First approach of a method to assess water quality for arid climate bay in the Gulf of California

Renato A. Mendoza-Salgado*, Carlos H. Lechuga-Devéze, Alfredo Ortega-Rubio

Centro de Investigaciones Biológicas del Noroeste (CIBNOR), Apdo. Postal 128, La Paz, Baja California Sur 23000, México

Received 9 July 2004; accepted 17 December 2004
Available online 4 February 2005

Abstract

This work proposes a water quality model based on the pooled effects of nitrate, nitrite, ammonium, and orthophosphate concentration as the main causatives of environmental water quality changes. One of the main characteristics of the model is assigning an environmental weight for each variable (Wi) according to threshold concentrations of nutrients capable of inducing water changes condition. The model validation demonstrated adequate sensitivity to different data arrangements; as observed in an arid climate bay, showing annual stratification resulting in a variable content in nitrogen-forms and phosphorous. The model can be continuously calibrated over time by adding more N and P data to specific nutrient functions, and tested on sites with high NO3, NO2 or NH4 concentrations.

© 2004 Elsevier B.V. All rights reserved.

Keywords: Gulf of California; Bahía Concepción; Arid climate; Environmental index; Quality assessment

1. Introduction

Different procedures for environmental assessment of coastal waters quality, using a biological index or nutrient monitoring, have been proposed (Hooper, 1969; Karydis et al., 1983; Theodorou, 1995). These methods have a reasonable use, but demand participation of water quality experts, inducing a qualitative rather than quantitative evaluation (e.g. Delphi procedure) (Sackman, 1974), and a complex development of proposed models (Ott, 1978; León, 1991, 2002; Van Straten, 1998). Literature review show different indices for assessing fresh and coastal water quality (Dunnette, 1979; Couillard and Lefebvre, 1985; Smith, 1990; National Research Council (NRC), 2000), discussing and describing different steps and theories for constructing a water quality index. Results and interpretations of water quality studies are variable (Moore et al., 1997), but there seems to be an agreement that phosphorus and nitrogen concentrations are useful for evaluating the trophic status of closed and open coastal waters (Jones and Lee, 1982; Tomasky et al., 1999; National Research Council (NRC), 2000). In
this paper, we propose an Arid Zone Coastal Water Quality Index (AZCI) model to evaluate environmental variability of coastal waters in arid climate regions based on detrimental effects of key variables capable of modifying water conditions, and at the same time, avoiding subjective human perceptions about the environmental weight of the water quality variables.

2. Methods

2.1. Developing the model

2.1.1. Selecting indicator variables

For assessing environmental water quality we chose NO3, NO2, NH4, and PO4, since it is known that an excess of any one of these variables, is responsible for water condition changes. Dissolved oxygen (D.O.) was utilized to develop a dimensionless index taking into account that the availability of dissolved oxygen is related to the N-form found in the environment (high D.O. availability: N–NO3; low D.O. availability: N–NO2 or N–NH4). This index is done calculating D.O./D.O.m related to the N-form available in the site.

2.1.2. Relative specific environmental index

A regression model was applied for obtaining a relative index (Ii), for NO3, NO2, NH4, PO4 using a pooled data base ranked low to high values independently of physical structure of water column (e.g. temperature, salinity), date, seasonality, and depth intervals; and paired with its corresponding values of D.O./D.O.m. The function for the NO2, NO3, NH4, and PO4 variables was constructed using Statistica© software. The best-fit function was potential regression under the premise that no linear relationship exists between independent (i) and dependent variables (D.O. index). This relative index must be multiplied by its importance weight to get the relative specific environmental index.

2.1.3. Environmental weight of variables

To obtain the environmental weight (value of environmental importance: ζi) for each variable, the following criteria were considered: (1) to get the concentration (mg L⁻¹) of specific nutrient reported to be responsible for water change conditions; this was the specific threshold for "good" and "not good" water quality for each nutrient. (2) To get the inverse of these concentrations to obtain the rank of environmental weights: the lower the value, the higher the environmental weight. (3) The weights of each variable were normalized in a 0 to 1 range (ζi/ζi max), ranking PO4 and NO3 with highest and lowest environmental weights, respectively.

2.1.4. The Arid Zone Coastal Water Quality Index

The general equation proposed for developing the quality index AZCI (Arid Zone Coastal Water Quality Index) is a linear sum:

\[ AZCI = \left( \sum_{i=1}^{n} I_i \xi_i \right) / \sum_{i=1}^{n} \xi_i \]

or

\[ AZCI = \frac{\sum_{i=1}^{n} I_i \xi_i}{\sum_{i=1}^{n} \xi_i} \]

where: Ii, ξi is the specific environmental index of variable i, and, n is the number of variables. The Arid Zone Coastal Water Quality Index ranges from 0 to 1.

2.1.5. Overall threshold limits

The overall threshold between "good" and "not good" environment quality is calculated substituting Ii with the minimal value of each variable multiplied by its specific weight, in the general Eq. (2).

2.2. Model validation

2.2.1. Data source

Weekly hydrographic surveys done in 1997, 2000, and 2001 in Bahía Concepción, Gulf of California were used as the database for NO2 (n=1,323), NO3 (n=1,321), NH4 (n=442), and PO4 (n=1,335). Water samples were obtained at four sampling stations in 1997 and 2000, and at two sampling stations in 2001 at intervals of 5 m to a depth of 30 m. Chemical
analyses for nitrates, nitrites, ammonium, and orthophosphates are described in other reports (Lechuga-Devéze et al., 2000, 2001; Bustillos-Guzmán et al., 2000; López-Cortés et al., 2003a,b).

Bahía Concepción (Fig. 1) is a moderately deep bay (30 m maximum depth) that is free of significant human influence (Lechuga-Devéze et al., 2000) and is located in a dry climate (annual average rain is 200 mm), with a summer rainy season (García, 1981). Mean surface water temperature is 24°C with a winter minimum of 16.6°C (Góngora-González, 2001) and a summer maximum of 34.8°C (Mateo-Cid et al., 1993). Mean salinity is 35.5 psu (Dressler, 1981). During a typical annual cycle, a summer thermal stratification develops. In winter, a mixed water column with temperature around 18°C prevails (Gilmartin and Revelante, 1978; Dressler, 1981).

To test the sensitivity of the environmental quality index, we used 2000 and 2001 year data from Bahía Concepción arranged by monthly means of (a) entire water column data, (b) surface to 10 m depth, (c) from 10 to 15 m depth, and (d) data >20 m. Thresholds and quality index were graphically compared.

3. Results

The regression to get the relative index \( I_i \) for each variable is shown in Fig. 2a, b, c, and d. The best-fit functions for each variable were:

- Nitrite: \( I_{\text{NO}_2} = 0.0359(\text{NO}_2)^{-0.32} \), (3)
- Nitrate: \( I_{\text{NO}_3} = 0.0864(\text{NO}_3)^{-0.27} \), (4)
- Ammonium: \( I_{\text{NH}_4} = 0.012(\text{NH}_4)^{-0.565} \), (5)
- Phosphorus: \( I_{\text{PO}_4} = 0.0183(\text{PO}_4)^{-0.794} \). (6)

All regressions were highly significant \((p < 0.05)\).

The minimum values for each variable causing water change conditions are shown in Table 1. Specific environmental weight for each variable gave phosphates the highest value, followed by ammonium, nitrites, and nitrates, in that order. These values \((\zeta_i)\) were used in Eq. (2) to obtain the environmental quality index.

The \( I_i \) and \( \zeta_i \) variables of Eq. (2) were substituted by each threshold and inverse, normalized values to get an overall threshold of 0.1172 \(( \approx 0.12)\). This is the

![Fig. 1. Bahía Concepción, Baja California Sur, México. Database was created from weekly samplings. 1—samplings during 1997 and 2000; 2—samplings during 2001. Samples were taken at 5-m intervals in the water column.](image)
Table 1

<table>
<thead>
<tr>
<th>Variable</th>
<th>Threshold (mg L⁻¹)</th>
<th>Inverse normalized (ζ_i)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO₄</td>
<td>0.08</td>
<td>12.50</td>
<td>Scottish Environment Protection Agency (SEPA), 1997</td>
</tr>
<tr>
<td>NH₄</td>
<td>0.50</td>
<td>2.00</td>
<td>National Environment Protection Counsel (NEPC), 2002</td>
</tr>
<tr>
<td>NO₂</td>
<td>3.00</td>
<td>0.33</td>
<td>National Environment Protection Counsel (NEPC), 2002</td>
</tr>
<tr>
<td>NO₃</td>
<td>20.00</td>
<td>0.05</td>
<td>Hutcheson, 2002</td>
</tr>
</tbody>
</table>

level used to define the overall environmental quality index. Above and below this threshold, good or poor quality is indicated.

Arranged data of Bahía Concepción, by monthly means, without any depth discrimination, for 2000 and 2001 yielded an average around 0.5 AZCI (Fig. 3a,b). The figures show that some monthly variations show tendencies to a better or poorer environmental quality, but overall, the AZCI for these data can be interpreted as good environmental quality for Bahía Concepción.

The pooled data from the surface to 10 m and 10 to 15 m depth, was chosen because a strong thermocline at 10 m appears in mid-spring and lasts until early autumn (Lechuga-Devéze et al., 2000). Fig. 4a and b show a significant change in the AZCI for the 10 to 15 m layer, compared to 0 to 10 m layer, starting in April. From January to April, both the surface and middle layers showed similar values for the AZCI. The AZCI reaches its lowest value in June and July, near the threshold for poor environmental conditions.

Using data from the 20 to 30 m layer (Fig. 5a,b), both years showed good conditions in the bottom layer from January to April–May. After that, the AZCI becomes marginal in 2000 and poor in 2001 until September. From January to April 2000, there is an improvement in the AZCI that suddenly changed in April, falling in May to its lowest values and remaining at this low level until September (Fig. 5a). In 2001, there is a gradual decrease in the value of
the AZCI until it reaches a poor condition that lasts from June through September.

4. Discussion

Previously, quantitative assessment of water quality had been based on upsurges of specific phytoplankton species and special population classes (Lee et al., 1981; Bas and Oguz, 1990), eutrophication and specific nutrient concentrations (Karydis et al., 1983; Ignatiades et al., 1992; HELCOM, 2002; López-Cortés et al., 2003a,b), or different complex models (Couillard and Lefebvre, 1985; Bas and Oguz, 1990; Humborg et al., 2000). Most studies involved freshwater lakes and rivers, and focus on public management (Beck, 1978; Couillard and Lefebvre, 1985) in temperate regions.

In this study, the water quality model showed sensitivity to combined effects of nitrogen and phosphorus sources, well known for their impact on the environment. The nutrient weights respond to environmental changes by itself (quantitative) and are not a subjective value (qualitative) assigned by panels of specialists (Dee et al., 1973; Dinius, 1987; Adler and Ziglio, 1996). The inverse normalized process is an approach to combine the specific weights, and using the lowest critical values, providing the model with a dimensionless threshold (critical AZCI).

It is well known that nitrogen and phosphorus introduced to estuaries, bays, and other coastal zones by natural processes of primary and secondary production or human activities (Smith et al., 2003) demand dissolved oxygen to produce inorganic forms. Increased nutrient loading requires a surplus of dissolved oxygen; otherwise, eutrophication occurs (Radach et al., 1990; Turner and Rabalais, 1994; Humborg et al., 2000; Kormas et al., 2000; De Jonge et al., 2002).
Sensitivity of this model was tested by different data arrangements. As expected, averaging whole data sets results in loss of sensitivity. A data set needs to be adjusted according to a previous examination of environmental factors, such as thermal or saline stratification, point or diffuse nutrient sources, fresh water inputs, or restricted water circulation.

Oxygen deficiency in Bahía Concepción occurs when the seasonal water column becomes stratified (Lechuga-Devéze et al., 2001). Respiration in the bottom layer (25 to 30 m) exhausts the dissolved oxygen, which then becomes eutrophic, producing hydrogen sulfide. This cyclic bottom layer dystrophy is thought to be responsible for shellfish mass mortality in the summer (Lechuga-Devéze et al., 2000). Once the system cannot cope with the available internal or external nutrient inputs, eutrophication occurs (De Jonge et al., 2002), as has been shown by this model through specific data arrangements.

The model also shows tendencies in the quality water index. In mid-autumn, northwesterly winds and cooling of surface seawater disrupt the thermocline, and the water column becomes completely mixed (Obeso et al., 1996; Lechuga-Devéze et al., 2001). At that time, good water quality remains until early spring, coinciding with extensive primary and secondary production (Martínez-López and Gárate-Lizárraga, 1994). During the strengthening of the stratification process, the AZCI reveals also a tendency to quality deterioration; in addition, the
model also indicates annual tendencies as a response to interannual variability: for 2000, there was a gradual increase of good bottom water quality, and an abrupt decrease in seasonal loss of water quality, and for 2001, there is a gradual decline of water quality in the bottom layer. This model was validated in one condition: excess of intermediate N-form (NO$_2^-$-NH$_4^+$) and phosphorous (PO$_4^{3-}$). Since PO$_4^{3-}$ has the higher environmental weight the results of AZCI were as expected. However, the model should also respond to an increase of NO$_3^-$ in the environment, (N-load anteceding eutrophication) and low values of phosphorous. The important value is not the concentration of the variable by itself but the variable multiplied by its environmental weight. In that case high values of nitrates and low values of phosphorous can also be reflected in the diminished values of AZCI. This can be tested in future work.

Environmental deterioration of coastal water can, therefore, be estimated by the use of this model through a program of continuous monitoring of N and P.

5. Conclusions

This is a first approximation to use quantitative water quality measures, instead of subjective criteria (e.g., Delphi Method), to determine an arid zone coastal water environmental quality index. The model proposed for assessment of coastal water quality is simple and easily to perform according to Hooper (1969). It can be continuously calibrated over time by adding more N and P data to specific nutrient functions. The model introduces an evaluation that combines nitrogen and phosphorus concentrations. It can also be modified for particular cases. When
applied to different environmental scenarios, the model demonstrated its sensitivity to specific data arrangements.

Acknowledgements

The authors express their sincere thanks to Centro de Investigaciones Biológicas del Noroeste for supporting this research (CIBNOR projects AYCG-8, AYCG-11, GEA-8, GEA-11, PC3.3, and PC3.4). The first author was supported by Consejo Nacional de Ciencia y Tecnología (CONACYT grant 114563) for graduate studies. At CIBNOR, J. Bustillos and D. López, members of the research team, supplied the database on Bahía Concepción; I. Murillo-Murillo and C. Beltrán-Camacho provided technical assistance. M. Talamanes provided library services, and the staff editor improved the English text.

References


León V. Índices de calidad del agua Instituto Mexicano de Tecnología del Agua (CNA). Inf Tech 1991;SH-9101/01:36.


