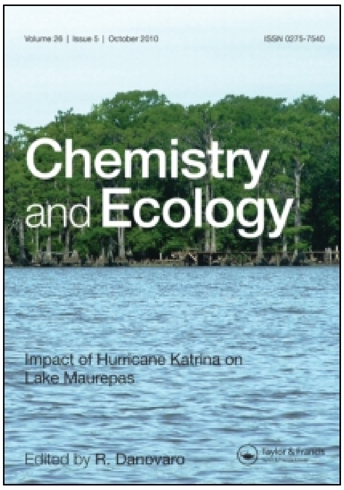

Chemistry and Ecology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455114

Response of a Fuzzy INdex of Ecosystem integrity (FINE) to water and sedimentary chemical data in two northern Adriatic lagoons

M. Mistri[a]; C. Munari[a]; R. Rossi[a]; A. Marchini[ab]
[a] Department of Biology and Evolution, University of Ferrara, Ferrara, Italy [b] Department of "Ecologia del Territorio", University of Pavia, Pavia, Italy

To cite this Article Mistri, M. , Munari, C. , Rossi, R. and Marchini, A.(2007) 'Response of a Fuzzy INdex of Ecosystem integrity (FINE) to water and sedimentary chemical data in two northern Adriatic lagoons', Chemistry and Ecology, 23: 6, 443 — 454

To link to this Article: DOI: 10.1080/02757540701702728

URL: http://dx.doi.org/10.1080/02757540701702728

Chemistry and Ecology
Vol. 23, No. 6, December 2007, 443–454

Taylor & Francis
Taylor & Francis Group

Response of a Fuzzy INdex of Ecosystem integrity (FINE) to water and sedimentary chemical data in two northern Adriatic lagoons

M. MISTRI*†, C. MUNARI†, R. ROSSI† and A. MARCHINI†‡

†Department of Biology and Evolution, University of Ferrara, Via L. Borsari 46, I-44100 Ferrara, Italy
‡Department of "Ecologia del Territorio", University of Pavia, Via S. Epifanio 14, I-27100 Pavia, Italy

(Received 30 June 2006; in final form 12 February 2007)

The European WFD (2000/60/EC) requires the assessment of the ecological quality status of water bodies, and gives great importance to the biological components of the ecosystem. A multimetric, fuzzy-based index for the evaluation of environmental quality (FINE: Fuzzy INdex of Ecosystem integrity) has been developed. The FINE index was calculated at 7 sites in the Sacca di Goro and the Valli di Comacchio (Adriatic Sea), where water and sedimentary chemical data were available for the years 2004 and 2005. A significant positive correlation was found between FINE values and dissolved oxygen, while significant negative correlations were observed between FINE values and transparency, nitrogen and phosphorous in the water column, and heavy metals and PCB in the sediments.

Keywords: Benthos; Transitional waters; Environmental quality; Multimetric index; Adriatic Sea

1. Introduction

The general objective of the European Water Framework Directive (WFD, 2000/60/EC) is to achieve good status for all surface waters by 2015. For this purpose, the WFD requires the classification of ecological quality status (EcoQ) of all water bodies into five status categories: BAD, POOR, MODERATE, GOOD and HIGH. Biological, hydromorphological and physical-chemical elements are to be taken into account for the quality assessment, with priority of the biological elements on the other ones. Therefore, the WFD recommends the development and application of biotic indices, which are straightforward and easy to present to potential end users.

With regard to estuarine and coastal waters, most indices proposed so far are based on the communities of benthic invertebrate fauna, which integrate environmental conditions and changes in a very effective way [1]; the most used ones are AMBI [2], BENTIX [3] and BQI [4]. Their application in brackish environments, however, appeared not always satisfactory [5], and the comparison amongst them showed controversial results [6–10]. The other biological

*Corresponding author. Email: michele.mistri@unife.it

Chemistry and Ecology
ISSN 0275-7540 print/ISSN 1029-0370 online
http://www.tandf.co.uk/journals
DOI: 10.1080/02757540701702728

elements suggested by the WFD for the quality assessment of transitional waters, namely phytoplankton, other aquatic flora and fish communities, have also been recently considered for the development of new classification tools [11–16]. Several of these indices are based on the concept of sensitive/tolerant species, deriving information from literature or, as in the case of BQI, from very large datasets.

Several authors, e.g. [1, 17] point out that none of the available measures on biological effects of pollution should be considered ideal: the use of a single approach does not seem appropriate due to the complexity inherent in assessing the environmental quality of a system. This issue is particularly relevant in naturally highly variable environments such as coastal lagoons, often inhabited by communities of only a few species, most of which are tolerant of disturbance [17]: methods based on species richness or sensitivity might be unable to identify anthropogenic impacts in these environments. Moreover, different biological elements may react in different ways to disturbances, because of (a) differences in the reaction to anthropogenic impact factors and (b) different acclimation ranges with respect to natural abiotic factors [18].

A more ecologically robust approach, therefore, is the combination of different biological elements and properties of these elements into a single classification tool, which can provide the integrated response of the community to different levels of EcoQ. Within this framework, we have recently developed a new multimetric index, the Fuzzy Index of Ecosystem Integrity, FINE [19], which is based on key-characteristics of the biota in transitional water environments. FINE takes into account 7 ecosystem attributes (variables or metrics), each having ecological relevance for lagoon ecosystems: (1) biomass of seaweeds, (2) presence of seagrass, (3) biomass of macrobenthos, (4) macrobenthic diversity (as Shannon's H'), (5)

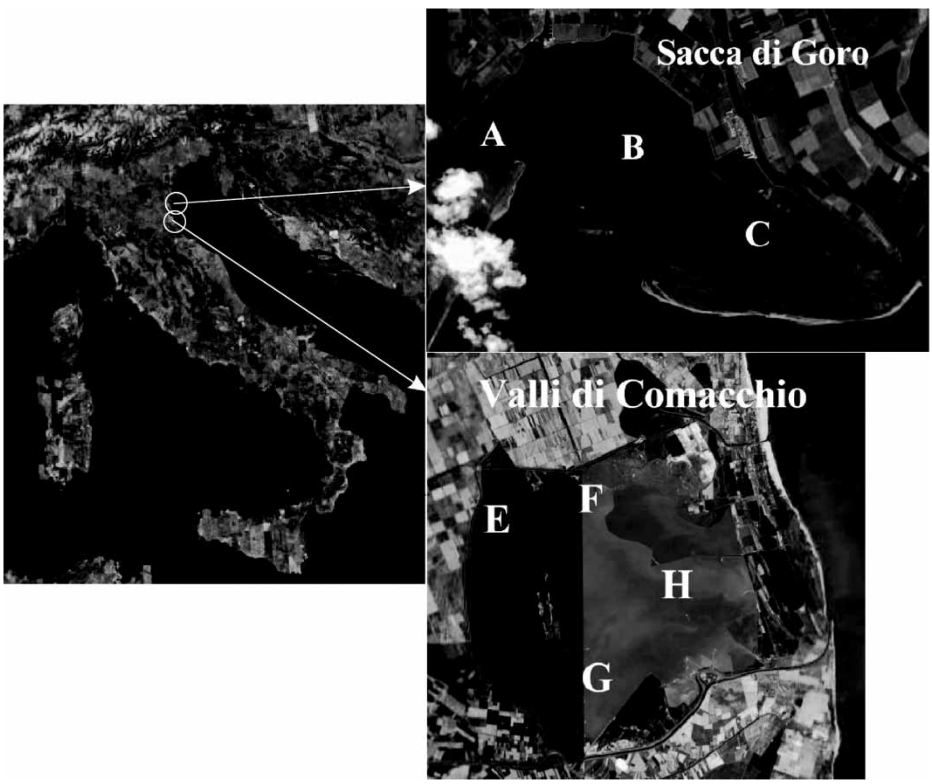

Figure 1. Study sites.

macrobenthic functional diversity, (6) abundance of macrobenthos, (7) number of macrobenthic taxa. The 7 variables are combined in a system of 768 logic rules, and the result is a number, ranging from 0 to 100, which expresses the EcoQ of the considered sample. All the algorithms for FINE calculation are based on the fuzzy set theory, which has repeatedly been proposed as a useful method to develop ecological models and indices of environmental conditions [20–26]. The online version of the index is freely available at: http://web.unife.it/progetti/FINE/.

This paper aims to evaluate the response of FINE to environmental pressures in two transitional environments of the northern Adriatic Sea, the Sacca di Goro and the Valli di Comacchio (figure 1). Several chemical parameters representative of anthropogenic impact are considered in the analysis, at the level of both water column (transparency, dissolved oxygen, total nitrogen, total phosphorous) and sediments (heavy metals, Cr, Ni, Pb, As, and polychlorinated biphenyls, PCB).

2. Materials and methods

2.1 *Index development*

The seven variables selected for FINE calculation are described by a number of modalities, from *low* to *very high*, represented by fuzzy membership functions, which in turn are associated with a general quality status of a lagoon. For instance, the number of macrobenthic taxa can be *low, medium* or *high*, *low* being associated with poor quality, and *high* with good quality. For most variables, ecological quality increases linearly as the variable values increase (figure 2, case a); for other variables, such as biomass of seaweeds and abundance of macrobenthos, ecological quality assumes a unimodal pattern, being poor at low variable values, then rising to a maximum before declining at very high variable values (figure 2, case b). Therefore, the modalities associated with 'worst' and 'best' ecological status generally are *low* and *high*, respectively, with the exception of some variables. The modality *medium*, for example, is the best case for the variable seaweeds biomass, while the modality *very high* is its worst case. FINE is based on such well-known ecological principles, thus the rules of the fuzzy inference system can be considered as objective rules, which are in the form of *if* ... *then* expressions, typical of fuzzy models. The following statements are clear examples of rules:

- *if* all variables are in their 'best' modalities, *then* ecological status is HIGH;
- *if* all variables are in their 'worst' modalities, *then* ecological status is BAD.

Besides these two cases, there are another 766 possible combinations of modalities of the 7 variables, and each combination is associated with each ecological status class at different

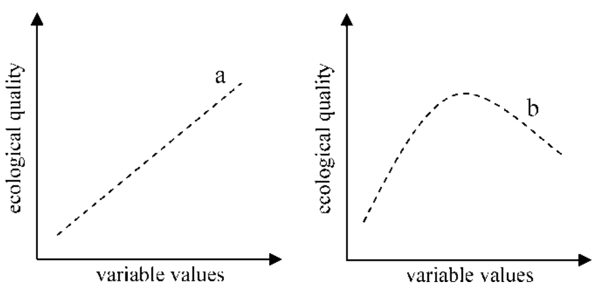

Figure 2. Types of response of ecological quality to increasing values of a variable: (a) linear increase, (b) unimodal increase.

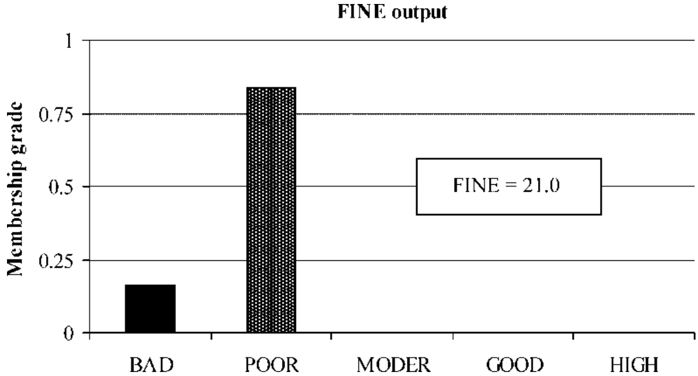

Figure 3. FINE output: in this example, the index value is 21.0 and the ecological status is POOR. The fuzzy output, i.e. membership grade 0.16 to BAD and 0.84 to POOR shows that in this case the status POOR is slightly inclined towards the condition BAD.

grades of membership. The number and shape of the membership functions relative to all variables and the development of the 768 inference rules are described in [19]. It is interesting to point out that the *if ... then* rules are not subjectively created, but automatically computed by means of a procedure proposed by [27].

FINE structure follows the canonical three steps of fuzzy models: (i) fuzzification through membership functions, (ii) inference through *if ... then* rules and (iii) defuzzification, which can be performed with several different methods [26]. The input data (measured values of the 7 variables in a station) are first 'fuzzified', *i.e.* transformed into membership grades for all variables modalities, then processed across the 768 model rules by means of some logic operators, such as '*and*', '*if ... then*' and '*or*'. The resulting output is a membership grade to all the five EcoQ classes (figure 3); it is then defuzzified, i.e. re-transformed into a 'crisp' output that can be easily understood without references to the fuzzy theory [22]. Defuzzification, which allows the calculation of FINE, is performed as a linear combination of the membership functions (μ) related to the five EcoQ classes, as in [28]:

$$\text{FINE} = 0 \cdot \mu_{BAD} + 25 \cdot \mu_{POOR} + 50 \cdot \mu_{MODERATE} + 75 \cdot \mu_{GOOD} + 100 \cdot \mu_{HIGH}.$$

The coefficients of the linear combination were chosen in order to make FINE range in the interval $[0, 100]$: the combination of all variables in their best modality is associated with HIGH ecological status and with the maximum value of the FINE index, namely FINE_{100}, whereas the combination of all variables in their worst modality is associated with BAD ecological status and with the minimum FINE value, namely FINE_0. The Ecological Quality Ratio (EQR), required by the WFD, can be easily computed dividing the FINE value obtained in a station by FINE_{100}:

$$\text{EQR} = \frac{\text{FINE}}{\text{FINE}_{100}}.$$

In absence of well-known quality gradients in the considered environments, the range of EQR was divided into classes of equal amplitude (table 1), relative to the five EcoQ classes, as done for other indices [15, 16].

2.2 *Biotic data collection*

The biotic data set was gathered in the European Transitional Waters Ecoregion no. 6 [31], in the Sacca di Goro and the Valli di Comacchio, from 2004 through 2005 with seasonal

Table 1. Boundaries for the Ecological Quality Ratio (EQR) and correspondence to the five classes of EcoQ.

Ecological Quality Ratio (EQR)	Ecological Quality Status (EcoQ)
$0 \leq EQR < 0.2$	BAD
$0.2 \leq EQR < 0.4$	POOR
$0.4 \leq EQR < 0.6$	MODERATE
$0.6 \leq EQR < 0.8$	GOOD
$0.8 \leq EQR \leq 1$	HIGH

frequency. Sampling surveys were carried out at Goro in May, July and November (2004), and February, May and July (2005); at Comacchio in March, May, July and November (2004), and February, May and July (2005). In this paper, data from 3 stations at Goro (A, B, C) and 4 stations at Comacchio (E, F, G, H) will be considered. At each station, 3 replicate benthic samples were collected for the analysis of the macrofaunal community using a Van Veen grab (sampling area: 0.027 m^2; sampling depth: 12 cm in muddy sediments); fauna retained on a 0.5 mm screen were identified to the species level and counted. Seaweeds and seagrass, when present, were also collected. The biomass of fauna was obtained by oven-drying to constant weight, and incineration (ash-free dry weight, gAFDW m^{-2}), while that of seaweed was obtained as wet weight (gWW m^{-2}).

2.3 *Environmental data*

Environmental data from the Sacca di Goro and the Valli di Comacchio were furnished by the Regional Agency of Environmental Protection (ARPA) [32]. Sampling stations were the same as for biotic data, since a join monitoring program is carried on at both lagoons. Environmental data regarded the water column (transparency, dissolved oxygen, total nitrogen, total phosphorous), and the sediments (heavy metals, Cr, Ni, Pb, As, and polychlorinated biphenyls, PCB). Data availability covered the years 2004–2005 for transparency, dissolved oxygen, and heavy metals, while only 2005 for total nitrogen, total phosphorous, and PCB. Sampling methods and analytical procedures are detailed elsewhere [32].

2.4 *Data treatment*

Relationships between FINE values and environmental data were assessed through regression analyses, and their significance through regression ANOVAs. The relationship of FINE basic parameters (*i.e.* macrobenthic abundance, diversity, functional diversity, etc.), taken one by one, and environmental data was also assessed through regression analysis and ANOVA.

3. Results

Seven stations were considered (3 at Goro, and 4 at Comacchio), corresponding to different environments and physico-chemical characteristics. Ecological conditions among selected stations varied greatly, as shown by the values of the input variables: (1) biomass of seaweeds (SwB) varied from 0 to 1759 gWW m^{-2}, (2) biomass of macrobenthos (BB) between 0.24 and 59.6 gAFDW m^{-2}, (3) macrobenthic diversity (H') between 0.13 and 1.75, (4) macrobenthic functional diversity (Hf) between 0.1 and 1.26, 5) abundance of macrobenthos (N) between

Table 2. Biotic and environmental data at the various sites. S: number of macrobenthic species; H′: benthic diversity; H′f: benthic functional diversity; BB: biomass of benthic fauna; SwB: biomass of seaweeds; Sg: seagrass (always absent).

Stn	S	Abundance (ind m^{-2})	H′	H′f	BB (gAFDWm^{-2})	SwB (gWWm^{-2})	Sg	FINE	Trasp (m)	O2 (mg l^{-1})	Ntot (mg l^{-1})	Ptot (g l^{-1})	Ni (mg kg^{-1})	Cr (mg kg^{-1})	Pb (mg kg^{-1})
A1	13	9225	1.04	0.65	7.3	25.5	abs	39.6	0.7	9.5	3.8	42.7			
B1	16	6216	1.68	0.92	1.4	29.5	abs	52.8	1.5	10.4	3	30			
C1	18	15232	1.53	1.02	29.3	1352.8	abs	62.5	1.5	10.9	3	30			
E1	5	456	1.31	0.70	1.4	0	abs	26.5	0.8	8.6	3.7	54.4			
F1	19	122532	0.59	0.39	61.6	0	abs	48.7	0.7	9	4	45.6			
G1	11	6167	0.59	0.44	22.4	0	abs	49.3	1	9.1	3.6	39.7			
H1	4	604	0.89	0.27	0.6	0	abs	15.3	0.6	4.2	5.9	66.2			
A2	6	4477	0.58	0.52	5.8	0.0	abs	32.7	0.6	7	4.2	57.4			
B2	5	173	1.13	0.90	2.0	186.5	abs	18.5	0.6	6.8	3.9	42.7			
C2	11	3416	1.26	0.82	20.3	86.3	abs	61.1	1.1	7.9	2.1	30			
E2	9	2997	1.17	0.81	9.0	0	abs	50.1	0.4	6.9	4	38.2			
F2	14	11014	1.57	0.91	32.8	0	abs	57.5	0.6	7	5.9	35.3			
G2	16	5723	1.96	1.27	21.7	0	abs	74.6	0.8	9	3.8	38.8			
H2	6	136	1.67	1.12	0.8	0	abs	32.4	0.3	6.5	6.3	35.3			
A3	6	2306	0.49	0.27	0.2	0.0	abs	28.7	0.8	5.4	3.9	75	83.6	64.1	18.6
B3	11	1591	1.57	1.01	0.9	864.3	abs	41.4	0.9	6.3	2.5	58.8	87.1	81.3	29.2
C3	6	2047	0.67	0.55	1.6	58.7	abs	24.9	0.6	4.5	5.7	51.5	83.7	86.2	42.4
E3	6	1591	1.12	0.89	5.0	0	abs	24.5	0.3	7	5.2	60.3			
F3	13	5488	1.89	1.01	66.9	0	abs	63.7	0.7	6.6	4	42.4	44.5	36.3	14.5
G3	15	5784	1.73	1.24	55.0	0	abs	74.5	0.8	10	3.5	42.7	35.1	28.4	14.4
H3	3	1443	0.82	0.33	1.9	0	abs	16.3	0.3	6.3	5.9	57.4			
A4	13	55241	1.03	0.5	5.7	0	abs	31.8	0.5	3.3					
B4	11	5834	1.05	0.64	0.75	449	abs	42.2	0.7	4.6					

C4	18	4724	1.7	1.03	4.71	1759	abs	56.1	0.9	5.6			
E4	8	3392	1.42	0.93	4.9	0	abs	47.7	0.4	7.9			
F4	7	8485	1	0.67	1.74	0	abs	25.8	0.4	7.5			
G4	5	1961	0.89	0.45	0.23	0	abs	21.9	0.4	7			
H4	4	4366	0.42	0.26	0.63	0	abs	32.7	0.4	8.4			
A5	5	1085	1.17	1.07	0.52	60.1	abs	28.8	1	7.2	103.5	79.3	24.6
B5	4	74	1.33	1.01	59.6	1.85	abs	32.1	1	7.3	85.3	68.6	23.3
C5	6	8078	0.99	0.48	1.59	0	abs	26.9	1	6.1	94.2	85.2	38.9
E5	7	8313	0.88	0.6	0.96	0	abs	26.4	0.3	8.3			
F5	13	26948	1.29	0.7	2.13	0	abs	39.4	0.3	8.5			
G5	17	157201	1.24	0.39	7.91	0	abs	40	0.3	9.1			
H5	4	4724	0.72	0.69	0.45	0	abs	32.7	0.3	9.2			
A6	5	27972	0.13	0.1	0.84	0	abs	25.4	1.3	6.6			
B6	21	16218	1.71	1.01	2	0	abs	49.5	1.5	9.9			
C6	19	27750	1.15	0.88	45.6	773	abs	52.4	1.3	9.9			
E6	8	5414	1.45	0.82	9.1	0	abs	51.7	0.3	5.5	68.1	41.1	22.2
F6	7	12161	1.03	0.86	0.61	0	abs	29.9	0.3	5.1	68.6	50.1	23.1
G6	15	33645	1.75	1.26	36.41	0	abs	69	0.7	6.7	70.5	40.5	17.6
H6	6	9225	0.74	0.52	0.45	0	abs	25.5	0.4	2.8	94.3	83.6	31.5
E7	4	4884	0.7	0.45	1.44	0	abs	32.7	0.4	8.5			
F7	17	40318	1.59	0.62	11.62	0	abs	50	0.4	8.7			
G7	4	1344	1	0.94	35.74	0	abs	35.4	0.4	8.1			
H7	4	5673	0.72	0.47	2.81	0	abs	32.6	0.4	8.4			

74 and 157201 ind m^{-2}, (6) number of macrobenthic taxa (S) between 4 and 21. Seagrass were always absent. The gradient of impact represented by the data set ranged from BAD (FINE = 16.3) at H3, characterized by an extremely depauperated benthic community, to GOOD (FINE = 74.6), at G2. A range of successional phases of the benthic community were also comprised in the data set (table 2).

Environmental data also varied greatly, depending on station and season. Considering water parameters, transparency ranged between 0.3 and 1.5 m, dissolved oxygen between 2.8 and 10.9 mg l^{-1}, nitrogen between 2.1 and 7.3 mg l^{-1}, phosphorous between 216.7 and 30 $\mu g\, l^{-1}$. Considering sediments, Cr ranged between 28.4 and 46.2 mg kg^{-1} dry weight, Ni between 35.1 and 103.5 mg kg^{-1} d.w., Pb between 14.4 and 38.9 mg kg^{-1} d.w., As between 4.8 and 14.8 mg kg^{-1} d.w., and finally PCB between 1.9 and 4.6 $\mu g\, kg^{-1}$ d.w. (as sum of congeners). Table 2 reports water and sedimentary chemical data at the various stations. Figure 4 shows the relationship between water chemical parameter values and FINE values for the selected stations during years 2004 and 2005. Figure 5 shows the relationship between sedimentary heavy metals concentration and FINE values in 2004 and 2005, and PCB concentration and FINE for year 2005 only. Regression ANOVAs were highly significant, and are summarized in table 3. A positive correlation was found between FINE values and dissolved oxygen, and negative correlations between FINE and all the other chemical parameters. In table 4, results of regression ANOVAs between FINE basic parameters and water and sedimentary variables are shown. A negative correlation was found between nitrogen and S, while phosphorous correlated negatively with S, H' and Hf. Dissolved oxygen correlated positively with S and BB, while transparency correlated positively with S but negatively with SwB. Significant negative correlations were found between heavy metals and S, H' and benthic biomass, while PCB correlated negatively with all macrobenthic basic parameters. In the table, only significant results are shown.

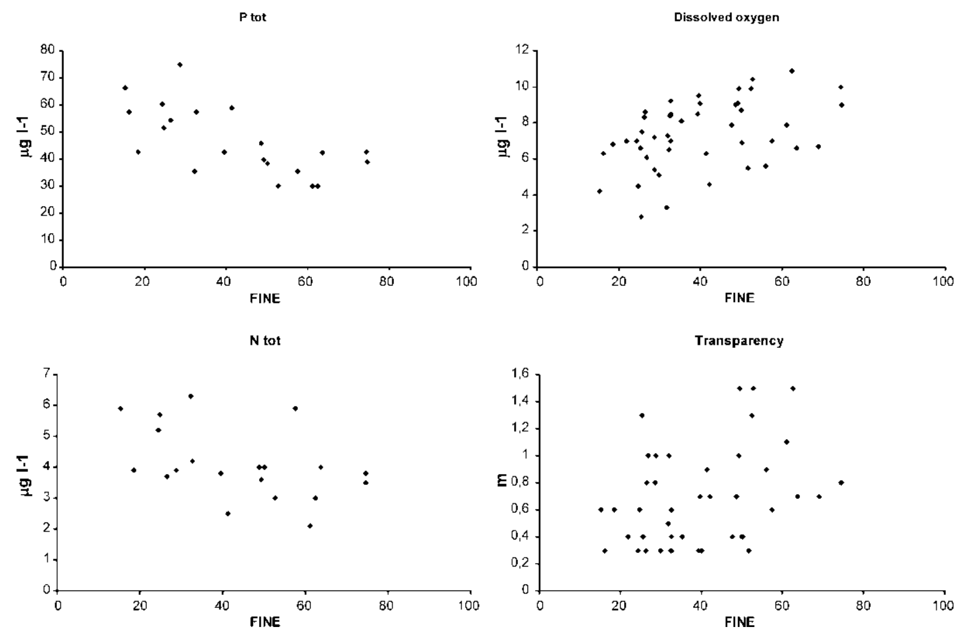

Figure 4. Relationship between water chemical parameter values and FINE values for the selected stations during years 2004 and 2005.

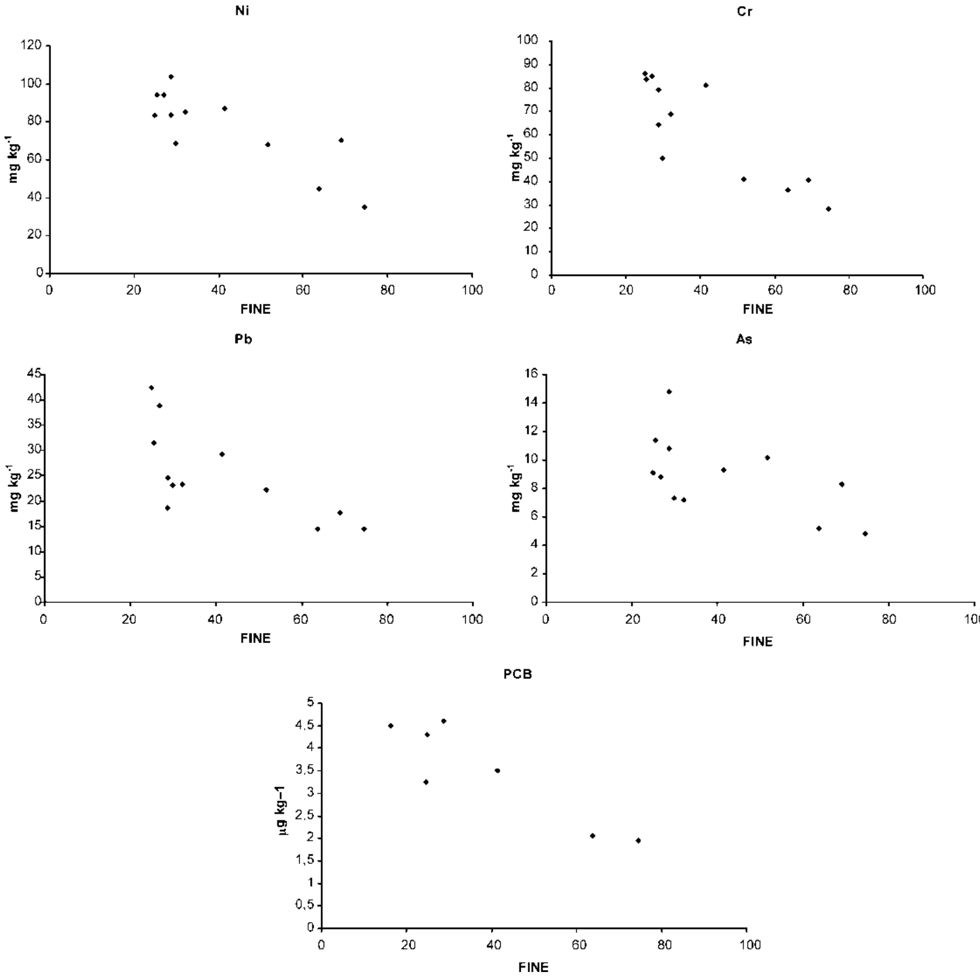

Figure 5. Relationship between sedimentary heavy metals concentration and FINE values in 2004 and 2005, and PCB concentration and FINE for year 2005 only.

Table 3. Regression coefficients and regression ANOVAs between FINE scores and values of chemical parameters.

Chemical parameter	r	df	F	p
Ntot	−0.46	1, 18	4.8	0.041
Ptot	−0.66	1, 18	14.9	0.001
Trasp	−0.37	1, 44	6.9	0.012
O2	−0.43	1, 44	9.9	0.003
Ni	−0.83	1, 10	21.8	0.001
Cr	−0.85	1, 10	26.9	0.001
Pb	−0.71	1, 10	9.9	0.010
As	−0.59	1, 10	5.3	0.044
PCB	−0.90	1, 5	22.2	0.005

Table 4. Regression ANOVAs chemical variables and FINE basic parameters.

		F	df	p
Transp	S	11.23	1, 44	0.002
	SwB	8.23	1, 44	0.006
O2	S	9.19	1, 44	0.004
	BB	4.29	1, 44	0.004
Ntot	S	6.3	1, 19	0.021
Ptot	S	11.96	1, 19	0.003
	H′	8.09	1, 19	0.01
	Hf	9.99	1, 19	0.006
Ni	S	12.87	1, 10	0.005
	H′	6.52	1, 10	0.029
	BB	8.89	1, 10	0.014
Cr	S	10.07	1, 10	0.01
	H′	7.74	1, 10	0.019
	BB	6.74	1, 10	0.027
Pb	S	4.6	1, 10	0.05
	H′	5.14	1, 10	0.047
	BB	6.08	1, 10	0.033
As	S	4.87	1, 10	0.05
	BB	11.04	1, 10	0.007
PCB	S	18.59	1, 5	0.008
	N	12.45	1, 5	0.017
	H′	28.81	1, 5	0.003
	Hf	24.52	1, 5	0.004
	BB	20.43	1, 5	0.006

4. Discussion

In order to achieve the classification of EcoQ in water bodies, the WFD requires the identification of reference conditions for that type of surface water at a HIGH status, *i.e.* sites with no, or with only a very minor, impact from human activities. A major problem in deriving reference conditions arises from the absence, in some European regions, of unimpacted areas [29]; this is the case of the northern Adriatic coastal environment. In the absence of pristine/undisturbed sites, the WFD identifies three alternative options for deriving reference conditions for HIGH status: historical data and information, models or expert judgement. Some efforts have been recently carried out in this direction by means of multivariate methods [13, 15]: first, some metrics are chosen; then a site is considered in an optimal ecological status when presenting the 'best' values of all the selected metrics, whereas it is considered in the worst ecological status when all metrics display their worst values [15]. FINE has a one-dimensional output ranging from 0 to 100, which synthesizes the multi-dimensional information provided by the combination of 7 biological variables (metrics). $FINE_{100}$ corresponds to the optimal conditions for all variables, whereas $FINE_0$ indicates that all the variables are displaying their worst modality; therefore, $FINE_{100}$ and $FINE_0$ can be regarded as reference for HIGH and BAD EcoQ, respectively. $FINE_{100}$ is derived from a fuzzy model, which is based on expert knowledge; therefore, it complies with the indications of the WFD. FINE one-dimensional output (0–100) is consistent with previous works [19]. However, taking into account that the WFD works with EQR values in the interval 0–1, FINE output will range between 0 and 1 by simply changing the factors of the FINE formula by 0.25, 0.5, 0.75 and 1.

The creation of quality indices naturally involves the incorporation of a certain amount of subjective knowledge that can be expressed, for example, in the definition of crisp boundaries, or in the assignment of species to ecological groups [30]. In the FINE index development we tried to restrict subjectivity to (a) choice of the input and output variables, and (b) design of the fuzzy functions relative to their modalities. The association of each variable modality to an ecological status is then based on universally accepted ecological principles, like: 'high diversity = high quality'. These general principles drive the 768 inference rules, which are automatically calculated from the fuzzy membership functions [27]: external interventions are not required in this assessment, thus the total amount of subjectivity is reduced.

While most of the recently developed indices have been calibrated for coastal habitats, FINE was specifically designed for the evaluation of Adriatic transitional ecosystems and considers attributes which are known to play major roles in the functioning of such ecosystems. Unlike the indices based on sensitivity/tolerance of species, e.g. [2, 3, 11], the rationale of FINE is that certain attributes, selected on the basis of established principles of benthic ecology, are fundamental for transitional ecosystem function: FINE is composed of 7 ecosystem attributes each of which have ecological relevance for transitional ecosystems. The strength of our model is appealing, but it must be acknowledged that the model was built specifically for Adriatic transitional ecosystems, incorporating only the variability observed within those systems.

In this paper, FINE has been tested in two northern Adriatic lagoons using chemical parameters, such as dissolved oxygen, total nitrogen, and total phosphorous in the water column, and metals and PCB concentration in the sediments. Results showed a high correlation between the concentration of chemical parameters and FINE quality scores. Higher EcoQ was always associated with lower contamination. FINE, in this specific case study, succeeded in producing an ecologically relevant classification, reflecting the environmental pressures as expressed in the chemical elements. Its basic parameters, taken one by one, did not show such an unequivocal response to environmental pressures, thus confirming the advantages of the FINE model when compared to the use of single measures for environmental assessment. The FINE index resulted in a ecologically and methodologically sound model structure that could have a wider validity and applicability in different lagoons from different geographical areas, given that a pre-emptive calibration of the input and output fuzzy functions is made on the basis of site-specific information and historical knowledge. The FINE model includes seaweeds, seagrass and benthos. The WFD states the need to evaluate each element separately, in order to determine the impacts from different pressures over each of the elements, and this cannot be assessed when all of them are evaluated together, as in FINE. This could be one of the limitations of our model.

Acknowledgements

This study was partially supported by MIUR, in the framework of NITIDA, and partially by Consorzio Parco Delta Po ER, in the framework of WETLANDS II. Dr Francesco Ghion (ARPA ER) is greatly acknowledged for sharing chemical data. Two anonymous reviewers provided constructive criticism that greatly improved the quality of the manuscript.

References

[1] F. Salas, C. Marcos, J.M. Neto, J. Patricio, A. Perez-Ruzafa, J.C. Marques. User-friendly guide for using benthic ecological indicators in coastal and marine quality assessment. *Ocean Coast. Manag.*, **49**, 308 (2006).

[2] Á. Borja, J. Franco, V. Pérez. A marine biotic index to establish the ecological quality of soft-bottom benthos within European estuarine and coastal environments. *Mar. Poll. Bull.*, **40**, 1100 (2000).

[3] N. Simboura, A. Zenetos. Benthic indicators to use in ecological quality classification of Mediterranean soft bottom marine ecosystems, including a new biotic index. *Medit. Mar. Sci.*, **3**, 77 (2002).

[4] R. Rosenberg, M. Blomqvist, H.C. Nilsson, H. Cederwall, A. Dimming. Marine quality assessment by use of benthic species-abundance distribution: a proposed new protocol within the European Union Water Framework Directive. *Mar. Poll. Bull.*, **49**, 728 (2004).

[5] M. Ponti, M. Abbiati. Quality assessment of transitional waters using a benthic biotic index: the case study of the Pialassa Baiona (Northern Adriatic Sea). *Aquatic Conserv: Mar. Freshw. Ecosyst.,* **14**, S31 (2004).
[6] L. Marin-Guirao, A. Cesar, A. Marin, J. Lloret, R. Vita. Establishing the ecological quality status of soft-bottom mining-impacted coastal water bodies in the scope of the Water Framework Directive. *Mar. Poll. Bull.*, **50**, 374 (2005).
[7] N. Simboura, P. Panayotidis, E. Papathanassiou. A synthesis of the biological quality elements for the implementation of the European Water Framework Directive in the Mediterranean ecoregion: the case of Saronikos Gulf. *Ecol. Indicators,* **5**, 253 (2005).
[8] C. Labrune, J.M. Amouroux, R. Sarda, E. Dutrieux, S. Thorin, R. Rosenberg, A. Grémare. Characterization of the ecological quality of the coastal Gulf of Lions (NW Mediterranean). A comparative approach based on three biotic indices. *Mar. Poll. Bull.*, **52**, 34 (2006).
[9] J.-C. Dauvin, T. Ruellet, N. Desroy, A.-L. Janson.The ecological quality status of the Bay of Seine and the Seine estuary: use of biotic indices. *Mar. Poll. Bull.*, **55**, 241 (2007).
[10] M.L. Zettler, D. Schiedek, B. Bobertz. Benthic biodiversity indices versus salinity gradient in the southern Baltic Sea. *Mar. Poll. Bull.*, **55**, 258 (2007).
[11] S. Orfanidis, P. Panayotidis, N. Stamatis. Ecological evaluation of transitional and coastal waters: a marine benthic macrophytes-based model. *Medit. Mar. Sci.*, **2**, 45 (2001).
[12] J.J. Breine, J. Maes, P. Quataert, E. Van den Bergh, I. Simoens, G. Van Thuyne, C. Belpaire. A fish-based assessment tool for the ecological quality of the brackish Schelde estuary in Flanders (Belgium). *Hydrobiologia,* **575**, 141 (2007).
[13] S. Coates, A. Waugh, A. Anwar, M. Robson. Efficacy of a multi-metric fish index as an analysis tool for the transitional fish component of the Water Framework Directive. *Mar. Poll. Bull.*, **55**, 225 (2007).
[14] M. Devlin, M. Best, D. Coates, E. Bresnan, S. O'Boyle, R. Park, J. Silke, C. Cusack, J. Skeats. Establishing boundary classes for the classification of UK marine waters using phytoplankton communities. *Mar. Poll. Bull.*, **55**, 91 (2007).
[15] J. Romero, B. Martínez-Crego, T. Alcoverro, M. Pérez. A multivariate index based on the seagrass *Posidonia oceanica* (POMI) to assess ecological status of coastal waters under the water framework directive (WFD). *Mar. Poll. Bull.*, **55**, 196 (2007).
[16] E. Wells, M. Wilkinson, P. Wood, C. Scanlan. The use of macroalgal species richness and composition on intertidal rocky seashores in the assessment of ecological quality under the European Water Framework Directive. *Mar. Poll. Bull.*, **55**, 151 (2007).
[17] J.-C. Dauvin. Paradox of estuarine quality: benthic indicators and indices, consensus or debate for the future. *Mar. Poll. Bull.*, **55**, 271 (2007).
[18] S. Sagert, D. Krause Jensen, P. Henriksen, T. Rieling, H. Schubert. Integrated ecological assessment of Danish Baltic Sea coastal areas by means of phytoplankton and macrophytobenthos. *Estuar. Coast. Shelf Sci.,* **63**, 109 (2005).
[19] M. Mistri, A. Marchini. The Fuzzy Index of Ecosystem Integrity (FINE): a new indicator of environmental integrity for lagoonal ecosystems. *Hydrobiologia*. In press.
[20] A. Salski, O. Franzle, P. Kandzia. Fuzzy logic in ecological modelling. *Ecol. Model.*, **85**, 1 (1996).
[21] W. Silvert. Ecological impact classification with fuzzy sets. *Ecol. Model.*, **96**, 1 (1997).
[22] W. Silvert. Fuzzy indices of environmental conditions. *Ecol. Model.*, **130**, 111 (2000).
[23] M. Enea, G. Salemi. Fuzzy approach to the environmental impact evaluation. *Ecol. Model.*, **136**, 131 (2001).
[24] R.S. Lu, S.L. Lo. Diagnosing reservoir water quality using self-organizing maps and fuzzy theory. *Water Res.*, **36**, 2265 (2002).
[25] S.-M. Liou, S.-L. Lo, C.-Y. Hu. Application of two-stage fuzzy set theory to river quality evaluation in Taiwan. *Water Res.*, **37**, 1406 (2003).
[26] V. Adriaenssens, B. De Baets, P.L.M. Goethals, N. De Pauw. Fuzzy rule-based models for decision support in ecosystem management. *Sci. Tot. Envir.*, **319**, 1 (2004).
[27] A. Marchini, C. Marchini. A fuzzy logic model to recognise ecological sectors in the lagoon of Venice based on the benthic community. *Ecol. Model.,* **193**, 105 (2006).
[28] D.L. Angel, P. Krost, W.L. Silvert. Describing benthic impacts on fish farming with fuzzy sets: theoretical background and analytic methods. *J. Appl. Ichthyol.,* **14**, 1 (1998).
[29] Á. Borja, J. Franco, V. Valencia, J. Bald, I. Muxika, M.J. Belzunce, O. Solaun. Implementation of the European water framework directive from the Basque country (northern Spain): a methodological approach. *Mar. Poll. Bull*. **48**, 209 (2004).
[30] Á. Borja. The biotic indices and the Water Framework Directive: the required consensus in the new benthic monitoring tools. *Mar. Poll. Bull.*, **48**, 405 (2004).
[31] EC. Common implementation strategy for the WFD (2000/60/EC). Guidance Document n. 5. Transitional and Coastal Waters. Tipology, reference conditions and classification systems. Working Group 2.4-COAST (2003).
[32] ARPA-ER. Annuario Regionale dei Dati Ambientali (2002–2005).Edizione 2006. ARPA Emilia Romagna, 658 pp. (2006).