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Eutrophication risk assessment in coastal embayments using simple statistical models

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Abstract

A statistical methodology is proposed for assessing the risk of eutrophication in marine coastal embayments. The procedure followed was the development of regression models relating the levels of chlorophyll *a* (Chl) with the concentration of the limiting nutrient—usually nitrogen—and the renewal rate of the systems. The method was applied in the Gulf of Gera, Island of Lesvos, Aegean Sea and a surrogate for renewal rate was created using the Canberra metric as a measure of the resemblance between the Gulf and the oligotrophic waters of the open sea in terms of their physical, chemical and biological properties. The Chl-total dissolved nitrogen-renewal rate regression model was the most significant, accounting for 60% of the variation observed in Chl. Predicted distributions of Chl for various combinations of the independent variables, based on Bayesian analysis of the models, enabled comparison of the outcomes of specific scenarios of interest as well as further analysis of the system dynamics. The present statistical approach can be used as a methodological tool for testing the resilience of coastal ecosystems under alternative managerial schemes and levels of exogenous nutrient loading.

Keywords: Eutrophication; Coastal management; Bayesian analysis; Risk assessment; Limiting nutrient; Renewal rate

Coastal zones undergo intense and continuous environmental pressure derived from a number of driving forces such as urbanization, industrialization and tourism development. Within only a few decades, numerous, previously pristine, oligotrophic estuarine and coastal waters have undergone a remarkably troubling transformation to more mesotrophic and eutrophic conditions, manifested as an increase in phytoplankton and macroalgal biomass, increased incidences of toxic and noxious algal blooms, consequent hypoxia and anoxia, and fish and benthos kills. An analogous scenario has long been recognized in freshwater systems, where eutrophication has been directly linked with excessive phosphorus loading and successfully predicted using a combination of chlorophyll *a*:total phosphorus regressions and phosphorus mass balance models (Vollenweider and Kerekes, 1982). Research on coastal eutrophication is lagging by about 20 years relative to that in freshwaters, so that models comparable to those for freshwater, derived from comparative analyses of hundreds of lakes and reservoirs, have not yet been developed for the coastal zone (Vidal et al., 1999). In the absence of models specific for coastal waters, the models derived for freshwaters are being applied and though their applicability has not been sufficiently tested, largely because of the paucity of studies on marine eutrophication, they are considered essential to the management of the quality of coastal waters (Meeuwig et al., 2000).

The basic objective for this study is the development of statistical models that link eutrophication responses with variables routinely monitored, and which have the potential to be proposed as a general methodology for analyzing the dynamics of semi-enclosed marine environments. The Bayesian perspective is also proposed as a complementary context, which provides an alternative interpretation of the cause–effect relationships and it makes possible to visualize and compare the outcomes of specific scenarios of interest.

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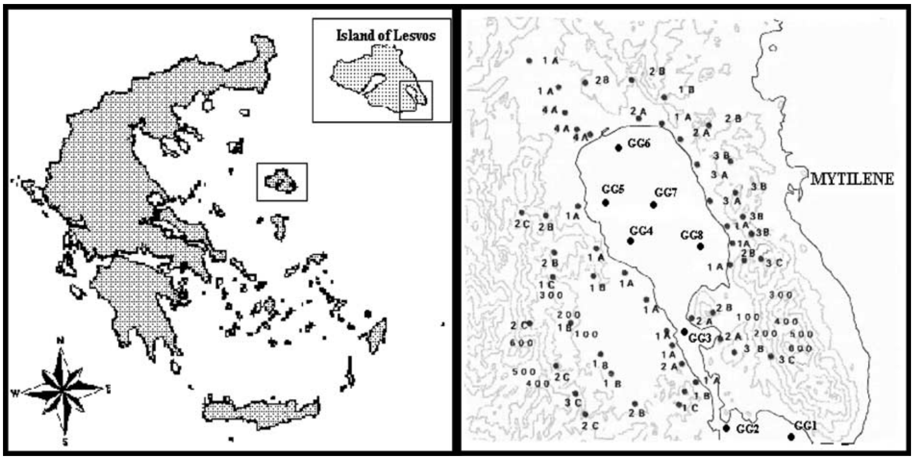

Fig. 1. The study area, the Gulf of Gera, Island of Lesvos, Greece. All the details about the sampling network are provided in Arhonditsis et al. (2000a,b).

The present study was conducted within the Gulf of Gera, Island of Lesvos, Greece (Fig. 1), a semi-enclosed marine ecosystem typical of the Aegean Sea, with a mean depth of 10 m and a total volume of 9×10^8 m^3, and extensively studied in the past (Katsiki, 1990; Arhonditsis et al., 2000b). The levels of its chemical parameters (mean values for nitrate, ammonium, phosphate and dissolved organic nitrogen were 0.55, 0.91, 0.19 and 7.93 μg at/l, respectively) are indicative of a mesotrophic environment with eutrophic trends according to a eutrophication classification system for the Aegean Sea (Kitsiou and Karydis, 1998). Significant factors for the function of the Gulf are its pattern of circulation and its exchanges with the open sea that regulate temporal variability of chemical and biological parameters (Arhonditsis et al., 2000a). In winter, there are periods when the ambient temperature and the inflows of the colder runoff make this shallow Gulf denser than the external system and the entrance of the oligotrophic waters of the Aegean Sea is limited. These slow renewal rates usually coincide with the period when the external loading is increased and non-point sources account for about 40–60% of the total nutrient stock (Arhonditsis et al., 2002a). Given the latitude and local climatic conditions, physical factors (light intensity, temperature) are, for most parts of the year, non-limiting for primary production and therefore significant peaks of the algal biomass (2–3 μg/l) occur, even in the middle of winter. Whenever, physical conditions (warm temperature, spring tides, north winds) are not unfavorable, the seawater can be renewed in less than ten days and the significant inflows of the oligotrophic waters of the Aegean Sea are able to flush excessive nutrient loads out of the system. Under these conditions, the Gulf is nitrogen limited and the phytoplankton biomass low (0.5–1 μg/l chla) (Arhonditsis et al., 2002b).

The above mentioned factors have restricted potential predictors for chlorophyll, so we tried to develop regression models using estimates for the ambient nitrogen concentrations and the renewal rates of the Gulf. The nitrogen availability (μg at/l) for the phytoplankton uptake was expressed as nitrate, ammonia, inorganic nitrogen, total dissolved nitrogen, and exogenous nitrogen loading weighted for the water volume of the Gulf (Arhonditsis et al., 2000b). The renewal rate was estimated using the surrogate Canberra metric, as a measure of the resemblance between the Gulf and the oligotrophic waters of the open sea, which is given by the formulation (Legendre and Legendre, 1998):

$$\mathrm{SI}_{\mathrm{CA}} = \sum_{i}^{n} \left(\frac{|x_{\mathrm{g}} - x_{\mathrm{o}}|}{(x_{\mathrm{g}} + x_{\mathrm{o}})} \right)$$

where x_{g}, x_{o} the values of a parameter in the gulf and the external system, and n the number of parameters used to assess the similarity between the two systems. The sensitivity of this index as a surrogate parameter for the renewal rate was tested against the complete set of the available parameters, including physical (sigma-*t*, temperature, salinity), chemical (nitrate, ammonia, nitrite, dissolved organic nitrogen, phosphate, silicate) and biological (chlorophyll *a* and total bacterial number) properties of the study area, as well as against only the physical subset (since it contains more conservative parameters, independent from biological sources and sinks). The similarity indices have been included in the regression analysis after normalization of their values between 0 and 1: $\mathrm{SI} = 1 - (1/n)\mathrm{SI}_{\mathrm{CA}}$. The Gulf of Gera was sampled from June 1997 until October 1998 and the data for all parameters used for the models were ''binned'' by week using averages determined by trapezoidal integration over time.

The regression analysis showed that total dissolved nitrogen was the best predictor of chlorophyll and the respective models had the highest coefficients of determination (r^2), about 60%, whereas the partial r^2's were nearly 35% (Table 1). This result is in accordance with

Table 1
Regression models developed for predicting the level of chlorophyll *a* (μg/l) in the Gulf of Gera

Regression equation	v	RMS	r^2	N-$r^2_{partial}$	SI-$r^2_{partial}$
(1) Chl $= 1.82NO_3 - 0.05SI_p$	72	0.08	0.55	0.32	0.23
(2) Chl $= 1.81NO_3 - 0.04SI_a$	72	0.07	0.55	0.33	0.22
(3) Chl $= 1.26NH_4 - 0.31SI_p$	72	0.24	0.31	0.14	0.17
(4) Chl $= 1.25NH_4 - 0.29SI_a$	72	0.22	0.32	0.15	0.17
(5) Chl $= 0.78IN - 0.42SI_p$	72	0.32	0.29	0.15	0.14
(6) Chl $= 0.77IN - 0.40SI_a$	72	0.32	0.28	0.14	0.14
(7) Chl $= 1.93N_{exog} - 0.08SI_a$	72	0.34	0.26	0.12	0.14
(8) Chl $= 1.93N_{exog} - 0.07SI_p$	72	0.34	0.26	0.12	0.14
(9) Chl $= 0.16TDN - 1.13SI_p$	72	0.06	0.60	0.35	0.25
(10) Chl $= 0.16TDN - 1.12SI_a$	72	0.06	0.61	0.35	0.26

Note: The symbols IN and TDN denote inorganic nitrogen and total dissolved nitrogen. N_{exog} is the exogenous nitrogen loading weighted for the water volume of the gulf (Arhonditsis et al., 2002a). All ambient nutrient concentrations are expressed in units of μg at/l. The symbol SI denotes the similarity between the gulf and the open sea, based on the Canberra metric. The subscripts p and a denote the calculation of this similarity index using only the physical parameters and the physical along with the chemical and biological parameters, respectively (see text). Weekly averages were used for all the parameters. All regression models are statistically significant at <0.001. The serial correlations (r) of residuals varied from 0.25 to 0.45, which were deemed acceptable and thus we did not difference the data.

the literature and indicates that the pool of dissolved organic nitrogen (DON) should be added to the nitrogen stock available for phytoplankton uptake, since it plays an important role in the regeneration of N in the water column (Harris, 1986). Residual mean square estimates (RMS) show that nitrate concentrations yielded a 70% more precise prediction than ammonium. This is probably due to the fact that nitrate is the dominant form of inorganic nitrogen in the winter when the system is isolated and therefore has a more straightforward relationship with chlorophyll; ammonium prevails in the summer when exchanges with the open sea also have an important impact on the dynamics of the system and its patterns with chlorophyll are less clear (Arhonditsis et al., 2000a). The poorest predictor for chlorophyll was the exogenous nitrogen loading followed by the total dissolved inorganic nitrogen. The renewal rate of the Gulf was a significant factor for all models (partial r^2 from 17% to 27%), and its weights vary from 70% to 120% relative to nitrogen weights depending the efficacy of the nitrogen surrogate. Interestingly, the two different ways of computing the similarity between the Gulf and the open sea (SI_p and SI_a) gave almost identical results for both total and partial r^2's.

Bayesian analysis of the models follows the standard normal theory, but the interpretation of the results is completely different. Bayesian analysis yields distributions that give probability for particular predicted values of chlorophyll to be actually observed, in contrast with conventional multiple regression analyses which predict confidence intervals that include the true value of the response variate in a given percentage of independent, identical studies. Given a non-informative prior, the posterior distribution of the model parameters (θ_1 the regression coefficient for the nitrogen, θ_2 the regression coefficient for the renewal rate and σ^2 the variance of the prediction error) is a multivariate t distribution, which is a joint distribution for all the parameters (Gelman et al., 1995). The present study focused on the parameters θ_1 and θ_2, while σ^2 was considered a nuisance parameter that complicates the interpretation and thus it was eliminated by integrating the joint distribution over it. We computed the joint and marginal posterior probability distributions for θ_1 and θ_2 of the model Chl–TDN–SI_a which presented the highest r^2 (Table 1). The variance of total dissolved nitrogen effects was greater than the variance of the renewal rate, as can be seen from the respective axes scale in Fig. 2A and the different x-axis scales in Fig. 2B and C. The thick lines in Fig. 2A are elliptical contours of constant probability for various pairs (θ_1, θ_2). The diagonality of these contours usually shows the degree of correlation between the two parameters, which in turn indicates the level of distinction between marginal intervals (probability statements about θ_1 and θ_2 individually) and joint regions (plausibility of the pairs θ_1 and θ_2). In this particular case, the two parameters are weakly correlated, since the major axes of the ellipsoids tend to be parallel to the x and y-axes of the diagram.

The predictive posterior distribution for chlorophyll conditional on the total dissolved nitrogen concentration and the renewal rate of the gulf is also the multivariate $t(\theta X', s^2(I + X'QX'^{\mathrm{T}}), v - 2)$, where θ and X' are the respective vectors for the regression coefficients and the explanatory variables, Q is the covariance matrix of the parameters, s^2 is the variance of the prediction error and v is the number of observations (Gelman et al., 1995). Predictions of mean chlorophyll and the probabilities of exceeding the level of 3 μg/l for various combinations of total nitrogen and renewal rates (expressed as percentage of similarity between the Gulf and the open sea) are shown in Fig. 2D and E. These plots were also subdivided into three zones according to the variations of the similarity index over specific periods of the year, associated

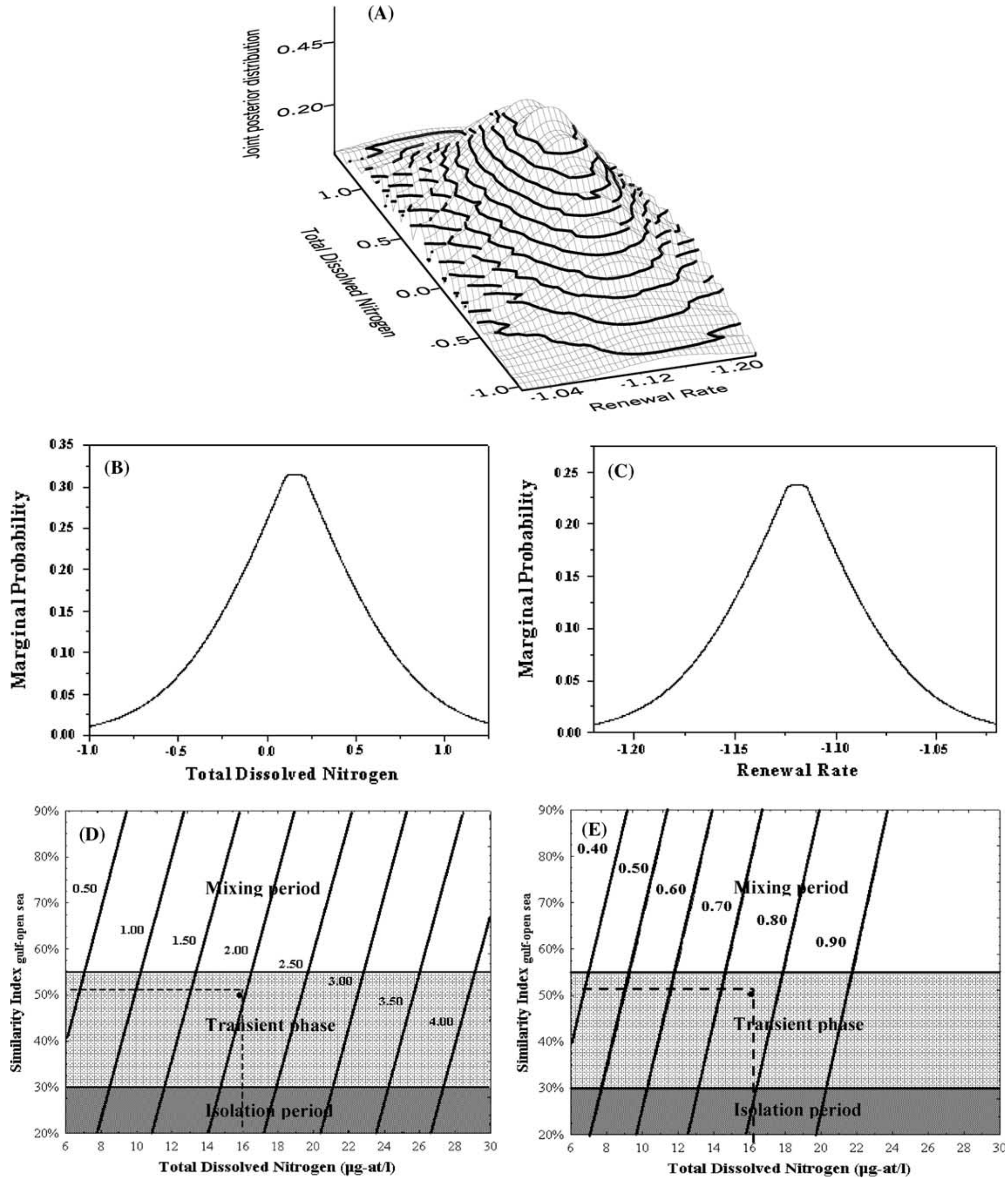

Fig. 2. (A–C) Joint and marginal posterior probability distributions for total dissolved nitrogen (θ_1) and renewal rate (θ_2) effects on chlorophyll *a* in the Gulf of Gera. (D–E) Predicted mean chlorophyll *a* concentrations (μg/l) and probability to exceed the n level of 3 μg/l vs the concentration of total dissolved nitrogen and the percentage of similarity between the gulf and the open sea. Note that the term "mixing period" is used to indicate favorable conditions for mass exchanges between the gulf and the open sea.

with different hydrodynamic regimes. Hence, the darkest area corresponds to the values observed during the winter period, when the system exhibits the greatest degree of isolation. The intermediate zone depicts periods of the year when the limiting conditions for the hydrodynamic transport are partially withdrawn (usually early spring or late fall), so it can be referred as the "transient phase". Finally, the white zone describes the summer values, when mass exchange between the two systems is complete. According to these plots, for example, the mean chlorophyll level in the gulf is predicted to be about 2 μg/l with a total dissolved nitrogen concentration of 16 μg at/l during the transient phase ($SI_a \approx 50\%$), while the probability to exceed the level of 3 μg/l is greater than 70% (dashed lines). It can also be seen that the angles of the contours are about 70°, but the scales of the two factors are not directly comparable so as to assign relative weights. However, it can be said that a 10% increase in the similarity between the Gulf and the open sea offsets an increase in total dissolved nitrogen of about 1 μg at/l.

The present analyses suggest that predictions of chlorophyll in semi-enclosed marine environments can be based on surrogates for nitrogen concentrations (the limiting nutrient) and renewal rates of the systems. The Bayesian interpretation of the models also seems to be a valuable statistical tool that enables translation of the results into probabilities of future ecosystem states which may be immediately useful to managers (Walters, 1986). Generally, attempts to analyze ecosystem dynamics with simple equations are suspected to impede the understanding of true ecological interactions, or at least not reveal all that might be of interest in a particular system (Stow et al., 1995). We agree that the second point of view holds for the present approach, but this does not impede its usefulness for insights into the behavior of such systems. An essential future test of the credibility of this methodology involves the representation of the renewal rates by measuring the similarity between study systems and control areas. It seems that the respective values are correlated with the annual changes in the hydrodynamics, but they can be influenced by other ecological factors (i.e. biological activity, food–web interactions) and hence it is still obscure if they can be sensitive for all their possible ranges and under different conditions. The inclusion of the flushing rate with the appropriate temporal resolution (Meeuwig et al., 2000), or the development of a formulation that has more mechanistic basis, might be more useful for the generalization of the present method.

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References

Arhonditsis, G., Tsirtsis, G., Angelidis, G., Karydis, M., 2000a. Quantification of the effects of non-point nutrient sources to coastal marine eutrophication: applications to a semi-enclosed gulf in the Mediterranean sea. Ecol. Model. 129 (2–3), 209–227.

Arhonditsis, G., Giourga, C., Loumou, A., 2000b. Ecological patterns and comparative nutrient dynamics of natural and agricultural Mediterranean-type ecosystems. Environ. Manage. 26 (5), 527–537.

Arhonditsis, G., Giourga, C., Loumou, A., Koulouri, M., 2002a. Quantitative assessment of agricultural runoff and soil erosion using mathematical modelling: applications in the Mediterranean region. Environ. Manage. 30 (3), 434–453.

Arhonditsis, G., Tsirtsis, G., Karydis, M., 2002b. The effects of episodic rainfall events to the dynamics of coastal marine ecosystems: applications to a semi-enclosed gulf in the Mediterranean sea. J. Mar. Syst. 35, 183–205.

Gelman, A., Carlin, J.B., Stern, H.S., Rubin, D.B., 1995. Bayesian Data Analysis. Chapman and Hall, New York, p. 518.

Harris, G.P., 1986. Phytoplankton Ecology: Structure, Function and Fluctuation. Chapman and Hall Ltd., New York, p. 394.

Katsiki, V.A., 1990. Ecological study of the Gulf of Gera. National Centre for Marine Research, Athens, Greece, p. 120.

Kitsiou, D., Karydis, M., 1998. Development of categorical mapping for quantitative assessment of eutrophication. J. Coastal Conserv. 4, 35–44.

Legendre, L., Legendre, P., 1998. Numerical Ecology. Elsevier Science Publications, Amsterdam, p. 853.

Meeuwig, J.J., Kauppila, P., Pitkanen, H., 2000. Predicting coastal eutrophication in the Baltic: a limnological approach. Can. J. Fish Aquat. Sci. 57, 844–855.

Stow, C.A., Carpenter, S.R., Cottingham, K.L., 1995. Resource vs ratio-dependent consumer-resource models: a Bayesian perspective. Ecology 76 (6), 1986–1990.

Walters, C.J., 1986. Adaptive management of renewable resources. Macmillan, New York, USA.

Vidal, M., Duarte, C., Sanchez, C.M., 1999. Coastal eutrophication research in Europe: progress and imbalances. Mar. Pollut. Bull. 38 (10), 851–854.

Vollenweider, R.A., Kerekes, J., 1982. Eutrophication of waters, monitoring, assessment and control. OECD, Paris, p. 154.