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Development of categorical mapping for quantitative assessment of eutrophication

Kitsiou, D.* **& Karydis, M.**

Aquatic Ecosystem Laboratory, Department of Environmental Studies, University of the Aegean, 81100 Mytilene, Greece;
**Author for correspondence; Tel. + 30 251 21286; Fax + 30 251 23783; E-mail dkit@env.aegean.gr*

Abstract. Spatial distribution of nutrient and phytoplankton variables is often illustrated using categorical mapping for each variable. However, the assessment of eutrophication cannot be derived from a single parameter since a synthesis of the environmental variables related to eutrophication is required. These shortcomings are further complicated since it is difficult to discriminate between distinct trophic states along natural environmental gradients. In the present work, a methodological procedure for quantitative assessment of eutrophication at a spatial scale was examined in the Gulf of Saronicos, Greece, based on a thematic map generated from the synthesis of four variables characterising eutrophication. The categorical map of each variable was developed using the Kriging interpolation method and four trophic levels were indicated (eutrophic, upper-mesotrophic, lower-mesotrophic and oligotrophic) based on nutrient and phytoplankton concentration scaling. Multi-criteria choice methods were applied to generate a final categorical map showing the four trophic levels in the area. This synthesis of categorical maps for assessing eutrophication at a spatial scale is proposed as a methodological procedure appropriate for coastal management studies.

Keywords: Coastal management; Inorganic nutrient; Marine eutrophication; Multiple criteria evaluation method; Phytoplankton; Thematic map.

Introduction

Coastal eutrophication has become a serious problem over the past three decades (Rosenberg 1985) due to the growth of the human population in the coastal zone. As a result, the inputs of nitrogen and phosphorus from agricultural and industrial activities as well as from domestic sewage have been increased (Tivy & O'Hare 1981; Anon. 1984). Consequently, eutrophication has become an acute environmental problem especially in semi-enclosed areas and gulfs with little water exchange with surrounding areas (Gray 1992). Many studies have been carried out to quantify eutrophication, using a number of parameters related to the phenomenon (Colombo et al. 1992; Vollenweider 1992). The use of nutrient concentrations for classifying coastal waters into oligotrophic, mesotrophic and eutrophic was established a long time ago (Rodhe 1969) and many attempts have been made to define concentration ranges for these trophic levels (Giovanardi & Tromellini 1992a; Ignatiades et al. 1992b; Karydis 1996).

A similar approach has been reported for estimators of phytoplankton taxonomy, diversity and biomass (Karydis & Tsirtsis 1996) in spite of the complex interrelations among these variables (Ignatiades et al. 1992a) and the large number of ecological indices used in water quality studies (Washington 1984). The large number of variables used to describe eutrophication complicates the quantitative assessment at a spatial scale since different variables tend to give different horizontal distributions (Okubo 1978; Therriault & Platt 1978; Steele & Henderson 1979; Powell et al. 1989). Nutrient loads tend to homogenize environmental gradients (Giovanardi & Tromellini 1992b) whereas phytoplankton parameters show spatial heterogeneity or patchiness (Platt et al. 1970; Mukai 1987; Li & Reynolds 1994). The different horizontal distribution patterns of the various eutrophication parameters renders the characterization of water quality at a spatial scale very difficult.

The purpose of the present study is to propose a methodological procedure for generating maps illustrating eutrophication at a spatial scale, based on nutrient and phytoplankton thematic maps, where the different trophic levels (eutrophic, upper-mesotrophic, lower-mesotrophic, oligotrophic) are clearly defined. The importance of the map synthesis in marine pollution studies and coastal management is discussed.

Material and Methods

Study area

The Gulf of Saronicos with an area of ca. 3000 km^2, can be divided into a western and eastern part (Fig. 1). The eastern part, also known as the inner Gulf of Saronicos, is a relatively shallow basin (maximum depth 100m) surrounded by the islands Aegina and Salamina.

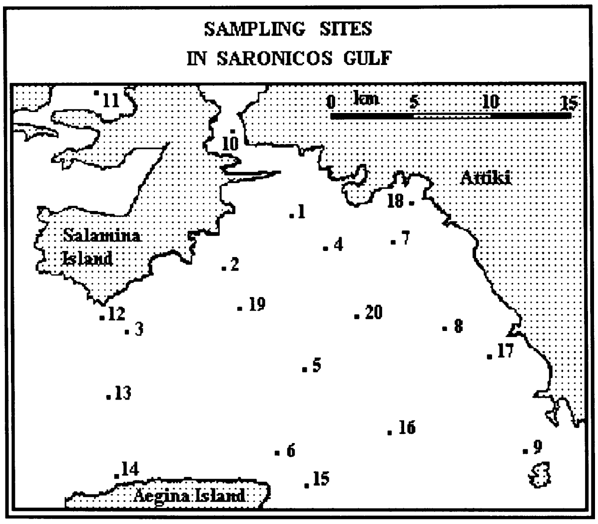

Fig. 1. Sampling sites in the Gulf of Saronicos, Greece.

The present study is concerned with the inner Gulf which receives sewage effluents from the metropolitan area of Athens. The water renewal takes place mainly through an opening about 18 km wide between the island of Aegina and the coast of Attiki.

Selection of parameters and source of data

Four parameters were selected for the development of categorical maps describing different levels of eutrophication. Previous work in quantitative assessment of eutrophication has shown that phosphate, nitrate and ammonia were sensitive in characterizing different eutrophic levels in the marine environment (Moriki & Karydis 1994) and that nitrite is not (Karydis 1996). Similar work on chlorophyll and phytoplankton cell number (Tsirtsis & Karydis in press) has shown that these two parameters were highly inter-correlated and therefore phytoplankton cell number was finally selected (Karydis & Tsirtsis 1996).

A survey performed in the Gulf of Saronicos, Greece during the period 1980-1982 for assessing the eutrophic state of the area formed the source of data for phosphate, nitrate, ammonia and phytoplankton cell number used for the development of the methodology described in the present work (Ignatiades et al. 1982; Ignatiades et al. 1983; Ignatiades 1984; Karydis & Corsini 1985). The data set was derived from samples collected from 20 stations (Fig.1) at 1m depth during the stratification period (April - September).

Phosphate determinations were carried out spectrophotometrically. The method is based on the formation of a phosphomolybdate complex and its subsequent reduction to highly coloured blue compounds. The method is described by Parsons et al. (1989). Nitrate was determined as follows: a cadmium- copper column was used to reduce nitrate to nitrite and nitrous acid was converted to a highly coloured azo dye (Parsons et al. 1989). Phytoplankton cell counting was carried out microscopically using a Leitz inverted epifluoremeter (Lund et al. 1988). The samples were fixed with lugol iodine. Ten or 20 ml aliqots were used for phytoplankton enumeration. These figures were extrapolated to numbers/l. The mean values of four parameters (phosphate, nitrate, ammonia, phytoplankton cell number) are shown in Table 1.

Data analysis

The generation of the four thematic maps (phosphate, nitrate, ammonia, phytoplankton cell number) was based on the application of the Kriging interpolation method (Lancaster & Salkauskas 1986). Kriging is an exact interpolator in the sense that the interpolated values will coincide with the values at the data points (Burrough 1996). The surface to be interpolated is regarded by this method as a regionalized variable that has a certain degree of continuity (Lam 1983). The Regionalized Variable Theory where Kriging is based, assumes a constant local mean and a stationary variance of the differences between places separated by a given distance and direction (Oliver & Webster 1990). This constitutes Matheron's (1965) Intrinsic Hypothesis. It is therefore assumed that:

(1) the expected difference between any two places **x** and **x** + **h** separated by a distance vector **h**, known as

Table 1. Mean values for phosphate, nitrate, ammonia and phytoplankton cell number, during the period of stratification (April - September), in the surface layer of the Gulf of Saronicos.

		Parameters		
Sampling Stations	Phosphate (µg-at P/l)	Nitrate (µg-atN/l)	Ammonia (µg-atN/l)	No. of cells/l
1	0.84	0.85	4.09	1485000
2	0.34	0.74	1.30	1636 000
3	0.09	0.45	0.93	198 000
4	0.15	0.59	1.14	302000
5	0.12	0.26	1.10	445 000
6	0.12	0.79	1.07	198 000
7	0.09	0.19	1.22	348 000
8	0.12	0.17	1.00	450000
9	0.08	0.60	0.91	502 000
10	1.48	3.28	5.50	1.4×10^9
11	0.23	1.71	1.15	1.15×10^9
12	0.13	0.79	0.85	117000
13	0.11	0.37	0.68	84500
14	0.11	0.85	0.87	74000
15	0.13	0.53	0.86	-
16	0.13	0.95	0.95	-
17	0.15	0.24	0.53	-
18	0.35	0.43	0.78	1708000
19	0.12	1.22	1.11	214000
20	0.12	0.50	0.62	106000

lag, will be zero $E\ [Z(\mathbf{x}) - Z(\mathbf{x}+\mathbf{h})] = 0$ and (2) the variance of differences depends only on the distance between sites (**h**), in a way that:

$$\mathrm{var}[Z(\mathbf{x}) - Z(\mathbf{x}+\mathbf{h})] = E[\{Z(\mathbf{x}) - Z(\mathbf{x}+\mathbf{h})\}^2] = 2\gamma(\mathbf{h}) \quad (1)$$

where $\gamma(\mathbf{h})$ is a function known as semivariance (Burrough 1996).

When the above assumptions are met, the function which relates γ to **h** and is given by the expression

$$\gamma(\mathbf{h}) = \frac{1}{2n} \cdot \sum_{i=1}^{n} \left\{ Z(\mathbf{x}_i) - Z(\mathbf{x}_i + \mathbf{h}) \right\}^2 \qquad (2)$$

where n is the number of pairs of observations separated by the lag **h**, is called experimental variogram and contains all the useful information about the spatial variation of the property, summarising the general form of the variation, its magnitude and spatial scale (Oliver & Webster 1990). This function is expected to increase as the distance between samples increases taking a value close to zero for small distances, and becoming a constant for distances larger than the zone of influence or range (Lam 1983).

To render the experimental variogram useful in the Kriging interpolation method, it must be fitted by a theoretical model. Consequently, a fitted or theoretical variogram is produced. There is a variety of models which could fit the experimental variogram. These most often used are the spherical, the exponential, the Gaussian and the power model (Pannatier 1996).

The expression used to predict the value at an unvisited point $\mathbf{x}_0$ is the following:

$$\hat{\mathbf{Z}}(\mathbf{x}_0) = \sum_{i=1}^{n} \lambda_i Z(\mathbf{x}_1) \qquad (3)$$

where $Z(\mathbf{x}_i)$ are the data values at points $\mathbf{x}_i$ and λ_i the weights needed for local interpolation with

$$\sum_{i=1}^{n} \lambda_1 = 1 \qquad (4)$$

The Kriging weights λ_i are determined by the variogram and the configuration of the data and are chosen to minimise the estimation variance (Cressie 1990).

Some preliminary data processing was carried out before the application of the Kriging interpolation method: (a) Exclusion of outliers (Barnett & Lewis 1987) and (b) Square root transformation was applied to the original data to reduce the range of the values for the phytoplankton cell number parameter. Thereafter, Kriging was applied with a spatial resolution of 100m ×100m and the thematic maps were produced using the program Arc-Info, version 6.1.1 (ARC-INFO-Version 6.1.1 - Environmental Systems Research Institute, Inc). The values of each generated continuous surface were categorised based on nutrient and phytoplankton concentration scaling (Ignatiades et al. 1992b) which is given in Table 2; four levels of eutrophication were defined on the thematic maps: eutrophic, upper-mesotrophic, lower-mesotrophic, oligotrophic.

Application of the multiple criteria evaluation method

The multiple criteria evaluation/choice methods are frequently used in the field of economics and policy analysis. Their principle is the classification of alternative choices on the basis of various criteria (Nijkamp & Voogd 1986). Multiple criteria evaluation offers a variety of methods, but all of them obey the same principle: the pairwise comparison of the values (scores) for all the alternatives and for each criterion (Nijkamp & Voogd 1986). In applications of multiple criteria methods concerning eutrophication (Moriki & Karydis 1994) the alternatives were the sampling sites and the criteria were the parameters used for eutrophication assessment. The scores form the Impact Matrix,

$$\text{Impact Matrix} = \begin{vmatrix} b_{11} & \ldots\ldots & b_{1j} \\ b_{i1} & \ldots\ldots & b_{ij} \end{vmatrix} \qquad (5)$$

where $\mathbf{b}_{ij}$ is the value (score) of alternative (sampling site) *i* according to the criterion *j*. In the case that $\mathbf{b}_{1j} > \mathbf{b}_{2j}$, the alternative I_1 dominates over the alternative I_2 as far as the *j*-criterion is concerned (Hartog et al. 1989). The main advantage of the multiple criteria method is their ability to deal with mixed qualitative and quantitative information (Nijkamp 1988); the regime multiple criteria method has also the advantage of assigning

Table 2. Eutrophication scaling based on nutrient (phosphate, nitrate, ammonia) and phytoplankton cell numbers. Oligotrophic, lower-mesotrophic, upper-mesotrophic and eutrophic ranges are given.

	Eutrophication Scaling			
Variable	Oligotrophic range	Lower-mesotrophic range	Upper-mesotrophic range	Eutrophic range
Phosphate (µg-atP/l)	0	0.07	0.14	0.68
Nitrate (µg-atN/l)	0	0.62	0.65	1.19
Ammonia (µg-atN/l)	0	0.55	1.05	2.20
Cell number (cells/l)	0	6×10^{3}	1.5×10^{5}	9.6×10^{5}

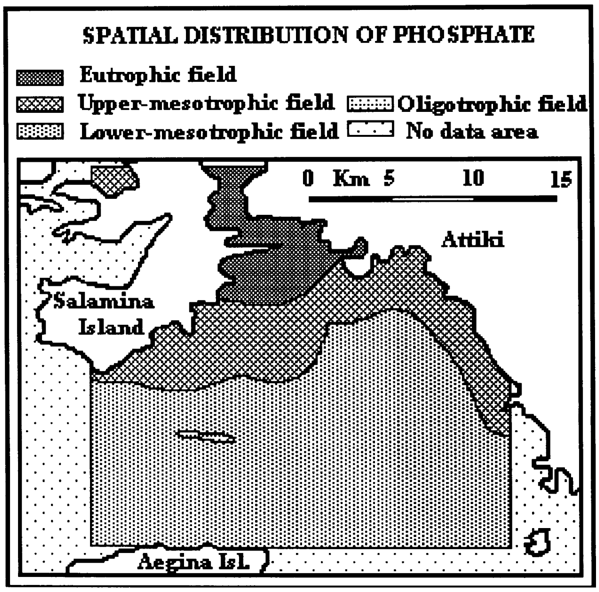

Fig. 2. Spatial distribution of phosphate in the surface layer of the Gulf of Saronicos.

weights to the criteria (Buckley 1988; Voogd 1988) and that was the reason for selecting it as a tool for assessing eutrophication in the present work.

According to the regime method, the pairwise comparison of the alternatives for each criterion results into the creation of regimes. The regimes are vectors of + and – signs that each alternative takes after the pairwise comparison with the rest of the alternatives. If the sign is + , alternative I_1 is preferred to I_2 and the reverse when the opposite holds true (Janssen 1991). If k is the total number of alternatives and λ the total number of criteria, there will be in total $k(k–1)$ regimes of λ dimension each. The matrix R with dimensions $k(k–1)^* \lambda$ is called Regime Matrix. If all the criteria are assigned the same weight, that means that they are all of equal importance, alternative I_1 dominates over the I_2 if the total number of + signs resulted after the comparison of I_1 with I_2, is larger than the total number of - signs. Then, the probability is computed that – given each regime – alternative i is more important than the other member of the pair. There are, therefore, formed $(k–1)$ probabilities for each alternative and the mean of these probabilities is the probability p_i alternative i wins a random pairwise comparison. The alternatives are then ranked according to diminishing values of their p_i. The alternative therefore with the highest value of p_i is considered to be the most important alternative (Janssen 1992).

In the present work, Saronicos Gulf was divided into 22 areas, 5295m ×4950m each. For each area, the mean of the interpolated values within its boundaries was calculated for every parameter. Each one of the 22 areas was therefore represented by only one value for each parameter examined. These values formed the criteria for the regime method, while the 22 areas formed the alternatives. The main objective of this methodology was the ranking of the 22 areas according to their eutrophic conditions, represented by the concentrations of the four parameters examined. The regime method was applied twice. During the first run all the criteria were given the same weights, that is they were considered of having equal priority. During the second run, weights/priorities were assigned to the criteria. The highest priority was given to the phytoplankton cell number as being the most representative parameter characterising eutrophication, the second highest weight was assigned to nitrate concentration as it represents a significant limiting factor in the phytoplankton's growth, the third to phosphate concentration and the last to ammonia concentration. Phosphate was determined spectrophotometrically (Parssons et al. 1989). Nitrate was determined using a cadmium-copper column to reduce nitrate to nitrite and nitrous acid was converted to a highly coloured azo dye. Phytoplankton cell counting was carried out microscopically using a Leitz inverted epifluoremeter (Lund et al. 1958). The samples were fixed with lugol iodine. Ten or twenty ml aliqots were used for phytoplankton enumeration.

The methodology applied resulted in the ranking of the 22 areas according to their eutrophic conditions, with the more polluted areas to be ranked first, followed by the areas with oligotrophic trends. The simple ranking of the areas according to the regime method without classification into different eutrophic levels (eutrophic, upper-mesotrophic, lower-mesotrophic, oligotrophic) is the main limitation of the method. Critical values for discriminating between these four eutrophic levels were drawn from the eutrophication scale given in Table 2.

Results

The spatial distribution of phosphate is given in Fig. 2. It was observed that the northern part of the Gulf where the dispersion field of sewage outfall of the metropolitan area of Athens is located, showed eutrophic trends. The upper-mesotrophic field extended in a narrow zone from the east coast of Salamina to the Attiki coast. The remaining area was characterised as lower-mesotrophic and only a very small part as oligotrophic. The horizontal spatial distribution of nitrate is illustrated in Fig. 3. It was observed that the eutrophic area is almost the same as that indicated by phosphate in Fig.2. The upper-mesotrophic and the lower-mesotrophic fields covered a limited area of the Gulf whereas, most of the Gulf was

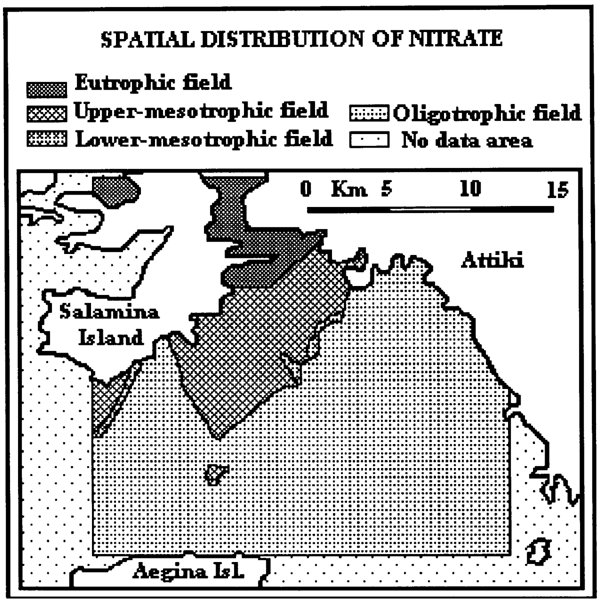

Fig. 3. Spatial distribution of nitrate in the surface layer of the Gulf of Saronicos.

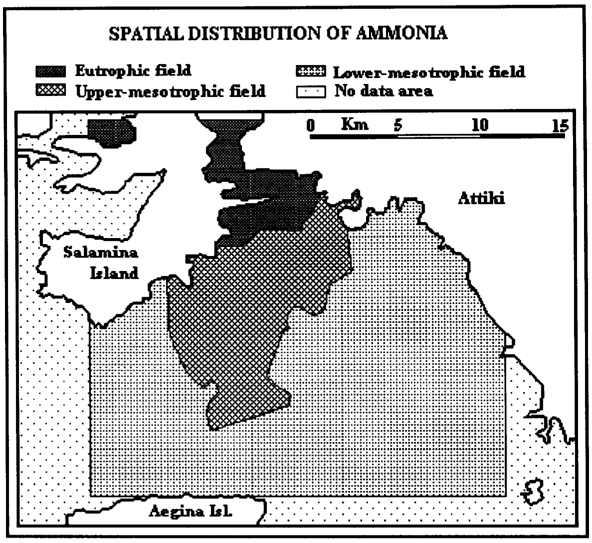

Fig. 4. Spatial distribution of ammonia in the surface layer of the Gulf of Saronicos.

characterised as oligotrophic according to the nitrate distribution. A similar pattern as far as the eutrophic field is concerned, is shown in Fig. 4. The area was dominated by the upper and lower-mesotrophic fields since oligotrophic waters were not indicated in ammonia horizontal distribution. The spatial distribution of phytoplankton cell number is given in Fig. 5. The eutrophic field covered a larger area compared to the field area of phosphate, nitrate and ammonia. The major part of the Gulf of Saronicos was characterised as upper-mesotrophic; the lower-mesotrophic field, being a limited area, was mainly located in the southwestern part and no oligotrophic field was observed.

It is also clear from the figures that the oligotrophic field was detected only through the distribution of nitrate, which covers a large area of the Gulf; in the distribution of the other variables the oligotrophic field was either too limited or non-existent. The categorical maps developed for the four variables examined illustrate the variation in the horizontal distribution patterns and define the boundaries of the four trophic states.

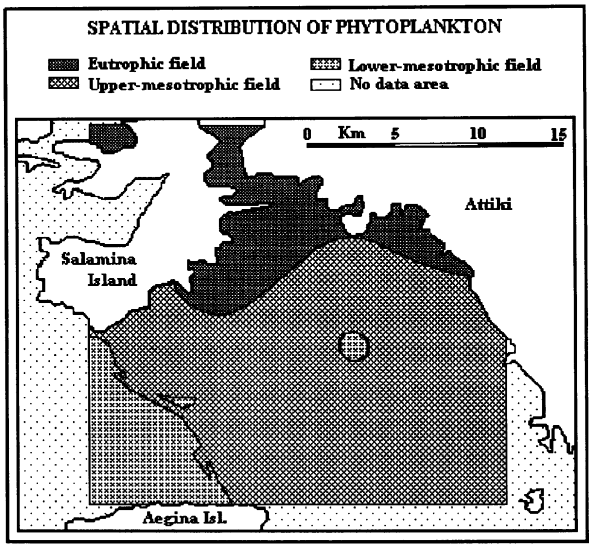

Fig. 5. Spatial distribution of phytoplankton cell number in the surface layer of the Gulf of Saronicos.

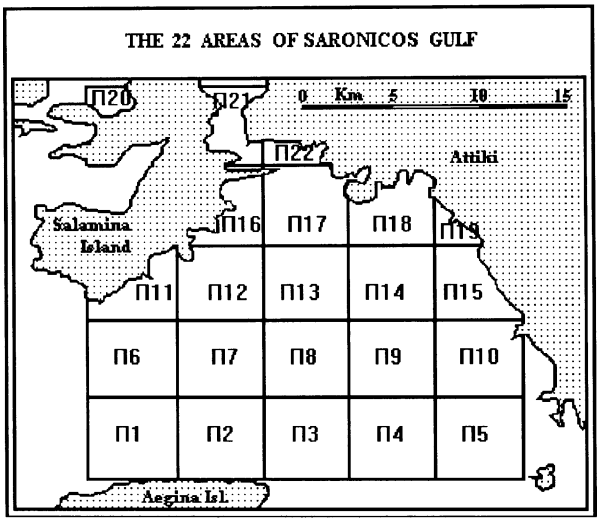

Fig. 6. Map showing the division of the inner Gulf of Saronicos into 22 subareas.

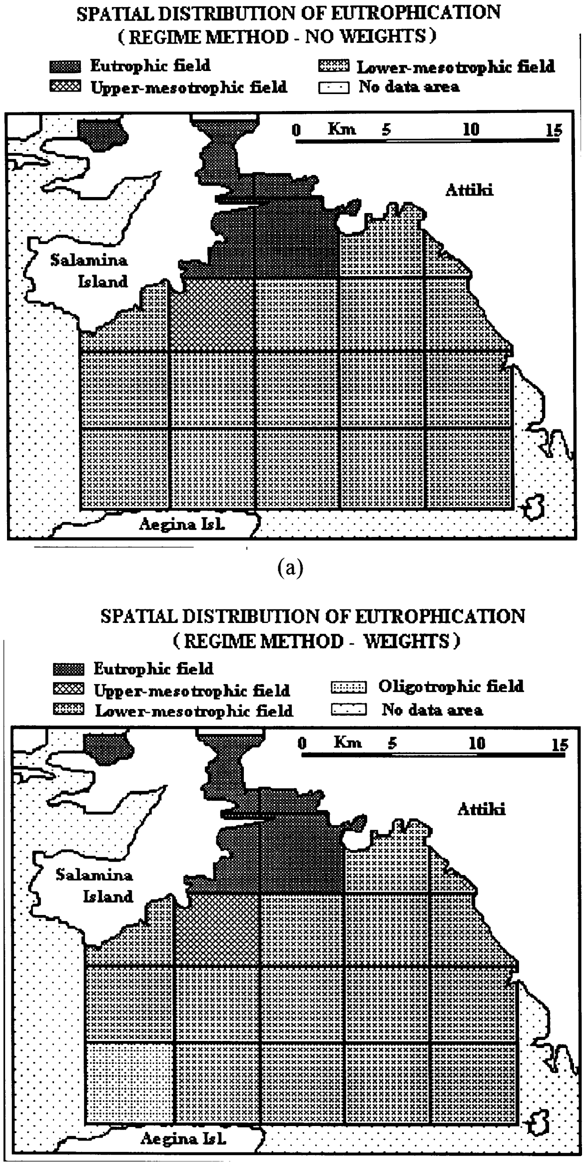

Fig. 7. Map generation of the Gulf of Saronicos showing the levels of eutrophication obtained with the regime multiple criteria choice method (**a**) without use of weights and (**b**) with use of weights.

The Gulf of Saronicos was successively subdivided into 22 areas about 5km ×5 km each, before the generation of the final maps. These areas are shown in Fig. 6; the mean values of phosphate, nitrate, ammonia and phytoplankton cell number were calculated for each area. The regime multiple criteria choice method was applied twice, once without use of weights and then with the use of weights. The map generation based on the regime method without the use of weights is given in Fig. 7a. It was observed that eutrophic waters were restricted to the area between Salamis Island and the mainland whereas upper-mesotrophic waters accounted for a small part of the Gulf in an area located south of Salamis Island. The remaining area was characterised as lower-mesotrophic. The application of the regime method with use of weights changed the eutrophic condition illustrated in Fig. 7b very little. The eutrophic field was indicated between Salamis and the mainland and the upper-mesotrophic field was limited to one square south to Salamis. However, the southwestern part of the grid area was indicated as oligotrophic.

Discussion and Conclusions

The study of spatial distribution of nutrients and phytoplankton variables characterising eutrophication is a complicated approach since the variables related to eutrophication show different spatial patchiness. Sewage outfalls enrich the marine environment with phosphate, nitrate, nitrite and ammonia that tend to disperse and induce increased phytoplankton cell number and chlorophyll a concentrations. Although these variables are interrelated (Ignatiades et al. 1985; Innamorati & Giovanardi 1992; Vukadin 1992) their horizontal distribution patterns are different, for a number of reasons: (1) There are different initial concentrations of nitrate, nitrite, ammonia and phosphorus in the raw sewage; (2) Ammonia is oxidized into nitrite and finally transformed into nitrate (Riley & Chester 1981); (3) Different uptake rates exist for the various nutrients (Raymont 1980); and (4) Phosphate ions are prone to be adsorbed by particulate material and are therefore distributed according to the dispersion mechanisms of suspended matter. On the other hand, the growth of phytoplankton is influenced by physical factors such as temperature and light transparency, chemical factors (organic matter and trace elements) and biological processes, mainly competition and grazing. These processes tend to favour spatial heterogeneity in the form of patchiness.

In spite of the differences in the horizontal distributions of inorganic nutrients and phytoplankton variables, all this information has to be taken into account if a general assessment of the eutrophic level of a coastal water body is required. Much research has been carried out so far on this complicated problem, using multivariate statistical analysis (Clarke & Green 1988; Clarke 1993; Clarke & Ainsworth 1993). In addition, multi-criteria choice methods have been used for the quantitative assessment of eutrophication (Moriki & Karydis 1994) due to a number of methodological advantages: (1) They are distribution-free, i.e. they do not depend on parametric procedures, neither do they require any other assumptions for the data; (2) Weights can be used if necessary so that the significance of certain variables can be adjusted; (3) They also integrate socio-economic information (Moriki et al. 1995) and they are therefore useful for decision makers and planners (Delft & Nijkamp 1977; Nijkamp et al. 1990). However, this type of research has been limited to the assessment of eutrophication levels of the sampling sites (Karydis 1992; Karydis 1996). The shortcoming of this approach is that the spatial information is discontinuous, since it is restricted to the sampling stations.

The present work combines methods of interpolation, used to generate categorical maps of continuous horizontal distributions of the variables under study, and multidimensional analysis. The synthesis of these two methodologies results in the generation of a final map that integrates information from the four thematic maps which were initially developed. In this way, the eutrophic status of an area is illustrated since, on the basis of the different loadings, the water bodies can be classified into oligotrophic, mesotrophic and eutrophic. This methodology is proposed for coastal management studies because of the simplicity and clarity in the presentation of eutrophic trends.

The step-by-step methodological procedure has been described using data from the Gulf of Saronicos as a case study. The following stages are involved: 1. Data manipulation may be required as a preliminary step such as detection and omission of outliers and/or data transformation to restrict the range of the values. 2. Interpolation of field data to produce continuous spatial surfaces for the examined parameters. At this stage, the Kriging interpolation method has been used with a spatial resolution of 100m × 100m. 3. Use of eutrophication scales based on nutrient concentrations and phytoplankton cell number. 4. Generation of thematic maps using the horizontal distributions and the eutrophication scaling. 5. Division of the maps into subareas (cells) in order to apply multidimensional analysis to the cell values. In the present study, the grid dimensions, ca. 5km × 5km, have been reported as the optimal approach in studies of the spatial heterogeneity of phytoplankton at the mesoscale level (Therriault & Platt 1978). In addition, the number of cells of the grid is manageable as far as the application of multi-criteria choice methods is concerned, which leads to sensible results without too much detail. 6. Calculation of the mean of the values within the boundaries of each cell/area of the grid for every parameter. 7. Formation of the final map based on the synthesis of the thematic maps, indicating eutrophication levels as a combination of all the variables used. The proposed methodology could possibly be applied to other forms of coastal pollution, finally providing an integrating approach for the quality of the marine environment.

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