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EDWARD L. MELNICK
New York University, New York, NY, USA

BRIAN S. EVERITT
Institute of Psychiatry, King's College, London, UK

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governance indicator of the 2005 Environmental Sustainability Index ($R^2 = 0.56$) [3]. Explanations for these linkages proposed in the literature [3–6] include that integrated thinking about environmental, economic, educational, and health-related issues combined with a political governance system that permits and encourages the finding of solutions leads – on average – to greater environmental net benefits than sectoral policies alone.

Outlook

The Pilot 2006 EPI work is in progress and is only the beginning of a deeper quantitative analysis of environmental performance and its drivers. At this stage of development, the emphasis is on identifying the appropriate components of a performance matrix, the building of the best possible indicators, and solving methodological questions in the aggregation procedure. The EPI is thus meant to stimulate discourse on these issues as well as to promote the use of quantitative assessments in environmental policy.

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Related Articles

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TANJA SREBOTNJAK

Environmental Remediation

Environmental remediation concerns the quality of the environment, and how to support decision making to decide on how to handle it. Research into exposure pathways has illustrated the dangers of pollutants, such as fine dust, *heavy metals* (*see* **Lead**; **Arsenic**), or volatiles exuded from former petrochemical sites. Additionally, there has been increasing insight provided into pollutant decay and reabsorption, as well as into complex phase transfer processes, e.g., between soil and groundwater, or air and surface water, allowing a more detailed and forward looking assessment of pollution evolution. Such understanding is necessary given (a) the growing demand for suitable land for habitation and agricultural/industrial use, (b) frequent changes in landuse types that tolerate different levels of contamination, and (c) growing awareness of the effects of pollution among the public. Strict laws detailing precise pollution and exposure limits exist, at least in industrialized nations. The cost of remediation is also rising, and identification of the most cost-effective approach requires detailed knowledge that allows correspondingly detailed treatment depending on specific local contamination.

Environmental remediation concerns assessment of the quality of the three main environmental compartments to define ways to reduce pollution levels to tolerable limits for a given landuse. This is done by assessing the hazard, the exposure, and the dose–response, together commonly called *risk characterization*.

We consider each of the three major environmental compartments: air, water, and soil (*see* **Air Pollution Risk**; **Environmental Risk Assessment of Water**

Pollution; Soil Contamination Risk). All can be contaminated and all require a very careful treatment. Soil is the most stable compartment, in the sense that contamination may remain more or less stable for years. Water and air are more fluid and immediate changes in quality may occur. Our main concern will be the soil, as here the major statistical contributions can be made. Remediation ranges from leaving as is, to a total excavation and cleaning of contaminated soil in order to reach a contamination level appropriate for a given landuse. For residential use, a near zero pollution level may be required, whereas only a reduced level may suffice for the soil below a parking lot. In the soil we generally work with two thresholds: a target value and an intervention value. The target value defines a clean quality of the environment, whereas the intervention value is a more operational value setting the threshold of intervention by either the government or local engineering companies.

We proceed as follows. First we consider the concept of risk in environmental remediation. Next, we consider spatial statistical methods (*see* **Spatial Risk Assessment**) to indicate their advantages in the remediation domain. We then proceed with *in situ* and *ex situ* remediation and decision support and make the step toward a model. We finish the entry with some concluding remarks.

What Is Risk?

While being easy to define at a general level, a detailed risk characterization makes data collection for a 100% accurate assessment for larger areas impossible or impractical. Various approaches have been developed to assess environmental pollution.

Risk is defined as the probability of a given adverse outcome, commonly calculated as the product of *hazard, social* and *physical vulnerability*, and *elements at risk.* A more complete assessment can also include *value*, i.e., the potential cost of a hazardous event. In the context of environmental remediation a similar definition is used [1]:

$$\text{Risk characterization} = \text{hazard} \times \text{exposure} \times \text{dose–response} \quad (1)$$

The overall risk is then a function of the hazard, in terms of its nature, concentration and distribution, the exposure of a given person or group of persons, in terms of intensity, frequency and duration, and the specific relationship between dose and adverse health effects [1, 2]. A similar definition also applies for adverse consequences on the environment or animals.

Hazard identification concerns identification of a substance or agent posing a risk, and assessing its potential to cause adverse effects to health or environment. In soils this translates into high spatial variability that depends on factors, such as soil types, impermeable layers, pollutant type and mobility, and groundwater seepage. In water and air, while more homogenous, distribution and concentration are subject to currents and wind direction, respectively. In all cases this translates into strong spatial and potentially temporal variability.

Exposure assessment aims at characterizing and quantifying the intensity, duration, and frequency of exposure to the given hazard, ideally for every person. This considers the various pathways of such contact, e.g., *via* direct ingestion of polluted soil, dust, water or air, consumption of soil or dust attached to vegetables, or consumption of pollutants *via* vegetables or meat. For an accurate assessment, mobility of people and local landuse may also be included.

Dose–response considers the specific relationship between the dose of hazardous agent and potentially adverse health or environmental consequences. It is a function of factors such as age, gender, health status, as well as frequency and intensity of contaminant ingestion (*see* **Dose–Response Analysis**).

In environmental remediation, we are mainly considering spatial risks, i.e., risks to be related to spatial variables. We consider risk as the relation between a spatial variable and a threshold. This is denoted as a spatial variable $X(s)$ in relation to a threshold x_c. We shall not consider the obvious extension toward time variables or toward space–time variables in this article. We can then formulate the hazard as a probabilistic concept:

$$\text{Hazard} = \Pr(X(s) > x_c) \quad (2)$$

It specifies therefore the probability that at a location s, a threshold value x_c is exceeded. In order to make valid statements, stationarity assumptions have to be made, leading to applicability of geostatistical methods. Because of the exploratory nature of this article, we shall not go very deep into these matters [3].

The existence of threshold values depends on the effect of exceeding or not exceeding these values in relation to the quality of life. In all environmental compartments there are critical values, which in case of exceeding require additional measures by local authorities. In air quality measurements, typical thresholds of current scientific concern exist for ozone, NO_x and SO_x. These values typically have a direct effect on the well-being of the population. In groundwater the effects are usually indirect, as much of the drinking water and the irrigation water is cleaned before further application. In groundwater, however, various chemical toxicants like heavy metals and polyaromatic hydrocarbons are of concern. Usually, the response time is relatively long between threshold exceeding and measurable effects on the (human) population. Even more, in soil studies the time between a measurement above a threshold level and measurable effects to the (human) population is usually rather long. Typical contaminants are heavy metals, mineral oils and polyaromatic hydrocarbons (*see* **What are Hazardous Materials?**).

The traditional approach to such a problem is a remedial action aimed at multifunctionality [4]. Thus, all the functions the soil can possess, given its natural characteristics, are to be reestablished. This single-perspective view is just one possibility to face the problem. Multiperspective views include elements other than soil protection and have caused a shift of attention from *ex situ* remediation to *in situ* remediation. Within the multifunctional framework, where concentrations are the norm, *in situ* techniques are aimed at reaching threshold values in the shortest possible time. In contrast, techniques in the triple-perspective REC-framework, where *risks, environmental merits*, and *costs* are taken into account simultaneously, aim at optimizing within the three-dimensional framework.

Risk Assessment Approaches

Deterministic Methods

A deterministic approach quantifies all parameters required in the risk equation. Soil pollutant concentrations are measured, as well as the amount a person is exposed to, and how that person will react to the pollutant. This leads to a simple source-pathway-receptor framework. First used in the early 1980s it is still being used, for example in the United Kingdom's site-specific assessment criteria (SSAC) procedure [2]. The SSAC approach is very detailed, taking account of exposure duration and time-averaged body weight or vegetable consumption rates of the receptor. The mathematical implementation of the approach, however, is straightforward. Point values used in the parameterization, e.g., pollutant concentrations collected from spot measurements, however, cannot reflect the high spatial-temporal variability of pollutant concentrations [1, 5]. They are, therefore, unsuitable for an assessment of how many people will be affected or exposed. Hence, such approaches calculate the maximum exposure, thus aiding the *precautionary principle* [6, 7]. Increasing safety factors have traditionally been added, to be on the safe side, leading to risk overestimation. Irrespective of isolated peak concentrations or exposures the entire area is assigned the maximum risk value, leading to excessive and unnecessary remediation costs.

Probabilistic Methods

In the early 1990s, methods were developed that incorporated a characterization of variability, i.e., the natural variation, as well as uncertainty, or lack or knowledge [1]. This allows one to consider the variability in pollutant concentration within the soil, as well as that between individuals, but also to assess the uncertainty in exposure estimation. An important method is Monte Carlo simulation (MCS), which takes account of the variability of the natural phenomenon [8]. Instead of producing a single risk map, MCS produces a distribution of plausible maps that all reasonably match the sample statistics. It shows both the uncertainty of the model parameters and how this uncertainty influences the final risk estimate. In addition to MCS, regression analysis, and analysis of variance (ANOVA) have been used. However, the temporal dimension, critical given the dynamics of natural systems, is frequently neglected.

MCS is further useful to assess the combined effect of several input parameters [1]. Given the multitude of parameter combinations and resultant assumptions and generalizations, a further problem is that it is often not possible to provide risk values with a certainty desired by decision makers. A related problem is the frequent use of precise parameter values and probability distributions [7]. One way to overcome this is by using intervals or probability bound analysis, although these do not reflect well the distribution shape or central tendency. Statistical analysis, however, should be more than a simple tool, and hence should include expert knowledge, especially for site-specific parameter estimation.

Beyond simple MCS the utility of geospatial statistics combined with probabilistic human health risk assessment can be assessed [8]. This allows for a more realistic assessment of spatial variability and local uncertainty, e.g., in soil contamination levels. Such a combined approach better incorporates the spatial dimension in contaminant concentration and distribution, thus allowing a more realistic analysis.

Hybrid of Probabilistic and Fuzzy Methods

To address the uncertainty in the evaluation criteria, Chen *et al.* [9] state that complex parameters such as landuse patterns or receptor sensitivities cannot be modeled with probability functions. Thus, approaches based on fuzzy set theory have been developed that are better equipped to represent the parameter uncertainties. The authors describe a hybrid approach that uses probabilistic methods to address the variability in pollution source and transfer modeling, and fuzzy tools for the evaluation criteria. They also provide a detailed methodology and illustrate with an example. A similar hybrid approach was used by Li *et al.* [10] to evaluate risk from hydrocarbon contamination, who also used the fuzzy set methodology to model different remediation scenarios (from partial to nearly complete cleanup), as well as the spatio-temporal risk variation over different time periods.

In situ and *ex situ* Remediation

In environmental remediation a distinction is made between *ex situ* and *in situ* remediation. *In situ* remediation concerns techniques like biorestoration, soil washing or extraction, and soil venting [11], whereas containment techniques prevent contamination to migrate. Soil washing uses the solubility of a contaminant, which will dissolve in the percolate and by means of a special withdrawal system the percolate is pumped up and treated. Soil venting aims at volatilization and biodegradation of the contaminant in the unsaturated zone, followed by a vapor treatment system to remove the contaminants from the vapor. Air sparging involves injection of air into the saturated zone for the dual purpose of volatilizing organic components and enhancing biodegradation [11]. *Ex situ* soil remediation concerns excavation of contaminated soil, cleaning this soil at an independent location and putting it back after cleaning, possibly at the same location.

Spatial Statistical Methods

In many remediation studies, the need to quantify risks can be solved by means of geostatistical and other spatial statistical methods. Indicator kriging and probability kriging have been usefully used for risk mapping. Optimal sampling procedures have been developed to sample an area such that maximum information is obtained given the limited amount of budget for taking observations. Optimization has also taken place for air quality networks and in groundwater (and surface water) observation networks. Spatial simulation methods have been used to show realizations of the random field underlying observations. Different types of observations (measured and organoleptic) have been combined in a geographical information system. Space–time statistics have in particular been useful to assess the changes in concentrations and quality of the environment (*see* **Spatiotemporal Risk Analysis**). Modern approaches by means of model-based Geostatistics are a recent step forward. Finally, the combination of spatial statistical methods with soil, air, and groundwater models has been performed in many systems and detailed case studies.

Example: a Cost Model for Environmental Remediation

Sanitation of contaminated soil is an expensive task, which is difficult to assess. Estimated costs are sometimes exceeded by 100% [12]. Here we show the use of a cost model to a former gasworks site in the harbor area of the city of Rotterdam [13]. In 1994, an integrated soil inventory was carried out (10 observations/ha). We concentrate on the upper layer (0–0.5 m), containing the largest set of the full vector of observations (Figure 1). The five contaminants indicative of the spatial extent of contamination are cyanide, mineral oil, lead, polyaromatic hydrocarbons PAH-total, and zinc.

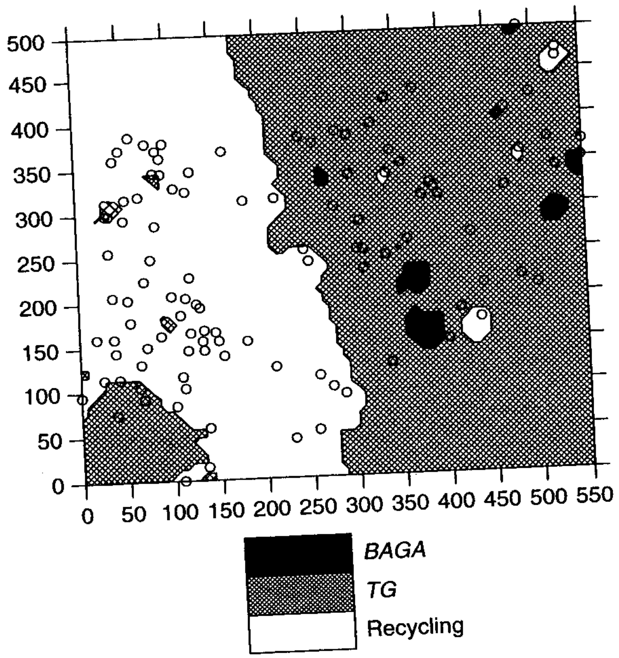

Figure 1 Location of sample points in the area

Table 1 Environmental thresholds for five contaminants. All thresholds are expressed in (mg kg^{-1})

Contaminant	*S* value	*T* value	*I* value	*BAGA*
Cn	5	27·5	50	50
Mineral oil	50	2525	5000	50 000
Pb	85	307·5	530	5000
PAH	1	20·5	40	50
Zn	140	430	720	20 000

Four environmental thresholds classify areas according to the degree of contamination: *S* value: (*Safe* or *Target level*): maximum concentration of a contaminant to maintain multifunctionality, *T* value: intermediate level between low and serious soil pollution, *I* value (*Intervention level*): if this value is exceeded the functional properties of the soil for humans, fauna, and flora are seriously degraded or are threatened to be seriously degraded and the BAGA level ("*Chemical waste*"): at this level the soil is chemical waste and should be carefully treated (Table 1).

A cost model combines the thresholds with remediation techniques. Ten classes with different processing costs are distinguished. The highest degree of pollution of any contaminant determines whether a soil cube should be excavated or not, depending upon different remediation scenarios. Dividing the area into 5760 squares of 7 by 7 m^2, we find that treatment of the area costs €3.11 M. More details can be found in Stein and Van Oort [14].

Concluding Remarks

Environmental remediation has received quite some recent attention, with the advance a growing awareness of the effects of contamination for health and the environment, and with the advance of spatial statistical methods to quantify the associated risks. A current trend is a further focus on individual risks, a better quantification of those, and a more realistic assessment. Advances can be expected at each of the components of risk assessment: realistic modeling, improved observation methods e.g., by using remote sensing derived methods, and realistic vulnerability assessments.

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Related Articles

Environmental Health Risk
Environmental Monitoring
Environmental Risk Regulation

ALFRED STEIN AND NORMAN KERLE

Environmental Risk Assessment of Water Pollution

Environmental risk due to water pollution is an ongoing every day problem. Municipal wastewater systems are one of the largest pollution sources to surface waters, however; other major sources include residential and industrial discharges, and agricultural runoff, dumped into rivers directly or by seepage from contaminated groundwater. Threats from chemicals may come from sources such as pesticide use and waste disposal. Air pollution and land pollution also affect water quality (*see* **Air Pollution Risk; Soil Contamination Risk**).

Water resources are considered as one of the main factors affecting our life, industries, agriculture, and economics. Therefore, we must properly assess the risk of water pollution from these resources. Consequently, measures should be taken in order to protect water sources from pollution. For these reasons, we have to identify its contents and detect the sources that cause these contents to deviate from their safety and healthy levels.

This work presents an illustration of two statistical techniques that can assess the risk of surface water pollution from bacterial and chemical sources, as applied to a sample from Tigris river water after it has passed through the Baghdad metropolitan area. The first is an adaptation of existing methods to lognormal data, while the second is an application of intervention analysis with time series data.

Data Description

The data consisted of samples collected over 48 weeks. At each sample point six measurements were made, three on bacterial variables (coliform, fecal coliform, and plate count), and three on chemical variables (chloride, T-hardness, and conductivity). Samples were taken from two selected locations on Tigris river during 1988. The first was located north of Baghdad, approximately 35 km from city center (upper stream), and the second was situated south of Baghdad, approximately 20 km from city center (downstream). These two locations bracket most of the pollution sources. Furthermore, to account for the river width and water current speed, measurements were replicated at four points across the river at time t. These measurements were also correlated. The study area brackets major pollution sources such as chemical factories and vegetation farms that use fertilizers. Almost all of these sources are on the west side of the river. These six measurements generated six time series, each of 48 observations (with four readings across the river) in which successive observations were serially dependent and may be nonstationary, or with seasonal effects.