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Stochastic fuzzy environmental risk characterization of uncertainty and variability in risk assessments: A case study of polycyclic aromatic hydrocarbons in soil at a petroleum-contaminated site in China

Yan Hu[a,b], Zesen Wang[a], Jingya Wen[a,c], Yu Li[a,*]

[a] MOE Key Laboratory of Regional Energy Systems Optimization, Resources and Environmental Research Academy, North China Electric Power University, Beijing 102206, China
[b] State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environment Sciences, Beijing 100012, China
[c] Institute of Hydropower and Environment Research, Beijing 100012, China

HIGHLIGHTS

- Deal with environmental quality guidelines absence in risk characterization.
- Quantitative represention of uncertainty from environmental quality guidelines.
- Quantitative represention of variability from contaminant exposure concentrations.
- Establishment of stochastic-fuzzy environmental risk characterization approach framework.

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ABSTRACT

Better decisions are made using risk assessment models when uncertainty and variability are explicitly acknowledged. Uncertainty caused by a lack of uniform and scientifically supported environmental quality guidelines and variability in the degree of exposure of environmental systems to contaminants are here incorporated in a stochastic fuzzy environmental risk characterization (SFERC) approach. The approach is based on quotient probability distribution and environmental risk level fuzzy membership function methods. The SFERC framework was used to characterize the environmental risks posed by 16 priority polycyclic aromatic hydrocarbons (PAHs) in soil at a typical petroleum-contaminated site in China. This relied on integrating data from the literature and field and laboratory experiments. The environmental risk levels posed by the PAHs under four risk scenarios were determined using the SFERC approach, using "residential land" and "industrial land" environmental quality guidelines under "loose" and "strict" strictness parameters. The results showed that environmental risks posed by PAHs in soil are primarily caused by oil exploitation, traffic emissions, and coal combustion. The SFERC approach is an effective tool for characterizing uncertainty and variability in environmental risk assessments and for managing contaminated sites.

1. Introduction

Anthropogenic activities that introduce contaminants to the environment pose severe risks to the environment and human health. Methods for assessing the likely environmental risks (ERs) posed by contaminants are therefore needed. However, great difficulties are involved in attempting to manage ERs because of uncertainty caused by insufficient information being available about the chances of risks occurring and because of variability caused by the complexities of environmental systems. Better decisions are made when uncertainty and variability are explicitly acknowledged and incorporated into risk assessment models [1].

Rapid economic development and accelerating industrialization and urbanization have led to soil contamination increasingly becoming a problem. Soil criteria based on human health risks have been set in most countries, and soil standards or criteria (and technical background documents) for protecting human health have been published. Soil quality guidelines, preliminary remediation goals, and intervention values or soil guideline values (both later called SGVs) have been developed so that it can be determined if

* Corresponding author.
E-mail address: liyuxx8@hotmail.com (Y. Li).

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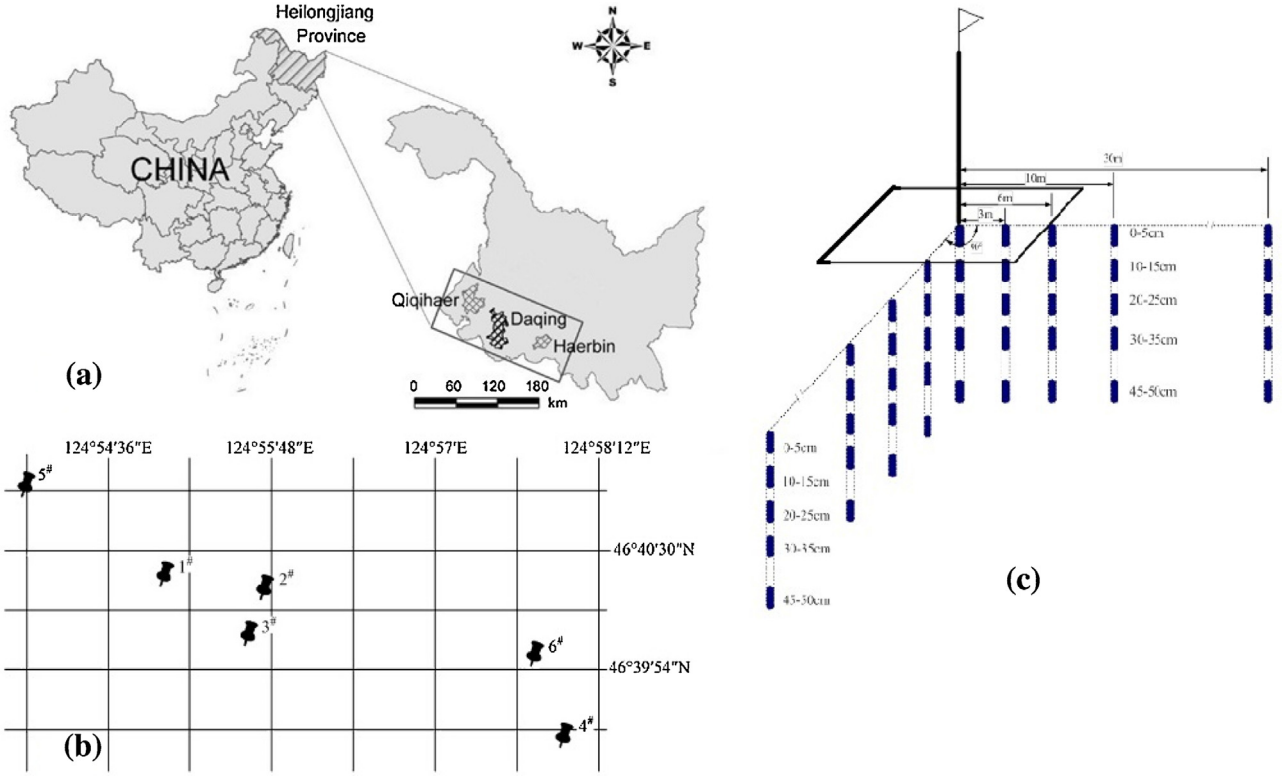

Fig. 1. (a) Map of Daqing City, Heilongjiang Province, China. (b) Locations of the six oil wells that were studied. (c) Locations of the 45 sampling sites around each well.

surveys and/or remediation measures are needed to protect the environment and human health [2–6]. However, SGVs have very different names, purposes, protection objectives, and thresholds in different countries, or even in different states within a country, because of differences in national environmental management policies, human activity patterns, and climatic conditions.

There is a great deal of concern about the effects of polycyclic aromatic hydrocarbons (PAHs) on the environment and human health because it is widely known that they are potentially toxic, having mutagenic, teratogenic, and carcinogenic effects [7,8]. Natural crude oil and refined petroleum both contain significant amounts of PAHs [9,10], and PAH chemicals often enter the environment in oil spills. The assessment and management of risks posed by PAHs in soil at petroleum-contaminated sites have therefore become important subjects. However, there are still no PAH SGVs in the Chinese environmental quality standard for soils [11], and it has become a key scientific issue to determine how the ERs posed by PAHs and similar contaminants can be assessed without scientifically justified and uniform SGVs being available. Minimum SGVs used in other countries have been used to assess the degree to which soil is contaminated with PAHs in previous research [12], but this can be considered to give unnecessarily cautious or unreasonable assessment results. However, using maximum SGVs would be inappropriately lax, and the underestimated ERs that would result could mean that effective measures would not be taken to remediate contaminated sites in a timely manner. A fuzzy environmental quality guideline was developed to deal with this problem [13], but exposure to contaminants was characterized in that guideline assuming that contaminant concentrations are exposed to follow uniform distributions. The ER will be overestimated or underestimated if the actual probability distributions of the contaminant concentrations are exposed to be ignored.

The quotient probability distribution method takes both the probability distributions of the contaminant concentrations are exposed to and the environmental quality guidelines into consideration. The probability that contaminant concentrations violate the environmental quality guideline (P_v) is determined in the quotient probability distribution method using a Monte Carlo simulation [14–17]. An assessment performed using the quotient probability distribution method will produce results with exact probability data, and uncertainty and variability in the risk assessment results can be quantitatively characterized. The objective of this study was to develop a stochastic fuzzy environmental risk characterization (SFERC) approach for characterizing uncertainty and variability in the ER assessment process using probability analysis and fuzzy theory. We expect this approach to offer benefits to the field of environmental management and remediation and provide a scientifically justified way of quantitatively characterizing uncertainty and variability in risk assessments.

2. Materials and methods

2.1. Study area and the sampling sites

The study area was a typical oilfield, in Daqing City, Heilongjiang Province, China. The location of the oilfield is shown in Fig. 1(a). Daqing is a typical resource-based city with oil wells spread throughout the city [18]. Daqing oilfield is the largest oilfield and the most important petrochemical center in China. There are abundant oil and gas reserves in the Daqing oilfield, and more than 40×10^6 t of petroleum are extracted each year by thousands of oil wells that operate every day. Contaminants derived from petroleum are emitted to the environment through different pathways, and soil has been found to be the main sink for these contaminants [19].

Soil samples were collected from around six oil wells in the study area, and the locations of the sites are shown in Fig. 1(b). The oil wells use different drive methods (water driven and polymer driven) and have been used for different lengths of time (1–2 y, 4–6 y, and 8–10 y). A total of 45 samples were collected from