Assessment of the Maximum Permissible Load of Pollutant in an opened coastal zone using a water quality model: a case study in Hainan of China

Xiyu Ouyang1, Peng Zhao1* and Hanbao Chen1
1 Tianjin Research Institute of Water Transport Engineering, Tianjin 300456, China
*Corresponding author’s e-mail: zhaopeng_tj@tiwte.ac.cn

Abstract. This study aims to estimate the maximum-permissible-loads of pollutant by means of water quality modelling, in order to maintain the concentrations of pollutants below prescribed water quality targets. Modelling of water quality used the Mike21 HD and ecolab modules, while the assessment of maximum-permissible-loads of pollution used the method of response factor coefficient. This research is descriptive quantitative parameters of COD. A scenario assessment was carried out by the flows from various point sources to understand the site-specific relationships between pollution sources and water quality conditions, as well as calculating the maximum-permissible-loads to determine the pollution point source discharge.

1. Introduction
The increasing development of coastal resources in recent years has brought marine environment concerns. The release of industrial and domestic sewage caused the water quality problems and accelerated water ecosystem deterioration. More and more studies and initiatives have been carried out to protect and restore ecological quality or integrity, within estuarine, coastal and offshore systems.

Since 1992, nutrient and sediment allocations have been developed and applied in the Chesapeake Bay total maximum daily load to reduce hypoxia and to restore living resources[1]. Since 1999, in Italy the maximum-permissible-loads(MPLs) policy have been implemented to restrict the level of emission of pollutant loads, and the implementation of this policy benefited from the mathematical models, which can be used to estimate the MPLs by determining the functional relationship between the set of different input loads and output variables which one decides to compare with the water quality targets[2]. In Korea, the local authorities have developed effective watershed protection strategies by means of the so-called total maximum daily load (TMDL) management which is a regulation system and first issued in US, with the goal to protect the rivers[3].

The water quality impacts of sewage discharge are characterized by complicated physical, chemical, and biological processes that interact formulating their ecological spatiotemporal dynamics[4]. Therefore, these management and strategies may clearly benefit from the insight into the water quality studies. One of the major concerns of these studies is hydrodynamic and water quality numerical modelling, which are developed to understand and predict the water quality changes due to the consequences of sewage and wastewater discharges. A considerable number of water quality models have been developed and applied widely in coastal, river and estuary. Such as, the EFDC (Environmental Fluid Dynamic Code), WASP (Water Quality Analysis Simulation Program), SMS (Surface-water Modelling System), CE-QUAL-W2 and DHI MIKE etc [5-7].
Paliwal et al. successfully applied the MIKE21, a hydrodynamic and water quality model, to simulate biological oxygen demand and dissolved oxygen profiles in the Hoogly estuary, and the simulation provided reasonably predictions[8]. El shemy et al. developed a 2-D hydrological and ecological model by MIKE21 modeling system and calibrated with measured data, the calibrated model was used to investigate the impacts of future climate changes on hydrodynamic and water quality characteristics of the Manzala lake and examined the different enhancement water quality scenarios for controlling the water quality status of the lake[9]. Xu et al. used MIKE21 to construct a two-dimensional eutrophication model of Douhe Reservoir and applied the model to simulate a situation in which variables like air temperature, transferred water volume, or exogenous pollutant load might reach extreme values[10].

This study aims to calculate the maximum-permissible-load (MPL) that is defined as the maximum permissible discharges of the point sources of sewage, which can maintain the concentrations of these substances in waterbody below the water quality standards. In this study, a coupled hydrodynamic and water quality model was established using MIKE21 HD and ECOLab modules and an opened coastal zone of Hainan was selected for this study. The model is developed to simulate the long-term transport and spatiotemporal distribution of pollutant substances and to understand the site-specific relationships between the point sources sewage and water quality conditions. The chemical oxygen demand(COD) can be used to easily quantify the amount of organics in water, the most application of COD is in quantifying the amount of oxidizable pollutants found in surface water (e.g. lakes and rivers) or wastewater. This study chosen the COD as prescriptive parameter to evaluate water quality. The high concentration indicates that the water is severely polluted and vice versa.

2. Material and methods

2.1. Model description

The HD module simulates water level variations and flows based on solution of the incompressible averaged Navier-Stoke equations. The ECOLab module simulates COD variations refer to the differential equation. The continuity equation, the two horizontal equations, transport equation and the mass balance equation of COD are written as

$$\frac{\partial h}{\partial t} + \frac{\partial h \bar{u}}{\partial x} + \frac{\partial h \bar{v}}{\partial y} = hS$$

$$\frac{\partial (h \bar{u})}{\partial t} + \frac{\partial (h \bar{u} \bar{u})}{\partial x} + \frac{\partial (h \bar{v} \bar{u})}{\partial y} = -f \bar{u} h - gh \frac{\partial \bar{u}}{\partial y} - \frac{h \bar{u} \rho a}{\rho_0 \bar{u}} - \frac{h^2 \rho g}{2 \rho_0 \bar{u}} + \frac{\tau_{xx}}{\rho_0} - \frac{\tau_{bx}}{\rho_0} - \frac{1}{\rho_0} \left( \frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xy}}{\partial y} \right)$$

$$\frac{\partial (h \bar{v})}{\partial t} + \frac{\partial (h \bar{u} \bar{v})}{\partial x} + \frac{\partial (h \bar{v} \bar{v})}{\partial y} = -f \bar{v} h - gh \frac{\partial \bar{v}}{\partial x} - \frac{h \bar{v} \rho a}{\rho_0 \bar{v}} - \frac{h^2 \rho g}{2 \rho_0 \bar{v}} + \frac{\tau_{xy}}{\rho_0} - \frac{\tau_{by}}{\rho_0} - h \frac{\partial s_{xy}}{\partial x} - \frac{\partial s_{yy}}{\partial y}$$

$$\frac{\partial \bar{C}}{\partial t} + \frac{\partial (\bar{u} \bar{C})}{\partial x} + \frac{\partial (\bar{v} \bar{C})}{\partial y} = hF_C - h k_p C + hC_s S$$

$$\frac{dCOD}{dt} = -K_{cod} \cdot COD \cdot \theta^{(T-20)}$$

Eq.1 is the continuity equation, Eq.2 and Eq.3 are the horizontal momentum equations for the x- and y- component, respectively, Eq.4 is the advection-dispersion equation, Eq.5 is the COD degradation equation. Where $h$ is the total water depth; $\eta$ is the surface elevation; $\bar{u}, \bar{v}$ are the depth-averaged velocity components in the $x, y$ direction; $f$ is the Coriols parameter; $g$ is the gravitational acceleration; $(\tau_{xx}, \tau_{xy})$ and $(\tau_{bx}, \tau_{by})$ are the $x$ and $y$ components of the surface wind and bottom stresses; $\rho_a$ is the atmospheric pressure; $\rho$ is the density of water; $\rho_0$ is the reference density of water; $s_{xx}, s_{xy}, s_{yx}$ and $s_{yy}$ are components of the radiation stress tensor; $T_{xx}, T_{xy}, T_{xy}$ and $T_{yy}$ are components of the lateral stress and estimated using an eddy viscosity formulation based on of the
depth average velocity gradients; $S$ is the magnitude discharge due to point source; $u_x, v_y$ is the velocity by which the water is discharged into ambient water. $codde$ is the COD degradation process, $K_{cod}$ is degradation constant for organic matter at 20°C, COD is the actual chemical oxygen demand concentration, $\sigma^{(r-20)}_{cod}$ is Arrhenius temperature coefficient.

The model domain lies between latitude 16.67° to 17.24° and longitude 111.89° to 112.65° of 74116 elements having a resolution of 10m-100m (Fig.1). The model bathymetry was generated using chart data obtained from the C-MAP. The south, west, and north boundaries of the domain were driven by the tidal elevations predicted using the Global Tide Model.

2.2. MPL calculation

2.2.1. Mixed zone.
The mixed zone is a limited coastal waters near the outfalls, in which the concentration of pollutant substances can exceed the water quality standards of related statutes and prescribed norms, but the concentration at the edge must satisfy the water quality standards. In this study, the mixed zone can be constituted as calculation domain for MPL which is an envelope of the pollutant concentration which exceeds the prescribed water quality standards. One of the MPL objectives is to ensure that the pollutant concentration outside the mixed zone below the prescribed standards.

2.2.2. Response factor field.
The water quality of waters in which the hydrodynamic conditions are constant only depends on the properties of point source discharges, such as the location, intensity, and chemical composition. In other words, the concentration filed constitutes corresponding relation between waters and point source discharge. The relationship between concentration field and point source discharge can be expressed by elementary function: $P = C/S$. Where $C$ is the concentration formed by point source discharge, $S$ is the discharge amount of point source, $P$ is response coefficient which reflects the relationship of water quality with a certain point source discharge. Obviously, the value of the response coefficient is the quantitative relationship between water quality and point source discharge and only related to the location of the point source. Different positions of waters have different response to a point source on account of the transport and diffusion characteristics of ocean water bodies. Thus, the response coefficient is not a constant in space and its spatial distribution is the response factor field.

2.2.3. MPL calculation.
MPL is the basis of total pollutant amount control, and the water quality standards are the restricted conditions for MPL, the hydrodynamic characteristics and the set-up of point source discharges are objective conditions of MPL calculation. The value of MPL can be determined by calculation formula which is decided by these prerequisites. The calculation formula is written as $S_0 = C_0/P_0$. Where $S_0$ is the MPL of a certain pollutant substance, $C_0$ is permissible concentration increment at the edge of
mixed zone which meet the requirements of water quality targets, \( P_0 \) is the response coefficient of control points at the edge of mixed zone.

2.3. Scenario settings
10 point sources are arranged around the island and Fig.2 is the position diagram of these point sources. The daily discharge amount of COD is 30 kg/d that is determined according to the regulation No.GB 18918-2002. Two seasons of summer and winter are considered due to the seasonal changes of certain factor, such as tide and water temperature, and the monthly average concentration field after 30 consecutive days of continuous discharge of pollutants are simulated, respectively.

![Figure 2. Diagram of point sources layout.](image)

3. Results and discussions
Fig.3 are the maximum current fields in the study area under the tide driven in summer and winter. The flow is affected by the tidal action, island geometry and bathymetry. There is a circulation around the island. In summer, the flow velocity is higher on east and west side of island. In winter, the flow velocity is higher on the east, north and south side.

![Figure 3. Model simulated maximum tidal current fields in (Left)summer and (Right)winter.](image)

The water quality model described in Section 2 was run using the scenario settings, thus obtaining the spatial distribution of the monthly average concentrations of COD. Fig 4 and Fig 5 show the monthly spatial distribution of the averaged COD concentration in summer and winter. The spatial distribution of concentration significantly changed among different seasons and point sources. In summer, the impact water area with high concentration were mainly located in the nearshore. In winter, the pollutants were diluted faster as the higher flow velocity and the concentration value became smaller.

In this study area, the grade I water quality standard (COD < 50mg/L) was set as the target. The size of water area in which the average COD concentration exceeded the target were calculated and depicted in Fig.6. Point sources of 1#, 2#, 3# and 10# where located on the northeast side of the island were relatively smaller than others.
The strict rules were prescribed for the size of mixed zone which must be less than 3km² in an open sea area referred to the regulation No.GB18486-2001. The mixed zone range and the control points at the edge were identified with the restriction and the concentration distribution of average COD and were shown in Fig.7 (the examples of 1#, 4# and 8#), the response factors of control points were calculated by the formula in section 2.2.2 and the MPL for COD of point sources were calculated by the formula in section 2.2.3, the results were shown in Tab.1. In summer, the highest value of MPL is the 10.76 t/d at 10# point source. In winter, the highest value of MPL is the 18.58t/d at 5# point source.

| Point Source | 1#   | 2#   | 3#   | 4#   | 5#   | 6#   | 7#   | 8#   | 9#   | 10#  |
|--------------|------|------|------|------|------|------|------|------|------|------|
| Season       |      |      |      |      |      |      |      |      |      |      |
| Sum.         | 4.04 | 8.59 | 7.00 | 0.24 | 5.62 | 5.34 | 3.43 | 6.77 | 6.48 | 10.67 |
| Win.         | 3.17 | 0.95 | 2.09 | 2.28 | 18.58| 16.88| 13.63| 0.92 | 3.66 | 10.30 |

Table 1. Results of maximum permissible load for COD. Unit: t/d
4. Conclusions
In this study, a coupled hydrodynamic and water quality model for an opened sea area was constructed with the MIKE21 HD and ECOLab modules and selected the COD as the prescriptive parameter to evaluate water quality. The model run using the scenario settings, thus obtaining the spatial distribution of the monthly average concentrations of COD to understand the relationships between pollution point sources and water quality conditions. The mixed zone range and control points at the edge were identified refer to the related restrictions and water quality targets, and the response fact coefficients of control points were calculated using the formula with respect to the relationship between waters and point source discharge. On the basis, the MPL for COD in this study area were determined which satisfied the grade I water quality standard.

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