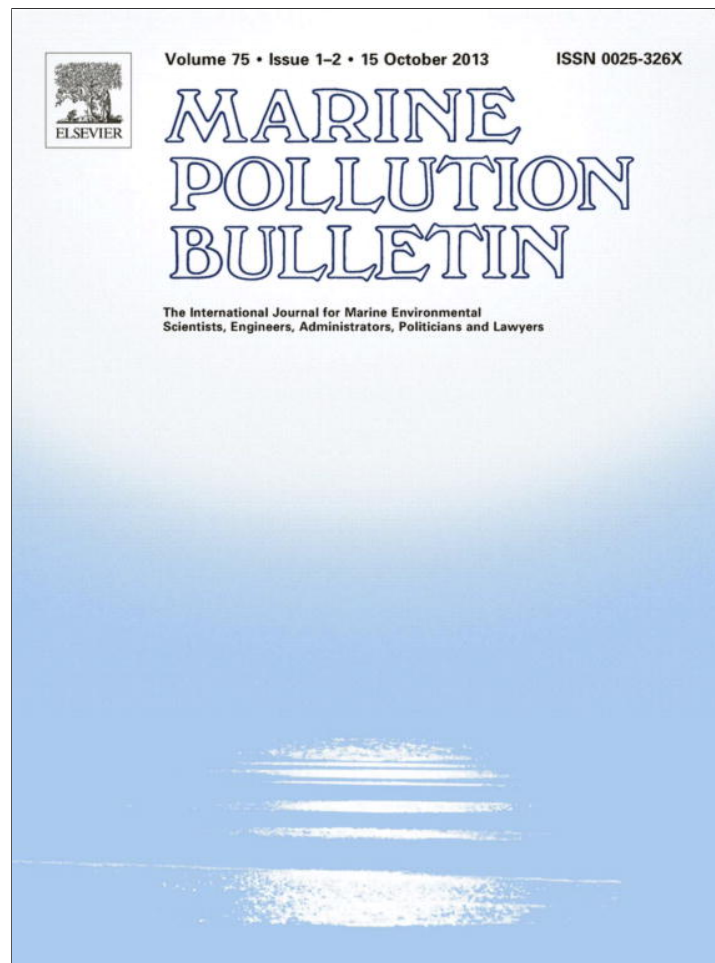


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Allocation of marine environmental carrying capacity in the Xiamen Bay

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ABSTRACT

Three optimization methods are employed to allocate Marine Environmental Carrying Capacity (MECC) in the Xiamen Bay. The hydrodynamic and pollutant fields are first simulated by the Princeton Ocean Model. Taking phosphorus as an index of the water quality, the response fields are then calculated. These response fields represent the relationship between the concentration of the sea zone and the pollution sources. Finally, MECC is optimized and distributed in the Xiamen Bay by three optimization methods. The results show classical linear optimization can only maximize the satisfaction level for one of the stake holders', e.g., dischargers or environmental protection bureau, satisfaction level. However, the fuzzy and grey fuzzy optimizations can provide a compromise, and therefore a fairer result, by incorporating the conflicting goals of all of the different stakeholders. Compared with fuzzy optimization, the grey fuzzy optimization provides a more flexible choice for the decision-makers.

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1. Introduction

Xiamen, located in semi-closed Xiamen Bay, is known for its beautiful sea beaches. Over the past 30 years, the economy has been growing rapidly in China. Xiamen, being the major city in southeast China, has benefitted from this rapid economic development, but it also has suffered from significant environmental deterioration. For example, the concentration of Active Phosphate (AP, PO₄-P) reaches a level of 0.06 mg/L, which is 2 times larger than the Chinese sea water quality standards allows, 0.03 mg/L. This serious problem indicates that significant aquatic pollution management is urgently required. Estimation and allocation of Marine Environmental Carrying Capacity (MECC), defined as the greatest pollutant load that marine environment can receive without violating water quality goal, is very important for aquatic pollution management. As a first step, it is necessary to assess environmental water quality and collect pollution source data. The National Fund Project, the study of marine environmental quality assessment and marine environmental carrying capacity in the Xiamen Bay, is carried out by Xiamen University (Cui and Zhang, 2009; Tu et al., 2009; Wang et al., 2010; Zhang et al., 2010). Once enough data has been collected, numerical ocean model is conducted to study the transport and fate of pollutant and MECC is allocated without violating water quality goals.

There are many approaches to allocate MECC. The trial-and-error approach (load sensitive testing) would be to reduce the pollutant loads of various sources in an eco-hydrodynamic model until

it predicts that the water quality standards can be met (Lee et al., 2008, 2005; Nikolaidis et al., 2006). Unfortunately, this approach is time-consuming and may ignore some feasible combinations of load reductions (Jia and Culver, 2006). As a result, an optimization method with the capability to efficiently determine the best allocation scenario is adopted. Han et al. (2011) and Deng et al. (2010), using a water quality model, employed classical linear optimization to allocate MECC based on the response fields. However, this method cannot incorporate the conflicting objectives of the dischargers and Environmental Protection Bureau (EPB). In addition, objectives such as specifying water quality criteria and fractional removal levels are generally vague. Therefore, fuzzy optimization was proposed to incorporate these conflicting goals and quantify the vagueness using a membership function (Sasikumar and Mujumdar, 1998). Furthermore, in order to best address the uncertainty, Karmakar and Mujumdar (2006) proposed using grey fuzzy optimization. The fixed upper and lower bounds of the membership functions (fuzzy membership parameters) could be relaxed by treating them as fuzzy and the membership parameters are expressed as interval grey numbers, a closed and bounded interval with known lower and upper bounds but unknown distribution information (Karmakar and Mujumdar, 2006). The fuzzy optimization and grey fuzzy optimization have been successfully used in river watersheds to allocate pollutant discharge amounts (e.g. Karmakar and Mujumdar, 2006; Sasikumar and Mujumdar, 1998). However, these methods have yet to be applied in a coastal area, such as Xiamen Bay, which is controlled by both river and tidal processes.

In order to solve the environmental problem in Xiamen Bay, these optimization methods are applied in this paper to allocate

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MECC to each pollution source and their utility will be evaluated. The paper is organized as follows: The model and method are introduced in Section 2, the water quality simulation and response fields are outlined in Section 3 and the results of the different optimization methods are discussed and compared in Section 4.

2. Model and methods

2.1. Numerical ocean model

An improved 3D ocean model based on the Princeton Ocean Model (Blumberg and Mellor, 1987) is used in this paper. First, the Alternating Direction Implicit method, which enhances the model's numerical stability, is applied in the external part of the model (Chau and Jiang, 2001, 2003; Jiang et al., 1997; Leendertse, 1970). Second, a two-way nested-grid strategy (Oey and Chen, 1992) is adopted to allow for increased resolution in specific sub-domains. Third, in order to study tidal areas in the Xiamen Bay, the model employs a dry and flood technology (Jiang and Wai, 2005) which allows some grid cells to go dry during a portion of the tidal cycle. In addition, a Geographic Information System is adopted for pre- and post-processing (Jiang et al., 2004). The improved model has been successfully used in the Taiwan Strait and its adjacent regions including Xiamen Bay (Jiang et al., 2011, 1997; Lin et al., 2007). In this application, because Xiamen Bay is 70 km-long and 50 km-wide, the averaged depth is about 10 m, and the bay is dominated by tidal processes with an average tidal range of 4 m. The stratification in the Xiamen Bay is weak and there are little differences between surface and bottom distributions of pollutants, temperature, and salt (Wang et al., 1998). In addition, only horizontal response coefficients and distribution of pollutant is needed in the study. Therefore, the two-dimensional version of the improved model is chosen for modeling efficiency.

The equation for the pollutant/tracer transport can be written:

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = \frac{\partial}{\partial x} \left(D_x \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_y \frac{\partial C}{\partial y} \right) + KC + S_c \quad (1)$$

where C is the pollutant concentration; t is the time; x and y are the latitudinal and longitudinal coordinates; u and v are the velocity components in the x and y directions, respectively; D_x and D_y are the spatially varying diffusion coefficients; K is the linear, comprehensive degradation coefficient; and S_c represents all pollution sources.

The coarse, outer grid of the model spans Xiamen Bay from 117.8°E to 118.6°E and 24.25°N to 24.75°N with a horizontal resolution of 275 m. Its eastern and southern boundaries are controlled by the water elevation formed by 16 tidal components (2N₂, J₁, K₁, K₂, L₂, M₁, M₂, MU₂, N₂, NU₂, O₁, OO₁, P₁, Q₁, S₂, T₂). The Jiulong River and Dongxi River are treated as point sources, i.e. source 22 and source 3, in the model. The discharges of Jiulong River and Dongxi River are 121.0×10^8 and 4.0×10^8 m³/a respectively. The inner, nested fine grid, with a horizontal resolution of 35.7 m, covers the key region that is studied. The key region, shown in Fig. 1, includes 5 zones with XB and XN in the Western Sea, and TW, TX and TD in Tong'an Bay. In order to reduce complexity and limit confusion, all the pollution sources in the key region are grouped into 22 conceptual pollution sources (Tu et al., 2009). Other outside pollution sources that may affect the key region through water flow are considered as the background/initial condition of the model. The pollutant loads, based on the data of 2008, are derived from the Ocean & Fisheries Bureau of Xiamen (<http://www.hyj.xm.gov.cn/Ocean/Index.aspx>) and the study of marine environmental quality assessment and MECC in the Xiamen Bay (Zhang et al., 2010). The locations of all the sources are shown in Fig. 1. Sources 4, 11, 15, 19, 20 and 21 are actual point sources (outlets of sewage treatment

plants and electric power plants) and the others are generated from merging non-point sources. The Jiulong River (Source 22) and Dongxi River (Source 3) provide the largest pollutant loads to the system.

2.2. Response fields

The response field is the concentration field due to a pollution source with a unit load of 1.0 g/s (Deng et al., 2010; Han et al., 2011). The concentration caused by the total load of the pollution source equals the product of the response field and the magnitude of the total load. Therefore, the total pollutant concentration field is the sum of the concentration of all pollution sources under total load. The relationship between concentration and load of pollution sources can be built with response field as

$$C_i = \sum_{j=1}^n P_{(ij)} Q_j \quad (2)$$

where i is the sea zone number, j is the source number, Q_j (g/s) is the pollutant load of source j , $P_{(ij)}$ ((g/m³)/(g/s)), that is s/m³ is pollutant concentration per unit load and can be defined as the response field of source j in sea zone i , and C_i (g/m³ or mg/L) is the concentration in sea zone i .

2.3. Optimization methods

The water quality management is viewed as a multiple objectives optimization problem accounting for the conflicting goals of the different stakeholders (e.g., EPB and dischargers). The aspiration of EPB is to improve water quality by imposing higher standards, while the dischargers prefer to minimize waste treatment costs by using the assimilative capacity of the environment (Sasikumar and Mujumdar, 1998). In this study, three types of optimization (classic linear optimization, fuzzy optimization and grey fuzzy optimization) are applied and their relative merits are evaluated.

Because of serious pollution problem in Xiamen Bay, if higher water quality standard was set as the goal, the reduction of pollutant load is too large to achieve. As a result, classic linear optimization is set to maximize the total pollutant load subject to strict constraints in the paper. In another word, while the method can represent the dischargers' interests, it cannot fully represent EPB's aspiration of simultaneously imposing higher standards to improve water quality.

$$\text{Max} \quad \sum_{j=1}^n Q_j \quad (3)$$

$$\text{Subject to} \quad C_i \leq C_i^p \quad (4)$$

$$Q_j^l \leq Q_j \leq Q_j^u \quad (5)$$

where C_i is calculated by Eq. (2), C_i^p is the water quality standard in sea zone i , Q_j^u and Q_j^l are the upper and lower pollutant load limits of source j , and Q_j is the optimized pollutant load of source j .

The second method, fuzzy optimization, has the capability to incorporate conflicting goals by maximizing all the satisfaction or goal fulfillment levels (Sasikumar and Mujumdar, 1998). Based on fuzzy sets theory, the satisfaction levels can be represented by the membership functions, $\mu_{E_i}(C_i)$ and $\mu_{F_j}(Q_j)$ given by:

$$\mu_{E_i}(C_i) = \begin{cases} 1 & C_i \leq C_i^d \\ \left[\frac{C_i^p - C_i}{C_i^p - C_i^d} \right] & C_i^d \leq C_i \leq C_i^p \\ 0 & C_i^p \leq C_i \end{cases}$$

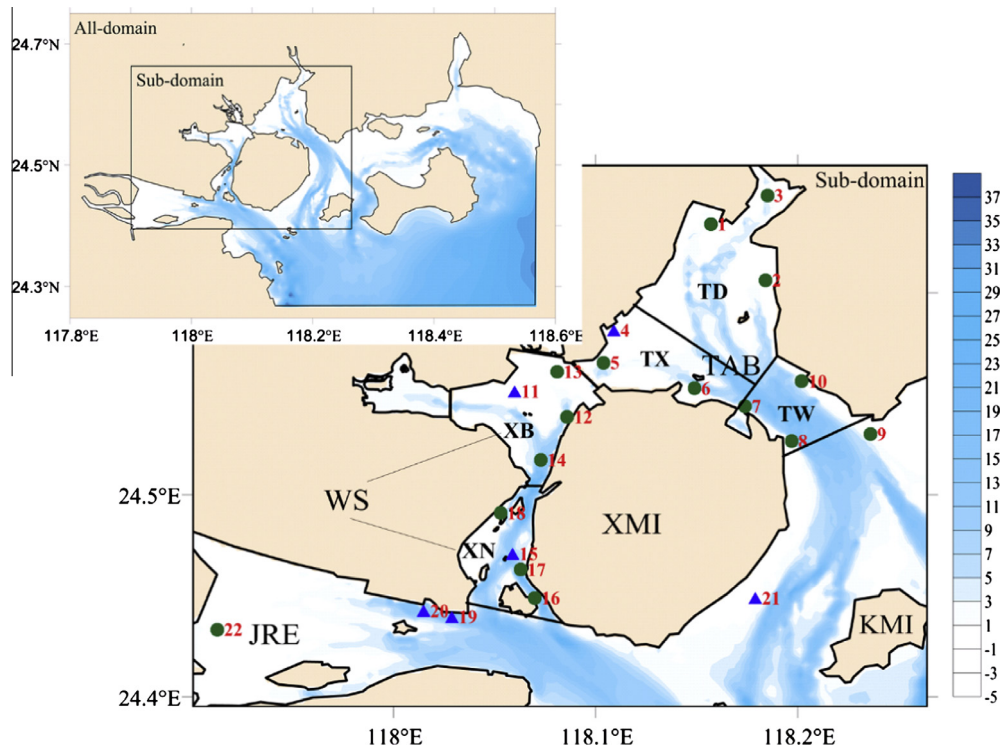


Fig. 1. All-domain and sub-domain of the nested model, 22 pollution sources are labeled; 5 sea zones, i.e. XB and XN in the Western Sea, TW, TX and TD in the Tong'an Bay. WS, TAB, XMI JRE and KMI denote the Western Sea, Tong'an Bay, Xiamen Island Jiulong River Estuary and Kinmen Island respectively. The triangle and circle is point source and non-point source respectively.

$$\mu_{F_j}(Q_j) = \begin{cases} 1 & Q^u \leq Q_j \\ \frac{Q_j - Q_j^l}{Q_j^u - Q_j^l} & Q_j^l \leq Q_j \leq Q_j^u \\ 0 & Q_j \leq Q_j^l \end{cases}$$

The membership function of EPB is expressed by $\mu_{E_i}(C_i)$ in Eq. (6). If the optimized water quality (C_i) is worse than permitted water quality (C_i^p), the satisfaction level exceeds the permission level with a membership value of 0. If the optimized water quality (C_i) is better than desirable water quality (C_i^d), the satisfaction level is desirable level with a membership value of 1. If the stakeholder is a discharger, the membership function is expressed by $\mu_{F_j}(Q_j)$, in Eq. (7). The satisfaction level of the discharger increases when optimized loads (Q_j) are close to the upper limit load (Q_j^u), starting from lower limit load (Q_j^l). The fuzzy optimization is expressed as:

$$\text{Max } \lambda \tag{8}$$

$$\text{Subject to } (C_i^p - C_i) / (C_i^p - C_i^d) \geq \lambda \tag{9}$$

$$(Q_j - Q_j^l) / (Q_j^u - Q_j^l) \geq \lambda \tag{10}$$

$$C_i^d \leq C_i \leq C_i^p \tag{11}$$

$$Q_j^l \leq Q_j \leq Q_j^u \tag{12}$$

$$0 \leq \lambda \leq 1 \tag{13}$$

The optimized value, λ , is the satisfaction level. Furthermore, Karmakar and Mujumdar (2006) indicated that the limitation of fuzzy optimization is the assumed fixed upper and lower bound of membership function. Therefore, grey fuzzy optimization was introduced to relax the upper and lower bounds of the membership function

(Karmakar and Mujumdar, 2006). The imprecise membership functions are expressed as:

$$\mu_{C_i^\pm}(C_i^\pm) = \begin{cases} 1 & C_i^+ \leq C_i^d \\ \frac{C_i^\pm - C_i^d}{C_i^+ - C_i^d} & C_i^d \leq C_i^\pm \leq C_i^p \\ 0 & C_i^p \leq C_i^- \end{cases}$$

$$\mu_{F_j^\pm}(Q_j^\pm) = \begin{cases} 1 & Q_j^{u+} \leq Q_j^- \\ \frac{Q_j^\pm - Q_j^l}{Q_j^{u+} - Q_j^l} & Q_j^l \leq Q_j^\pm \leq Q_j^{u+} \\ 0 & Q_j^+ \leq Q_j^- \end{cases}$$

where the superscripted \pm indicates upper and lower bound of the interval grey numbers. Based on grey system theory, the grey fuzzy optimization is represented as

$$\text{Max } \lambda^\pm \tag{16}$$

$$\text{Subject to } (C_i^{p\pm} - C_i^\pm) / (C_i^{p\pm} - C_i^{d\pm}) \geq \lambda^\pm \tag{17}$$

$$(Q_j^\pm - Q_j^{l\pm}) / (Q_j^{u\pm} - Q_j^{l\pm}) \geq \lambda^\pm \tag{18}$$

$$C_i^{d\pm} \leq C_i^\pm \leq C_i^{p\pm} \tag{19}$$

$$Q_j^{l\pm} \leq Q_j^\pm \leq Q_j^{u\pm} \tag{20}$$

$$0 \leq \lambda^\pm \leq 1 \tag{21}$$

The optimal value of λ^\pm is obtained as an interval grey number from two separate submodels. Submodel 1 (grey fuzzy plus) maximizes the upper bound (λ^+) while submodel 2 (grey fuzzy minus) maximizes the lower bound (λ^-). Meanwhile, the upper and lower

bounds of C_i^{\pm} and Q_j^{\pm} are also obtained from these two submodels as follows: Submodel 1:

$$\text{Max } \lambda^+ \quad (22)$$

$$\text{Subject to } (C_i^{p+} - C_i^-) / (C_i^{p-} - C_i^{d+}) \geq \lambda^+ \quad (23)$$

$$(Q_j^+ - Q_j^{l-}) / (Q_j^{u-} - Q_j^{l+}) \geq \lambda^+ \quad (24)$$

$$C_i^{p-} \leq C_i^- \leq C_j^{d+} \quad (25)$$

$$Q_j^{l-} \leq Q_j^- \leq Q_j^{u+} \quad (26)$$

$$0 \leq \lambda^+ \leq 1 \quad (27)$$

Submodel 2

$$\text{Max } \lambda^- \quad (28)$$

$$\text{Subject to } (C_i^{p-} - C_i^+) / (C_i^{p+} - C_i^{d-}) \geq \lambda^- \quad (29)$$

$$(Q_j^- - Q_j^{l+}) / (Q_j^{u+} - Q_j^{l-}) \geq \lambda^- \quad (30)$$

$$C_i^{p-} \leq C_i^- \leq C_j^{d+} \quad (31)$$

$$Q_j^{l-} \leq Q_j^- \leq Q_j^{u+} \quad (32)$$

$$0 \leq \lambda^- \leq 1 \quad (33)$$

3. Water quality simulation and response fields

COD_{Mn} , dissolved inorganic nitrogen (DIN) and AP are simulated as independent components within the numerical ocean model. In Table 1, the model results are compared with observational data, showing the similar pattern that the concentration is higher in the Tong'an Bay (TW, TX and TD) and lower in the Western Sea (XB and XN). The relative errors of COD_{Mn} range from 0.09% to 21.59%, with a mean of 12.54%; the mean relative errors of DIN and AP are 12.31% and 27.39%, respectively. Compared with Tong'an Bay, the relative error is larger in the Western Sea, indicating that the impact of pollution sources in the Western Sea is more complicated. These differences between model results and observations may be caused by inaccurate coefficients or poor estimates

Table 1
The observed and calculated concentration of COD_{Mn} , DIN, and AP in five zones.

| Parameters | Value names | XB | XN | TW | TX | TD |
|------------|-------------------------|-------|-------|-------|-------|-------|
| COD_{Mn} | Calculated value (mg/L) | 1.19 | 1.19 | 0.96 | 0.89 | 1.49 |
| | Observed value (mg/L) | 1.11 | 1.5 | 0.84 | 0.89 | 1.9 |
| | Relative error (%) | 6.92 | 20.43 | 13.65 | 0.09 | 21.59 |
| DIN | Calculated value (mg/L) | 1.16 | 1.26 | 0.92 | 1.13 | 1.18 |
| | Observed value (mg/L) | 1.48 | 1.42 | 0.84 | 1.00 | 1.12 |
| | Relative error (%) | 21.65 | 10.90 | 9.81 | 13.60 | 5.61 |
| AP | Calculated Value (mg/L) | 0.046 | 0.044 | 0.064 | 0.082 | 0.120 |
| | Observed Value (mg/L) | 0.063 | 0.051 | 0.045 | 0.061 | 0.101 |
| | Relative error (%) | 27.17 | 14.48 | 41.25 | 34.78 | 19.26 |

of the pollutant loads. Although the model needs to be improved, the agreement between the observed and simulated values suggests that the response fields calculated by the ocean model are reasonably reliable.

In Xiamen Bay, both DIN and AP concentrations exceed the Chinese water quality standard for seawater. However, for simplicity, we chose to only allocate AP. The reason for this choice is that the ratio of DIN/AP in the Xiamen Bay is 19.6, which exceeds 16 and indicates that AP is the limiting factor in the Xiamen Bay.

The modeled AP under normal load conditions is plotted in Fig. 2. In Tong'an Bay, the concentration of AP ranges from 0.04 mg/L to 0.12 mg/L, increasing from outer part of the bay to the inner bay due to both dilution and diffusion processes. In the Western Sea, the AP distribution is more complicated. The concentration does not decrease significantly from inner bay to the outer bay implying the strong impact of the Jiulong River inputs into the Western Sea. The concentration is comparatively high in the Tong'an Bay relative to the Western Sea, which is in accordance with the observed patterns. This suggests that Tong'an Bay's pollution problem is more serious than that in the Western Sea, but the Western Sea's problem is more difficult to solve because of the strong impact of the Jiulong River whose watershed includes many cities in addition to Xiamen.

Fig. 3 shows the response fields of the 22 pollution sources in the five sea zones. In Tong'an Bay, sources located in the shallow, inner bay (e.g., 1, 3, 4) have the larger values than those from outer sources (e.g., 8), the pollutant of which can be more easily diluted by outside sea water. In the Western Sea (XB and XN), Sources 11, 12 and 13, near regions with weak diffusion capability, have larger response fields than other sources, such as 16 and 17. Sources located near a deep water channel with good diffusion ability (e.g., Source 16) have smaller values than those for the other two nearby sources (15 and 17). The impact of Sources 19, 20, 21 and 22, which are located outside the Western Sea and Tong'an Bay, are less than that due to the other sources.

4. Results and discussion

With increased urbanization, the pollutant loads from non-point sources will be decreased, while the loads from point sources (e.g., sewage treatment plants) will be increased because of higher sewage collecting capacity. According to Xiamen city planning documents (<http://www.xmgh.gov.cn/>) and the report of Zhang et al. (2010), the goals of EPB and the dischargers are given in Tables 2 and 3. However, the load of each source is very different, the

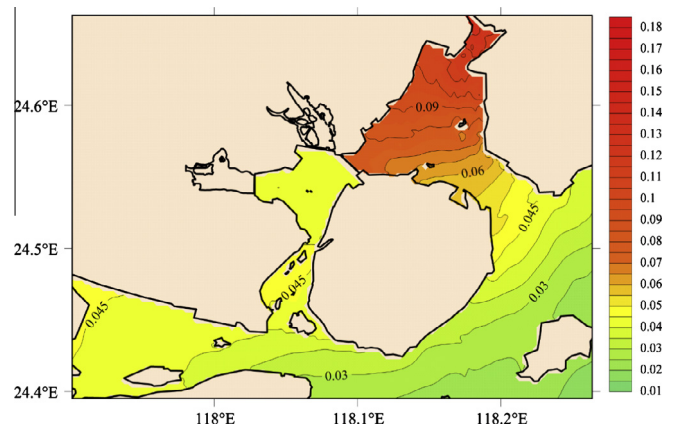


Fig. 2. The simulated distribution of AP (mg/L) under normal load conditions in Xiamen Bay.

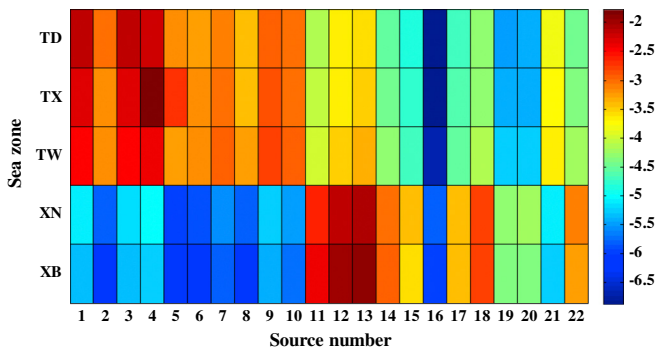


Fig. 3. The logarithm of response fields at each sea zone (units: s/m^3 , which can be defined as the concentration per unit load and shown in Eq. (2)).

Table 2
Details of Environmental Protection Bureau membership functions (mg/L).

| | C^{p+} | C^{p-} | C^{d+} | C^{d-} |
|---------------|----------|----------|----------|----------|
| Water quality | 0.030 | 0.026 | 0.015 | 0.013 |

Table 3
Details of discharger membership functions (t/a).

| Sources | Present load | Q_i^{l-} | Q_i^{u+} | Q_i^{u-} | Q_i^{u+} |
|---------|--------------|------------|------------|------------|------------|
| 1 | 69.0 | 5.9 | 7.9 | 90.6 | 122.5 |
| 2 | 24.2 | 2.1 | 2.8 | 21.8 | 29.5 |
| 3 | 367.9 | 31.3 | 42.3 | 312.7 | 423.1 |
| 4 | 8.0 | 0.7 | 0.9 | 23.2 | 31.4 |
| 5 | 1.1 | 0.1 | 0.1 | 0.9 | 1.3 |
| 6 | 10.1 | 0.9 | 1.2 | 8.6 | 11.6 |
| 7 | 29.9 | 2.5 | 3.4 | 25.4 | 34.4 |
| 8 | 1.9 | 0.2 | 0.2 | 1.6 | 2.2 |
| 9 | 4.9 | 0.4 | 0.6 | 97.9 | 132.4 |
| 10 | 8.9 | 0.8 | 1.0 | 7.5 | 10.2 |
| 11 | 59.0 | 5.0 | 6.8 | 50.2 | 67.9 |
| 12 | 11.7 | 1.0 | 1.3 | 9.9 | 13.5 |
| 13 | 6.7 | 0.6 | 0.8 | 5.7 | 7.7 |
| 14 | 11.7 | 1.0 | 1.3 | 9.9 | 13.5 |
| 15 | 150.0 | 12.8 | 17.3 | 127.5 | 172.5 |
| 16 | 51.6 | 4.4 | 5.9 | 43.8 | 59.3 |
| 17 | 11.6 | 1.0 | 1.3 | 9.8 | 13.3 |
| 18 | 4.6 | 0.4 | 0.5 | 3.9 | 5.2 |
| 19 | 24.0 | 2.0 | 2.8 | 33.2 | 44.9 |
| 20 | 259.0 | 22.0 | 29.8 | 220.2 | 297.9 |
| 21 | 39.0 | 3.3 | 4.5 | 72.8 | 98.5 |
| 22 | 1238.0 | 315.7 | 427.1 | 1052.3 | 1423.7 |

largest being Source 22 (the Jiulong River), which can reach 1238 t/a, while the load of Sources 4, 5, 6, 8, 9, 10, 13 and 18 are all less than 10 t/a. For classical linear optimization and fuzzy optimization, the upper and lower limit loads are Q_i^{l-} and Q_i^{u+} of Table 3. The water quality standard of classical linear optimization is C_j^{p+} in Table 2, while fuzzy optimization has an upper and lower limit, which are C_j^{d-} and C_j^{p+} in Table 2. Details of these symbols can be seen in Section 2.3.

The results obtained from the three different optimization methods are shown in Figs. 4 and 5 and presented in Table 4. The classical linear optimization result (Fig. 4a) shows that Sources 2, 4, 9, 19 and 21 possess low response fields (due to good diffusion conditions) and would be permitted to increase their loads. Sources 5, 6, 7, 8, 10, 15, 16, 17 and 20, remain unchanged, while sources 1, 3, 11, 12, 13, 14, 18 and 22, with high response fields, would be required to cut their loads. However, the corresponding optimized concentrations (Fig. 4b) in the three sea zones (XN, TD and TX) equal the water quality standard (0.03 mg/L), indicating the risk

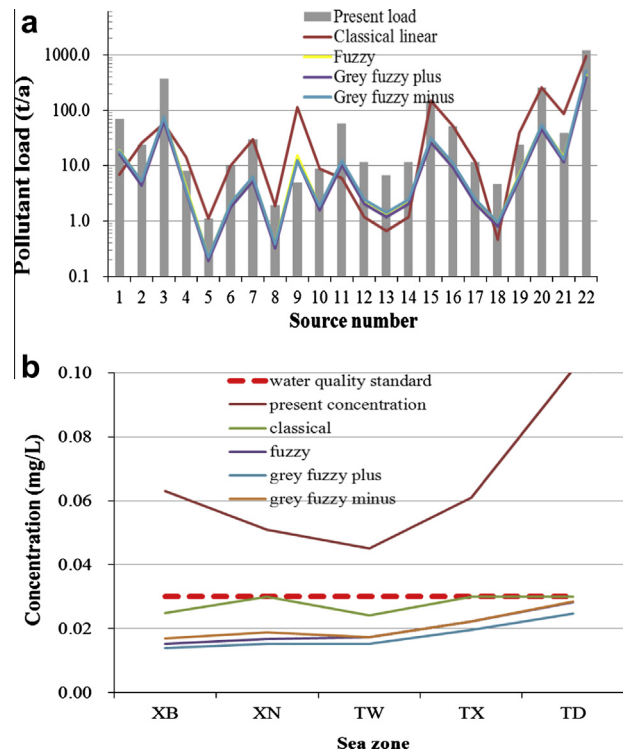


Fig. 4. The optimized results of load (t/a, a) and concentration (mg/L, b).

of a pollution accident exceeding the standard is very high, especially during extreme events (such as a hurricane or a significant power failure). Furthermore, Fig. 5a shows that the concentration exceeds the water quality standard (>0.03 mg/L) in the Jiulong River estuary, which is out of the focus area of this study, indicating that the classical linear optimization does not take these adjacent areas into consideration. Through the classical optimization, the satisfaction levels of most dischargers are maximized and the total load shall be cut by only 23%, while the satisfaction level of EPB in the five sea zones is as low as 0–39% (Table 4). This means that classical linear optimization maximizes total load, but neglects to balance all dischargers' or account for EPB's satisfaction level, which causes the total satisfaction level to be 0%.

The fuzzy optimization provides a compromise result which incorporates the conflicting goals of dischargers and the EPB. Most of the sources would be required to cut their loads to improve water quality (Fig. 4a). Fig. 5b shows that the AP concentration of the fuzzy optimization is lower than that of the classical case, especially in JRE. The load of Source 22 (Jiulong River) would be decreased greatly (by 70%) from 1238.0 t/a to 473.3 t/a, which leads to an improvement of water quality in the XN (the AP concentration decreases nearly 50%, from 0.03 mg/L to 0.017 mg/L). The loads of sources 1, 2, 3, 4, 5 and 6 also need to be cut to improve water quality in the TD and TX. Unlike the classical linear optimization, most sources do not need to be cut as much (Fig. 4a). As a result, the total satisfaction level of all the dischargers rises to 9–11%. The other stakeholder's (EPB) satisfaction level rises to 11–98% (Table 4). The total satisfaction level is 9%, indicating both stakeholders are comparatively satisfied with the compromised allocation. In addition, the buffer between optimized concentration and water quality standard ensures a low risk of a pollution accident.

When it comes to the grey fuzzy optimization, it offers upper and lower limits for both the load and concentration results (Figs. 4, 5c and d), which contain the fuzzy optimization results. If the loads are cut according to Fig. 4a, the total load would be cut by 67–74%

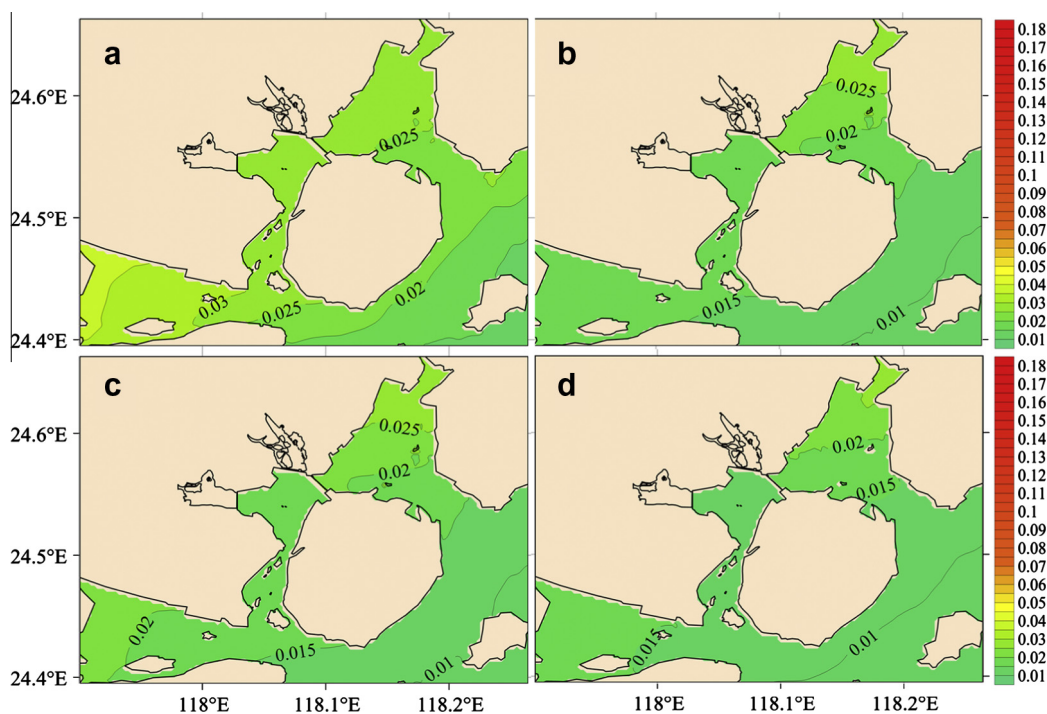


Fig. 5. The simulated distribution of AP (mg/L) under optimized load conditions of classical (a), fuzzy (b), grey minus (c) and grey plus (d) optimizations.

Table 4
The satisfaction level of different optimization methods (satisfaction level: 0% means not satisfactory, 100% means totally satisfactory).

| | Classical | Fuzzy | Grey fuzzy plus | Grey fuzzy minus |
|---|-----------|-------|-----------------|------------------|
| Average optimized water quality (mg/L) | 0.028 | 0.020 | 0.018 | 0.021 |
| Average fractions remove level (%) | 23 | 70 | 74 | 67 |
| EPB's average satisfaction level (%) | 0–39 | 11–98 | 12–100 | 9–78 |
| Dischargers' average Satisfaction level (%) | 0–100 | 9–11 | 11–12 | 8–9 |
| Total satisfaction level (%) | 0 | 9 | 11 | 8 |

and the water quality will be improved to 0.018–0.021 mg/L. For example, the largest source, 22, is cut from 1,238 t/a to 392.9–526.1 t/a, and the corresponding water quality in the Western Sea will be improved to 0.014–0.020 mg/L. In the Tong'an Bay, the load of Source 3 is cut from 367.9 t/a to 64.0–77.3 t/a and Source 1 is decreased from 69 t/a to 16.1–18.4 t/a. As a consequence of these cuts the water quality is improved to 0.015–0.029 mg/L. Grey fuzzy results show dischargers' satisfaction level falls in a range of 8–12% (Table 4), including fuzzy optimization's result (9–11%), which suggests the impact of relaxed upper and lower bounds on the membership function. The EPB's satisfaction level is 9% to 100%, which also covers fuzzy optimization's result (11–98%). From Figs. 4 and 5 and Table 4, the grey fuzzy plus optimization offers a larger satisfaction level with less load and better water quality than does the grey fuzzy minus optimization. Because sea water quality and load-cutting rate are full of uncertainties in reality, it is proper to specify a desirable range based upon a strict criterion. Therefore, the upper and lower limits of the optimized results provide both dischargers and the EPB not only flexible results but also a further direction to improve the water quality. A range of optimal solutions is helpful to make a final decision according to technical and economic feasibility of the pollutant treatment levels.

Notably, the total load calculated by fuzzy and grey fuzzy optimizations is cut by 67–74%, which is significantly larger than classical linear optimization (23%). The reason for this large difference is that classical linear optimization maximizes the total

load of all the sources, while the objectives of fuzzy and grey fuzzy optimizations are to maximize the satisfaction level of every source. If fuzzy and grey fuzzy optimizations were set instead to take into account the total load of all the sources as a whole and maximize it as the classical linear optimization does, the total load would be cut by 32–40%, which is closer to the result of classical linear optimization. However, everyone has the right to develop the economy to improve the quality of life. Economic development inevitably increases pollutant discharge, especially in a developing country like China, and every source should have the equal right to emit pollutants and the same duty to reduce them. Consideration of every stakeholder is one of the advantages of the fuzzy optimization. Karmakar and Mujumdar (2006) also took every pollution source into consideration in the application of grey fuzzy optimization at river watershed. Therefore, unlike classical linear optimization, fuzzy and grey fuzzy optimizations take every discharger and every sea zone into consideration, reflecting equal environmental rights for everyone.

These three optimization methods offer three possible management solutions for the water quality problem in the Xiamen Bay. The classical optimization gives the largest total load with a low satisfaction level of the EPB and some pollution sources, fuzzy optimization can maximize all the satisfaction levels of every stakeholder by offering a compromise result, while the grey fuzzy optimization can provide a more feasible and fairer choice. However, they are not mutual exclusive. Because of the great

competition between the pollution problem and economy development, especially in China, it is not possible to solve the problem immediately and easily. According to the results of these three methods, the classical linear optimization result may be the best initial choice to ensure the water quality meets the national standards because of its least removal levels. Subsequently, the other two solutions, especially the grey fuzzy method, can offer a direction for the further steps to improve the water quality as they provide more feasible and fairer methods.

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