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# A new tool for assessing sediment quality based on the Weight of Evidence approach and grey TOPSIS

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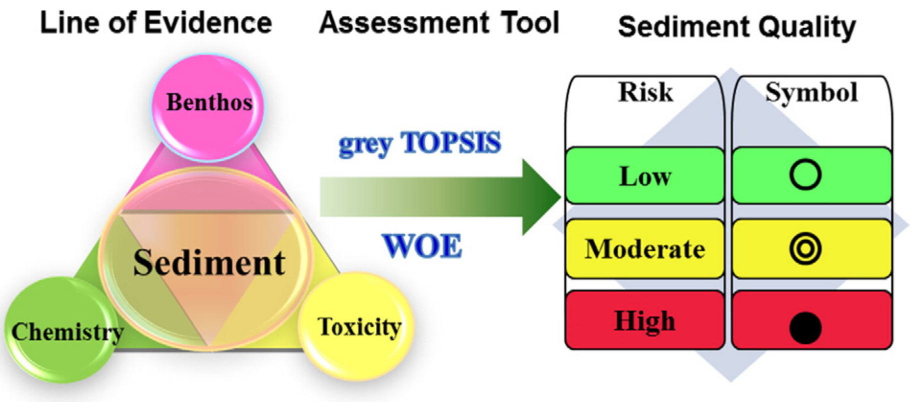
## HIGHLIGHTS

- We developed a new sediment quality assessment tool using WOE and grey TOPSIS.
- This tool can process data from different analyses and generate individual results.
- This tool can rate each sampling site with high, moderate, or low ecological risk.
- A case study demonstrated its successful application in sediment quality assessment.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Sediment is an important part of an aquatic ecosystem, so it is essential to develop an effective sediment quality assessment tool. This study aims to develop a new sediment quality assessment tool using a Weight of Evidence approach in combination with the grey TOPSIS (Technique for Order Preference by Similarity, a mathematical calculation of multi-criteria decision analysis). This tool can analyze data from chemical analyses, laboratory toxicity tests and benthic community structure analyses to generate individual results from each line of evidence, and integrate data from these three lines of evidence to obtain an overall assessment through an Excel Visual Basic for Application program. The tool can compare the relative magnitude of risks among sites and rate each site with high, moderate, or low ecological risk, thus guiding us to take pertinent measures toward polluted sediment. A case study of the sediment of Dongjiang River basin, south China, demonstrated the successful application of this tool. It proved that this assessment tool can provide a comprehensive and accurate assessment of sediment quality and efficiently discriminate risks among different sites, suggesting it is a powerful tool for environment risk assessment.

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## 1. Introduction

Sediment is an important part of an aquatic ecosystem, providing a habitat and food source for the benthos. Thus contaminated sediment has become one of the focuses of environmental regulations around the world. However, due to the complexity of sediments, it is often not easy to make an accurate assessment of the risk posed by sediment contaminants (Apitz et al., 2005; Burgess et al., 2013). Therefore, it is crucial to develop an effective approach for sediment quality assessment.

The Weight of Evidence (WOE) approach measures and integrates metrics from different lines of evidence (LOEs) to conduct a comprehensive assessment of the quality of sediment, thus it has been widely applied to the sediment risk assessment (Weed, 2005). The basic LOEs of the WOE are chemical analyses (chemical LOE), sediment toxicity tests (toxicological LOE) and benthic community structure analyses (ecological LOE), although these can be complemented by others such as bioaccumulation, or the use of biomarkers.

The most challenging part of a WOE approach is to analyze and combine information provided by a large number of metrics from different LOEs. There are many WOE information processing approaches, but most of which are qualitative or semi-quantitative. Considering the complexity of sediment quality assessment, the WOE approach increasingly prefers modern quantitative methods (Linkov et al., 2011). Among which, multi-criteria decision analysis (MCDA) has emerged as a formal methodology in environmental decision making (Huang et al., 2011; Sorvari et al., 2013).

MCDA is a set of methods designed to ensure that a synthesis of multiple sources of information is documented and directed toward a stated goal, which can help the comparison of alternatives based on decision matrices (Linkov et al., 2011). MCDA has been used in many fields. Huang et al. (2011) have summarized MCDA applications in the environmental field between 2000 and 2009. Recently, risk-based ranking based on MCDA was increasingly applied in many other research field such as nanomaterial science (Tervonen et al., 2009), contamination sources in groundwater (Pizzol et al., 2015), contaminated landfill site (Sorvari et al., 2013) and decision making (Yatsalo et al., 2007).

Various MCDA tools can be used in decision making, and TOPSIS (Technique for Order Preference by Similarity) is one promising technique (Critto et al., 2007; Huang et al., 2011; Qin et al., 2008; Samvedi et al., 2012). TOPSIS compares a set of alternatives by calculating distances of each alternative from the theoretic ideal alternative and negative ideal alternative (consists of the best and worst values of each metric, respectively), and the alternatives that near the ideal alternative and far from the negative ideal alternative are preferred (Huang et al., 2011). TOPSIS has become a widely accepted multi-criteria decision analysis method for the following reasons: providing complete ranking results; more suitable to be combined with stochastic analysis; depending on the weights and objective data to calculate relative distances; producing smoother tradeoffs by dealing with non-linear relationship and converted into programmable computation procedure easily (Huang et al., 2011; Qin et al., 2008; Samvedi et al., 2012). However, TOPSIS faces the constraint of not being able to handle vague assessments (Gu and Song, 2009). So it would be better to combine TOPSIS with a fuzzy evaluation method if applied in sediment quality assessment.

Grey relational analysis (GRA) has proven useful in dealing with poor, incomplete, and uncertain information (Chan and Tong, 2007; Lin and Lin, 2002). GRA determines the similarity of changing trend between two different sequences of data. With GRA, global comparison between two sets of data is undertaken instead of local comparison by measuring the distance between two points. TOPSIS can be used in combination with GRA to become grey TOPSIS, as it reflects the similarity degree of both the position and shape of data spatial distribution between an alternative and the ideal alternatives, thus considers the reality and fuzziness of the data (Gu and Song, 2009). Treating each sampling site as an alternative, grey TOPSIS calculates the distances and grey relational grades between each alternative and the ideal alternatives so that sediment quality or risk can be compared. To the best of our knowledge, the grey TOPSIS has not been used in a WOE method for environmental studies.

The objective of this paper is to develop a new tool for sediment quality assessment which uses the WOE approach to organize different LOEs and applies the grey TOPSIS to analyze and integrate information provided by all of the evidences to gain an exhaustive conclusion about sediment risk. A case study in the Dongjiang River, South China, was used to demonstrate feasibility of this approach.

## 2. Methodology

### 2.1. Development of a sediment quality assessment tool

A new sediment quality assessment tool was developed using the WOE approach and grey TOPSIS based on three independent LOEs involving chemical analyses, sediment toxicity tests, and benthic community structure analyses. Each LOE contains several metrics and finally all metrics are integrated into a WOE evaluation system using the grey TOPSIS. This assessment tool involves various steps: selecting metrics, identifying alternatives, measuring performance of alternatives (including assigning weight and integrating information of the selected metrics), and synthesizing information to determine the risk (or impact). For sediment quality assessment, detailed procedures in the tool are shown in Fig. S1 (Supporting Information) and further described as follows.

#### 2.1.1. Select metrics

The site-specific sediment quality assessment requires selecting a suitable set of chemical, toxicological and ecological measurement endpoints for the WOE evaluation. According to Fairey et al. (2001), effectively representing toxicological modes of action may be more important to predictive accuracy than simply including additional toxic chemicals, so metrics in the assessment should be limited and representative.

For chemical metrics, two aspects should be considered in selecting metrics: ecological significance and bioavailable concentration profile. Considering the difficulty in obtaining bioavailable concentrations, total concentrations are often used in the assessment. Chemicals that are toxic to aquatic organism, represent anthropogenic contamination or have published SQGs (Sediment Quality Guidelines) can be selected as candidate metrics (Fairey et al., 2001). Furthermore, chemicals that have large concentration differences among sites can be selected using statistical tools such as principal component analysis (PCA).

For toxicological metrics, the selection depends on what toxicity tests have been performed for the sediments. The design of toxicity tests should involve different taxonomic groups of test organisms, like bacteria, plants, invertebrates and vertebrates; different test matrices, like whole sediment and pore water; different endpoints, like survival, growth, reproductive output and behavioral responses; and careful consideration of exposure routes (dissolved and dietary). Toxicity metrics should ideally be chronic, with good inherent quality and accuracy (Critto et al., 2007; McDonald et al., 2007; Simpson et al., 2011).

For ecological metrics, we can use the procedure described by Stoddard et al. (2008) to select metrics: classify metrics into different functional groups, such as taxonomic richness, tolerance and trophic; compare the distribution of metric values and eliminate metrics that have very small ranges or that have similar values at most sites; quantify metric reproducibility with a variant of the signal: noise ratio (S/N) and eliminate metrics with low S/N; use t-tests to compare mean values of each metric between least- and most-disturbed sites and choose the metrics that have high responsiveness (t-scores); choose the most responsive metric from each metric category; check for metric redundancy by performing Pearson correlation analysis for all the ecological metrics that are still retained at this step, and keep the most responsive metric among those with correlation coefficients greater than 0.71.

### 2.1.2. Identify alternatives

Each sampling site that participates in the assessment is a basic alternative of this evaluation method. In order to demonstrate the ecological risk rating of the sampling sites, two artificial alternatives are included, namely the better site that serves as the boundary between low and moderate ecological risks and the worse site which divides moderate and high ecological risks. With the same metrics as the sampling sites, the better site and worse site are composed of some metric values that represent acceptable and unacceptable situations respectively. For example, the chemical metric values in the better site and worse site can be the threshold effect and median effect sediment quality guidelines respectively, e.g., the threshold effect concentration (TEC) and the probable effect concentration (PEC) of Consensus-Based SQGs (MacDonald et al., 2000). For metrics of toxicological and ecological LOE, the better site and worse site consist of 20% and 50% of the biggest attainable metric values for cost metrics (which are the smaller the better) respectively, or 80% and 50% of the biggest attainable metric values for benefit metrics (which are the bigger the better) respectively. The selection method of metric values of the better site and worse site used in our case study is given in Table 1.

### 2.1.3. Integrate information of the selected metrics

The most important part of this tool is to assess the quality of each sampling site through integrating information of the selected metrics by the grey TOPSIS. The grey TOPSIS prefer sites that have shorter distances and bigger grey relational grades to the ideal alternative but have longer distances and smaller grey relational grades to the negative ideal alternative. The main steps of the grey TOPSIS are: arranging raw data (chemical concentrations, toxic effects and ecological index) and converting benefit metrics to cost metrics; normalizing the raw data; assigning weight to each metric; getting weighted normalized decision matrix; getting the ideal alternative and negative ideal alternative; calculating the Euclidean distances, grey relational coefficients, grey relational grades and relative closeness of each sampling site to the ideal alternative and negative ideal alternative; calculating the relative similarity of each sampling site to the ideal alternative (Gu and Song, 2009; Zhou, 2009). The details of the calculation steps of the grey TOPSIS are provided in Text S1 (Supporting Information) and all of the calculations can be accomplished by an Excel Visual Basic for Application (VBA) program.

Then the sampling sites are sorted in descending order according to the relative similarity and rated as high, moderate, or low ecological risk. Symbols for the three ecological risk ratings are used to provide a convenient and rapid visual assessment of risks (Table 2).

### 2.1.4. Assign weight

Within a framework of WOE, not all metrics contribute to the overall conclusion the same, so weighting is an important part of the WOE method, including weighting each metric and weighting categories of metrics (Suter Ii and Cormier, 2011). A weighting method for each metric is shown in Fig. S2 (Supporting Information). Weighting metric itself is based on its strength that is the size of the metric value, such as the concentration of chemicals. Metric values that are worse than the worse site, between worse site and better site, and better than the better site can be assigned 6.0, 2.0, 1.0 respectively or 3.0, 1.5, 1.0 respectively for strict or relax effect. Different effects produce similar relative ecological risk magnitude between sites but different risk ratings, so assessing some places like water source can choose strict effect while assessing the lower reaches of the city can choose relax effect. Users can also assign different weights to get ideal effect.

Weighting the category of a metric should base on two considerations: different inherent weights of different categories of evidence and the number of metrics within a category (Suter Ii and Cormier, 2011). Actually, different LOEs have different inherent relevance and representative to sediment risk: ecological LOE is most representative of risk because it provides information about actual conditions at one site; toxicological LOE can reflect synthetic toxicity of sediment, but there are uncertainty in extrapolating from laboratory-generated data to field conditions; chemical LOE is least relevant because the presence of a contaminant in the sediment does not necessarily imply an adverse ecological effect (McPherson et al., 2008). Therefore, ecological LOE receives a high weight (1.5), toxicological LOE receives a medium weight (1.2) and chemical LOE receives a low weight (1.0) (Chapman and Anderson, 2005; McDonald et al., 2007). In order to eliminate the influence of different numbers of metrics within a category, the weight should be divided by the number.

### 2.1.5. Schemes for using the assessment tool

The use of WOE and single LOEs in the assessment can provide complementary information for decision-making (Chapman et al., 2002). To make it easier for the wide variety of stakeholders to understand and use the results, two schemes for integrating information of the selected metrics can be used to assess the ecological risks (or impacts). In order to obtain more detailed information to guide what action should be taken next, the first scheme integrates the selected metrics of each LOE individually using the grey TOPSIS algorithm described above to sort each LOE of each site as high, moderate, or low ecological risk. Subsequently, the next action is decided based on the results of each LOE. However, if conflicting results are obtained from different lines of evidence, a WOE assessment is required to get a more definitive assessment result. The second scheme integrates the selected metrics of all LOEs simultaneously using the grey TOPSIS algorithm to sort each site as high, moderate, or low ecological risk. This generates simplified overall assessment results.

## 2.2. Case study

### 2.2.1. Study area and sampling campaigns

The case study was carried out in the Dongjiang River basin of the Pearl River Delta region, south China (Fig. 1). This region is a rapidly urbanized region with a huge population and various industrial activities. Considering degree of contamination, sampling sites were selected from the upper stream to the downstream. The 20 sampling sites were located in the Danshui River (S1–S7), Shima River (S8–S15, due to accessibility, sediment samples were not obtained at site S11), Xizhijiang River (S16–S18) and the lower reach of Dongjiang River (S19–S21).

**Table 1**
Selection method of metric values of the better site and worse site used in the case study.

| | Chemical metric | Toxicological metric | Ecological metric |
|---|---|---|---|
| The better site | CB-TECs [a] | 0.2 × (100% inhibition rate or the maximum FTI index [c]) | 0.2 × the 95th percentile of cost metric values or 0.8 × the 95th percentile of benefit metric values [d] |
| The worse site | CB-PECs [b] | 0.5 × (100% inhibition rate or the maximum FTI index) | 0.5 × the 95th percentile of cost metric values or 0.5 × the 95th percentile of benefit metric values |

[a] CB-TECs = threshold effect concentration of Consensus-Based Sediment Quality Guidelines (MacDonald et al., 2000).

[b] CB-PECs = probable effect concentration of Consensus-Based Sediment Quality Guidelines (MacDonald et al., 2000).

[c] FTI index is the fish teratogenic index of zebrafish embryo, whose range is 0–3.

[d] Cost metric is the metric that smaller is better, while benefit metric is the metric that bigger is better.

**Table 2**
Ecological risk ranking and final management decision.

| Ecological risk | Corresponding symbol | Sequence | Definitive final decision of overall evaluation |
|---|---|---|---|
| Low | ○ | In front of the better site | No further actions needed |
| Moderate | ◎ | Between the better site and worse site | Additional assessment required |
| High | ● | Behind the worse site | Management actions required |

Sediment sampling campaigns were carried out in July 2012. Sediment samples (top 10 cm of surface) were collected by a grab sampler and placed into clean amber bottles. Three replicate samples were obtained from each site. All collected sediment samples were then placed in coolers and transported to laboratory immediately. Sediment samples were stored at 4 °C in the dark before toxicity tests, or vacuum-freeze dried within a week for chemical analyses. Pore water of each sediment was also obtained for toxicity tests by centrifuging at 3500 g. General properties of the collected sediments and their overlying water samples were measured and are given in Tables S1 and S2 (Supporting Information).

### 2.2.2. Determination of metric values

Metals and polycyclic aromatic hydrocarbons (PAHs) were selected as chemical indicators of anthropogenic stress in sediments of the Dongjiang River basin. The various metal elements (28) in sediments were measured by an inductively coupled plasma-mass spectrometer (ICP-MS) after the sediments were digested by a mixture of concentrated nitric acid and hydrofluoric acid solution (W.F. Zhang et al., 2012). The sixteen PAHs in sediments were extracted by using a pressurized liquid extractor with acetone/dichloromethane (50:50; v/v) followed by purification on silica gel, and then analyzed by gas chromatography–mass spectrometry (GC–MS) according to a previous study (Tao et al., 2002). In addition to the sediment samples, metals and PAHs were also analyzed for overlying water samples (Table S3, Supporting Information).

Various replacement tests instead of traditional amphipods or bivalves tests were performed for sediment toxicity. Two bioassay methods using alginate immobilized microalgae *Pseudokirchneriella subcapitata* and zebrafish embryos were carried out to assess the toxicity of both whole-sediment samples and pore water samples (Hollert et al., 2003; L.J. Zhang et al., 2012). Another bioassay method using genetically modified lux-based biosensors *Escherichia coli* HB101 pUCD607 was carried out to assess the toxicity of pore water samples only according to our previous method (Fang et al., 2012).

Benthic invertebrate survey was carried out along with the sediment sampling according to McGee et al. (2009). Invertebrate samples were taken from soft sediment and sieved through a 250-μm mesh and then transferred into a jar and stored in 4% formalin solution. Then the invertebrates were identified in the laboratory under a dissecting microscope to the lowest practical taxonomic level, then counted and weighed. Metrics such as total taxa, biomass, evenness index, Margalef's index and diversity index were calculated to represent the condition of invertebrate community structure in the sediments.

Detailed methods for chemical analyses, sediment toxicity tests and benthos survey can be referred to Text S2 (Supporting Information). Detailed process of metrics selection of the three LOEs can be referred to Text S3 and Tables S4–S8 (Supporting Information).

### 2.2.3. Data analyses and the tool application

The statistical software SPSS 13.0 (t-test, analysis of variance (ANOVA), PCA and Pearson correlation coefficient analysis) was used to examine relationships among the various parameters and sites, and to select metrics that were suitable for integration. Metric values that meet the requirements (Table 3) were used to assess the sediment quality of the Dongjiang River basin based on the WOE and grey TOPSIS approaches. Metric calculations and integrations of the grey TOPSIS method were programed using Microsoft Excel VBA. After we input the raw data, the program can calculate automatically and quickly, and show the finally results in a table which lists the relative similarity to the ideal alternative, ordinal of risk in all the sites, risk grade and final decision of each sampling site. We can learn the relative risk magnitude between sites and the risk grade of each site from the table which will conduct us to next action. The Excel VBA program software is available free of charge in the Supporting Information.

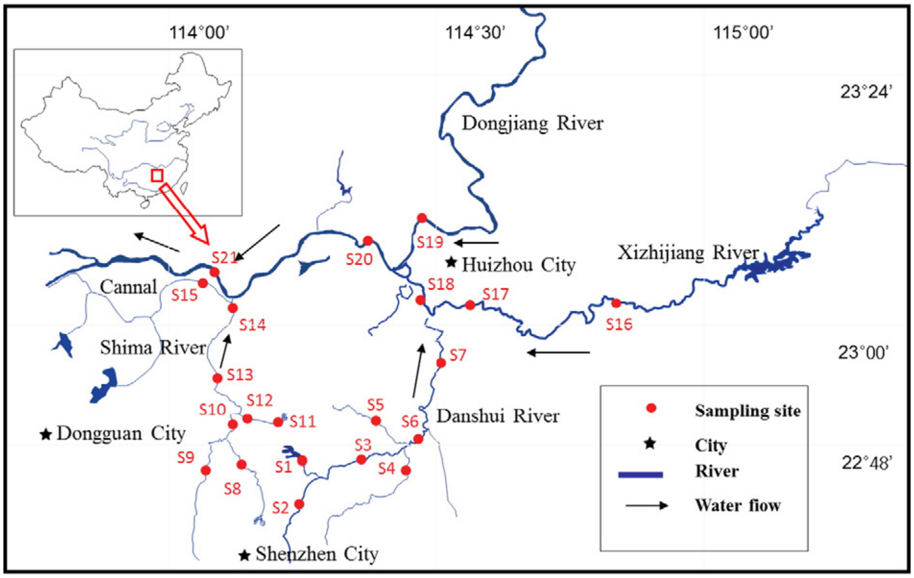

**Fig. 1.** Location map showing sampling sites in the Dongjiang River basin, South China.

**Table 3**
Metric values of different LOEs.

| Sites | Chemical metrics | | | | | | | | | | | | Toxicological metrics | | | | | Ecological metrics | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cr[a,b] | Ni | Cu | Zn | As | Cd | Hg | Pb | Phe | Ant | Fl | Pyr | FTIp | FTIs | GIRp | GIRs | LIR | Tot | Bio | Eve | Mar | Div |
| Better site [c] | 43.4 | 22.7 | 31.6 | 121 | 9.79 | 0.990 | 0.180 | 35.8 | 204 | 57.2 | 423 | 195 | 0.600 | 0.600 | 20.0 | 20.0 | 20.0 | 4.84 | 111 | 2.66 | 1.16 | 1.35 |
| Worse site [c] | 111 | 48.6 | 149 | 459 | 33.0 | 4.98 | 1.06 | 128 | 1170 | 845 | 2230 | 1250 | 1.50 | 1.50 | 50.0 | 50.0 | 50.0 | 3.02 | 69.6 | 1.66 | 0.723 | 0.844 |
| S1 | 47.6 | 8.66 | 13.2 | 51.5 | **41.6**[d] | 0.312 | 0.048 | 18.5 | 18.7 | 12.0 | 18.4 | 21.5 | 0.210 | **1.51** | 0.000 | **69.8** | 0.000 | 6.00 | **14.7** | 2.14 | 1.13 | 1.67 |
| S2 | 77.3 | 35.7 | 78.2 | 61.8 | **61.1** | 1.58 | 0.087 | 40.4 | 30.2 | 34.8 | 42.0 | 54.8 | **1.87** | **3.00** | 17.9 | **52.2** | 16.6 | 4.00 | **8.66** | **0.680** | **0.450** | **0.410** |
| S3 | **129** | **85.3** | **187** | 137 | **71.1** | 1.64 | 0.197 | 48.5 | 52.3 | 53.0 | 66.7 | 93.8 | **2.92** | **2.07** | 17.3 | 13.4 | 13.8 | **2.00** | **3.42** | **1.27** | **0.300** | **0.380** |
| S4 | **150** | **129** | **239** | 88.2 | **42.1** | 3.52 | 0.034 | 28.4 | 8.69 | 9.97 | 10.1 | 19.7 | 0.520 | 0.880 | 0.000 | 0.000 | 0.000 | **3.00** | **0.160** | 2.70 | **0.720** | **0.810** |
| S5 | 57.7 | 15.8 | 74.2 | 58.1 | **42.0** | 0.445 | 0.152 | 32.2 | 26.5 | 27.4 | 56.3 | 79.4 | 0.170 | **1.68** | 32.4 | **76.0** | 26.1 | 6.00 | 132 | **1.53** | 1.00 | 1.19 |
| S6 | 47.1 | 30.6 | 62.9 | 77.8 | **43.4** | 0.553 | 0.163 | 40.7 | 34.5 | 35.6 | 43.6 | 64.7 | 0.740 | **2.83** | 42.2 | **52.3** | 0.000 | 4.00 | **59.2** | 2.26 | **0.470** | 1.36 |
| S7 | 70.4 | 48.3 | 112 | 74.9 | **35.9** | 0.714 | 0.144 | 24.7 | 145 | 22.4 | 125 | 99.2 | 0.440 | **2.68** | 0.000 | 38.0 | 0.000 | **2.00** | **22.3** | 3.33 | **0.190** | 1.00 |
| S8 | **120** | **55.6** | 137 | 165 | **49.7** | 0.699 | 0.188 | 31.8 | 70.4 | 70.7 | 74.9 | 104 | 0.300 | **2.83** | 0.000 | **67.6** | 19.2 | **1.00** | **0.300** | **0.000** | **0.000** | **0.000** |
| S9 | 32.7 | 9.70 | 17.5 | 40.1 | **33.5** | 0.106 | 0.075 | 27.1 | 26.2 | 27.4 | 30.1 | 34.6 | **2.46** | **2.69** | **70.1** | **55.2** | 16.8 | **2.00** | **0.690** | 2.99 | **0.340** | 0.900 |
| S10 | 47.2 | 25.6 | 39.5 | 58.9 | **40.3** | 0.343 | 0.088 | 26.2 | 65.6 | 48.0 | 71.6 | 87.8 | 0.250 | **2.77** | 0.000 | 43.4 | 21.6 | **2.00** | **1.83** | **1.42** | **0.260** | **0.430** |
| S12 | 90.3 | 33.2 | 103 | 204 | **37.9** | 0.392 | 0.219 | 24.0 | 72.4 | 0.000 | 99.2 | 217 | **3.00** | **2.96** | 36.9 | 47.5 | 14.0 | **2.00** | **10.3** | **0.260** | **0.210** | **0.080** |
| S13 | 52.8 | 25.0 | 56.0 | 78.6 | **36.0** | 0.334 | 0.106 | 28.9 | 53.9 | 0.000 | 63.8 | 98.8 | **2.34** | **3.00** | 24.2 | 44.7 | 13.9 | **1.00** | **0.360** | **0.000** | **0.000** | **0.000** |
| S14 | 105 | **50.0** | 117 | 80.1 | **41.3** | 0.516 | 0.118 | 21.9 | 44.2 | 45.1 | 22.6 | 36.9 | 0.000 | 0.320 | 11.4 | 44.9 | 29.5 | 5.00 | **17.0** | **0.160** | **0.620** | **0.120** |
| S15 | 52.3 | 22.9 | 30.6 | 40.8 | **38.7** | 0.268 | 0.068 | 17.9 | 41.7 | 42.5 | 33.6 | 48.1 | **2.18** | **2.08** | 21.2 | 44.6 | 0.000 | **3.00** | **15.8** | **0.510** | **0.330** | **0.240** |
| S16 | 8.35 | 2.41 | 3.24 | 17.2 | **35.3** | 0.106 | 0.031 | 11.6 | 5.01 | 6.49 | 0.000 | 0.000 | 0.530 | 1.40 | 0.000 | 0.000 | 0.000 | **2.00** | **23.5** | 3.32 | 1.44 | 1.00 |
| S17 | 19.7 | 8.29 | 11.1 | 54.4 | **46.4** | 0.245 | 0.099 | 23.3 | 16.6 | 0.000 | 18.3 | 23.5 | 0.150 | 0.880 | **69.1** | **69.8** | 6.64 | 5.00 | **41.1** | 2.35 | 1.31 | 1.64 |
| S18 | **124** | **77.8** | **169** | 113 | **57.0** | 0.790 | 0.178 | 40.7 | 23.5 | 0.000 | 37.3 | 54.7 | 0.650 | 1.25 | 0.000 | 43.6 | 23.8 | **2.00** | **3.78** | 2.70 | **0.260** | **0.810** |
| S19 | 37.5 | 12.9 | 14.7 | 40.1 | **47.1** | 0.279 | 0.114 | 30.4 | 12.4 | 13.7 | 15.9 | 19.0 | 0.720 | 0.780 | **79.8** | 40.0 | 13.6 | 4.00 | **10.8** | 1.83 | 0.770 | 1.10 |
| S20 | 64.9 | 31.4 | 52.7 | 81.6 | **49.2** | 0.503 | 0.136 | 29.3 | 14.5 | 15.4 | 14.4 | 17.5 | 0.220 | 1.00 | 0.000 | **70.8** | 16.4 | 7.00 | **39.5** | 2.41 | 1.55 | 2.04 |
| S21 | 75.5 | 22.4 | 44.5 | 62.4 | **49.5** | 0.410 | 0.118 | 35.9 | 45.2 | 46.0 | 65.9 | 72.6 | 0.280 | 1.10 | 0.000 | **73.2** | 27.1 | **3.00** | 277 | **0.370** | **0.300** | **0.180** |

[a] The full names of the metrics are: Cr — chromium; Ni — nickel; Cu — copper; Zn — zinc; As — arsenic, Cd — cadmium; Hg — mercury; Pb — lead; Phe — phenanthrene; Ant — anthracene; Fl — fluoranthene; Pyr — pyrene; FTIp — fish teratogenic index of zebrafish embryo pore water test; FTIs — fish teratogenic index of zebrafish embryo whole sediment test; GIRp — algal growth inhibition rate of algae pore water test; GIRs — algal growth inhibition rate of algae whole sediment test; LIR — luminescence inhibition rate of luminescent bacterium pore water test; Tot — total taxa; Bio — biomass; Eve — evenness index; Mar — Margalef's index; and Div — diversity index.

[b] The unit of metals is mg/kg dw; the unit of polycyclic aromatic hydrocarbons is μg/kg dw; the unit of biomass is g/m$^2$; other metrics are dimensionless; an average of three replicates for each site is presented in the table.

[c] The values for the better site and the worse site were obtained according to Table 1.

[d] The bold type indicated that the metric value is worse than the metric value of the worse site.

## 3. Results

Two schemes were used to integrate information of the selected metrics to assess the ecological risks of sediments at 20 sites of the Dongjiang River basin. The first scheme integrated the selected metrics of each LOE individually using the grey TOPSIS algorithm (relax effect only) (Table 4). The second scheme integrated the selected metrics of all three LOEs simultaneously using the grey TOPSIS (both relax effect and strict effect) to produce overall assessment of the sites (Table 5).

### 3.1. Sediment chemistry

Eight metals (Cr, Ni, Cu, Zn, As, Cd, Hg and Pb) and four PAHs (phenanthrene, anthracene, fluoranthene and pyrene) were selected as chemical metrics based on the PCA of the concentration data for all chemicals analyzed. Their chemical concentrations in the sediments of the Dongjiang River basin and the normative limits from the Consensus-Based SQGs (MacDonald et al., 2000) are given in Table 3. Those chemicals that are below the detection limits were treated as zero. For those metals, the highest concentrations for Cr, Ni, Cu, Zn, As, Cd, Hg and Pb were detected at the site S3, S4, or S12, while the lowest concentrations were measured at the site S9 or S16. Chemical analyses revealed particularly high concentrations of As with all sites exceeding the Consensus-Based PEC (33 mg/kg dw), and to a lesser extent, Cr, Ni and Cu exceed the Consensus-Based PECs (111, 48.6 and 149 mg/kg dw, respectively) in the sediments of some sites like S3, S4, S8 and S18. The concentrations for the rest metals were all less than their corresponding Consensus-Based PECs (Table 3). The total concentrations of the four PAHs in the sediments ranged from 11.5 (S16) to 392 (S7) μg/kg dw. The four PAHs concentrations were less than their corresponding Consensus-Based TECs (204, 57.2, 423 and 195 μg/kg dw, respectively), suggesting minimal risks to benthic organisms.

When these chemical data were elaborated using the grey TOPSIS, the model calculated the value of relative similarity of each sampling site from the overall best site and ranked the level of contamination effects (Table 4). The sites S16 and S9 were classified as ‘low’, while the other sites were ‘moderate’. According to the sequence, the sites S4, S3, S18 and S8 were rated as more contaminated sites, while the sites S16, S9, S15 and S1 were regarded as less contaminated sites, which is in good agreement with the chemical concentration data.

**Table 5**
Overall assessment of sediment quality based on the three LOEs.

| Sites | Relax effect | | | Strict effect | | |
|---|---|---|---|---|---|---|
| | C+[a] | Sequence[b] | Symbol[c] | C+ | Sequence | Symbol |
| Better site | 0.711 | 1 | ○ | 0.765 | 1 | ○ |
| Worse site | 0.499 | 14 | ◎ | 0.537 | 9 | ◎ |
| S1 | 0.623 | 4 | ◎ | 0.613 | 5 | ◎ |
| S2 | 0.451 | 18 | ● | 0.445 | 18 | ● |
| S3 | 0.412 | 19 | ● | 0.399 | 19 | ● |
| S4 | 0.538 | 10 | ◎ | 0.523 | 11 | ● |
| S5 | 0.615 | 5 | ◎ | 0.615 | 4 | ◎ |
| S6 | 0.563 | 8 | ◎ | 0.561 | 8 | ◎ |
| S7 | 0.543 | 9 | ◎ | 0.537 | 10 | ● |
| S8 | 0.390 | 22 | ● | 0.377 | 22 | ● |
| S9 | 0.473 | 16 | ● | 0.464 | 16 | ● |
| S10 | 0.482 | 15 | ● | 0.473 | 15 | ● |
| S12 | 0.391 | 21 | ● | 0.388 | 21 | ● |
| S13 | 0.399 | 20 | ● | 0.393 | 20 | ● |
| S14 | 0.526 | 11 | ◎ | 0.520 | 12 | ● |
| S15 | 0.464 | 17 | ● | 0.455 | 17 | ● |
| S16 | 0.637 | 3 | ◎ | 0.626 | 3 | ◎ |
| S17 | 0.609 | 6 | ◎ | 0.600 | 6 | ◎ |
| S18 | 0.508 | 13 | ◎ | 0.500 | 14 | ● |
| S19 | 0.589 | 7 | ◎ | 0.593 | 7 | ◎ |
| S20 | 0.639 | 2 | ◎ | 0.629 | 2 | ◎ |
| S21 | 0.518 | 12 | ◎ | 0.506 | 13 | ● |

[a] Relative similarity of each sampling site from the best site.
[b] The sequence number of rank according to the C+.
[c] Symbol of the risk rating according to Table 2.

### 3.2. Sediment toxicity

The toxicity metrics used in the case study include the zebrafish embryo FTI (fish teratogenic index) of whole sediment and pore water tests, algal growth inhibition rate (GIR) of whole sediment and pore water tests, and bacteria luminescence inhibition rate (LIR) of pore water tests (Table 3). The results obtained from the battery of bioassays are given in Table 3. It should be noted that those with stimulating effect were regarded as no inhibition and the inhibition rate was set to zero.

**Table 4**
Assessment of sediment quality based on each LOE.

| Sites | Chemical LOE | | | Toxicological LOE | | | Ecological LOE | | |
|---|---|---|---|---|---|---|---|---|---|
| | C+[a] | Sequence[b] | Symbol[c] | C+ | Sequence | Symbol | C+ | Sequence | Symbol |
| Better site | 0.743 | 3 | ○ | 0.704 | 3 | ○ | 0.766 | 1 | ○ |
| Worse site | 0.378 | 22 | ◎ | 0.522 | 11 | ◎ | 0.682 | 5 | ◎ |
| S1 | 0.721 | 5 | ◎ | 0.553 | 8 | ◎ | 0.666 | 6 | ● |
| S2 | 0.627 | 17 | ◎ | 0.405 | 20 | ● | 0.405 | 16 | ● |
| S3 | 0.446 | 20 | ◎ | 0.488 | 14 | ● | 0.314 | 18 | ● |
| S4 | 0.443 | 21 | ◎ | 0.777 | 1 | ○ | 0.494 | 11 | ● |
| S5 | 0.700 | 10 | ◎ | 0.468 | 18 | ● | 0.720 | 2 | ◎ |
| S6 | 0.690 | 12 | ◎ | 0.472 | 16 | ● | 0.604 | 8 | ● |
| S7 | 0.690 | 11 | ◎ | 0.580 | 6 | ◎ | 0.499 | 10 | ● |
| S8 | 0.558 | 18 | ◎ | 0.471 | 17 | ● | 0.167 | 22 | ● |
| S9 | 0.748 | 2 | ○ | 0.269 | 22 | ● | 0.491 | 12 | ● |
| S10 | 0.711 | 8 | ◎ | 0.542 | 9 | ◎ | 0.322 | 17 | ● |
| S12 | 0.667 | 15 | ◎ | 0.384 | 21 | ● | 0.238 | 20 | ● |
| S13 | 0.718 | 6 | ◎ | 0.425 | 19 | ● | 0.167 | 21 | ● |
| S14 | 0.650 | 16 | ◎ | 0.681 | 4 | ◎ | 0.414 | 15 | ● |
| S15 | 0.722 | 4 | ◎ | 0.506 | 13 | ● | 0.302 | 19 | ● |
| S16 | 0.753 | 1 | ○ | 0.754 | 2 | ○ | 0.596 | 9 | ● |
| S17 | 0.713 | 7 | ◎ | 0.478 | 15 | ● | 0.689 | 4 | ◎ |
| S18 | 0.503 | 19 | ◎ | 0.666 | 5 | ◎ | 0.443 | 14 | ● |
| S19 | 0.707 | 9 | ◎ | 0.520 | 12 | ● | 0.607 | 7 | ● |
| S20 | 0.678 | 13 | ◎ | 0.570 | 7 | ◎ | 0.710 | 3 | ◎ |
| S21 | 0.675 | 14 | ◎ | 0.540 | 10 | ◎ | 0.454 | 13 | ● |

[a] Relative similarity of each sampling site from the best site.
[b] The sequence number of rank according to the C+.
[c] Symbol of the risk rating according to Table 2.

Only limited effects were registered for the luminescent bacteria exposed to various sediment pore waters with the LIR values of 0–30%, while more heterogeneous responses were obtained for other bioassays. The high algal growth inhibition rates (40–80%) for the pore water were only observed at the sites S6, S9, S17, and S19, but for the whole sediments, such high growth inhibition rates were exhibited at most of the sampling sites. Zebrafish embryos were found to be the most sensitive test organism with quite high FTI values (close to the highest limiting value 3) at the sites S3, S9, S12 and S13 for pore water, and at S2, S6–S10, S12 and S13 for whole sediment, respectively.

The data elaboration within the toxicological LOE generated the value of relative similarity of each sampling site from the overall best site, and ranked the level of toxicity using the grey TOPSIS (Table 4). In terms of toxicity level, only two sites S4 and S16 were regarded as 'low', while totally 11 sites were evaluated as 'high'. According to the obtained sequence, S4, S16, S14 and S18 were the less toxic sites while S9, S12, S2 and S13 were the more toxic sites, which reflected the real situations well.

### *3.3. Benthic community structure*

Five ecological metrics including total taxa, biomass, evenness index, Margalef's index and diversity index were chosen to assess the variation of benthic invertebrate communities (Table 3). Only a few taxa (<7) were found at each site, especially in the Shima River (1–2 for most sites). The biomasses were low at the sites of the Danshui River and Shima River, but somewhat higher at the sites of the Dongjiang River. The evenness indices were high at the sites of the Danshui River sites compared to other sites. A similar pattern was determined for the diversity indices. Margalef's indices were low at all sites and reached 0 at the sites S8 and S13 of the Shima River.

Data on benthic invertebrate communities were elaborated within ecological LOE, which calculated the value of relative similarity of each sampling site from the overall best site and ranked the level of benthos alteration using the grey TOPSIS (Table 4). The benthos alteration was rated as 'high' (impaired) for most sites, among which the sites S8, S13, S12 and S15 showed the worst benthos alteration. Only the sites S20, S17 and S5 were 'moderate', and no site was ranked as 'low'. This suggests ecological LOE being much more serious than the other two LOEs, and a relatively high level of ecological degeneration in the whole river basin.

### *3.4. Overall assessment of three LOEs*

When the metric values of all LOEs were integrated into the WOE approach simultaneously by the grey TOPSIS, the model calculated the value of relative similarity of each sampling site from the overall best site and ranked the overall level of impact (Table 5). We used both relax and strict effect to evaluate the overall risk, and their only difference was the weight (Fig. S2). The modeling under the two effects produced similar sequence results, but with some differences in risk rating at five sites (S4, S7, S14, S18 and S21). The results of "moderate risk" at these sites were changed into "high risk", suggesting adverse ecological impact ranged from medium to high degree. The results from the second scheme under strict effect showed that high risk was detected at thirteen sites (S2–S4, S7–S15, S18 and S21), while moderate risk was observed at seven sites (S1, S5–S6, S16–S17, and S19–S20), which are mainly located at the upper stream of Danshui River, and the main streams of Xizhijiang River and Dongjiang River. According to the sequences, the seriously affected sites like S8, S12, S13, S3 and S2 are mainly located in the Shima River and Danshui River, which are impacted by urban wastewaters from Shenzhen and Dongguan cities. For those sites with high risks, management actions are needed. Considering the heavy contamination of the Shima River and Danshui River, remediation action for the two contaminated rivers is suggested to local governments based on the assessment results.

## 4. Discussion

The results of the present study showed successful application of the sediment quality assessment tool to the case study based on the WOE and grey TOPSIS approaches (Tables 4 and 5). The overall assessment suggest much higher contamination at some sites of the Shima River (S8, S12 and S13) and Danshui River (S2–S3) resulting in higher risks, but much lower contamination at the upper stream sites of Dongjiang River (S19–S20), Xizhijiang River (S16–S17) and Danshui River (S1). This is in general agreement with the bulk sediment properties and overlying water quality parameters (Tables S1–S3). The Shima River and Danshui River are more polluted than the other two rivers in the region as found by our previous study on sewage indicators of household biocides (Chen et al., 2014).

The ordinal ranking method proposed by Chapman and Anderson (2005) is an important approach for assessing sediment quality used in North America. When this approach was applied to the same data set from the present case study, the assessment results of toxicological LOE and ecological LOE from the two methods were similar. However, as to chemical LOE, the existing method assessed all sites as high risk (Table S9) while our method assessed most sites as moderate risk. When the results from individual LOE were fitted into the decision matrix in Chapman and Anderson's approach (2005), almost all sites would require management actions with exception of only three sites (S4, S16 and S20). According to the information of sediment quality parameters, water quality parameters and chemicals concentrations of overlying water (see Tables S1–S3) and the toxicity data, we believe that the results of our method are more consistent with the monitoring data and observation.

A lot of WOE information processing approaches have been proposed and used, including best professional judgment (BPJ), logic, index and quantification (Chapman et al., 2002; Linkov et al., 2009; Linkov et al., 2011; Weed, 2005). Our method requires BPJ as well in deciding LOEs, metrics, effect and weights. Limiting BPJ in the above four parts can minimize subjectivity while still consider the opinions of experts and make the method flexible and relevant. To help others to understand the decision-making process like the logic method, our method involves a framework which helps users to carry out the assessment. Index makes it easier to judge and facilitate non-professional managers to understand and use the assessment result, however, their transparency, reproducibility and ability to handle nonlinearity cannot compare with quantification (Linkov et al., 2009). The relative similarity of our method can be regard as an index, but is produced by a formal decision analysis — the grey TOPSIS. As a quantitative method, our method combined TOPSIS with GRA to evaluate each site according to the similarity with the ideal alternative and the difference with the negative ideal alternative from both the position and trend relationship, which is transparent and effective. Moreover, an Excel VBA program is used to simplify the assessment. In summary, our method has many advantages of other WOE methods and makes up their disadvantages so it is a powerful tool in sediment quality assessment.

In the present study, three LOEs including sediment chemistry, sediment toxicity and benthic community structure were used to assess the sediment quality; however, different LOEs may point to different conclusions. The occurrence of conflicting results is not surprising in sediment quality triads (Wolfram et al., 2012). That is exactly why we should use a WOE approach instead of those qualitative approaches. In fact, different or more LOEs such as biomagnification, biomarkers, and overlying water quality can be accommodated into the assessment tool developed in the present study. This makes users to apply the assessment tool flexibly.

Parameters such as sediment oxygen demand, redox potential, total organic carbon and particle size distribution will govern the chemical bioavailability and hence are very important to sediment risk. Some of these parameters can be integrated into the grey TOPSIS method as physicochemical LOE as long as there is a best value or an acceptable range can be defined for each parameter, for instance, pH (6–8) and redox potential (0 − +400 mV). However, there is still a great deal of work to do before the values of these parameters at better site and worse site can be defined reasonably.

## 5. Conclusion

The results from this study have demonstrated the feasibility of assessing the sediment quality by the WOE and grey TOPSIS in an Excel VBA program. The assessment tool not only compares the relative ecological risk magnitude of sites but also sorts each site as different grades. In addition, this method can be applied in other fields such as surface water risk assessment.

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## Appendix A. Supplementary data

Detailed description of the model framework and calculation, chemical analyses, sediment toxicity tests and invertebrate survey, metrics selection process and tables of water quality parameters and sediment properties. Supplementary data to this article can be found online at doi: http://dx.doi.org/10.1016/j.scitotenv.2015.08.004.

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