The Dredge Disposal Sediment Index (D2SI): A new specific multicriteria index to assess the impact of harbour sediment dumping

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ABSTRACT

At present, there are few operational indexes to assess the impact of a given human pressure taken alone. Nevertheless, the current challenge in the management of coastal marine environments in the framework of cumulative impacts and climatic change is to identify the relative contribution of each activity on ecosystem functioning. The objective of the present study is to propose an integrative approach to assess the environmental impacts of dumping operations, *via* the development of a new index, the Dredge Disposal Sediment Index (D^{2}SI). From the selection of two types of station: impacted and unimpacted, D^{2}SI integrates six sub-indices considering the biological and physical changes generated by dredge disposal on the seabed. A final score is proposed, according to the five classes of the European Water Framework Directive. The initial development of D^{2}SI was conducted on the experimental dumping site of Machu (Bay of Seine), by applying a BACI (Before-After-Control-Impact) approach. An additional implementation (D^{2}SI$_2$) is used in the case of absence of data on ichthyofaunal or biological traits of life of macrobenthic fauna, which yields a comparable assessment of dumping pressure.

In the future, the D^2SI or D^2SI_2 indexes should be tested on other dumping sites with a view to comparing the assessment of this dumping activity.

Keywords: multicriteria indicator, integrative approach, dredge disposal impact, anthropogenic impact, benthic habitat, fine particles, morphological changes, Traits of Life, Bay of Seine.

Highlights

- Aim: Assessment of the impact of dumping on benthic ecosystems.
- A multicriteria index [Dredge Disposal Sediment Index (D^2SI)] is developed.
- D^2SI integrates six sub-indices based on biological and physical elements.
- Application on the experimental dumping site of Machu (Bay of Seine).

Introduction

The EEA (European Environment Agency, https://www.eea.europa.eu/) has implemented the DPSIR model [Drivers (driving forces, responsible for nuisance); Pressures (quantitative or qualitative); States (describing a component of the environment at a given moment); Impacts (on the studied biological/physical/chemical compartment) and Responses (reactions implemented for decision-making and management applied to minimize the impact)]. DPSIR is an approach that describes the interactions between society and environment and proposes recommendations for the development of an environmental assessment strategy (Kristensen, 2004). In this framework, indicators are developed to classify the degree of impact in relation to a pressure and to allow management to minimize its impact. In the future, the DPSIR (Drivers, Pressures, State, Impact and Response) approach should be extended to DAPSI(W)R(M) [Drivers-Activities-Pressures-State changes-Impacts (on Welfare)-Responses (as Measures)], according to the complexity of a given managed sea area in terms of multiple activities (Elliott et al., 2017). The aim of this approach is also to prevent confusion surrounding the terminology of the various elements, in particular between the definitions of Drivers and Pressures, between State and State changes as well as between these elements and Impact (Elliott et al., 2017).

Dredging is necessary to maintain sufficient water depth in harbour basins and provide access channels for the purpose of navigation and port activities. The dredged sediment, in cases where they do not contain hazardous products, can be dumped at sea or in rivers (Engler et al., 1991; Marmin et al., 2014, 2016). Nevertheless, dumped sediment may have different physical and chemical characteristics compared to the native sediments, which produces multiple effects on the environment. A first and direct effect is the covering of sediment and benthos compartments (mechanical effect), which leads to the destruction of local habitats at least temporarily (Chauvin et al., 1986; Olenin, 1992; Boutin, 2000; Desprez, 2000; Smith and Rule, 2001; Bolam et al., 2006a, 2006b; Hermand, 2008; Marmin et al., 2014, 2016; Dauvin et al., 2017b; Méar et al., 2018). The environmental impact of dredging activities is one of the most important problems in coastal zone management (O'Connor, 1998).

Nevertheless, most scientific studies generally focus only on studying the structure of benthic invertebrates, in relation to their environment. The objectives of these studies are to assess the impacts generated and/or the recovery of the system (Van Dolah et al., 1984; Olenin, 1992; Harvey et al., 1998; Smith and Rule, 2001; Witt et al., 2004; Bolam et al., 2006a; Vivan et al., 2009; Marmin et al., 2016). There are a large number of indexes, based on benthic macrofauna, which generally classify taxa according to their membership in functional ecological groups. These indexes are frequently used in environmental studies, but few of them are related to specific pressures (Ware et al., 2009; Munari and Mistri, 2014). Indeed, most of the Benthic Indices were initially developed to assess the impact of Organic Matter (OM) enrichment or the impact of oil pollution on benthic organisms; this was the case for AMBI, BOPA, I2EC, BENTIX, BO2A, BQI etc. (Borja et al., 2000; Simboura and Zenetos, 2002; Dauvin, 2007, 2018; Pinto et al., 2009; Dauvin et al., 2016). However, these indices are not specific to the response of the benthos, to assess bottom perturbations and the impact of sediment disposal (Ware et al., 2009; Munari and Mistri, 2014). To our knowledge, only few indicators are specifically designed to identify the impact of dredge sediment disposal. Roberts et al. (1998) proposed a Macrofauna Monitoring Index based on the selection of species in response to spoil disposal, and calculating a ratio between the abundance of each species at impacted and unimpacted stations. Twenty years later, this approach was reconsidered by Dauvin et al. (2018a) who suggested to modify the Robert's index to a Dredge Spoil Disposal (DSD) index, which takes into account a more objective method for selecting and scoring species. Nevertheless, this index is also based on the benthic macrofauna response to a human pressure. In fact, the impact of dredging activities and disposal of dredge sediment produces multiple effects on the sedimentology, morphology and biological compartments of the environment (Van Dolah et al., 1984; Chauvin et al., 1986; Olenin, 1992; Boutin, 2000; Desprez, 2000; Smith and Rule, 2001; Bolam et al., 2006a, b;

Hermand, 2008; Vivan et al., 2009; Marmin et al., 2014, 2016; Méar et al., 2018; Pezy et al., 2018). Therefore, it appears essential to develop a multicriteria index, which includes both biological and physical changes generated by the impact of dredge sediment disposal.

The objective of this study is to improve the index developed by Roberts et al. (1998) and modified by Dauvin et al. (2018), considering the biological and physical changes that are generated, to assess objectively the impact of dumping operations at sea and take into account the degradation or improvement of environment conditions. In the framework of the INDICLAP project ("INDicateurs de CLAPage") funded by the French Biodiversity Agency (FBA), a multicriteria approach was proposed, which includes benthic macrofauna (invertebrates >1mm) and ichthyofauna (benthodemersal fish), as well as morpho-sedimentary environment changes (bathymetry, sedimentary facies and deposit thickness). The new index proposed was named D²SI (Dredge Disposal Sediment Index). In the present study, we apply this index to a monitoring survey on an experimental dredge spoil disposal site (Machu site) located in the eastern part of the Bay of Seine (English Channel) using a BACI (Before-After-Control-Impact) approach (Pezy et al., 2017, 2018).

1. Materials and methods

1.1. Dredge Disposal Sediment Index (D²SI) concept

The multicriteria D²SI index is calculated considering the selection of two types of stations: impacted stations (under the direct influence of harbour sediment disposal) and unimpacted stations (without direct or indirect influence of harbour sediment disposal). Both impacted and unimpacted stations must be located on the same benthic community and sediment habitat at the beginning of dredge spoil operations. The D²SI is composed of six sub-indices taking into account the biological and physical changes generated by dredge disposal on the seabed. A score is calculated for each sub-index (Fig. 1). The addition of these scores yields a final score (D²SI) which allows us to classify the environment from "bad" to "excellent", according to the five classes of the European Water Framework Directive. Intervals are defined according to data from the Machu experimental dumping (eastern part of the Bay of Seine).

The six sub-indices are:

- D²SI-Benthos (D²SI$_B$), based on benthic macrofauna (invertebrates >1 mm), i.e. presence of the species and their abundances.

- D^2SI-Ichtyofauna (D^2SI_I), based on demersal fish i.e. presence of the species and their abundances.
- D^2SI-Sediment (D^2SI_S), based on the percentage of sediment modification between the natural sediment before disposal and the deposited sediment after the disposal.
- D^2SI-Thickness (D^2SI_T), based on the thickness of the accumulated deposit each year (measured with bathymetric differentials) and considering the initial bathymetry before operations at the dumping site.
- D^2SI-Resistance to dredge spoil sedimentation (D^2SI_R), based on the ability of species to resist deposition of dredge spoil during harbour sediment disposal.
- D^2SI-Drifting (D^2SI_D), based on the ability of drifting individuals of a species to recolonize an area after disturbance near the sea bed.

Calculation methods for each sub-indices and D^2SI index applications are available in additional online data.

1.2. Dredge Disposal Sediment Index (D^2SI) computation

1.2.1. D^2SI-Benthos (D^2SI_B)

The benthic macrofauna of soft-bottom habitats is known to be a good indicator of environmental quality because the constituent species live on and within the substrate. Since the benthic macrofauna is specific to a particular habitat if the sediment is normally unperturbed, any perturbations of the substrate induces a modification of the benthic communities (Dauvin, 1993; Borja et al., 2000). Numerous studies have highlighted the negative impacts on this compartment caused by physical and chemical modifications induced by dredge spoil deposition (Van Dolah et al., 1984; Olenin, 1992; Desprez, 2000; Bolam et al., 2006a; b; Hermand, 2008; Vivan et al., 2009; Marmin et al., 2014, 2016; Pezy et al., 2017, 2018).

The D^2SI-Benthos is constructed following the DSD index (Dauvin et al., 2018), and the resulting values are scored from 0 to 1.

Calculations are based on successive steps (Robert *et al.*, 1998; Dauvin et al., 2018) which are performed separately for each campaign (Fig. 1):

1) The first step is similar to that carried out for the DSD index (Dauvin et al., 2018). The sum of the macrofauna abundances is calculated for each species for impacted and unimpacted

stations; the ratio of the sum of the impacted stations and unimpacted stations is then calculated for each species. A first score from 1 to 10 is attributed based on each species ratio, reflecting the impact of dumping operations on the macrofauna abundances (Table 1). A score of 10 indicates a species present only at the unimpacted stations, while a score of 1 indicates a species tolerant of dumping operations with high abundances at impacted stations (abundance at unimpacted samples ten times higher than those at impacted samples). A score of 0 indicates the species is present only at impacted stations (ratio not predictable; Table 1). In this case, the ratio is not calculable. Then, a mean score is computed which corresponds to the sum of the species scores (Table 1) divided by the number of species present in the sample. This mean score varies between 0 and 10.

In a second step, the mean score is divided in five classes corresponding to a scale varying from 0 to 1 in order to give more weight to the middle classes, thus taking account of natural variations in the macrofauna abundances (Table 2). For a mean score between 4 and 6 corresponding to an undisturbed environment, a D^2SI_B score of 0 is attributed; then, with an increase in perturbation of the environment, scores of 0.25, 0.50, 0.75 and 1 are attributed following the threshold defined in Table 2.

1.2.2. D^2SI-Ichtyofauna (D^2SI_I)

Pelagic fish species living in the water column are mobile and are thus less impacted by dumping operations (Wilber et al., 2007). Demersal fishes, which feed mainly on benthic organisms, can be heavily impacted by the destruction and alteration of benthic environments (Alzieu, 1999). Moreover, fish eggs and larvae are sensitive to turbid plumes and the release of nutrients or chemical contaminants into the water column when the sediments are deposited.

The D^2SI-Ichtyofauna (D^2SI_I) is calculated similarly to the D^2SI_B (Fig. 1), taking into account the species richness and abundances of the demersal fish species, it is scored from 0 to 1 in the same way of D^2SI_B (Table 2).

1.2.3. D^2SI-Sediment

Dumping operations induce changes of bottom sediment at the dumping site and surrounding areas, locally causing the release of fine particles and increasing the turbidity near the seafloor (Chauvin et al., 1986; Boutin, 2000; Smith and Rule, 2001; Marmin et al., 2016; Baux et al., 2019).

This sub-index reflects the difference between deposited sediment and native sediment, regardless of any differences in their grain-size characteristics. The working hypothesis adopted here is that large differences between native sediment and deposited sediment lead to higher impacts than when the sediments are similar. In the Bay of Seine, the enhanced impact is related to the massive inputs of fine particles (<63 µm) from harbour basins and the Seine estuary (Lesourd et al., 2016; Méar et al., 2018; Baux et al., 2019).

The D^2SI_S is based on the difference of fine particles (<63 µm; noted "FP" in Eq. 1) content (in percentage) between impacted and unimpacted stations (Eq. 1).

$$D^2SI_S = \left|\frac{\%\,FP\ at\ impacted\ stations - \%\,FP\ at\ unimpacted\ stations}{\%\,FP\ at\ impacted\ stations + \%\,FP\ at\ unimpacted\ stations}\right| \quad (Eq.1)$$

As with other sub-indices, calculations are performed separately for each campaign and a score from 0 to 1 is attributed based on the results (Eq. 1) to allow classification of the disturbance (Table 3). The score interval limits (interval of 0.2, except for the first scale and last scale) are defined according to results from the Machu site. A score of 0 corresponds to an undisturbed environment, in contrast to a score of 1, which corresponds to the maximal degree of defined disturbance (Table 3).

1.2.4. D²SI-Thickness

A large amount of research has highlighted the changes in bathymetry (formation of underwater relief) induced by dumping operations (Desprez, 2000; Fredette and French, 2004), generating a modification of physical conditions (modification of local marine currents near the seabed and sedimentary types).

To calculate D²SI-Thickness, the *in-situ* thickness is obtained by bathymetric measurements, integrating initial bathymetry (before operations at the dumping site) and the accumulation of deposits over time between each survey included in the study (Eq. 2). It is preferable to keep the same method of measuring bathymetry for all surveys, in order to eliminate measurement bias. Multibeam measurements are recommended.

$$D^2SI_T = \left(TH^n_{Impacted} - TH^n_{Unimpacted}\right) + \left(e^{\left(Th^n_{Impacted} - Th^n_{Unimpacted}\right)} - 1\right) \quad (Eq.\ 2)$$

$$With\ TH^n = Initial\ bathymetry - bathymetry\ measured\ at\ time\ n$$
$$and\ \ Th^n = bathymetry\ measured\ at\ time\ n - bathymetry\ measured\ at\ n+1$$

TH^n corresponds to the thickness variation (bathymetric differential) measured from the initial state to time n. Th^n corresponds to the variation in thickness (bathymetric differential) between time n and n+1 (Eq. 2).

As with the other sub-indices, a score from 0 to 1 is attributed based on the calculation results (Eq. 2) to allow classification of the disturbance (Table 3). A calculated value of ≤0 corresponds to no change in thickness or sediment loss by erosion. Also, a D^2SI_T value of 0 leads to classification as an undisturbed environment. In contrast, D^2SI_T 1 (calculated value >6) corresponds to a significant and gradual increase of thickness compared to the state before dumping (Table 3).

1.2.5. D²SI-Drifting and D²SI-Resistance to landfill

The use of biological and ecological traits of life in the assessment of the quality of marine habitats is relatively recent and offers some interesting perspectives (Dauvin et al., 2017b). Several authors have hypothesized that specific modifications of the combination of community life-history traits in disturbed ecosystems depend on the nature and intensity of the disturbance (Usseglio-Polatera et al., 2000; Bremner et al., 2003, 2006; Bolam et al., 2006a; Janson, 2007; Dauvin et al., 2017a,b)

Two Biological Traits of Life are selected here and integrated into the calculation of the D²SI index:

(1) Resistance to landfill (resistance to sediment spoil deposition), which corresponds to the capacity of the macrofauna to resist increases in thickness of the sedimentary layer during sediment disposal. Indeed, benthic species that live in close contact with the seabed and have reduced mobility are highly exposed to the effects of dumping. In general, a large majority of the fauna disappear or are very strongly reduced just after the dumping (Witt et al., 2004; Bolam et al., 2006b). Some species are more resistant than others as the bivalves and polychaetes, partly owing to their ability to migrate vertically (Maurer and Aprill, 1979; Maurer et al., 1981a, 1981b, 1982; Miller et al., 2002; Janson, 2007). Very little information

on this biological trait of life exists in the literature and the behaviour of species is often based on laboratory experiments or studies in the wild, and concern only a small number of species (Trevor, 1978; EPA, 1989; Chandrasekara and Frid, 1998; Essink, 1999; Bolam et al., 2004; Powilleit et al., 2006; Janson, 2007; Powilleit et al., 2009).

(2) Drifting corresponds to the ability of macrofauna juveniles and adults to colonize following a disturbance, by their active or passive movements mainly due to currents near the seabed. Drifting is an important part of recolonization phenomena in the eastern part of the Bay of Seine (Olivier et al., 1996; Desroy and Retière, 2001; Janson, 2007; Marmin, 2013).

For calculation of the D^2SI_R and D^2SI_D sub-indices, the data are grouped into five categories identifying the ability of macrofauna to resist sediment spoil deposition: G1 = <1cm; G2 = 3 to 10 cm; G3 = 10 to 30 cm; G4 = 30 to 50 cm; G5 = >50 cm] and into three categories quantifying the ability to recolonize by drifting (drifting and associated categories: G3 = high; G2 = low or possible; and G1 = absent). The calculations of both sub-indices are based on the assumption that the most sensitive species will disappear first after dumping operations [low capacity to resist to increase in thickness of the sedimentary layer (G1 and G2) or absence/low capacity of recolonization by drifting (G1 and G2)], and the proportion of species that show a high resistance to sediment spoil deposition (G3- G5) or high ability to recolonize by drifting (G3) will increase. The calculation takes into account the percentage of G1 and G2 taxa (Eq. 3) that will be the most sensitive during sediment disposal. The respective percentages of G1 and G2 (% G1 and % G2; Eq. 3) are calculated on all taxa that can be included into a category. Taxa that are not categorized as belonging to any of the groups are excluded from the calculation (taxa that have no group may be sensitive or resistant).

$$D^2SI_{R\ or\ D} = 1 - (\%G1 + \%G2) \qquad (Eq.\ 3)$$

As with the other sub-indices, D^2SI_R and D^2SI_D are determined separately for each campaign and a score from 0 to 1 is attributed to allow classification of the disturbance (Table 3). Low calculated values indicate the presence of sensitive species, poorly resistant to spoil deposition or with very little ability to recolonize by drifting, and which thus reflect an undisturbed environment (score of D^2SI_R and D^2SI_D = 0). A high calculated value highlights the disappearance of sensitive species impacted by dumping operations.

1.2.6. D²SI, final calculation

The D²SI is calculated by adding respective scores of each sub-index (Fig. 1; Eq. 4).

$$D^2SI = D^2SI_B + D^2SI_I + D^2SI_S + D^2SI_T + D^2SI_R + D^2SI_D \quad (Eq. 4)$$

As with the other sub-indices which are calculated separately for each campaign, a score of 0 to 1 is attributed to allow classification of the disturbance (Table 4). A D²SI score of 0-0.2 corresponds to an undisturbed environment. The degree of impact increase gradually up to a D²SI score of 0.8-1, classifying the disturbance at the highest level (extremely disturbed; Table 4).

1.3. Study site

The experimental dumping site of Machu (eastern part of the Bay of Seine) was used to develop and test the application of D²SI. A dumping experiment was carried out in 2012-2013, according to a BACI (Before-After-Control-Impact) approach (covering the 2010-2015 period; Fig. 2). Dredged material was deposited at two experimental sites with two distinct approaches to study two dumped sediment methods. At the first site (MASED), 1×10^6 m^3 of sediment was deposited on a single point at 16 m water depth, with the dredger remaining stationary from 13 May 2012 to 15 December 2012, with two interruptions in dumping (1-26 July and 9 October-22 November 2012). At the MASED site, the dumping generated a conical deposit 5 m in height (Marmin et al., 2016). At the second site (MABIO), 999,800 m^3 was deposited and spread out over a rectangular area of about 100 ha (1400 m x 700 m) at 13 m depth. On this site, a wider area was covered, leading to the formation of a smaller deposit 2 m in height (Marmin et al., 2016). At the MABIO site, the dumping took place during four periods with about 250,000 m^3 deposited per season: spring (16 April-14 May 2012), summer (1-26 July 2012), autumn (10 0ctober-7 November 2012) and winter (24 January-21 February 2013). Both zones correspond to a fine to medium clean sand *Ophelia borealis-Nephtys cirrosa* community (Marmin, 2013). The dumped sediment consisted of muddy fine sand, and the spoil material accumulated on or near the two dumping sites, with a maximum mud content (i.e. particles < 63 µm) of 50% compared to < 5% in the natural sediment in place before dumping operations. Due to hydrodynamic forcing (wave climate and tidal currents), about 50% (MABIO) and 75% (MASED) of the volume of dredged material remained at the end of the dumping periods (Marmin et al., 2016).

Following the experimental dumping operations, the Rouen harbour authority (*Grand Port Maritime de Rouen*, GPMR) has used the Machu dumping site since 2016, replacing the saturated Kannik dumping site, historically used since 1977 (Fig. 2; Marmin et al., 2014).

1.4. Data used in the study

All of the benthic macrofauna data (invertebrates >1mm) come from Marmin (2013), while the bathymetry and sedimentological data are due to Marmin et al. (2016) and the ichthyofauna (demersal fishes) observations of the GMPR were acquired by the technical studies office "Cellule du Suivi du Littoral Normand (CSLN)".

1.4.1. Macrofauna, sediment and ichthyofauna data

Two WSW – ENE transects (named AK4 for MASED and AK7 for MABIO, Fig. 2) were defined to study the sediment characteristics and macrofauna (Marmin et al., 2016). Seven stations spaced at intervals of 500 m were defined for each transect. To develop and test the new index, four stations were selected within the MABIO site: AK4 C and AK4 D as impacted stations, AK4 A and AK4 F as unimpacted stations; and two stations were selected within the MASED site (due to the presence of conical deposit which reduce the impacted area surface): AK7 D as an impacted station and AK7 A as an unimpacted station (Fig. 2).

Sediments and macrobenthos were sampled using a Van Veen grab. Three replicates were sampled (unit sampling surface area: 0.1 m², for a total of 0.3 m²; Marmin, 2013). Grab sampling was carried out 14 times from 2010 to 2015: twice before dumping (April 2010 and November 2011), seven times during the overall dumping period (May, June, July, October and November 2012 and January and March 2013) and five times after dumping (May, August and November 2013, March 2014 and March 2015). The sampled macrofauna material was sieved on a 1-mm circular mesh. Only species with an occurrence >4 and/or with a total abundance >20 individuals were selected (61 species for MABIO and 41 for MASED; see Dauvin et al., 2018). Fine granulometric fractions (<63 µm) were obtained by wet sieving (Marmin et al., 2016).

Ichthyofauna data were collected from 19 bottom trawl surveys (headline rope: 9 m; mesh size cod end: 10 mm knot-to-knot; trawling at night for 15 min at a speed of approximately 2.5 knots) on the MABIO site, comparable to the benthos sampling (Fig. 2): before the dumping operations (April, July, October 2010 and January 2011); during the dumping operations (May, June, July, October and November 2012 and January and February 2013) and after dumping (April, July and October 2013, January 2014,July, November 2014 and February, May 2015). There are no fish data from the MASED site.

1.4.2. Bathymetric data

Bathymetric data were acquired by multibeam echo-sounder by Rouen harbour staff. A first campaign was conducted in April 2010, before experimental dumping, on the MABIO and MASED sites. These data represent the initial bathymetry of the two dumping sites. On MABIO site, ten campaigns were conducted: one campaign before dumping (November 2011), three campaigns during dumping operations (May, August and October 2012) and six campaigns after dumping operations (May, July and September 2013, April and September 2014 and December 2015). Seven campaigns were conducted on the MASED site one campaign before dumping (November 2011), two campaigns during dumping operations (July and December 2012) and four campaigns after dumping operations (September 2013, September 2014, March 2015 and December 2016).

1.4.3. Biological traits of life

A literature search allowed us to create a database of biological traits characterizing ‘Resistance to landfill’ and ‘Drifting’ for taxa whose abundances represent 95% of the total abundance (40 taxa on MABIO and 35 taxa on MASED).

1.5. Statistical analysis

To validate the index, Spearman’s correlation coefficients were calculated, and the non-parametric Kruskal-Wallis test and multiple comparison tests were performed with the R 3.4.1 software, after testing normality of data with the Shapiro test.

Standard deviation (Eq. 5) for D²SI scores were calculated from sub-indices scores (D^2SI_B, D^2SI_I, D^2SI_S, D^2SI_T; D^2SI_D and D^2sI_R) at each survey for MABIO and MASED sites and presented on figures 3 and 4.

$$s_x^2 = \sqrt{\sum \frac{(xi - \bar{x})^2}{(n-1)}} \quad (Eq. 5)$$

$$with\ \bar{x}: mean\ of\ sample\ and\ n: size\ of\ sample.$$

1.6. Benthic indicators comparisons

The D²SI results and environmental classification were compared with other biotic indices: A) indices based on species classification in ecological groups: AMBI (AZTI Marine Biotic Index; Borja et al., 2000; Muxika et al., 2005), M-AMBI (modified AMBI; Muxika et al., 2007) and BO2A (Benthic Opportunistic Polychaete Amphipods index; Dauvin and Ruellet, 2009); B) index based on diversity: H’ (Shannon-Wiener index; Shannon, 1948); and C) index based on trophic groups: ITI (Infaunal Trophic Index; Mearns and Word, 1982). To compare the results, the environmental classification associated with the five EcoQs (ECOlogical Quality Status) classes recommended by the WFD (Water Framework Directive) are used (“high”= unpolluted sites or normal; “good”= slightly polluted sites; “moderate”= Moderately polluted sites; “poor”= heavily polluted sites and “bad” for extremely polluted and azoic sites). The several ecological statuses considered for the selected benthic indicators come from: Borja et al. (2004) and Muxika et al. (2007) for AMBI and M-AMBI; Dauvin (2018) for BO2A (revisited from De-la-Ossa Carretero et al., 2010), Vincent et al. (2002) for H’, and Bellan (2008) for ITI.

2. Results

Values are calculated for the six sub-indices and a score is assigned to each station; then, a final score is calculated for the index (D²SI). The scoring results are presented with the volumes of spoil dumped on both sites (Fig. 3).

The D²SI-Benthos (D²SI$_B$) scoring (Fig. 3 A) reveals an immediate impact of dumping on benthic communities, with an increase in score from 0 to 1 during dumping on MASED and from 0.25 to 1 on MABIO. The scores increase on both sites during dumping operations, thus reflecting an impact, and decrease during periods without dumping. At the end of the experiment, both sites show a score equal to 0, highlighting a cessation of the impact of dumping on the benthic communities. Nevertheless, on the MABIO site, the score increases after the cessation of dumping and takes several months to return to 0. The correlation coefficients between D²SI$_B$ and dumped volumes (Table 5) are 0.60 and 0.54 for the MABIO and MASED sites, respectively, which represent statistically significant values. D²SI$_B$ scoring variations are in agreement with the results of Marmin (2013) and Pezy et al. (2017, 2018), who have highlighted the impact of dumping on benthic communities of Machu site, finding a higher taxonomic richness and abundances before and after dumping in comparison to the dumping period, which is associated with lower values. The dumping impact is correctly identified by the higher D^2SI_B values

The D²SI-Sediment (D^2SI_S) scoring for MABIO and MASED (Fig. 3C) shows a modification in sediments characterized by an increase of score during the dumping period. The score is 0 before dumping for both sites but increases rapidly after the first dumping operation (score= 1). Although variations in this sub-index are observed, the scores remain relatively high throughout the dumping period. The scores observed after cessation of experimental dumping are high, reflecting a persistent impact. These scores are in agreement with variations in observed fine particle percentages. On the MABIO site, the average percentage of fine particles measured (< 63 µm) before, during and after dumping operations are, respectively, 0.4%, 21.2% and 10.5% on impacted stations and only 0.9%, 3.2% and 1.8% on unimpacted stations. On the MASED site, the average percentage of fine particles (< 63 µm) measured before, during and after dumping operations are, respectively, 4.3%; 20.7% and 11.7% on impacted station, and only 0.7%, 2.4% and 0.6% on unimpacted station. The increase of the percentage of fine particles is clearly observed on the impacted zone of the MABIO and MASED sites during dumping operations (21.2% and 20.7%), and remains high after cessation of dumping (10.5% and 11.7%). The D^2SI_S score correctly reflects the sedimentary modification caused by the inputs of fine particles during dumping operations and the persistent impact after dumping operations. However, there is no direct correlation between the D^2SI_S and dumped volumes (-0.098 on MABIO and 0.25 on MASED; Table 5), since this sub-index is not linked to the deposited volumes but rather the difference between original and deposit types of sediment surface.

The D²SI-Thickness (D^2SI_T) score highlights a gradual increase of sedimentary thickness, characterized by a gradual increase of values, especially for the MASED site (Fig.3 D), which shows a stronger increase in the score (0 before dumping and 1 from the third operation, on the MASED site), in comparison to the MABIO site (0 before dumping, 0.5 from the second operation). At the end of the experiment, the score for the MASED site is higher than for the MABIO site (respectively, 0.50 and 0.25). In addition, the D^2SI_T allows us to differentiate both dumping methods and reflects the two different impacts produced. These high scores observed on MASED site are linked to the experimental dumping method, which consists of creating a conical deposit on the impacted zone (initial bathymetry: 16.4 m; bathymetry on the last survey: 12.2 m). This contrasts with the MABIO site, where the sediment was spread out over a rectangular area on the impacted zone (initial bathymetry: 14.3 m; bathymetry on the last survey: 12.2 m). In the same way as described for the previous sub-index, D^2SI_T is not directly correlated with dumped volumes (0.14 on MABIO and 0.12 on MASED; Table 5), but reflects the dumping method used.

The scores obtained for the other sub-indices, D^2SI_I, D^2SI_R and D^2SI_D, show few distinct trends (Fig. 3 B, E and F). The D^2SI_I scores are low during the main dumping periods (0-0.25) and high after dumping operations (0.50-1), with large fluctuations (Fig. 3B) but no apparent link with dumping operations or dumped volumes (Table 5). In the same way, the D^2SI_R and D^2SI_D scores are difficult to understand, with very high values for D^2SI_R, for both sites, before and after the dumping operations (Fig.3 E) and no significant correlations with dumped volumes (-0.083 for MABIO and -0.21 for MASED; Table 5). D^2SI_D shows clearer trends (Fig. 3F), with increased scores during dumping operations for both sites, but with many fluctuations during and after dumping operations and no significant correlations with dumped volumes (0.27 for MABIO and 0.35 for MASED; Table 5).

Finally, the final score (D^2SI) on MABIO and MASED sites (Fig. 3G, H) shows low values before dumping operations (respectively, 0.25 and 0.20; site classified as Slightly disturbed) in comparison with values during deposition of spoil (max 0.85 in July, 2012 and January 2013 and min 0.60 in November 2012 on the MABIO site; max 0.80 in January 2013 and min 0.65 in June 2012), which yields classification of site as Heavily disturbed to Extremely disturbed. After, several months without dumping operations, the scores return to relatively low values (0.35 for MABIO and 0.45 for MASED), the sites being classified as Slightly disturbed on MABIO and Moderately disturbed on MASED. These results highlight the persistence of the impact following spoil deposition, with a higher impact on the conical site (MASED). A non-parametric Kruskall-Wallis test and multiple comparison tests were carried out on the MABIO and MASED data to study score differences between the three periods. These tests reveal significant differences between D^2SI before-during dumping and before-after dumping (KW test = 8.964; df = 2, p-value = 0.011). However, many fluctuations are observed, with poor correlations between the final index and the dumped volumes (0.13 on MABIO and 0.39 on MASED; Table 5).

4. Discussion

The BACI method conducted on the experimental Machu site allows to identify the link between the pressures induced by sediment deposal at sea and various physical and biological parameters of the environment (Marmin, 2013; Marmin et al., 2016; Pezy et al., 2017, 2018). The data collected on this site are favourable to the development and the test of new indicators as a textbook case. Based on the data collected from this site, we propose an integrative approach, coupling biological and physical data, to assess the impact of dumping operations, *via* a new multicriteria index: The Dredge Disposal Sediment Index (D^2SI).

4.1. Dumping impact on Machu site

Previous studies have highlighted the impact caused by dumping operations on benthic macrofauna and the trophic web, as well as on physical and chemical conditions (Bolam et al., 2006; Ware et al., 2010; Marmin, 2013; Marmin et al., 2016; Pezy et al., 2017, 2018).

On the Machu site, on the one hand, taxonomic richness and abundances in the impacted zone are significantly lower than values obtained in the unimpacted zone (Marmin, 2013; Marmin et al., 2016; Pezy et al., 2018). Changes in the species composition and abundances of the benthic community are observed during and after dumping operations. Before the dumping operation, there was a typical *Nephtys cirrosa* community in medium sand characterized by the polychaetes (*Magelona filiformis/johnstoni, Nephtys cirrosa*) and amphipods (*Megaluropus agilis, Urothoe elegans*,) as found in the eastern part of the Bay of Seine (Marmin, 2013). After dumping, the Machu site corresponds to a mixture of the *Nephtys cirrosa* and *Abra alba* communities in medium and muddy fine sand (with the bivalves *Phaxas pellucidus*, *Spisula subtruncata*, and the polychaete *Owenia fusiformis*; Marmin, 2013; Marmin et al., 2016; Pezy et al., 2018).

On the other hand, the study of food web modelling and the ENA (Ecological Network Analysis; Ulanowicz, 2004) carried out by Pezy et al. (2017, 2018) reveals changes in the food-web structure and functioning induced by dumping operations as well as the high resilience of the affected zones after a short dumping phase.

Regarding these results, the D^2SI proposed here yields consistent results, with increased values during dumping and a persistent impact after dumping, highlighted by the maintenance of higher values than before the dumping experiment.

4.2. Determining sub-indices

Among the six sub-indices proposed, three of them (D^2SI_B, D^2SI_S and D^2SI_T) allow to correctly highlight the impact caused by dumping at sea. These three sub-indices, which are based on benthic abundances, sedimentary type and thickness of deposit, show an increase of scores according to the dumping periods. These three factors are determinant in calculating the final index score (D²SI), with significant correlations (respectively 0.69, 0.67 and 0.60 for MABIO and 0.80, 0.64 and 0.48 for MASED; Table 5). Moreover, they are significantly correlated with each other (D^2SI_B-D^2SI_T: 0.51 and D^2SI_S-D^2SI_T: 0.65 on MABIO; D^2SI_B-D^2SI_T: 0.60 on MASED; Table 5), reflecting conjoint response to dumping operations.

Conversely, the sub-index based on ichthyofauna (D^2SI_I) shows large temporal fluctuations (Fig. 3B) which affect the calculation of the final index score (D^2SI_I-D²SI correlations: 0.16 on MABIO, no data on MASED; Table 5). In fact, the mobility of the ichthyofauna and the sparse knowledge of the consequences of dumping impacts on this compartment makes it difficult to establish a reliable index. The previous study on the MABIO site (no ichthyofauna data on MASED site) shows an increase in abundances and biomass of demersal fish during the dumping period, reflecting an attraction of surrounding populations (Pezy et al., 2018). This phenomenon has also been documented, before and after deposition from a sewage effluent outfall into the ocean at Hawaii (Russo, 1982) and suggests that changes in fish abundance are related to variations in the distribution and abundance of benthic preys (Spies, 1984). On the Machu site, dumping operations caused a modification of invertebrate benthic communities with high abundances of some dominant species (Marmin, 2013), allowing a constant availability of prey. Moreover, the D^2SI_I results highlight the problem of selecting stations, which are rarely identical to those chosen for sampling of other compartments (invertebrate benthic macrofauna), which may introduce a bias into the study of a very local anthropogenic impact.

The choice of both biological traits (resistance to dumping of spoil and drifting) is based on a knowledge of the study site and the fact that several authors have hypothesized a specific modification of the combination of community life-history traits in disturbed ecosystems, depending on the nature and intensity of the disturbance (Stearns, 1976, 1977; Usseglio-Polatera et al., 2000; Bremner et al., 2003; Bolam et al., 2006a,b; Janson, 2007; Dauvin et al., 2017a,b). The capacity of invertebrate benthic species to resist the deposition of spoil sediment does not seem to be a determining factor to assess the impact of dumping on the studied site (low correlations with dumped volumes: -0.083 on MABIO and -0.21 on MASED and with D²SI: 0.31 on MABIO and -0.064 on MASED). In fact, the benthic communities of the eastern part of the Bay of Seine are characterized by very resistant and resilient species, particularly well adapted to the particular oceanographic and anthropogenic conditions in this shallow coastal area (high-energy hydrodynamic regime, many anthropic activities, frequent silt input, etc.; Marmin, 2013). D^2SI_R does not allow us to account for the impact caused by the increase in thickness of the sediment layer (negative correlations between D^2SI_T and D^2SI_R: -0.20 on MABIO and -0.18 on MASED; Table 5). Conversely, the sub-index based on capacity of drifting shows better correlations with D^2SI (0.62 on MABIO and 0.70 on MASED; Table 5), but the poor correlations with dumped volumes (Table 5) and with D^2SI_B (0.37 on MABIO and 0.42 on MASED; Table 5) suggest that this biological trait characterizes only a small number of species with high abundances on the studied site. On the Machu site, the ability of drifting has been observed in the bivalve *Abra alba* (Olivier et al., 1996), which has shown an immediate recolonization of the site, with high abundances of adults on the MABIO site in June 2012, just one month after the end of the first dumping phase (Marmin, 2013). The displacement of juveniles but also some adults drifting near the seabed can lead to a rapid colonization of defaunated and impacted zones in this eastern part of the Bay of Seine (Olivier et al., 1996). As the biological traits are variable from one site to another and from area to another in relation to local and general current conditions near the seabed, this sub-index appears inappropriate to assess the impact of dumping on the D^2SI score.

4.3. Additional approaches

In this study, we use a calculation test by adding different weighting coefficients for each sub-index according to the consistency of the data (x3 for D^2SI_B, x2 for D^2SI_S and D^2SI_T, x1 for D^2SI_I, D^2SI_D and D^2SI_R). There is no statistical difference between the unweighted (D^2SI) and the weighted ($D^2SI_{weighted}$) indices for the MABIO and MASED sites (KW test= 25.462; df= 16; p-value= 0.062) and both indices are significantly correlated (0.95 for MABIO and 0.95 for MASED; Table 5 and Fig. 4 A, B). Nevertheless, D^2SI is less strongly correlated with dumped volumes (0.13 on MABIO and 0.39 on MASED; Table 5) than $D^2SI_{weighted}$. The weighted index shows higher correlations with dumped volumes, especially on the MASED site (0.25 on MABIO and 0.51 on MASED). By giving a greater weight to the scores of sub-indices based on benthic compartment, sedimentary and thickness modification included in the final index calculation, we can achieve a better assessment of the impact of dumping according to the dumped volumes (Fig. 4 A, B). However, in comparison with the results of statistical tests carried out on D^2SI for each dumping period (before, during and after dumping, presented in the Results section), the statistical tests on $D^2SI_{weighted}$ for each dumping period only show differences between before-during dumping operations (KW test=

10.08; df= 2; p-value= 0.007). Therefore, the weighting of scores of sub-indexes yields a better correlation with the dumped volumes, but reduces the differences between scores after dumping periods, indicating a persistent impact.

In the light of the above observations, D^2SI is calculated using only the scores of D^2SI_B, D^2SI_S and D^2SI_T (considering unweighted scores for these three sub-indices), without including the scores of D^2SI_I, D^2SI_R and D^2SI_D (Fig. 4 C, D). The resulting index is named D^2SI_2 (Fig. 1). Graphically, the absence of these three latter sub-indices changes the ecological classification status for MABIO (Fig. 4C) and MASED (Fig. 4D), with generally lower scores. The Kruskal-Wallis test highlights significant differences between the scores of D^2SI and D^2SI_2 (KW= 20.69; df = 10; p-value = 0.02). Correlations between D^2SI_2 and dumped volumes are stronger, especially on the MASED site (0.31 on MABIO and 0.54 on MASED; Table 5), in comparison with correlations between dumped volumes and original index (D^2SI) or between dumped volumes and weighted index ($D^2SI_{weighted;}$ Table 5). As with the previous index, the statistical tests on D^2SI_2 for each dumping period only show differences between before-during dumping operations (KW test= 10.679; df= 2; p-value= 0.005), indicating a persistent impact. Therefore, the index calculated without considering ichthyofauna and biological traits of the macrofauna allows a better assessment of the environmental impact caused by dumping operations.

4.4. Biotic indices comparison

In comparison with other biotic indices based on species classification in ecological group (AMBI, M-AMBI, BO2A), on diversity (H') and on trophic groups (ITI), the D^2SI is specific to dumping impact and allows a better categorization of this impact (Table 6). In fact, all index mean values obtained for the Machu site correspond to "very good" and "good" ecological status, before, during and after dumping (except for ITI value before dumping on MASED site). These results characterize the Machu site as being unpolluted (or normal, with ITI classification) to slightly stressed, whatever the period studied (Table 6). Conversely, D^2SI and D^2SI_2 mean values classifies the impact as ranging from Undisturbed to Moderately disturbed before dumping, Heavily disturbed during and after dumping operations (on non-average D^2SI values, during dumping: from Moderately to Extremely disturbed; after dumping: Slightly to Extremely disturbed; Fig. 3). Also, D^2SI and D^2I_2 differentiates periods before dumping from other periods and reflecting the impact caused by physical and biological modifications.

4.5. Further work

After developing D²SI on the Machu experimental site in full compliance with the BACI approach, this index is being tested on two other dumping sites in eastern part of the Bay of Seine: Octeville (used by Le Havre harbour) and Kannik (used by Rouen harbour; Fig. 2). These sites differ from the Machu site because they have been used historically (from 1947 for Octeville and from 1977 to 2015 for Kannik), with higher accumulated dumped volumes (mean of 2-2.5x10^6 $m^3.y^{-1}$ on the Octeville site and 3.5-4x10^6 $m^3.y^{-1}$ on the Kannik site). The application of D²SI to these two dumping sites leads to more complicated understanding in comparison with the textbook case of the experimental Machu site, especially due to: (1) a lack of initial data conditions, before the beginning of spoil deposition (especially on the Octeville site); (2) a lack of accurate and regularly sampled bathymetric data (or data only available from stations without initial conditions) and (3) spatial and temporal gaps between samplings. These elements are quite often lacking in surveys of French dumping sites, thus preventing a precise study of the impact caused by harbour dumping activities and the use of the D²SI multicriteria index. To use this index for other dumping sites, it would be necessary to acquire regular data on impacted and unimpacted zones, and to have at least some information on macrofauna, bathymetry and sediment composition as a function of time.

5. Conclusion

An integrative approach is proposed, using a new multicriteria approach, the Dredge Disposal Sediment Index (D²SI), to assess the impact of dumping and attribute a degree of impact according to the pressure undergone by the system. This index is developed on the experimental Machu site in the eastern part of the Bay of Seine. The appropriate assessment of the impacts of dumping on this experimental site and application of the BACI approach allow to differentiate three distinct periods (before, during and after dumping; Marmin et al. 2016; Pezy et al, 2017, 2018). The assessment of the impact of dumping at the Machu site offers a textbook example that appears very favourable for the development of a new index designed to measure the response of the benthic environment to the pressure of dumping dredge spoil.

The D^{2}SI is calculated by considering impacted (under the direct influence of harbour sediment disposal) and unimpacted stations (without direct or indirect influence of the harbour sediment disposal) and is composed of six sub-indices that take into account the biological and physical impacts generated by dredge disposal at sea (integrating data on benthic macrofauna, demersal fish, sedimentary types, bathymetry, resistance to dredge sediment deposition and drifting capacity). A final score is calculated using each sub-index, allowing us to classify the disturbance. In the absence of data on ichthyofauna and biological traits of life of macrobenthic fauna, an additional approach (D^{2}SI$_2$) shows that results based on only three sub-indices, including at least benthic macrofauna, sedimentary types and thickness, appear sufficient surrogate to provide a similar assessment of dumping pressure.

The first application of the D^{2}SI to the Machu site yields a good estimation of the dumping impact, in comparison with other biotic indices (AMBI, M-AMBI, etc.; Pezy et al., 2018). The D^{2}SI and D^{2}SI$_2$ indexes highlight the disturbance induced by dumping at the beginning of sediment deposition, with an increase in their values as well as the degree of associated impact. The multicriteria index also allows to highlight the persistence of the impact after cessation of deposition, while comparing the different methods of dumping (spread out or concentrated deposit) and shows a return to the values before dumping two years after the end of the pressure.

In the future, depending on the availability of data, the D^{2}SI or D^{2}SI$_2$ indexes should be tested on other dumping sites to estimate its robustness and with a view to comparing the assessment of the impact of this human activity. The present study opens up prospects for the development of multicriteria indices as well as indices that are specific of dumping impact.

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Figure captions

Fig. 1: D^2SI and D^2SI_2 workflow. A: abundances; S: specific richness; I: impacted station; U: unimpacted station; G: group; +: addition (see text for other explanations).

Fig. 2. Map of the eastern part of the Bay of Seine showing location of the Machu experimental dredge spoil disposal zone. Distribution of sampling stations (point: benthic macrofauna and sediment; line: ichthyofauna) over the two dumping sites (MASED and MABIO). In red: impacted stations; in blue: unimpacted stations.

Fig. 3. Sub-indices and final index scores (black and red points) with standard deviation (error bars on G and H, calculated with n=6 for D^2SI MABIO and n=5 for D^2SI MASED, for each period. No error bars in graphs A to F because n=1 for each period) for each survey and cumulated dumped volumes (m^3; histograms), for MABIO and MASED sites. MABIO and MASED points can be superimposed. The y-axis and x-axis are the same for each graph.

Fig. 4. A and B: comparison between D^2SI and $D^2SI_{weighted}$ (calculated with different degrees of weighting for each sub-index); C and D: comparison between D^2SI and D^2SI_2 (calculated without D^2SI_I, D^2SI_R and D^2SI_D), for each survey with cumulated dumped volumes (m^3; Histograms), for MABIO and MASED sites. Standard deviation is illustrated by error bars and calculated for each period with n=6 for D^2SI and $D^2SI_{weighted}$ MABIO; n=5 for D^2SI and $D^2SI_{weighted}$ MASED; n=3 for D^2SI_2 MABIO and MASED. The y-axis and x-axis are the same for each graph.

Table captions

Table 1: Ratio, threshold and scores for species used in calculation of D^2SI-Benthos and D^2SI-Ichthyofauna [from DSD index (Dauvin *et al.,* 2018)]. Example for reading assistance: a score of 1 indicates high abundances at impacted stations (abundance at unimpacted samples is ten times higher than those at impacted samples).

Table 2. D^2SI-B and D^2SI-I score and site disturbance classification.

Table 3. D^2SI_S, D^2SI_T, D^2SI_R and D^2SI_D scores associated with results of calculation and site disturbance classification.

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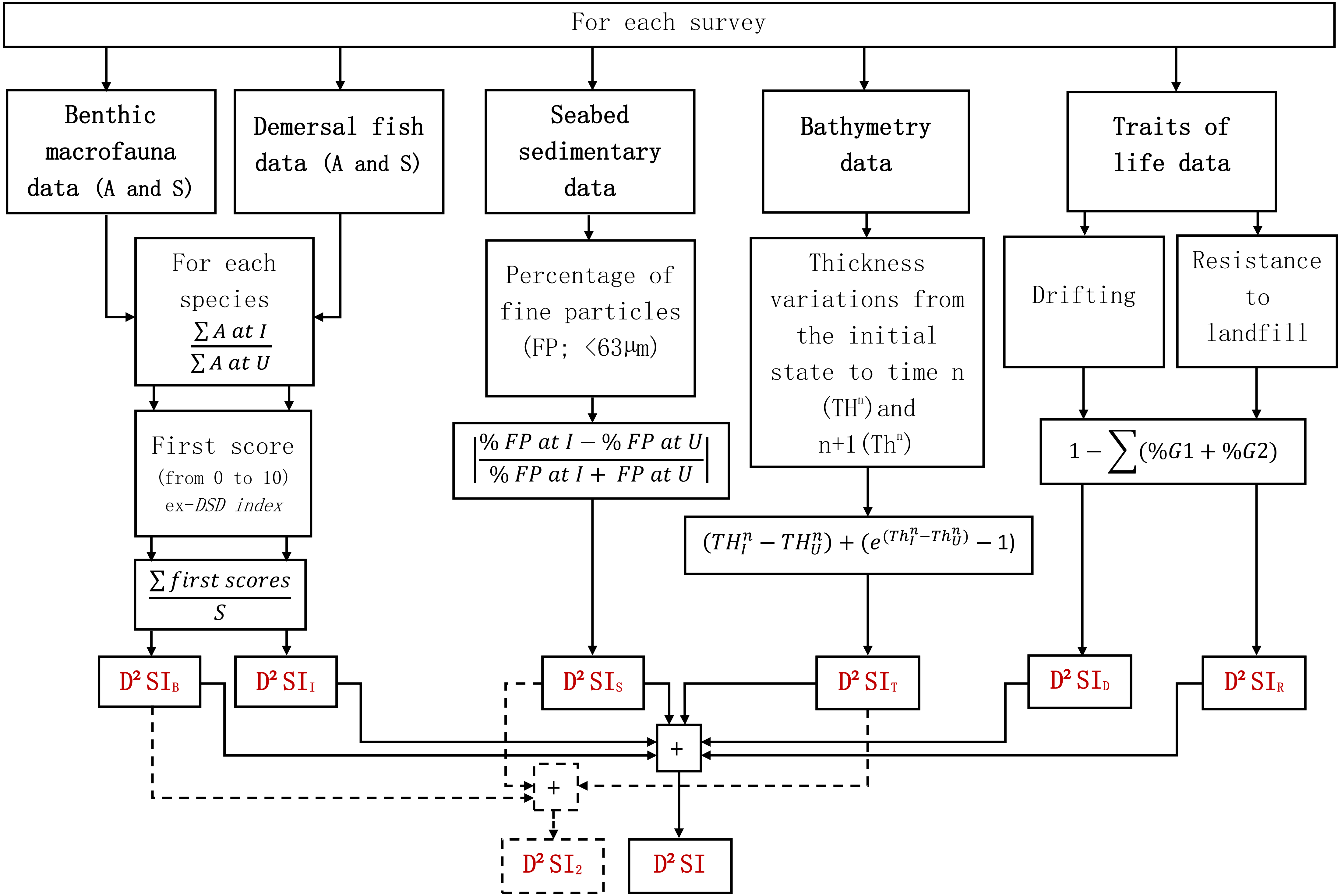

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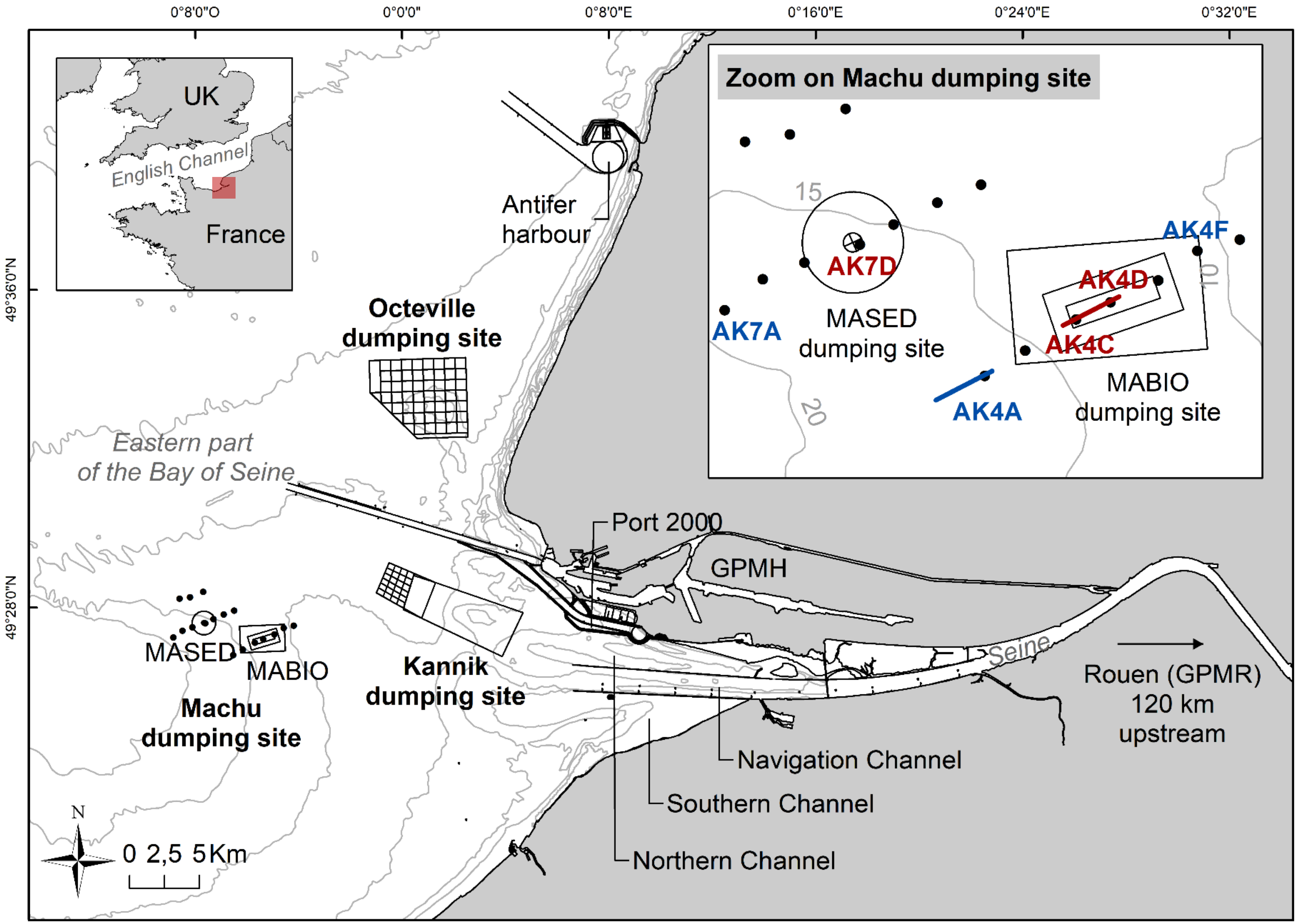

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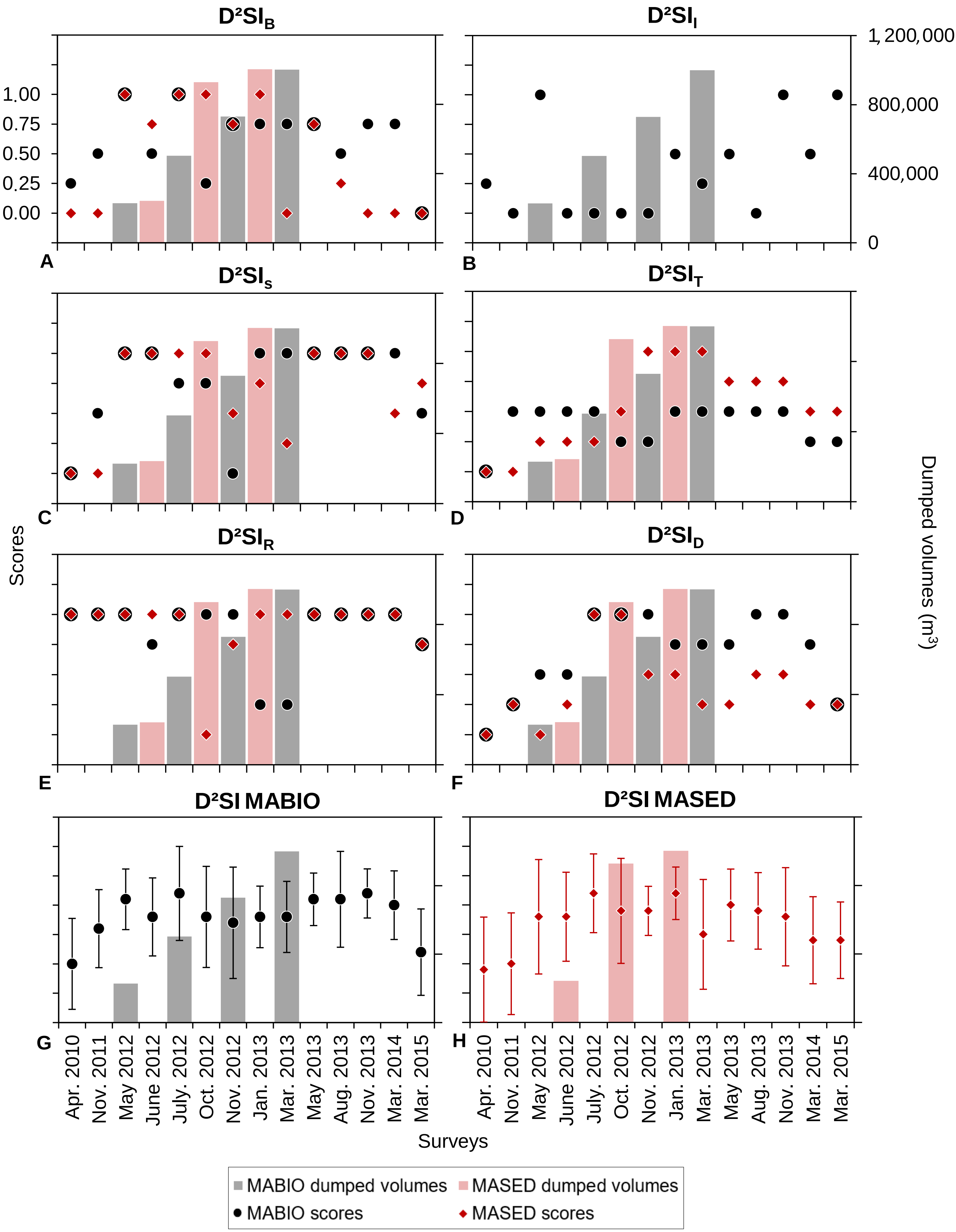

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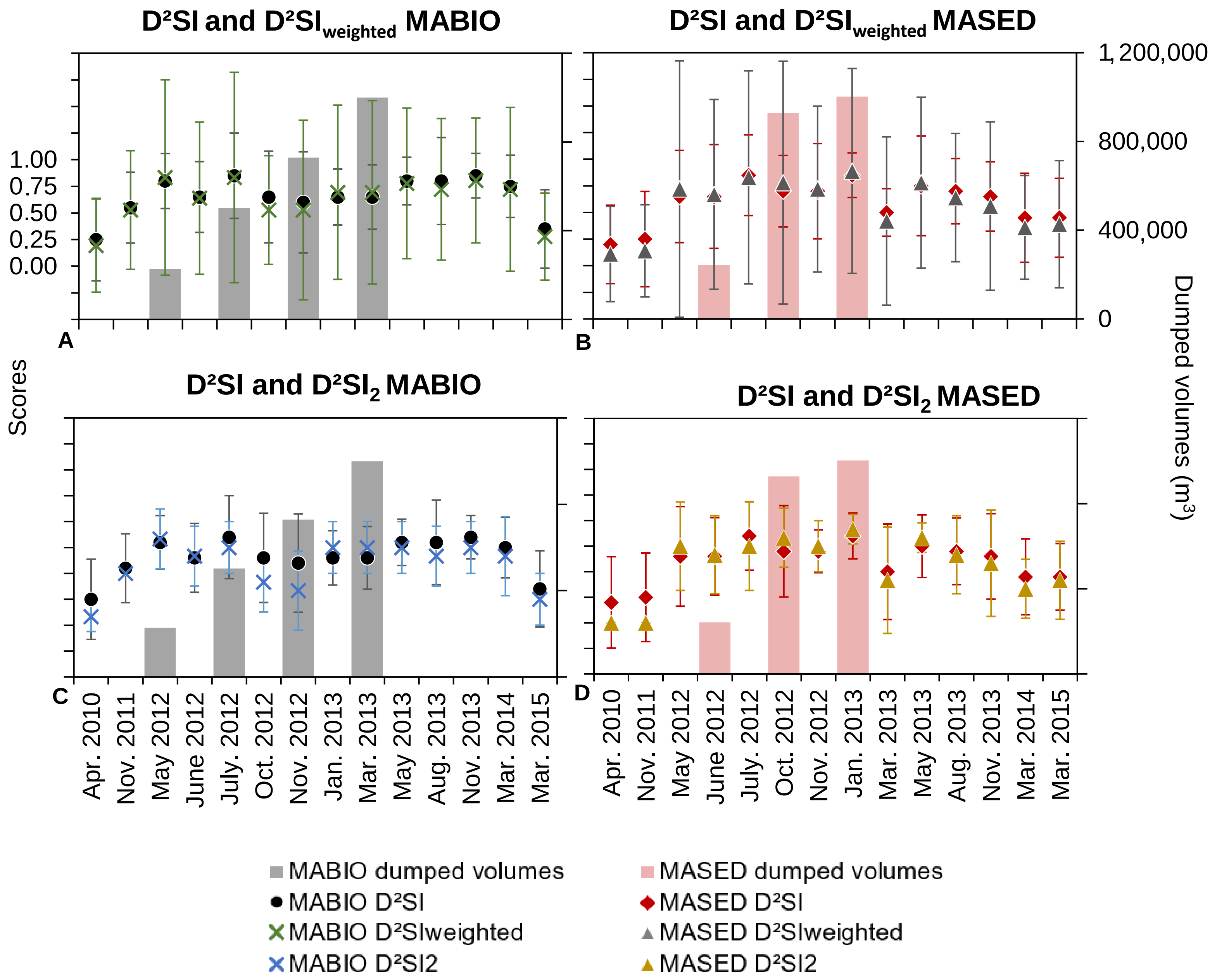

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Ratio Impacted/unimpacted		**Group**		**Score for species**
Ratio = 0		Species found only at the unimpacted stations		10
0.2 ≥ Ratio		>5 times higher		9
0.2 < Ratio ≤ 0.4		>2.5–5 times higher		8
0.4 < Ratio ≤ 0.6		>1.75–2.5 times higher		7
0.6 < Ratio ≤ 0.8	Abundance at unimpacted samples	>1.25–1.75 times higher	than at impacted samples	6
0.8 < Ratio ≤ 1		>1–1.25 times higher		5
1 < Ratio ≤ 2		>1–2 times lower		4
2 < Ratio ≤ 4		>2–4 times lower		3
4 < Ratio ≤ 10		>4–10 times lower		2
10 < Ratio		>10 times lower		1
Ratio not calculable		Species absent from unimpacted stations and present only at impacted stations		0

Table 2: D^2SI_B and D^2SI_I score and site disturbance classification.

Score for species / taxonomic richness	**D^2SI_B and D^2SI_I Score**	**Site disturbance classification**
[10 - 8]	1	Extremely disturbed
]8 - 7]	0.75	Heavily disturbed
]7 - 6.5]	0.5	Moderately disturbed
]6.5 - 6]	0.25	Slightly disturbed
]6 - 4]	0	Undisturbed
]4 - 3.5]	0.25	Slightly disturbed
]3.5 - 3]	0.50	Moderately disturbed
]3 - 2]	0.75	Heavily disturbed
]2 - 0]	1	Extremely disturbed

Table 3: D^2SI_S, D^2SI_T, D^2SI_R and D^2SI_D scores associated with results of calculation and site disturbance classification.

Index	Results of calculation	Score	Site disturbance classification
D^2SI_S	[0 - 0.1[	0	Undisturbed
	[0.1 - 0.3[	0.25	Slightly disturbed
	[0.3 - 0.5[	0.50	Moderately disturbed
	[0.5 - 0.7[	0.75	Heavily disturbed
	> 0.7	1	Extremely disturbed
D^2SI_T	≤ 0	0	Undisturbed
	[0 - 2[	0.25	Slightly disturbed
	[2 - 4[	0.50	Moderately disturbed
	[4 - 6[	0.75	Heavily disturbed
	> 6	1	Extremely disturbed
D^2SI_R and D^2SI_D	[0- 0.1[	0	Undisturbed
	[0.1 – 0.3[	0.25	Slightly disturbed
	[0.3 – 0.5[	0.50	Moderately disturbed
	[0.5 – 0.7[	0.75	Heavily disturbed
	[0.7 – 1]	1	Extremely disturbed

Table 4: Results of D²SI calculation and associated site disturbance classification.

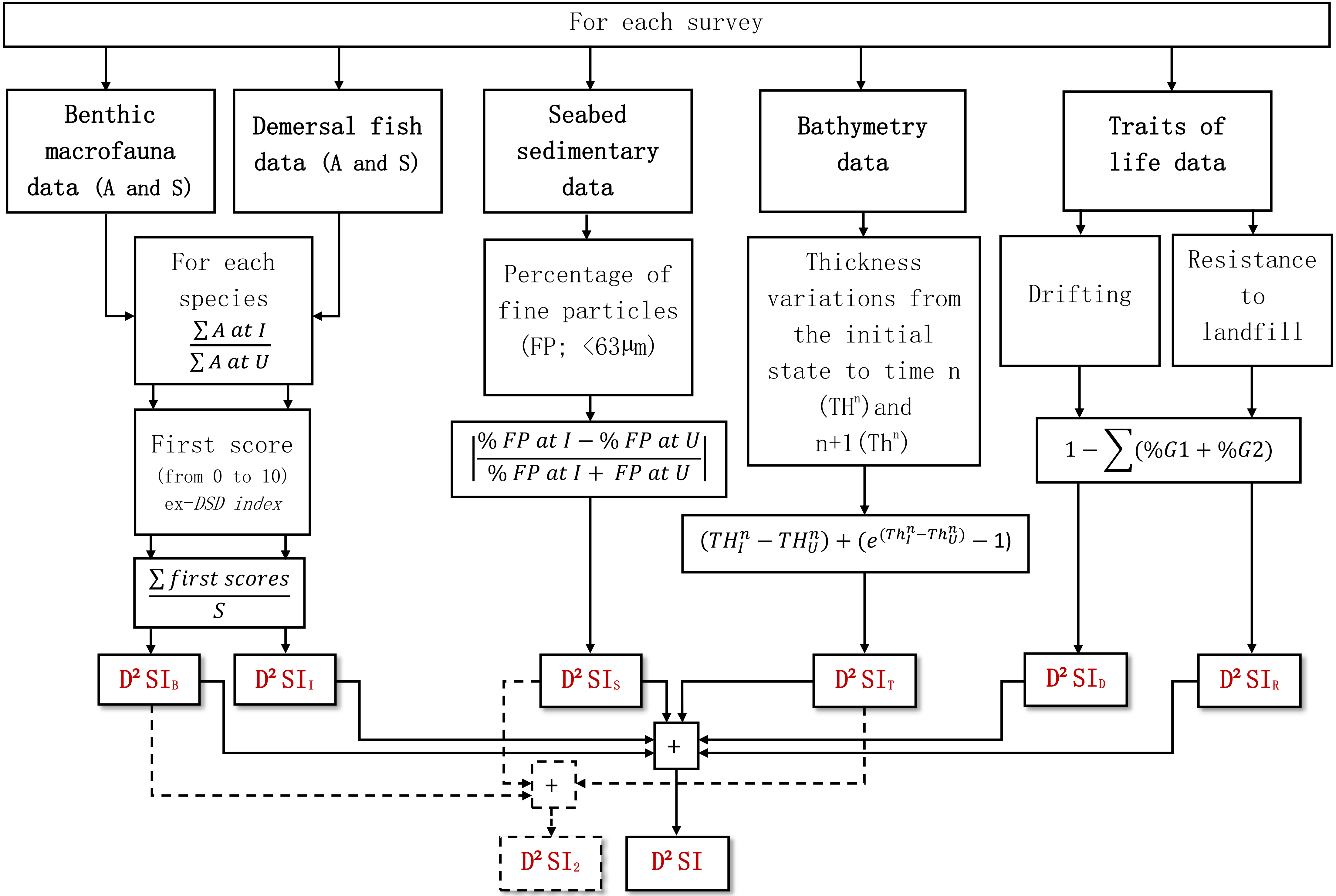
D²SI	**Site disturbance classification**
[0 – 0.2[	Undisturbed
[0.2 – 0.4[	Slightly disturbed
[0.4 – 0.6[	Moderately disturbed
[0.6 – 0.8[	Heavily disturbed
[0.8 – 1]	Extremely disturbed

Table 5: Spearman's correlation coefficients and significance tests (p-value 0: ***; 0.001: **; 0.05: *; 0.1: ‘) between each sub-index, final D^2SI and dumped volumes, for MABIO and MASED sites. $D^2SI_{weighted}$: final index with weighting coefficient; D^2SI_2: final index calculation without scores integrating D^2SI_I, D^2SI_R and D^2SI_D; Volumes: *in situ* dumped volumes. Numbers in bold: significant values. In red: p-value.

	D^2SI_B	0.20	0.44	‘ **0.51**	0.13	0.37	** **0.69**	*** **0.83**	*** **0.82**	* **0.60**	
	NA	**D^2SI_I**	0.34	0.00	-0.17	-0.28	0.16	0.27	0.35	-0.15	
	* **0.60**	NA	**D^2SI_S**	* **0.65**	-0.26	0.22	** **0.67**	** **0.69**	** **0.78**	-0.098	
	0.074	NA	0.072	**D^2SI_T**	-0.20	0.18	* **0.60**	** **0.66**	*** **0.80**	0.14	
MASED	-0.15	NA	-0.013	-0.18	**D^2SI_R**	0.28	0.31	0.23	-0.11	-0.083	MABIO
	0.42	NA	0.40	0.41	-0.35	**D^2SI_D**	* **0.62**	0.45	0.27	0.27	
	*** **0.80**	NA	* **0.64**	‘ **0.48**	-0.064	** **0.70**	**D^2SI**	*** **0.95**	*** **0.79**	0.13	
	*** **0.91**	NA	* **0.65**	0.38	-0.14	* **0.59**	*** **0.95**	**$D^2SI_{weighted}$**	*** **0.89**	0.25	
	*** **0.89**	NA	* **0.64**	0.44	-0.23	‘ **0.52**	*** **0.92**	*** **0.97**	**D^2SI_2**	0.31	
	* **0.54**	NA	0.25	0.12	-0.21	0.35	0.39	‘ **0.51**	* **0.54**	**Volumes**	

Table 6: Ecological indicators mean values and environmental classification (EcoQS) for MABIO and MASED sites according to dumping periods (before, during and after dumping) and considered stations (AK4 A, C, D, F and AK7 A, D). The several ecological statuses considered for the selected benthic indicators come from: Borja et al. (2004) and Muxika et al. (2007) for AMBI and M-AMBI; Dauvin (2018) for BO2A (revisited from De-la-ossa Carretero et al., 2010), Vincent et al. (2002) for H' and Bellan (2008) for ITI. Colours correspond to the WFD classification.

		AMBI		**M-AMBI**		**BO2A**		**H'**		**ITI**		**D^2SIF**		**D^2SIF_2**	
		Values	EcoQS	Values	EcoQS	Values	EcoQS	Values	EcoQS	Values	EcoQS	Values	EcoQS	Values	EcoQS
	Before	1.10	Undisturbed	0.75	Slightly	0.0035	Undisturbed	4.81	Undisturbed	59	Perturbed	0.4	Moderately	0.0	Undisturbed
MASED	**During**	1.10	Undisturbed	0.81	Undisturbed	0.0080	Undisturbed	4.78	Undisturbed	68	Normal	0.7	Heavily	0.7	Heavily
	After	1.23	Slightly	0.81	Undisturbed	0.0042	Undisturbed	4.83	Undisturbed	74	Normal	0.7	Heavily	0.6	Heavily
	Before	1.21	Slightly	0.71	Slightly	0.0088	Undisturbed	4.39	Undisturbed	62	Normal	0.2	Slightly	0.3	Slightly
MABIO	**During**	1.85	Slightly	0.74	Slightly	0.0289	Slightly	4.35	Undisturbed	70	Normal	0.7	Heavily	0.6	Heavily
	After	0.67	Undisturbed	0.76	Slightly	0.0078	Undisturbed	3.70	Slightly	84	Normal	0.6	Heavily	0.6	Heavily



For each survey
Benthic macrofauna data (A and S)
Demersal fish data (A and S)
Seabed sedimentary data
Bathymetry data
Traits of life data
For each species
$\frac{\sum A\ at\ I}{\sum A\ at\ U}$
Percentage of fine particles (FP; <63µm)
Thickness variations from the initial state to time n (TH^n) and n+1 (Th^n)
Drifting
Resistance to landfill
First score (from 0 to 10) ex-*DSD index*
$\left|\frac{\%\ FP\ at\ I - \%\ FP\ at\ U}{\%\ FP\ at\ I + FP\ at\ U}\right|$
$1 - \sum(\%G1 + \%G2)$
$(TH_I^n - TH_U^n) + (e^{(Th_I^n - Th_U^n)} - 1)$
$\frac{\sum first\ scores}{S}$
D^2SI_B
D^2SI_I
D^2SI_S
D^2SI_T
D^2SI_D
D^2SI_R
+
+
D^2SI_2
D^2SI