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Assessing the environmental quality status in estuarine and coastal systems: Comparing methodologies and indices

A. Borja [a,*], *D.M. Dauer* [b]

[a] *AZTI-Tecnalia, Marine Research Division, Herrera Kaia, Portualdea s/n, 20110 Pasaia, Spain*
[b] *Department of Biological Sciences, Old Dominion University, Norfolk, VA 23529, USA*

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ABSTRACT

Increasingly on a worldwide scale, legislation has been adopted to determine the ecological integrity of surface waters including streams, rivers, lakes, estuaries and coastal waters. An integral part of determining ecological integrity is the measurement of biological integrity, typically emphasizing analyses of plankton, benthos, macroalgae and fish. In the development of protocols for evaluating biological integrity, benthic macroinvertebrate communities are the most consistently emphasized biotic component of aquatic ecosystems. A plethora of methodologies with hundreds of indices, metrics and evaluation tools are presently available. An ecologically parsimonious approach dictates that investigators should place greater emphasis on evaluating the suitability of indices that already exist prior to developing new ones. Hence, the authors organized within the American Society of Limnology and Oceanography 2006 Summer Meeting, 4–9 June 2006, in Victoria, BC, Canada, a special session with the objective to compare methodologies, applications and interpretations existing in various countries and attempting to contribute to an improved understanding of the suitability of such approaches when using benthic communities. From the 25 contributions presented in this session, eight manuscripts were selected to be included in this special issue of Ecological Indicators including new index development, novel validation approaches, assessment of spatio-temporal applications, interpretations relative to management needs and potential adaptive management modifications to maximize the robustness, sensitivity, and representativeness of environmental information conveyed to management.

1. Overview

On a worldwide-scale coastal, estuarine and transitional waters have been affected by man's activities. Historically, developing human civilizations has often been concentrated in coastal areas where access to water promoted trade, commerce, and disposal of wastes (e.g., van Andel, 1981). As a consequence, human alteration of natural ecosystems is profound in coastal areas and a central theme of environmental management is to develop policy to balance socio-economic growth and environmental protection. A central concept of environmental management is maximizing beneficial sustainable development while minimizing impacts to ecological integrity (Müller, 2005). In order to deal with the complexities of socio-environmental issues, many countries have adopted the DPSIR (drivers–pressure–state–impact–response) approach (e.g., OECD, 1993; EEA, 1999; Turner et al., 1998; Elliott, 2002; Bricker et al., 2003; Hameedi, 2005; Smeets and Weterings, 2005; Aubry and Elliott, 2006; Borja et al., 2006a). DPSIR is an environmental management

* *Corresponding author*. Tel.: +34 943 004800.
E-mail addresses: aborja@pas.azti.es (A. Borja), ddauer@odu.edu (D.M. Dauer).
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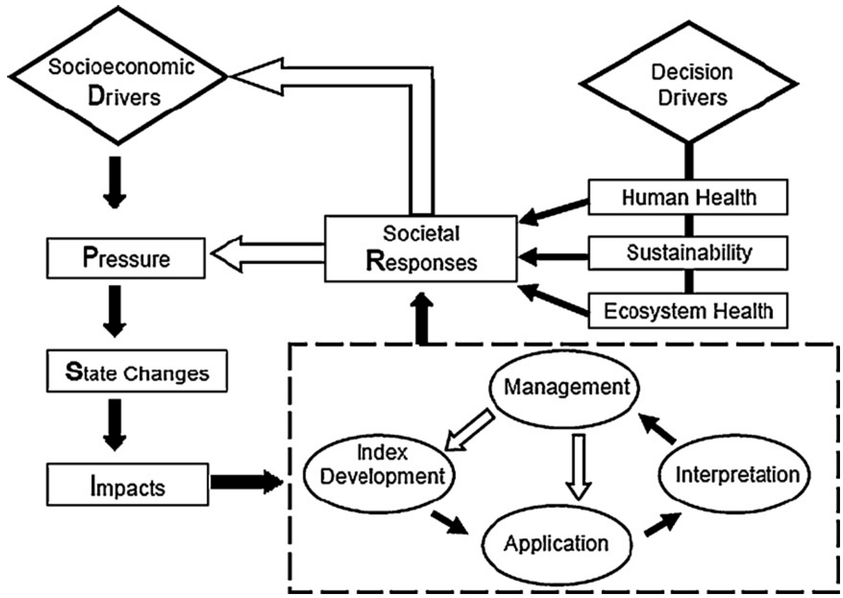

Fig. 1 – The DPSIR approach showing relationships between drivers–pressure–state–impact–responses variables. Also indicated are the primary drivers of management decisions. Societal responses meant to halt, ameliorate, mitigate or reverse unacceptable conditions are shown by open arrows. Dashed inset shows the impact assessment components with open arrows indicating adaptive monitoring feedback loops.

paradigm as a feedback loop system in which driving forces (*D*) of social and economic development exert pressure (*P*) on the environment thereby changing its state (*S*), potentially resulting in impacts (*I*) on human health and/or ecosystem function that may elicit an environmental management response (*R*) (Fig. 1). This conceptual framework is intended to identify causal relationship within the DPS component and most importantly to determine and evaluate human and ecological impacts (*I*).

2. Ecological (environmental) indicators

All of the components of the DPSIR paradigm that lead to management responses are typically represented by environmental indicators. Relative to the benthic community focus of this special issue, the predominant driver indicator would be population density changes in coastal regions (with associated activities such as, industry development, port uses, etc.); pressure (stressor) indicators relate large-scale anthropogenic impacts and would include changes in land-use patterns and nutrient, sediment and contaminant loads to coastal watersheds; state (exposure) indicators would include levels of chlorophyll *a*, low dissolved oxygen events, and sediment contaminant concentrations; and impact (ecological response) indicators would include indices of benthic community condition (see examples in Borja et al., 2006a). Increasingly on a worldwide scale, legislation has been adopted to determine the ecological integrity of surface waters including streams, rivers, lakes, estuaries and coastal waters, i.e. the Oceans Act 2000 of the USA, the US Clean Water Act (1972 amended in 1977), the European Water Framework Directive (Borja, 2005), the European Marine Strategy (Borja, 2006), etc. Integrating environmental protection legislation and the DPSIR paradigm, the Impact component (see dashed inset of Fig. 1) requires (1) assessing ecological integrity, (2) evaluating if significant ecological degradation has occurred, (3) identifying the spatial extent and location of ecological degradation, and (4) determining causes of unacceptable degradation in order to guide management actions. Feedback loops (open arrows within the dashed inset of Fig. 1) between environmental management and index application-interpretation represent adaptive monitoring changes (*sensu* Ringold et al., 1996) that are necessary before developing and finalizing societal responses (*R*). The societal response (*R*) component of DPSIR constitutes environmental management strategies to halt, ameliorate, mitigate or reverse unacceptable conditions and protect human health and a healthy ecosystem (*sensu* Costanza and Mageau, 2000) while promoting sustainable development.

An integral part of determining ecological integrity is the measurement of biological integrity, typically emphasizing analyses of plankton, benthos, macroalgae and fish. In the development of protocols for evaluating biological integrity, benthic macroinvertebrate communities are the most consistently emphasized biotic component of aquatic ecosystems. A plethora of methodologies with hundreds of indices, metrics and evaluation tools are presently available (e.g., see summary in Diaz et al., 2004). An ecologically parsimonious approach dictates that investigators should place greater emphasis on evaluating the suitability of indices that already exist prior to developing new ones (Diaz et al., 2004). Hence, the authors of this contribution organized within the American Society of Limnology and Oceanography 2006 Summer Meeting, 4–9 June, 2006, in Victoria, BC, Canada, a special session with the objective to compare the methodologies existing in various countries, for different systems, trying to improve the knowledge of the suitability of such approaches when using benthic communities. This special issue of Ecological Indicators includes eight manuscripts contributed by authors of some of the 25 presentations of our special session and includes new indices, application and evaluation of existing indices and comparison between different methodologies.

3. Benthic index development

The impact (*I*) component of DPSIR requires the use and/or development of indices, their appropriate application in space and time, and justifiable and defensible interpretation of results. Emphasizing marine and estuarine benthic indicators, we present a brief review of the steps in developing an index including essential characteristics of an index (Table 1) and utility of an index relative to the impact (*I*) component of DPSIR (Fig. 2).

3.1. *Spatio-temporal scale of intended application*

In large part the spatio-temporal scale of applicability is an interaction of all the steps in index development—conceptual foundation, spatio-temporal characteristics of the index development data set, selected metrics, combinatorial strategy and spatio-temporal characteristics of the validation process. Indices developed based upon ecological theory applicable at higher levels of ecological organization, e.g. the ecosystem level, should be more broadly applicable in contrast to indices developed primarily with a utilitarian approach to metric selection and metric combinatorial strategies. Spatially, important limitation considerations include applications beyond the geographical region from which the data used in index development were collected including (1) latitudinally and longitudinally distinct biogeographic provinces or ecoregions, (2) water depths not initially included (e.g., intertidal versus subtidal habitats), and (3) substratum type (hard versus sedimentary bottom). Finally, temporal characteristics of the index development data set may limit the application of an index depending upon whether such data were collected over many years and the frequency of intra-annual collection (seasonal, monthly, etc.). We will discuss the scale of applicability issue further in Section 4 concerning Application and Interpretation.

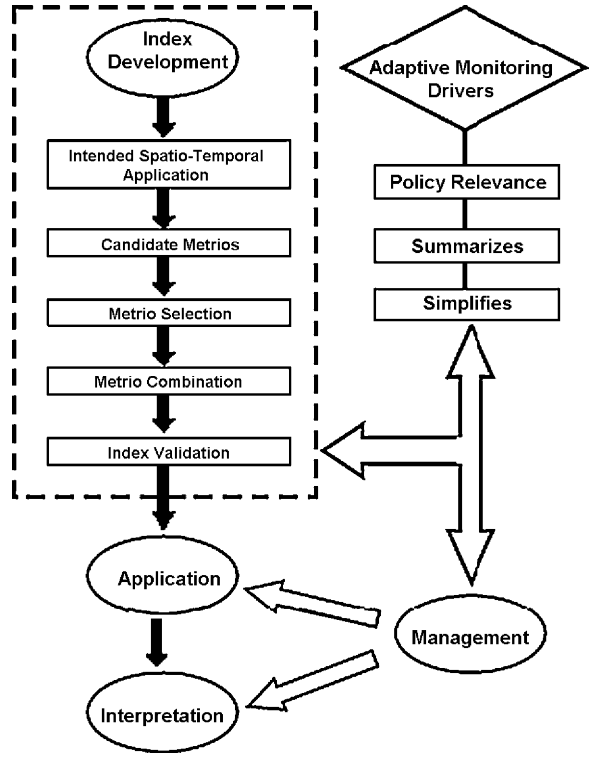

Fig. 2 – Index development, application and interpretation. Dashed rectangle encloses the primary steps in index development. Adaptive monitoring feedback loops and adaptive change decision drivers are indicted by open arrows.

Table 1 – Environmental indicators

Purpose
Summarizes and simplifies complex data
Conveys information—easily understood by the public, media, resource users, and decision-makers
Characteristics
Ecological relevance—based upon a conceptual model (theoretically, empirically or heuristically well founded)
Feasible—data to calculate index can be reliably and cost-effectively collected
Threshold or reference value—users are able to assess significance of indicator value
Representative—able to measure status and trends that are relevant to policy decisions
Sensitivity—reflects response to management actions

Note: an index that is representative and sensitive captures information relevant to anthropogenic actions—degradative and restorative.

3.2. *Candidate metrics*

In general candidate metrics are selected emphasizing the feasibility of measurement and ecological relevance characteristics of an index (Table 1). Candidate metrics could include measures of species diversity, productivity (abundance, biomass), tolerance to and/or indication of association with anthropocentric sources of stress (pollution-indicative or sensitive taxa), and taxocene dominance measures (some major taxa are more tolerant of stress than others). Many of the currently used indices in benthic assessment have as an ecological foundation the empirically derived Pearson and Rosenberg's paradigm (Pearson and Rosenberg, 1976, 1978; Quintino et al., 2006) that depicts community responses to a gradient of organic pollution or disturbance. Although, the Pearson and Rosenberg empirical model has been modified, again empirically, to depict benthic community responses to sediment contamination (Rakocinski et al., 2000), no consensus of expected benthic community response to contamination has yet occurred. When the ecological relevance is based upon very specific ecological concepts then candidate metrics are basically *a priori* selected or limited. For example, an index such as AMBI (Borja et al., 2000) that is based upon the relative distribution of sensitivity/tolerant species groups or the ABC method (Warwick and Clarke, 1994) based upon *k*-distribution curves consists of predetermined metrics. Indices developed with a utilitarian approach will typically begin with a large list of candidate metrics (e.g., see Table 1 in Paul et al., 2001 with over 40 candidate metrics).

3.3. *Metric selection criteria*

From a list of feasible, ecologically relevant candidates, selection should emphasize metrics that are sensitive (respond to anthropocentric action—both degradative and restorative) and representative (able to measure status and trends relative to policy decisions and management actions). Theoretically, metric nomination and/or selection is based upon community level characters (see previous section) that represent key community aspects. Such community characteristics are typically part of, or inherent to, the diversity of definitions of biotic integrity that include elements of species diversity, abundance, energy-flow-food-web structure, maintenance of complexity and self-organization. Metric selection protocols include (1) *a priori* selection based upon a specific ecological foundation and/or best professional judgment (e.g., use of a single species diversity index; AZTI marine biotic index (AMBI) of Borja et al., 2000; abundance-biomass curves (ABC) of Warwick and Clarke, 1994), (2) selection based upon a univariate statistical tests comparing undegraded and degraded samples from a calibration data (e.g., Weisberg et al., 1997), and (3) utilitarian selection based upon multivariate tests using a calibration data set (e.g., Engle et al., 1994; Paul et al., 2001).

3.4. *Metric combination*

The most difficult challenge in index development is selecting and combining metrics in a manner that is complex enough to capture the dynamics of essential ecological processes but not so complex that its meaning is obscured (NRC, 2000). Without a sound and obvious ecological foundation, an index will not be policy-relevant and therefore difficult to use to make policy choices, i.e. societal responses (*R*) (Fig. 1).

Once developed such benthic condition indices can be grouped into three classes (ICES, 2004), based upon their complexity, information content and method of metric combination:

- Univariate individual-species data, or community structure measures; such as the Shannon–Wiener diversity index (Shannon and Weaver, 1949); the benthic pollution index (BPI) (Leppäkoski, 1975); the infauna trophic index (ITI) (Word, 1979, 1980); the ABC (Warwick and Clarke, 1994); the annelid index of pollution (Bellan, 1980); the Shannon–Wiener evenness proportion index (McManus and Pauly, 1990); the taxonomic diversity index and taxonomic distinctness (Warwick and Clarke, 1995); and the ecological evaluation index (EEI) (Orfanidis et al., 2001).
- Multimetric indices, combining several measures of community response to stress into a single index; including: the pollution coefficient (CoP) (Satsmadjis, 1982, 1985); the biological quality index (BQI) (Jeffrey et al., 1985); the infauna ratio-to-reference of sediment quality triad (RTR) (Chapman et al., 1987); the biotic index (Hily, 1984; Hily et al., 1986; Majeed, 1987; Grall and Glémarec, 1997); the benthic index of estuarine condition (BIEC) (Schimmel et al., 1994; Strobel et al., 1995); the benthic condition index (BCI) (Engle et al., 1994; Engle and Summers, 1999; Paul et al., 2001); the benthic index of biotic integrity (B-IBI) (Ranasinghe et al., 1994; Weisberg et al., 1997; Van Dolah et al., 1999; Llansó et al., 2002a,b); the AMBI (Borja et al., 2000, 2003, 2004b; Muxika et al., 2005); the Bentix (Simboura and Zenetos, 2002); the ecofunctional quality index (EQI) (Fano et al., 2003); the indicator species index (Rygg, 2002); and the benthic quality index (BQI) (Rosenberg et al., 2004). A review and intercomparison between 64 such indices can be found in Diaz et al. (2004).
- Multivariate methods describing the assemblages pattern, including modelling, such as the benthic response index (Smith et al., 2001); the estuarine trophic status (Bricker et al., 2003); the principal response curves (PRC) (Pardal et al., 2004); multi-dimensional scaling (MDS) (Warwick and Clarke, 1991); canonical correspondence analysis (CANOCO) (ter Braak and Šmilauer, 1998); PRIMER (Clarke and Ainsworth, 1993; Clarke and Gorley, 2001); Multivariate-AMBI (M-AMBI) (Borja et al., 2004a; Muxika et al., 2007); and the community disturbance index (CDI) (Flåten et al., 2007).

In this special issue, there are two contributions from Hale and Heltshe (2008) and Juanes et al. (2008), which are focused on the development of a soft-bottom benthic index for the Gulf of Maine and a multimetric index for assessing macroalgae quality in rocky bottom substrata, respectively.

3.5. *Index validation*

Index validation should ideally include (1) testing of the index using an independent data set, different than the index development data set (calibration data set), (2) setting *a priori* correct classification criteria and/or (3) presentation of a strong *a posteriori* justification for use based upon best professional judgment. In the development of some benthic indices, calibration and validation data sets were initially available and samples were allocated between the two data sets based upon different years of collection (e.g., Weisberg et al., 1997; Paul et al., 2001) or randomly assigned from all data collection years (e.g., Llansó et al., 2002b). More commonly after index development, newly collected data are used as validation data. In such cases strong putative gradients are deliberately selected for validation testing (e.g., Borja et al., 2000, 2003, 2006b; Muxika et al., 2005; Quintino et al., 2006). Independent validation, by scientists other than those proposing the index should be done. In the particular case of AMBI some of these comparisons were made elsewhere, e.g. in this special issue, two contributions are focused on its applicability for benthic ecological status assessment, evaluating its dependency on sediment characteristics and immersion/emersion (Blanchet et al., 2008) and the comparison with other indices in estuarine systems (Puente et al., 2008).

Finally, some degree of intercalibration (see Borja et al., 2007) or validation can be achieved by determining the level of agreement provided by an index with best professional judgment to assess the condition of benthic infaunal communities (see Weisberg et al., 2008) or by comparing the level of agreement between indices of different geographical origin, such as Borja et al. (2008), when comparing results of indices from Europe and USA.

4. Index application and interpretation

The application and interpretation of data by environmental scientists involves numerous internal intellectual and pragmatic feedback loops affecting monitoring design and interpretive paradigms. Common aspects of index application and interpretation of results are continuous re-validation with each use and consideration of application beyond known or assumed limits. For most indices the interaction of ecological foundation and characteristics of development data set may set spatio-temporal limits of application. As we stated earlier in Section 3.1, there may be reasonable spatial concerns when applying any index to (1) latitudinally or longitudinally distinct biogeographic provinces or ecoregions, (2) different water depth habitat types (e.g., intertidal versus subtidal habitats), and (3) different substratum types (hard versus sedimentary bottom). Obviously indices that can be demonstrated to be robust in space and time will facilitate communication to environmental managers. Such robust indices will allow comparisons among environmental managers responsible for different ecosystem types and between different countries and continents, thus encouraging the adoption and application of policies and actions that represent effective societal responses of the DPSIR paradigm. In this issue, Teixeira et al. (2008) conducted an applicability study to different habitats within a system, the Mondego estuary in Portugal, and Dauer et al. (2008) tested the applicability and interpretation of patterns of benthic community degradation as a function of water depth in Chesapeake Bay, USA.

5. Adaptive management (feedback and modification)

Within the DPSIR approach, policy consideration (societal response) may result in changing (1) data needs, (2) data analysis procedures and (3) data interpretation needs (Figs. 1 and 2). As such, environmental scientists must be receptive and amenable to adaptive monitoring changes (Ringold et al., 1996). Adaptive monitoring may necessitate additional modification of the index development process, including additional effort to demonstrate ecological relevance, representativeness and sensitivity (Table 1); further testing of index applicability; and maximizing information and understanding by management of the interpretation process. We hope that the contributions within this special issue of Ecological Indicators can assist in such tasks and approaches.

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