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Stochastic environmental research risk assessment

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ARTICLE INFO

Article history:
Received 13 September 2005
Received in revised form
20 July 2006
Accepted 5 September 2006
Published on line 7 November 2006

Keywords:
Environmental indices
Ecosystems
Environmental impact
Risk Assessment
Pollution

ABSTRACT

In a briefly approach, sustainability can be defined as the ability to achieve economic prosperity while protecting the natural systems of the planet, and providing a higher quality of life for its people. Nowadays it is a prime and very active area of research, fundamental for human development. Several concepts based on economics, social and environmental concerns have been considered in the development of sustainability indices. The sustainability concept is, not only but necessarily, dependent on "quantification of the environment health", necessary to determine its effectiveness in achieving or increasing the environmental capacities of ecosystems, as well as to compare alternative plans and policies, to influence decision-makers.

Environmental indices are a very important tool for the analysis of some environmental assessment factors, providing quantitative criteria and synthesizing the available information. A good index should be simple to use, transparent, and expandable across other issues. In particular, environmental indices are a useful tool for several audiences, to aid environmental decision making and to allow the media to keep score of and reduce complex information to a smaller, more easily retained, amount of information [Hardi, P., DeSouza-Huletey, J.A., 2000. Issues in analyzing data and indicators for sustainable development. Ecol. Model. 130, 59–65].

The goal of this work is the development of environmental indices, based on stochastically simulated scenarios, using probabilistic approaches. This study was applied to assess the impact of particulate air contamination on the Setúbal Peninsula ecosystems (South of Lisbon, Portugal).

1. Introduction

Regarding the issue of environmental impact assessment, EPA (Environmental Protection Agency, USA) provides a regulatory framework for ecological risk assessment (ERA) to evaluate the potential adverse impact of human activities (USEPA, 1997). Suter (1993) referred that ERA approaches were based on spatially invariant concepts. Some authors (Haines-Young et al., 1993; Hunsaker et al., 2001, a.e.) started incorporating the techniques of geographic information systems (GIS) but a critical need has arisen for adopting spatially explicit modeling approaches for ERA to handle the dynamics imposed by heterogeneous environments (Sample and Suter, 1994). Chow et al. (2005) presented a briefly review about ERA developments and proposed a model based on GIS methodologies and using Monte Carlo simulations.

The objective of spatial analysis methods is the assessment of spatial uncertainty (Goovaerts, 1997) or the evaluation of critical scenarios through risk maps, environmental costs maps, a.o. Space-time simulation of a physical phenomenon

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doi:10.1016/j.ecolmodel.2006.09.003

can also be used to achieve identical purposes of evaluation of responses to critical situations. This is the objective of this paper: the presentation of some environmental indices to quantify the response of an air pollution phenomenon of a given region in a space-time domain.

A geostatistical simulation methodology, integrating spatial and temporal dispersion patterns, was used to generate several equiprobable scenarios to assess the particulates contamination of the Setúbal Peninsula (Nunes and Soares, 2005). This study is not concerned with space-time simulation models, which is a very specific research area. Its goal is to use stochastically generated scenarios (reproducing the observed spatial and temporal continuity and variability of the phenomena) to develop environmental indices. Other geostatistical models and applications for the characterization and simulation of spatiotemporal natural-resources phenomena can be referred: deposition of atmospheric pollutants (Eynon and Switzer, 1983; Bilonick, 1985), estimation of rain fall or piezometric head fields (Bras and Rodrigues-Iturbe, 1984; Rouhani and Wackernagel, 1990; Armstrong et al., 1993), spatiotemporal characterization of main flow patterns of wood pigeons (Santos et al., 2000), characterization of population dynamics in ecology (Hohn et al., 1993) and design of sampling networks for monitoring spatiotemporal processes (Switzer, 1979).

Once the natural phenomenon is simulated using a spatiotemporal stochastic process (Nunes and Soares, 2005), the time-series values of these scenarios, obtained for each location, can be used to compute several environmental indices. These scenarios can be summarized using several statistical measures, according to concepts like reliability, resilience and vulnerability.

There are many studies dedicated to the development of environmental indices, using different types of data and different mathematical approaches. Clerici et al. (2004), using a large amount of information, developed environmental indices based on principal component analyses. Pykh et al. (2000) compared four different approaches to develop environmental quality indices. Silvert (2000) proposed a fuzzy approach to the definition of environmental condition indices.

In this study, several environmental indices were developed for the assessment of extreme and risk situations of air quality impact on the study area's ecosystems (which are identified through satellite image classification with prior local knowledge), based on several scenarios obtained from a space-time stochastic simulation model. These indices describe air quality (particulate matter concentrations) and its regeneration capability (regeneration index, mean regeneration time, maximum regeneration time). The study is not about space-time simulation models as such, but aims to use their results (several equiprobable scenarios) to build environmental indices based on probabilistic concepts.

2. Methodology: environmental indices development

Considerer $Z_k(x, t)$ as the variable corresponding to the k simulation scenario of the variable $Z(x, t)$, in a certain location x, at time t. To develop environmental indices one must identify the ranges of values for this variable that are considered satisfactory, and those considered unsatisfactory. Of course these ranges may change within a year and over multiple years. Satisfactory and unsatisfactory ranges of criterion values can be subjective, based on statistical measures (quantiles) or can be defined considering, for example, environmental laws (based on well-defined health standards).

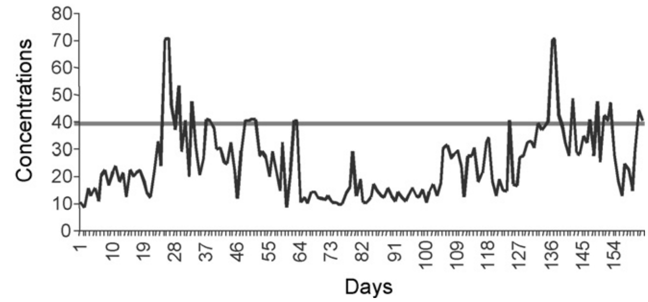

Fig. 1 – Simulated time series example, for a given localization; values above 40 are considered unsatisfactory.

Fig. 1 illustrates a possible time series plot of simulated $z_k(x, t)$ values for a certain location x, with a designated range of values considered satisfactory; here, below the threshold line. These satisfactory values could also be considered bound between some upper and lower limits. Each criterion will have its own unique ranges of satisfactory and unsatisfactory values.

2.1. Critical quality index

This first index is based on the indicator formalism function. Considerer $Z_k(x, t)$ as the simulated value at spatial location x, at time t, $t = 1, \ldots, Nt$, for the scenario k, $k = 1, \ldots, Nk$. Based on a given threshold z, an indicator variable can be defined as follows:

$$I_k(x, t) = \begin{cases} 1, & Z_k(x, t) > z \\ 0, & Z_k(x, t) \le z \end{cases}$$

The probability that a given spatial location x is polluted (with values above the threshold z), for a time period t and scenario k, can be defined as:

$$\mathrm{CQI}_k(x) = \frac{\sum_{t=1}^{Nt} I_k(x, t)}{Nt} \tag{1}$$

This can be denoted as a critical quality index and corresponds to the probability of any particular value to be within the range of values considered non-satisfactory (polluted).

Each simulated scenario produces a CQI map. To analyze the Nk scenarios' indices and to identify areas with bigger differences between scenarios, mean and variance maps were computed for all Nk scenarios. The variance map constitutes an index uncertainty measure.

2.2. Regeneration index

To evaluate the regeneration capability from a polluted (or unsatisfactory) situation, for a certain location, a regeneration index was developed, $\mathrm{RI}_k(x)$. This index represents the