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Review

A review of chemical-based sediment quality assessment methodologies for the marine environment

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ABSTRACT

This review of 19 chemical approaches used in assessing sediment quality are classified into empirical, mechanistic and sediment quality indices (SQI) groups. Empirical sediment quality guidelines (SQGs), based on matching chemical and biological-effects data and the mechanistic techniques, founded on equilibrium partitioning principals (EqP), are well established and most used. Empirical SQGs provide a useful screening tool to initially identify locations and chemicals of most concern, but are not regulatory criteria. The EqP approach is causally linked however, the scheme assumes porewater chemistry largely controls sediment toxicity. SQIs are not based on matching chemical-biological data and combine schemes with multiple narrative intents. The 41 SQGs reviewed show a considerable range in upper and lower guideline values. Grain size and organic content should be included into SQGs, however inclusion of suspended sediment into SQGs raises concerns. SQGs are built into decision-tree schemes with other lines-of-evidence and evaluated in a weight-of-evidence framework.

1. Introduction

1.1. Sediment ecosystems

Sediment ecosystems are governed by interrelated physical, chemical and biological processes, which influence the ability of sediment to support a functioning, active and diverse biological population. 'Sediment ecosystem health' may be assessed by measuring the structure and abundance of biological communities in the field, or in laboratory bioassays (Maher et al., 1999). However, these measurements are time consuming and expensive and consequently sedimentary chemicals associated with adverse biological effects have been used as a surrogate in the development of sediment quality guidelines (SQGs) (a full list of Abbreviations used in this text is given in Supplementary Material Table S1).

1.2. Sediment quality

SQGs provide a framework for evaluating the risks posed by contaminants to good ecosystem health. Where 'risk' is the probability of impairment, or adverse effect due to the presence of a contaminant, whereas the anthropogenic chemical is a possible 'hazard' that has the potential to cause harm. Sediment Quality Values (SQVs) assess hazards and are used in the derivation of guidelines, whereas SQGs are employed in an initial, screening assessment of risk of adverse effects to benthic populations.

SQGs are used either for individual chemicals, or for a mixture of substances to screen contaminants posing a risk to biological resources. SQGs are also used in combination with other chemical and biological indicators in a weight-of-evidence approach to assess risk to benthic health. SQGs are well established in scientific and managerial communities and have been used for over 25 years to aid initial screening of chemical contaminants for potential adverse biological effects. Sediment quality has emerged as an important consideration for the protection of benthic ecosystem health, conservation and protection of marine environments (Kwok et al., 2013).

1.3. Previous reviews

Some of the more important SQG reviews are summarised. SQGs were reviewed in the derivation of screening values for Hong Kong (Chapman et al., 1999a, 1999b) and in the implementation of equilibrium partitioning by the US EPA (McCauley et al., 2000). Workshops to review SQGs were conducted in 2000 (GIPME, 2000) and 2005 (Wenning et al., 2005) amongst others. Methods, advantages, assumptions and limitations in the use of SQGs for chemical mixtures were provided by Long et al. (2006) and SQGs were reviewed for global use by Burton (2002). A review by Hubner et al. (2009) concluded empirical guidelines have a high degree of comparability and predictability for identifying sediments having potentially adverse biological effects. The DEA (2012) review provided limitations of schemes in setting a dredging sediment assessment framework for the Republic of

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South Africa. Strategies of assessment methods were reviewed by Belin et al. (2014) and recently O'Brien et al. (2016) summarised the frequency and location of SQGs used globally.

1.4. Current objectives

The status of marine bottom sediments may be described by two attributes: the magnitude of anthropogenic-induced change from the pristine condition (contamination); and the potential for adverse effects to benthic populations (pollution). The use of sedimentary metals as environmental indicators of contamination (enrichment over background) has been reviewed elsewhere (Caeiro et al., 2005; Belin et al., 2014; Birch, 2016). The objective of the present work is to review sediment-chemical methods employed to assess risk of adverse effects to benthic communities (pollution). The objective is not to determine sediment quality, or to set SQVs, or assess chemical measures, but to review chemical schemes used in sediment quality assessment. Emphasis is placed on advantages and limitations of SQGs and new research into further development of these guidelines is reviewed.

2. Methodologies

A variety of sediment chemistry-based approaches has been developed from empirical and mechanistic relationships (Wenning et al., 2005; OSPAR, 2008) to assess risk of adverse effects to benthic communities. In the current work, schemes based on matching chemical and biological data are grouped into Empirical (correlative) Approaches, while Mechanistic Approaches, founded on equilibrium partitioning (EqP), address factors controlling bioavailability, chemical uptake and toxicity, i. e. provide a theoretical basis for an understanding of cause and effect. Schemes not based on matching chemical and biological data, or EqP, but still assess biological risk have been grouped under Sediment Quality Indices (SQIs) as these approaches use chemical weighting, scoring, factoring, or a combination of these techniques (Table 1). These methods are separate from indices used to assess contamination, or enrichment, i. e. schemes unrelated to biological risk (for enrichment indices see Caeiro et al., 2005).

2.1. Empirical approaches (effects-based schemes)

Paired contaminant concentrations and biological-effects data are correlated in empirical guidelines using a range of statistical techniques. Empirical SQGs have broad applicability and use routine monitoring data, however these guidelines do not identify the cause of effect and are not criteria.

2.1.1. Screening Level Concentration (SLC)

The SLC is the highest contaminant concentration that can be tolerated by a defined percentage of benthic species (Neff et al., 1986; US EPA, 1999). The 95th percentile (or any other specified percentile) of a frequency distribution of matching chemical concentration and co-occurrence of a species is deemed the SLC. A frequency distribution is compiled for all species to estimate the concentration that can be tolerated by a specified percentage of species.

2.1.2. Screening Ecological Risk Assessment (SERA)

The risk of adverse effects on benthic organisms within sediments of Venice Lagoon was determined by comparing sediment concentrations with ‘ecotoxicological benchmarks’, which were SQVs of MacDonald (MacDonald et al., 1996) (Critto et al., 2005). The number of contaminants exceeding ecotoxicological benchmarks at each site were used to produce contaminant risk maps.

2.1.3. Effects range and effects level assessments

The two most commonly used SQGs are those derived by Long (Long and Morgan, 1990; Long et al., 1995a) and MacDonald (MacDonald et al., 1996), both of which determine two values for each contaminant, i. e. a concentration below which adverse effects are seldom observed (Effects Range Low, ERL and Threshold Effect Level, TEL, respectively) and the concentration above which adverse effects are common (Effects Range Median, ERM and Probable Effects Level, PEL, respectively). The ERL and ERM are calculated as the 10th and 50th percentile concentrations of an effects data base, respectively and the TEL and PEL are calculated on the geometric mean of the 50th percentile concentration of an effects database and the 85th percentile concentration of a no-effects data set. Concentrations between the two values of each approach exhibit inconsistent biological effects.

2.1.4. Logistic regression modelling (LRM)

The LRM approach is based on statistical analysis of matching chemical and biological effects data for amphipod toxicity (Field et al., 1999, 2002). The LRM method does not provide specific SQGs for each chemical, but describes the relationship between contaminant concentrations and the probability of toxicity. The relationship may be used to calculate SQGs based on the level of protection required.

2.1.5. Apparent effects threshold (AET)

The AET sets the concentration of a contaminant above which a statistically significant adverse effect is always observed for a stated endpoint, e. g. toxicity in sediment and the water column and benthic community structure (Barrick et al., 1988).

2.1.6. Laboratory spiked sediment (LSS)

Dose-response relationships are determined by exposing test animals to sediments that have been spiked with a known concentration of a contaminant under laboratory-controlled conditions. Various organisms and chemicals are used with a variety of endpoints, e. g. mortality, growth size/weight and reburial (Persaud et al., 1993; MacDonald, 1994).

2.1.7. Ecological risk factor (ERF)

The ERF is the total metal surficial sediment concentration minus the highest concentration of that metal not associated with an adverse effect divided by the latter value (Kabir et al., 2011). The ERF has been used in a multivariate analysis combined with an enrichment factor and metal species data into a ‘potential ecological risk factor’ to assess the significance of a mine waste spill (Riba et al., 2002). The highest no-effects concentration is site specific and the ERA does not provide a classification scheme for single, or mixture of metals and includes Cd, Cu, Fe, Mn, Pb and Zn only.

2.1.8. Mean weighted chemical category score (CCS)

The CCS is a SQG-type indicator based on the association between chemicals and the magnitude of biological response, including toxicity and benthic community disturbance (SWRCB, 2006). Three chemical concentrations define the biological level of response, i. e. low-; moderate-; and high-effect and a weighting factor reflecting the strength of association for each chemical is applied to produce a CCS. The chemical values and weighting factor are determined for each contaminant by a statistical process that identified the chemical ranges producing the best agreement with biological response. Individual CCSs are combined to determine the effects of chemical mixtures. Scores are summed for all chemicals in the sample and divided by the sum of weighting factors to produce the mean weighted CCS.

2.1.9. Consensus median effect concentration (CMEC)

The aim of consensus-based approaches is to achieve agreement amongst a number of SQGs hosting similar stated objectives for a particular chemical to strengthen the relationship between stressor and effect and to account for contaminant mixtures (Chapman and Wang, 2001). The CMEC guidelines have been developed for three levels of biological effect: The Threshold Effect (TEC) being concentrations