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Development of a decision support system to manage contamination in marine ecosystems

A. Dagnino *, A. Viarengo

DiSIT, Università del Piemonte orientale "Amedeo Avogadro", Viale Teresa Michel 11, 15121, Alessandria, Italy

HIGHLIGHTS

- An innovative DSS for managing pollution in marine coastal ecosystems is developed.
- Pollutant levels (single compound & mixtures) are compared to effect-based thresholds.
- Triad data are used to assess the risk of biodiversity loss.
- Sublethal biomarkers indicate the level of biological stress.
- Chemical & ecotoxicological data are used to determine risk related to sediments.

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ABSTRACT

In recent years, contamination and its interaction with climate-change variables have been recognized as critical stressors in coastal areas, emphasizing the need for a standardized framework encompassing chemical and biological data into risk indices to support decision-making. We therefore developed an innovative, expert decision support system (Exp-DSS) for the management of contamination in marine coastal ecosystems. The Exp-DSS has two main applications: (i) to determine environmental risk and biological vulnerability in contaminated sites; and (ii) to support the management of waters and sediments by assessing the risk due to the exposure of biota to these matrices. The Exp-DSS evaluates chemical data, both as single compounds and as total toxic pressure of the mixture, to compare concentrations to effect-based thresholds (TELs and PELs). Sites are then placed into three categories of contamination: uncontaminated, mildly contaminated, and highly contaminated. In highly contaminated sites, effects on high-level ecotoxicological endpoints (i.e. survival and reproduction) are used to determine risk at the organism-population level, while ecological parameters (i.e. alterations in community structure and ecosystem functions) are considered for assessing effects on biodiversity. Changes in sublethal biomarkers are utilized to assess the stress level of the organisms in mildly contaminated sites. In Triad studies, chemical concentrations, ecotoxicological high-level effects, and ecological data are combined to determine the level of environmental risk in highly contaminated sites; chemical concentration and ecotoxicological sublethal effects are evaluated to determine biological vulnerability in mildly contaminated sites. The Exp-DSS was applied to data from the literature about sediment quality in estuarine areas of Spain, and ranked risks related to exposure to contaminated sediments from high risk (Huelva estuary) to mild risk (Guadalquivir estuary and Bay of Cadiz). A spreadsheet-based version of the Exp-DSS is available at the MEECE and DiSIT web sites (www.meece.eu and www.disit.unipmn.it).

1. Introduction

Marine coastal environments face the presence of and exposure to many pollutants originating from terrestrial, atmospheric, and marine systems (Islam and Tanaka, 2004). Therefore, sound monitoring activities are essential to guarantee correct environmental management in line with recent environmental policy strategies on water quality assessment and control at the international level (Foden et al., 2008). Conventional techniques for environmental pollution monitoring in marine ecosystems are mainly based on the determination of contaminants in water and sediment samples, but ecotoxicological testing to assess the biological effects of pollutants is rarely associated with chemical analyses (Allan et al., 2006). In fact, regulatory requirements on the risk assessment of chemicals are largely based on the quantification of individual substances (Connon et al., 2012) although, in the last decades, strategies aimed to integrate chemical and biological data in monitoring programs have been developed (Van der Oost et al., 2003; Viarengo et al., 2007). Recently, the scientific knowledge gained in pilot-studies realized by different international organizations

* Corresponding author. Tel.: +39 0131 360384; fax: +39 0131 360390.
E-mail addresses: dagnino@unipmn.it, aledagnino@virgilio.it (A. Dagnino).

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(e.g. UNEP-MAP, RAMOGE Agreement, ICES Convention, OSPAR Convention, and HELCOM Commission) has been used for revising the European legislation on marine ecosystem monitoring and control introducing the ecosystem approach (Law et al., 2010).

Chemicals entering marine ecosystems undergo various weathering processes that may alter their bioavailability and toxicity, reducing the reliability of the chemical approach for assessing environmental quality (Jonker et al., 2006). Coupling exposure and effects lowers the uncertainty in the determination of environmental risks due to contamination (Benedetti et al., 2012; Borja et al., 2011; Dagnino et al., 2008; Lyons et al., 2010).

Chemical data per se can only provide partial information on the system under study. In addition to the unpredictability of speciation processes in marine environments that may alter pollutant bioavailability, 100–120 chemical compounds are usually evaluated during characterization campaigns, while the list of substances classified by the American Chemical Society as potentially toxic contains more than 296,000 compounds (CAS, 2013), rendering complete screening of chemical contamination impossible. Furthermore, toxicity resulting from interactions among chemicals in a pollutant mixture (additive, antagonistic, synergic, etc.) may be only partially estimated from analytical data (Dondero et al., 2011; Jonker et al., 2005).

Many pollutants can be sequestered in the sedimentary matrix as a result of environmental processes driven by various factors (pH, redox potential, oxygen concentration, and temperature) by forming insoluble or poorly soluble compounds, or by adsorbing onto suspended particles (Chapman and Anderson, 2005). Changes in boundary conditions may lead to the mobilization of pollutants accumulated in sediments toward the water column, with consequent impacts on biota. This phenomenon may be related to the resuspension of sedimentary particles due to the mechanical action of waves and currents, which may cause drastic changes in chemical and physical parameters and anthropic activities such as sediment dredging (Eggleton and Thomas, 2004). Nevertheless, the control of sediment contamination is important for protecting marine environments (Piva et al., 2011) because pollutant levels in this matrix can be much higher than those detected in the water column, where contaminant concentrations are often near analytical detection limits (Zoumis et al., 2001).

Considering the capacity of sediments to accumulate contaminants and the importance of benthic food chains in marine coastal ecosystems, effect-based environmental quality standards (EQS) for marine coastal sediment have been proposed for several priority contaminants. Threshold effect levels (TELs) and probable effect levels (PELs) were previously determined by MacDonald et al. (1996) based on results from numerous ecotoxicological studies.

The present study proposes a two-leg procedure that combines chemical and ecotoxicological data to support the assessment of risk related to exposure to waters and sediments. In addition, a Triad data integration system that also integrates ecological data is proposed to evaluate environmental risk related to contaminated sites in marine coastal areas. The main purpose of this expert decision support system (Exp-DSS) is to support technicians and environmental managers in planning actions and interventions for marine coastal management (e.g. sediment dredging, management of contaminated sites) by clearly determining the potential environmental risks associated with exposure to water and sediment samples.

A first application of this integration system has been realized using data from Riba et al. (2004c) on polluted marine coastal sediments from various estuarine areas in the region of Cadiz, Spain, one of the most polluted and intensively studied areas in the world (DelValls and Chapman, 1998; Morillo et al., 2004; Nocete et al., 2005; Ruiz, 2001). The Cadiz region has been heavily impacted by mining activities for approximately 5000 years (Gonzalez et al., 2007), and is therefore characterized by high concentrations of inorganic compounds. Rivers in this area have discharged huge amounts of metals by erosion of important ore deposits such as the Iberian Pyrite Belt (Gonzalez-Perez et al., 2008).

2. Materials and methods

2.1. Architecture of the Exp-DSS

The Exp-DSS structure basically consists of four modules: a chemical module that integrates data on the concentration of pollutants, an ecotoxicological module that integrates data on high-level and sublethal effects in model organisms, an ecological module that integrates data on community structure and ecosystem functions, and an integration module that combines the various lines of evidence into risk indices. Outputs from the Exp-DSS depend on the aim of the study and the input data. In principle, a variety of indices are calculated by the integration module. Example indices include an index of water quality termed the Water Risk Index (WatRI), an index of sediment quality termed the Sediment Risk Index (SedRI), an index of risk of biodiversity decline called the Environmental Risk Index (EnvRI), and an index of biological vulnerability termed the Biological Vulnerability Index (BVI).

2.1.1. Chemical module

The algorithm applied as part of the chemical module calculates a chemical risk index (ChemRI) by evaluating the levels of selected chemicals in waters, sediments, or both. The integration framework is based on five main points: (i) subtraction of background concentrations for naturally occurring chemicals; (ii) comparison of the measured concentrations with TELs and PELs; (iii) calculation of two toxic pressure coefficients (TPC_{TEL} and TPC_{PEL}) by summing the ratios calculated for TEL and PEL, respectively, for each selected chemical (Eq. (1)); (iv) classification of the studied sites as uncontaminated, mildly contaminated, or highly contaminated; and (v) comparison of TPC_{TEL} with specific thresholds and calculation of ChemRI, which ranges between 0 and 1 (Eq. (2)). For Eq. (1),

$$\begin{aligned} TPC_{TEL} &= \sum_i \frac{\left(C_i^s - C_i^{bg}\right)}{TEL_i} \\ TPC_{PEL} &= \sum_i \frac{\left(C_i^s - C_i^{bg}\right)}{PEL_i} \end{aligned} \tag{1}$$

where TPC_{TEL} and TPC_{PEL} are the toxic pressure coefficients; C_i^s is the concentration of the ith substance in the analyzed samples, C_i^{bg} is the background concentration of the ith naturally occurring substance, TEL_i is the TEL for the ith substance, and PEL_i is the PEL for the ith substance. For Eq. (2),

$$\begin{array}{ll} TPC_{TEL} < Th_1 & ChemRI = \alpha \cdot \dfrac{TPC_{TEL}}{Th_1} \\ Th_1 \le TPC_{TEL} < Th_2 & ChemRI = \alpha + \dfrac{(TPC_{TEL} - Th_1)}{(Th_2 - Th_1)} \cdot (\beta - \alpha) \\ Th_2 \le TPC_{TEL} < Th_3 & ChemRI = \beta + \dfrac{(TPC_{TEL} - Th_2)}{(Th_3 - Th_2)} \cdot (1 - \beta) \\ TPC_{TEL} \ge Th_3 & ChemRI = 1.00 \end{array} \tag{2}$$

where Th_1, Th_2, and Th_3 are thresholds to convert TPC_{TEL} into ChemRI, and α and β are the values of ChemRI when TPC_{TEL} equals Th_1 and Th_2, respectively.

TELs and PELs are target concentrations selected as thresholds for each contaminant to guarantee protection of the environment. TELs are the concentrations below which no effect will probably be evident, and PELs are the concentrations above which negative effects are likely to occur (Long et al., 2006). The value of Th_1 is set equal to 1.00, while the values of Th_2 and Th_3 are site-specific and are calculated considering the mean of the ratios between the TELs and PELs of the chemicals analyzed for each sample (Eq. (3)).