodology section, it has been found that 4 of the 7 parameters represent cases in which the target risk level falls between the lower and upper limits on the risk estimate when the parameter value is varied. These four parameters are TCE concentration, vegetable yield, deposition interception fraction of vegetables, and plant surface loss constant (Ma, 2002).

Table 4 presents the results of following steps 1 to 6, but with separation of uncertainty and variability as described in the methodology section. It shows that for the TCE concentration, the target risk level, 1E-5 in the case, always falls between the two extremes (denoted as "yes" in Table 6) for all combinations of uncertainty and variability percentiles explored in this study. As for the two parameters representing irrigation rate and bathroom size, the target risk level always falls outside of the range between the two extremes (denoted as "no" in Table 6) for all combinations. Therefore information on TCE concentration is always essential in this decision problem, while the values of the latter two parameters do not affect the decision. However, for the remaining four parameters, whether the target level falls between the two extremes varies with different combinations of uncertainty and variability percentiles. Comparing these results to the case where both forms of stochasticity were combined into a single pdf, it can be seen that separation of stochasticity into uncertainty and variability yields a different decision regarding the determination of significant parameters in this case problem. For example, when higher percentiles (95/95, 95/90, 90/95, and

Table 4. Whether the specified target risk level falls between the two extremes for different combinations of uncertainty and variability percentiles. For a particular parameter, its plausible minimum and maximum values, respectively, are used when the Monte Carlo simulation is performed to obtain two extremes of total risk estimation. If the specified target risk level falls between the two extremes of risk estimation for a particular parameter, the variation of that parameter may lead to different decisions

Uncertainty and variability percentile combination	TCE concentration	Ingestion rate of drinking water	Yield of vegetables	Irrigation rate	Fraction of deposition retained on plant surface	Plant surface loss coefficient	Bathroom size
95/95	Yes	No	No	No	No	No	No
95/90	Yes	No	No	No	No	No	No
95/85	Yes	No	No	No	No	No	No
95/80	Yes	No	No	No	No	No	No
90/95	Yes	No	No	No	No	No	No
90/90	Yes	No	No	No	No	No	No
90/85	Yes	No	Yes	No	No	No	No
90/80	Yes	No	Yes	No	No	No	No
85/95	Yes	No	Yes	No	No	No	No
85/90	Yes	No	Yes	No	No	No	No
85/85	Yes	No	Yes	No	No	No	No
85/80	Yes	No	Yes	No	Yes	Yes	No
80/95	Yes	No	Yes	No	No	No	No
80/90	Yes	No	Yes	No	Yes	No	No
80/85	Yes	No	Yes	No	Yes	Yes	No
80/80	Yes	No	Yes	No	Yes	Yes	No

Note: "Yes" means the target level falls between the two extremes. "No" means otherwise

90/90) are considered, which is normally used as the basis of policy making, TCE concentration is the only parameter that would influence the decision, instead of the four parameters identified previously when the two forms of stochasticity were not separated.

6
Conclusion

The case study has shown that a decision based on multimedia risk assessment may differ from one based on risk resulting from groundwater only. This is because considering the risk from well water only will cause a 15% underestimation of the total risk and considering only ingestion of groundwater will cause a 60% underestimation of the total risk in this case problem. In particular, the transfer from groundwater to air imposes a health threat to some degree. By using a methodology that combines Monte Carlo simulation, a rank correlation coefficient, and an explicit decision criterion to identify information important to the decision, the results obtained when uncertainty and variability are separate differ from the ones without such separation. In particular, when higher percentiles of uncertainty and variability distributions are considered, the method separating uncertainty and variability identifies TCE concentration as the single most important input parameter, while the method that does not distinguish the two identifies four input parameters as the important information that would influence a decision on risk reduction. In sum, in spite of increased complexity, stochastic multimedia risk assessment with separation of forms of stochasticity does provide a better basis for risk management decisions.

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