Uncertainty in Environmental Risk Assessment

A. K. Ghorai

Abstract — **To determine the possible impact on human health and other biota due to hazardous substances into the environment the idea of environmental risk assessment is very much important. Environmental data are often questionable as well as imprecise and as such uncertainty is associated in any study related with these kind of data. Randomness and incompleteness are two main origins of uncertainties in risk assessment. To model and analyze these uncertainties there are two main ways viz. probability theory and fuzzy logic set theory. The random variability in environmental parameters can be described by probability functions defined by stochastic approach. On the other hand, the lack of information regarding environmental parameters is analyzed by possibilistic theory i.e. fuzzy logic.**

Index Terms — **Environmental Risk, Uncertainty, Fuzzy Logic, Monte Carlo Method.**

1. INTRODUCTION

The unprecedented increase in environmental risk evoked by human activities as well as new technologies has brought about a global concern for the restoration of harmonious relationship between man and nature. Environmental degradation is induced by many factors including economic growth, population growth, urbanization, intensification of agriculture, rising energy use and transportation. The manufacturing technology adopted by most of the industries has placed a heavy load on environment especially through intensive resource and energy use, as is evident in natural resource depletion, water, air and land contamination, health hazards and degradation of natural eco-systems. Air pollution and exposure to hazardous chemicals are important causes of the environment-related burden of disease. The transport and energy sectors are major contributors to air pollution, while important sources of chemical pollution are agriculture, industry, and waste disposal and incineration.

In recent years the study of environmental risk assessment which is a critical and essential part of any decision making process has assumed a greater interest to know the risks in one hand and the possible steps that should be introduced to mitigate these risks on the other. Risk management is the systematic application of policies, practices, and resources to the assessment and control of risk affecting human health and safety or the environment. Environmental risk assessment is the solid basis in assuming and ranking potential pollution of the environment due to anthropogenic activities and accordingly the proper steps can be taken in alleviating their impacts on natural resources [1]. The results of the environmental risk assessment are very much helpful for the decision makers of the ecological policy and management to justify their decision [2].

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A. K. Ghorai, *Physics Department, Kalimpong College, Darjeeling - 734301, West Bengal, INDIA.*

For a complete environmental assessment in any ecological system a huge amount of data is necessary. But it, however, is very common that the most of the environmental data are qualitative, vague and imprecise [3]. The imprecision of the environmental data together with variability of the system and the role of human judgment propagate uncertainty in risk assessment. The proper management of this uncertainty is a major concern to study environmental risk assessment [4].

1.1 Ecological Risk

The word ‘risk’ is only used when there is a chance, but not certainty. Higher the risk the more dangerous is the activity. Risk may basically be of two types– pure risk and speculative risk. Pure risk exists when there is uncertainty as to whether loss will occur and no possibility of gain is presented. But speculative risk exists when there is uncertainty about an event that can produce either a profit or a loss. In the field of environmental risk we are only concerned about pure risk. Thus ecological risk can be defined as the likelihood or probability of a given hazard of a given level causing a particular level of loss of damage in respect of living being, property and efficacy [5]. Here hazard is the capability of a substance to cause an adverse effect. Thus,

$$Risk = Probability \times Loss.$$

Probability depends on our state of knowledge, which is usually different for different people. In other words, probability is unavoidably subjective. Probability theory [6] and uncertainty theory [7] are complementary mathematical methods. Uncertainty is interpreted as personal belief degree whereas probability is studied as frequency. The measure of uncertainty refers only to the probabilities assigned to outcomes, while the measure of risk requires both probabilities for outcomes and losses quantified for outcomes.

1.2 Uncertainty

Uncertainty may arise due to measurement error, sampling error, descriptive errors, and inappropriate professional judgment. It may also be generated due to model uncertainty which is the result of simplification of real-world processes, incorrect model structure, and use of inappropriate assumptions. Since uncertainty refers to things that are unknown or unsure, the collection of additional site-specific information can reduce the degree of uncertainty.

Again, variability of a system refers to the differences in measurements or responses arising because of the diversity in a population or exposure parameter. Variability is estimated as standard deviation or variance and it represents natural random processes which can be evolved from environmental, lifestyle, and genetic differences among individual organisms. Variability cannot be reduced through additional measurements or studies, although the uncertainty of variability can be improved.

Thus two kinds of uncertainty viz. Epistemic uncertainty and Aleatory uncertainty are involved with the environmental risk modeling. Epistemic uncertainty arises mainly due to the imperfection of our knowledge. This form of uncertainty is associated with many aspects of modeling and policy analysis– e.g., limited and inaccurate data, data censoring and detection limit, measurement error, incomplete knowledge, limited understanding, imperfect models, subjective judgment, ambiguities, etc. Such uncertainty may be reduced by more research and empirical efforts [3].

Aleatory or ontological uncertainty, on the other hand, arises due to inherent variability, which is especially applicable in human and natural systems and concerning social, economic, and technological developments. Many empirical quantities of the real-world systems vary over space or time in a manner that is beyond control, simply due to the nature of the phenomena involved. Different sources of such uncertainty can be distinguished as [8]

- *Inherent randomness of nature*: the chaotic and unpredictable nature of natural processes.
- *Human behavior*: 'non-rational' behavior, discrepancies between what people say and what they actually do (cognitive dissonance), or deviations of 'standard' behavioral patterns (micro-level behavior).
- *Social, economic, and cultural dynamics*: the chaotic and unpredictable nature of societal processes (macro-level behavior).
- *Technological surprise*: new developments or breakthroughs in technology or side-effects of technologies.

Different types of uncertainty in ecological system and their causes are depicted in Fig.1.

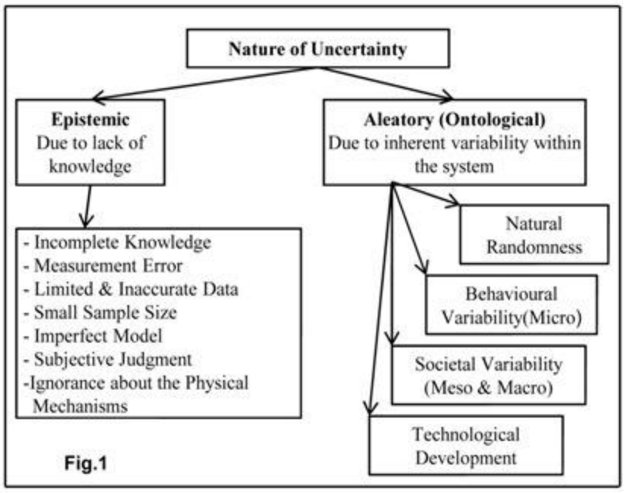

Fig.1

2. DEALING WITH UNCERTAINTY

Environmental risk assessment is basically based on two processes viz. exposure and effect assessment. Both have to deal with different kinds of uncertainties. Risk and uncertainties are key features of most environmental problems. Huge data are necessary for environmental assessment in any ecological system and such data are usually vague and imprecise resulting uncertainty.

There are different methods used to deal with uncertainties associated with risk-modeling inputs and outputs. To study Epistemic uncertainty, we use 'human reasoning model' based on linguistic parameters and qualitative assessment. For the analysis of such model the following approaches are applied.

- Fuzzy set theory [9]
- Possibility theory [10]
- Evidence Theory [11]

On the other hand, Aleatory uncertainty can be studied by stochastic technique which is considered as a 'scientific reasoning model'. Such uncertainty is modeled and analyzed by probability theory. There are basically five categories of probabilistic approaches for uncertainty propagation [12]. Those are-

- *Simulation-based methods*: Monte Carlo simulations, importance sampling, adaptive sampling, etc.
- *Local expansion-based methods*: Taylor series, perturbation method, etc.
- *Functional expansion-based methods*: Neumann expansion, orthogonal or Karhunen-Loeve expansions.
- *Most probable point-based methods*: first-order reliability method and second-order reliability method.
- *Numerical integration-based methods*: Full factorial numerical integration and dimension reduction.

For risk assessments in environmental systems cognitive uncertainties are basically accommodated by Fuzzy set theory and the uncertainties due to variability of phenomena are studied by probability theory. Among various probabilistic methods to determine uncertainties, the most widely used approach is simulation-based technique like Monte Carlo Method.

2.1 Fuzzy Logic Set Theory

Fuzzy logic is a mathematical tool to model inaccuracy and uncertainty of the real world and human thinking. It may be viewed as an attempt at formalization of two remarkable human capabilities. Those are– (i) the capability to converse reason and to make rational decisions in an environment of imprecision, uncertainty, incompleteness of information, conflicting information, partiality of truth and partiality of possibility; (ii) the capability to perform a wide variety of physical and mental tasks without any measurements and any computations [9]. The fuzzy logic was formulated from fuzzy set theory, introduced by mathematician Lotfi A. Zadeh in 1965, to risk management. Unlike probability theory, fuzzy logic theory admits the uncertainty of truth in an explicit way; it also can easily incorporate information described in linguistic terms.

The fundamental difference between traditional set theory and fuzzy set theory is the nature of inclusion of the elements in the set. In traditional sets, an element is either included in the set or is not. In a fuzzy set, an element is included with a degree of truth normally ranging from 0 to 1. Fuzzy logic models allow an object to be categorized in more than one exclusive set with different levels of truth or confidence. Fuzzy logic recognizes the lack of knowledge or absence of precise data, and it explicitly considers the cause-and-effect chain among variables. Most variables are described in linguistic terms, which make fuzzy logic models more intuitively similar to human reasoning.

Fuzzy logic has four principal facets. First, the logical facet- FL, which is fuzzy logic. Second, the set-theoretic facet- FLs, which is concerned with classes having unsharp boundaries. Third, the relational facet- FLr, which is concerned with linguistic variables, fuzzy ‘if-then’ rules and fuzzy relations. And fourth, the epistemic facet- FLe, which is concerned with knowledge, meaning, and linguistics.

Assessment of environmental risk involves identifying the events that imply hazards and assessing the magnitude of their consequences and frequency. A lot of data are necessary for a complete ecological risk assessment. If sufficient statistical material is available, the task in many cases can be achieved successfully. There are many studies, describing the analysis of ecological risks estimating the statistical data [13, 14].

McKone and Deshpande [15] considered how fuzzy logic and fuzzy arithmetic could be applied for a case study on risk assessment of water quality in the Ganges River in India. For groundwater-risk assessment, fuzzy-set approach and a decision-support system based on fuzzy logic were considered as useful planning tool for decision makers involved in the management of sustainable use of natural resources [3,16]. Lein [17] calculated the environmental risk from a hazardous waste facility using fuzzy logic. The evaluation of the risk of polluted sites through fuzzy logic were also reported [18,19]. Fuzzy logic was a tool that could be used to characterize uncertainty in soil information [20] so that a risk-based method of soil interpretations could be implied. For agriculture, Van der Werf and Zimmer [21] proposed a fuzzy expert system to assess the potential risk of environmental impact of the application of a pesticide in a field crop. For releases of eco-toxic substances in chemical plants, Darbra et al. [22] presented a fuzzy-logic methodology to assess the risk of such releases.

2.2 Monte Carlo Method for Probability Theory

For probability bound analysis the most widely used technique is Monte Carlo Method which quantifies uncertainty in a probabilistic framework using computer simulation. This method comprises that branch of experimental mathematics which is concerned with random numbers. Initially it was extensively used in the field of operational research and nuclear physics, where there is variety of problems beyond the available resources of theoretical mathematics. But later on, these methods are employed sporadically in numerous fields, including chemistry, biology, medicine, commerce, management and others [23,24].

The theoretical foundation of Monte Carlo method was known for a long time when in 1777, Buffon [25] used a needle to determine the value of π. The method was conventionally given the scientific and mathematical shape by Stan Ulam and von Neumann [26]. Monte Carlo method is the representation of the solution of a problem as a parameter of a hypothetical population and using a random sequence of numbers to construct a sample of the population, from which statistical estimation of the parameter can be obtained [27].

Because of uncertainty and variability, the value for many environmental variables cannot be known until a direct observation is made. The variability for a parameter can be represented as a probability density function (PDF), alternatively referred to in the literature as a probability function, frequency function, or frequency distribution. Probability density functions are used as the basis of a Monte Carlo analysis and the proper selection of PDFs is essential to a meaningful analysis. Probability density functions can take on a variety of shapes like normal, lognormal, exponential, uniform, Poisson, and binomial distributions etc. The PDF selected for each input parameter in a model will be used to identify the likelihood that particular input values will occur when a Monte Carlo analysis is applied. The shape of PDFs can greatly affect the outcome of a Monte Carlo analysis and must, therefore, be selected with care.

A methodology to predict health risks to individuals from contaminated groundwater using probabilistic techniques aided by a series of conditional Monte Carlo simulations was developed by Maxwell et al [28]. For the exposure assessment procedure, the exposure point concentration was predicted by performing Monte Carlo simulation using a one-dimensional vertical, soil-water solute-transport model coupled with a two-dimensional, horizontal groundwater fate and transport model [29]. A comprehensive study on risk assessments related to the underground disposal of nuclear waste has been done using a computer simulation environment – GTMCHEM [30] considering six variables viz. past data, future observables, scenario, and structural, parametric and predictive uncertainties as inputs. The risk generated by a municipal waste incinerator was assessed by Schumacher et al[31] using Monte-Carlo simulation techniques. A two-dimensional fire growth and behavior model was studied, using Monte Carlo simulations of fire spread [32]. Thus, Monte Carlo simulations of a fire spread model may produce high-resolution fire-risk maps that could be used for long-term strategic planning of fire prevention activities.

2.3 Hybrid Approach

For environmental risk For environmental risk assessment, both Fuzzy logic set theory and Probability theory have their limitations. When uncertainty is considered to be exclusively a result of randomness, probability theory and statistics are adequate to deal with such uncertainty. Again, when the environmental data cannot be treated statistically, then fuzzy arithmetic can be applied. Thus the suitability of the probabilistic and possibilistic approach depends upon the diversity of environmental parameters. So, it would be more realistic to assign probability distributions to certain parameters, while others would be represented by fuzzy-logic numbers. Recently, some researchers have explored the possibility of carrying out environmental risk assessment by combining two different modes of representation of uncertainty in a single computational procedure, known as the ‘hybrid approach’.

Recently, fuzzy-stochastic risk assessment technique has been applied to study the risk associated with groundwater contamination by xylene [33] and to examine a groundwater quality management system [34]. Both Monte Carlo and fuzzy logic approaches were used to estimate human exposure via vegetable consumption to cadmium present in the surface soils of an industrial site [35] and to determine the risk in a river water quality management [36]. Kentel and Aral [37] proposed the use of fuzzy set theory together with probability theory to incorporate uncertainties into the health risk analysis due to exposure to contaminated waters.

3. CONCLUSIONS

Uncertainty is an inherent parameter to any environmental system and it is of two types – Epistemic and Aleatory. Thus uncertainties associated with environmental parameters involved in risk assessment are dealt with two main ways viz. probability theory or fuzzy logic. Again considering the many-fold uncertainties and variability of complicated environmental systems a combined approach in the name of 'Hybrid Approach' is considered to be the best method for environmental risk assessment.

Risk assessment is the capacity to provide the basis of a decision-making process. The results of such decisions should be presented to the environmental managers and public in plain language and in line with the way humans think, rather than as difficult numbers or calculations. Fuzzy logic expresses results in a natural language, in line with human reasoning, together with the possibility of dealing with uncertainties makes it highly recommended as a tool for use in communicating risk. Probabilistic methods are really effective when the information and the environmental data are available. In risk assessment, however, the components like 'safe', 'tolerable', 'alarming', 'severe', etc. are linguistic statements and any numerical value assigned to them is very complicated. Thus the research on risk assessment in different environmental systems assumes more and more interest day by day.

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