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Environmental risk assessment in a contaminated estuary: An integrated weight of evidence approach as a decision support tool

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A B S T R A C T

Environmental risk assessment of complex ecosystems such as estuaries is a challenge, where innovative and integrated approaches are needed. The present work aimed at developing an innovative integrative methodology to evaluate in an impacted estuary (the Sado, in Portugal, was taken as case study), the adverse effects onto both ecosystem and human health. For the purpose, new standardized lines of evidence based on multiple quantitative data were integrated into a weight of evidence according to a best expert judgment approach. The best professional judgment for a weight of evidence approach in the present study was based on the following lines of evidence: i) human contamination pathways; ii) human health effects: chronic disease; iii) human health effects: reproductive health; iv) human health effects: health care; v) human exposure through consumption of local agriculture produce; vi) exposure to contaminated of water wells and agriculture soils; vii) contamination of the estuarine sedimentary environment (metal and organic contaminants); viii) effects on benthic organisms with commercial value; and ix) genotoxic potential of sediments. Each line of evidence was then ordinally ranked by levels of ecological or human health risk, according to a tabular decision matrix and expert judgment. Fifteen experts scored two fishing areas of the Sado estuary and a control estuarine area, in a scale of increasing environmental risk and management actions to be taken. The integrated assessment allowed concluding that the estuary should not be regarded as impacted by a specific toxicant, such as metals and organic compounds hitherto measured, but by the cumulative risk of a complex mixture of contaminants. The proven adverse effects on species with commercial value may be used to witness the environmental quality of the estuarine ecosystem. This method argues in favor of expert judgment and qualitative assessment as a decision support tool to the integrative management of estuaries. Namely it allows communicating environmental risk and proposing mitigation measures to local authorities and population under a holistic perspective as an alternative to narrow single line of evidence approaches, which is mandatory to understand cause and effect relationships in complex areas like estuaries.

1. Introduction

Estuaries are among the most productive natural systems on Earth, providing an array of human welfare benefits, if well managed, but people fail to realize their true value until ecological status is lost beyond remediation (Guo and Kildow, 2015). These

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ecosystems are also among the most pressured, including environmental contaminants resulting from anthropogenic activities, alterations due to global change, from pollution to invasion by exotic invasive species (Elliot et al., 2014). Nonetheless, environmental risk assessment (ERA) of these different pressures in complex ecosystems such as estuaries is often challenging and methods for the improvement of the process are needed (Ribeiro et al., 2016).

Integrated environmental assessment of estuarine areas is, at least in part, intricate because of the ever-expanding number of stressors, and their interactions, caused by human activity (Chapman et al., 2013). Thus, integrated assessment of estuarine areas should be based on a holistic perspective of ERA, i.e., one that integrates the multiple sources of stressors, routes of exposure for humans and biota, as well as the ecological features of the area (Xu et al., 2015). Given the interactions of multiple stressors, the assurance of meaningful integrated assessment is provided by integrating multiple Lines of Evidence (LOE) that reflect different biological, chemical, and physical data. This should also consider bioavailability and its potential consequences to relevant species and food web (Chapman and Maher, 2014). While many studies have documented the individual effects of the multiple sources of anthropogenic stress on species and ecosystems, research on cumulative and interactive impacts of multiple stressors is still limited (Costa et al., 2012; Ellis et al., 2015). As a consequence, managerial action in transitional waters relies yet on incomplete information, hindering the much needed process of prioritization and adequate resource allocation towards specific impacts (see Chapman et al., 2013).

The integration of LOE, through Weight of Evidence (WOE) approaches provides the best information for informed decision-making (Weed, 2005). Overall, a WOE approach is the process of considering strengths and weaknesses of different types of information in order to make a decision among competing alternatives (Burton et al., 2002; Hope and Clarkson, 2014). By other words, WOE is a way of synthesis and integration, as recommended for estuaries and can incorporate relative risk modeling (Chen et al., 2012).

Presently, in the absence of quantitative cause-effect relationships between stressors and impacts, WOE relies mostly on Best Professional Judgment (BPJ) (Burton et al., 2002; Chapman and Anderson, 2005; Linkov et al., 2009; Hope and Clarkson, 2014). The BPJ approach can be used to address the limitation of field and laboratory investigations (Chapman et al., 2002; Bay et al., 2007) or as a way to integrate, validate or communicate complex data (Clark et al., 2016; Murray et al., 2016; Wu et al., 2016; Ysebaert et al., 2016). Usually these WOE and BPJ methods are mainly used for ecological risk assessment (with usual LOE for chemical assessments, toxicity and biological surveys). However, human health assessment can also be added by considering epidemiological data, often based on questionnaire surveys (Hope and Clarkson, 2014), albeit the general lack of research on methodologies that can link ecological with human health risk assessment in a integrative and understandable way for decision makers.

The aim of the present research was to develop an integrative and innovative methodology to evaluate the adverse effects of contaminated estuary to human and ecosystem health, based on different and complementary lines of evidence. The integrative qualitative assessment herein presented was based on a best professional expert judgment and as support decision tool. A southern European estuary was used as case study – the Sado Estuary in Portugal. The work derives from the findings and methodology developed under the scope of the research project *HERA - Environmental Risk Assessment of a contaminated estuarine environment: A case study* (2010–2013). The reader is diverted to acknowledgements for funding information and to the research project's detailed report (Caeiro, 2013), though the link http://repositorio.insa.pt/handle/10400.18/2322 for further details.

2. Study area

The Sado estuary is located in SW Portugal, with an area of approximately 240 km^2, being characterized by its wide biogeographical diversity and high ecological and socioeconomic importance. The basin includes the city of Setúbal, with its harbor and heavy-industry belt located in the northern area. Although a large part of the estuary is classified as a natural reserve, the area is very important for tourism, aquaculture, local fisheries, maritime transport and upstream agriculture. The Sado estuary is included in NATURA 2000 (PTCON0011) therefore protected under EU legislation (see Directives 2009/147/EC and 92/43/EEC, respectively the Birds and Habitats Directives). However, the estuary is generally threatened by several sources of anthropogenic pressure: urban pollution (from the city of Setúbal), industrial pollution (from heavy-industry belt that includes chemical plants, a thermo-electrical unit, shipyards, ore deployment facilities and others), and from runoffs from the agriculture grounds (Costa et al., 2012; Caeiro et al., 2009) (Fig. 1). The presence of these potential pollution sources gave rise to a point and diffusively contaminated estuary, particularly in areas near industrial areas and the lower estuary where levels of concern for many contaminants, both organic and inorganic, with adverse toxicological consequences to biota, have been found in recent studies (see Caeiro et al., 2009; Costa et al., 2012, 2014; Carreira et al., 2013; Costa et al., 2014).

The Carrasqueira village is a small fishermen community, which is located on the south margin of the Sado Estuary (refer to Fig. 1 – Sado 2 area) and has an estimated population of approximately 350 residents (Martins and Souto, 2000). The Carrasqueira fishermen use trawl nets in the area to capture estuarine species that inhabit the sedimentary environment and are important natural resources for humans. Food habits among Carrasqueira residents has been previously characterized through ethnographic studies which suggest exposure to estuarine products, water in daily activities and farming products (Martins and Souto, 2000). So this population constitutes a good target population to be used for human health risk assessment.

Within the ERA framework, the planning and scoping and problem formulation phases (Hope and Clarkson, 2014; Ribeiro et al., 2016), have been somehow already established for the management of the estuary, but phases of risk analysis and characterization (Ribeiro et al., 2016), are still not well developed.

Due to the features of this potentially contaminated estuarine environment a research project was developed by a large multidisciplinary team. The main aim of this project was to develop and apply an innovative methodology to evaluate the environmental risk, including ecologic and to human health. As a reference and non-exposed area the Mira Estuary and Vila Nova de Mil Fontes Village in the south east coast were used (Fig. 1). The Mira estuary is considered one of the estuarine basins least impacted by human pressures in Portugal, without reference to any direct or significant sources of pollution, being thus regarded as a pristine estuary (Ferreira et al., 2003; Vasconcelos et al., 2007; Carreira et al., 2013). Commercial fishing activities are conducted in the surrounding Atlantic coastal waters and not inside the estuary.

3. Methods

3.1. Lines of evidence

Considering the data provided in previous works focused on the Sado Estuary, and criteria defined for LOE selection (Hope and