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Three-Dimensional Numerical Modeling Study of Thermal Pollution and its effect on dissolved oxygen and chlorophyll

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There are large volume of industrial activities in Bushehr coast (Iran).To study thermal pollution and its effects on dissolved oxygen and chlorophyll in this area, the COHERENS has been employed based on a vertical sigma coordinate. The model has been applied 120×40 grid and 5 sigma level from the surface to the bottom. The Cartesian lateral grid spaces are Δx = 1 km (east-west direction) and Δy = 1 km. We included an ecological part of the model to calculate oxygen and chlorophyll variations in the domain. The model is forced by tidal data extracted from Persian Gulf tide table and climatological monthly mean atmospheric forces (wind speed, air temperature, humidity, cloud cover, and precipitation) derived from 54 years (1952-2006) of NOAA (National Oceanic and Atmospheric Administration) data. Findings of the model suggest that temperature, oxygen and chlorophyll concentration change with the discharging of heated water in the study area. In order to prevent this pollution and its destructive impacts, similar studies can be performed before construction of industrial units and power plants.

[**Keywords:** Thermal Pollution, COHERENS, Dissolved Oxygen, Chlorophyll]

Introduction

Water temperature is a fundamental and important water quality variable. For example, most chemical and biological activities are a function of temperature that affects fish habitats in particular, which are sensitive to water temperature. Temperature also affects the solubility of gases in water, such as O_2, CO_2, N_2 and CH_4. In warm waters, respiration and growth rates increase. As growth of bacteria and phytoplankton population occurs in a short period, the effect of rising water temperature is remarkable and algal blooms could be observed[1]. For this reason, it is important to understand how water body temperature is affected by heated wastewater discharge. Water temperature can change by various environmental processes, both natural and anthropogenic. For example, thermal and nuclear power plants use large quantities of cooling water to condense the exhaust steam from the turbines. The hot water inflow and the cold water outflow generate a flow field in the water body that may result in a temperature increase in the cold water intake for the power plant and a harmful increase in water temperature in streams, rivers, lakes, or occasionally, coastal ocean waters, which is called thermal pollution[2]. This hot water recirculation, therefore, adversely affects the efficiency of the power plant, since it raises the temperature at the inlet channel. Increases in water temperature can impact aquatic organisms by decreasing oxygen supply as well. Kinouchi et al. (2007) investigated stream temperature in the central Tokyo area and its suburbs from 1978 through 1998 to understand long-term temperature changes in urban streams. Their results suggest that the increase in the anthropogenic heat input from wastewater is the main cause of the long-term increase in stream temperature and distinct stream temperature increase occurs only during winter and early spring months[3]. Sehgal and Jaluria (1982) carried out an analytical study of the steady horizontal recirculation generated due to heated wastewater discharge into a shallow water body. The effect on the cold water intake temperature and the dependence of the flow on various governing parameters were studied as well. The resulting recirculation is obtained in terms of streamlines and isotherms[4]. Both physical and numerical surface water hydro-dynamic and transport models have been historically applied to predict power plant thermal impacts under design conditions, but predicting the effect of temperature into environmental parameters such as dissolved oxygen and chlorophyll has not been reported. So modeling environmental aspects of heated wastewater discharge is the main goal of this study. According to the literature review, the present study is one of the first modeling studies based on environmental impact assessments of thermal pollution. This type of study is useful in order to prevent this kind of pollution and its destructive impacts, so similar studies can be performed before construction of industrial units and power plants that need huge amount of water for their coolant water system.

Materials and Methods

Concern over water quality during recent years has given rise to the development of coupled physical-biological numerical models as tools for understanding the relevant physical and biological processes and the influence of human activity on ecological conditions[5]. The aim of this study is to predict the effect of the changing thermal conditions on the biota and to simulate the input and dispersion of thermal pollution using the COHERENS model in Bushehr province, Iran. Bushehr is in the south of the Iran, with a long coastline onto the Persian Gulf. On the one hand the industrial corridor of Assalouyeh is located in this area and On the other hand in environmental impact assessment (EIA), all aspects of plants and industrial units should be concerned before establishing or developing and one of these aspects are thermal pollution via coolant water. In this case, we choose this area as a developing industrial area. We employed the COHERENS to study thermal pollution in rectangular domain in Bushehr coastline (Fig. 1). Due to the main aim of this study is to investigate environmental impact assessment (ecological effects) of thermal pollution in water body and since the maximum impact of this phenomenon is on the surface, we have applied the constant depth in the model. In our study, wastewater discharge site is situated on the southern boundary of the domain. North, east and west boundaries are open and have water exchange with the open sea. The model has been applied (120×40 grid and 5 sigma level) from the surface to the bottom. The Cartesian lateral grid spaces are Δx = 1 km (east-west direction) and Δy = 1 km (north-south direction). Atmospheric and tidal forces and heated wastewater discharge rate have been employed in this model as well. Four major tidal constituents (O_1, K_1, M_2, and S_2) are denoted in Table 1. These values extracted from the Persian Gulf Tide Table. The model is forced by climatologic monthly mean atmospheric forces (wind speed, air temperature, humidity, cloud coverage and precipitation) derived from 54 years (1952-2006) of NOAA (National Oceanic and Atmospheric Administration) data.

Fig. 1— Bushehr coast, Iran

Table 1— Tidal constituents applied in the model

280	265	238	211	Phase (Deg)
0.31	0.12	0.2	0.34	Amplitude (m)
K_1	S_2	O_1	M_2	Tidal constituents

The model was initialized in winter when vertical stratification is weak throughout the Gulf using uniform temperature and salinity fields with values of 19°C and 39PSU, respectively, which are reasonably close to observational evidence. At the open boundary we prescribed temperature and salinity, derived from the previous numerical modeling in the Persian Gulf on a monthly basis[6]. Dissolved oxygen and chlorophyll concentration at the open boundaries were applied in the model as well. The model was running for 2 years to reach the steady state and then again for another year.

COHERENS (Coupled Hydrodynamical Ecological model for Regional Shelf Seas) is a three-dimensional hydrodynamic multi-purpose model for coastal and shelf seas that is coupled to biological, resuspension and contaminant models, and resolves the mesoscale to seasonal scale processes[7]. The program is written in FORTRAN 77 and has four major components that we used physical part with a general module for solving advection-diffusion equations and microbiological module that deals with the dynamics of microplankton, detritus, dissolved inorganic nitrogen, and oxygen. The physical characteristics of the program that are used in this study are:

- The mode-splitting technique is used to solve the 2-D and 3-D momentum and continuity equations.
- It is possible to include temperature, salinity or both in the simulation.
- The absorption of solar radiation in the upper part of the water column is implemented by an optical module.
- Density effects in the momentum and turbulence equations are included via an equation of state.
- Various types of radiation conditions can be used at the open sea and river boundaries.
- A graphics interface program that converts model output into the portable “netCDF” format[8&9], supported by several graphical software platforms (PV-Wave, IDL, Matlab, FERRET, etc.)[7].

The program allows formulation of he model equations either in Cartesian coordinates (x_1, x_2, x_3) or in spherical coordinates (λ, φ, x_3), where the x3-axis is directed upwards along the vertical. The Cartesian system uses the f-plane approximation (uniform Coriolis frequency) so that the (x_1, x_2)-axes can be oriented arbitrarily in the horizontal plane. In the spherical system λ and φ represent respectively the longitude (positive in the eastern, negative in the western hemisphere) and the latitude (positive in the northern, negative in the southern hemisphere). The vertical coordinate is chosen such that the surface $x_3 = 0$ corresponds to the mean sea water level. The equations of the free surface and sea bottom then take form:

$$x_3 = \zeta(x_1, x_2, t) \quad \text{or} \quad x_3 = \zeta(\lambda, \varphi, t) \qquad (1)$$

$$x_3 = -h(x_1, x_2) \quad \text{or} \quad x_3 = -h(\lambda, \varphi) \qquad (2)$$

Where ζ is the sea surface elevation and h is the mean water depth, so that the total water depth H is given by $H = h + \zeta$.

The hydrodynamic part of the model uses the following basic equations:

- The momentum equations using the Boussinesq approximation and the assumption of vertical hydrostatic equilibrium
- The continuity equation
- The equations of temperature

The basic equations for the three-dimensional mode in the Cartesian coordinates are as follows:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x_1} + v\frac{\partial u}{\partial x_2} + w\frac{\partial u}{\partial x_3} - fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x_1} + \frac{\partial}{\partial x_3}(\upsilon_T\frac{\partial u}{\partial x_3}) + \frac{\partial}{\partial x_1}\tau_{11} + \frac{\partial}{\partial x_2}\tau_{21}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x_1} + v\frac{\partial v}{\partial x_2} + w\frac{\partial v}{\partial x_3} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial x_2} + \frac{\partial}{\partial x_3}(\upsilon_T\frac{\partial v}{\partial x_3}) + \frac{\partial}{\partial x_1}\tau_{12} + \frac{\partial}{\partial x_2}\tau_{22} \qquad (3)$$

(4)

$$\frac{\partial p}{\partial x_3} = -\rho g$$

$$\frac{\partial u}{\partial x_1} + \frac{\partial v}{\partial x_2} + \frac{\partial w}{\partial x_3} = 0 \qquad (5)$$

(6)

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x_1} + v\frac{\partial T}{\partial x_2} + w\frac{\partial T}{\partial x_3} = \frac{1}{\rho_0 c_p}\frac{\partial T}{\partial x_3} + \frac{\partial}{\partial x_3}(\lambda_T\frac{\partial T}{\partial x_3}) + \frac{\partial}{\partial x_1}(\lambda_H\frac{\partial T}{\partial x_1}) + \frac{\partial}{\partial x_2}(\lambda_H\frac{\partial T}{\partial x_2})$$

(7)

where (u, v, w) are the components of the current, T denotes the temperature, $f = 2\Omega\sin\varphi$ the Coriolis frequency, $\Omega = 2\pi/86164$ rad/s the rotation frequency of the Earth, g the acceleration of gravity, p the pressure, ν_T and λ_T the vertical eddy viscosity and diffusion coefficients, λ_H the horizontal diffusion coefficient for salinity and temperature, ρ the density, ρ_0 a reference density, c_p the specific heat of seawater at constant pressure and $I(x_1, x_2, x_3, t)$ solar irradiance.

The horizontal components of the stress tensor are defined by:

$$\tau_{11} = 2\upsilon_H\frac{\partial u}{\partial x_1}$$

$$\tau_{21} = \tau_{12} = \upsilon_H(\frac{\partial u}{\partial x_2} + \frac{\partial v}{\partial x_1}) \qquad (8)$$

$$\tau_{22} = 2\upsilon_H\frac{\partial v}{\partial x_2} \qquad (9)$$

(10)

Where ν_H is the horizontal diffusion coefficient for momentum.

The numerical solutions of the model equations are greatly simplified by introducing a new vertical coordinate that transforms both the surface and the bottom into coordinate surfaces. The following coordinate transformation is applied

$$(\tilde{t}, \tilde{x}_1, \tilde{x}_2, \tilde{x}_3) = (t_1, x_1, x_2, Lf(\sigma)) \qquad (11)$$

Where

$$\sigma = \frac{x_3 + h}{\xi + h} = \frac{x_3 + h}{H} \qquad (12)$$

That is commonly used σ-coordinate varying between

0 at the bottom and 1 at the surface.

Taking f(0) = 0 and f(1) = 1 the equation of the bottom takes the simple form ˜x3 = 0, while the moving surface transforms into ˜x3 = L[7].

Results

Heated wastewater discharge rate injected into the water body was 60 m^3/s and the wastewater temperature was assumed at 35ºC. The model results for the temperature field affected by thermal discharge for 4 seasons in terms of isotherms are shown in Fig. 2 to Fig. 5. In all seasons, temperature increased near the thermal discharge site and thermal plume turned to the right as well. Temperature difference between the domain and heated wastewater discharge site in winter was more than in summer. Fig. 2 shows that the temperature of domain in spring was 27ºC and in the discharge site it was 30ºC. Fig. 3 shows a slight difference between the domain (29ºC) and discharge site (31º) in summer. During autumn the temperature in the domain was 26ºC and in the discharge site it was 30ºC as shown in Fig. 4. Finally, in winter the temperature in the domain and discharge site was 19ºC and 26ºC respectively (Fig. 5).

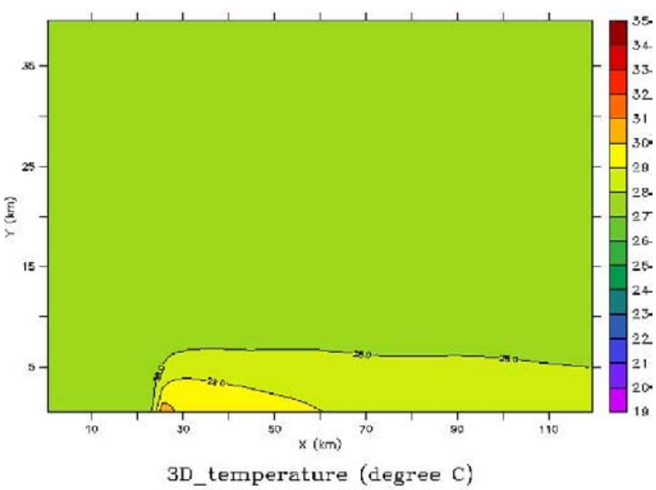

Fig. 2— Surface temperature field in spring

Dissolved Oxygen (DO) variations due to thermal discharge are an important feature of thermal pollution that can occur in relation to temperature[1]. Reference DO proportional to a temperature of 19ºC (500mmol/m^3) was applied in the model, as well as heated wastewater DO proportional to 35ºC (12.5 mmol/m^3)[10] and monthly variations of DO in open boundaries were also applied in the model. Seasonal DO changes due to heated wastewater discharge with a flow rate of 60 m^3/s are shown in Fig. 6 to Fig. 9.

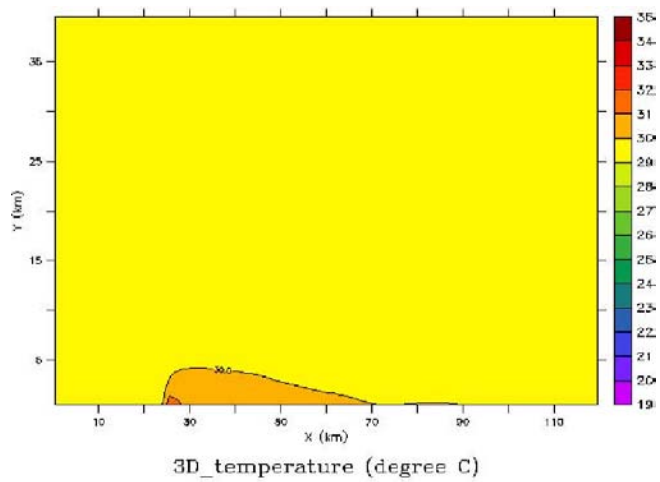

Fig. 3— Surface temperature field in summer

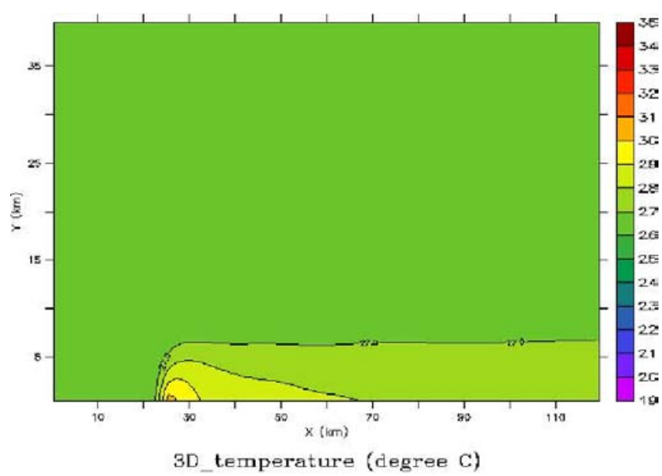

Fig. 4— Surface temperature field in autumn

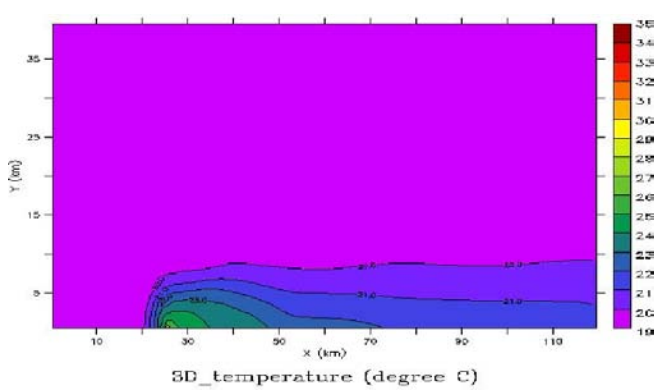

Fig. 5— Surface temperature field in winter

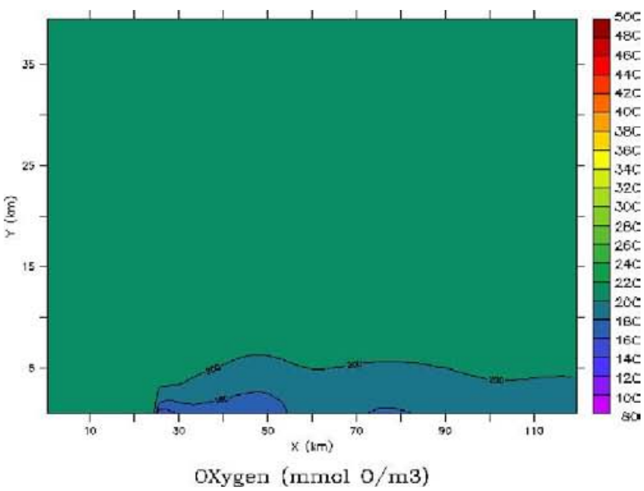

Fig. 6— Surface DO variations in spring

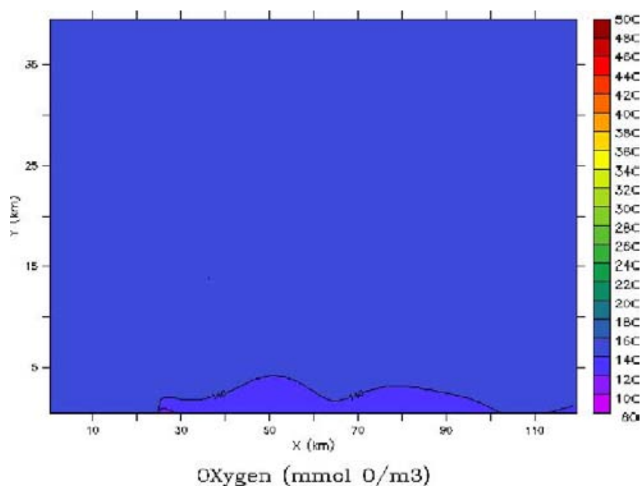

Fig. 7— Surface DO variations in summer

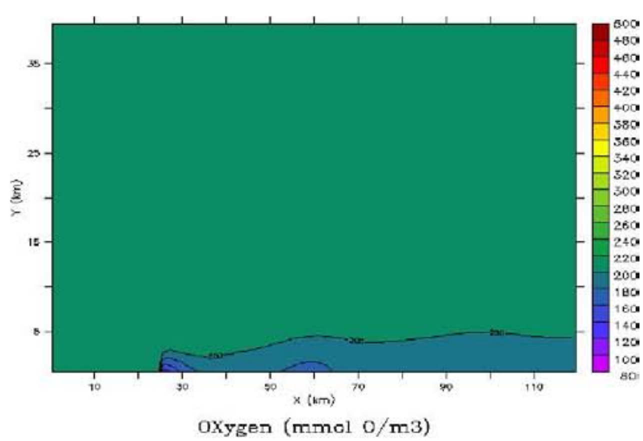

Fig. 8— Surface DO variations in autumn

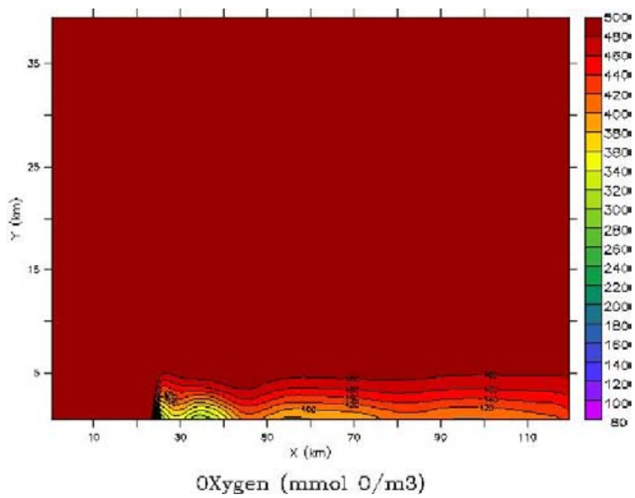

Fig. 9— Surface DO variations in winter

As these figures show, when we approached the thermal discharge site, DO decreased. Dissolved Oxygen variations were observed on the right side of the heated wastewater discharge, and between the domain and discharge site the variations in winter were more practical than summer. Dissolved Oxygen concentration throughout the domain in warm seasons was lower than the cool seasons. According to Fig. 6, in spring DO concentration in the domain was equal to 204 mmol/m^3 and in the discharge site it was 145mmol/m^3. These quantities in summer are 151 mmol/m^3 and 110 mmol/m^3 (Fig. 7). Fig. 8 presents DO in the surface in autumn. At this time DO concentration in the domain was 217 mmol/m^3 and in the discharge site it was 130 mmol/m^3. In winter these quantities increase to the values of 500 mmol/m^3 and 290 mmol/m^3 respectively (Fig. 9).

Photosynthesis rate and plant growth increased with a temperature increase of less than 40 ºC, leading to an increase in chlorophyll concentration[11]. Irradiance, day length, temperature, and nutrient availability are key factors for modeling the phytoplankton growth[12], and not only temperature but residual chlorine could affect the chlorophyll concentration due to the plant's heated wastewater discharge[13]. We assumed that there was no chlorine or any other pollutant in the wastewater. Reference value for chlorophyll was 0.1 mg/m^3 and this value was used in the model[10].

Also monthly chlorophyll concentration variations in open boundaries were applied in the model. Chlorophyll concentration at the surface for different seasons is shown in Fig. 10 to Fig. 13. These figures show that chlorophyll concentration near the discharge site was more in respect to the domain. Also, chlorophyll concentration throughout the domain in cold seasons was less than warm seasons. Chlorophyll variations due to thermal discharge were obvious at the right side of the discharge site, like temperature variations. Chlorophyll differences between the domain and discharge site in winter was more practical than summer.

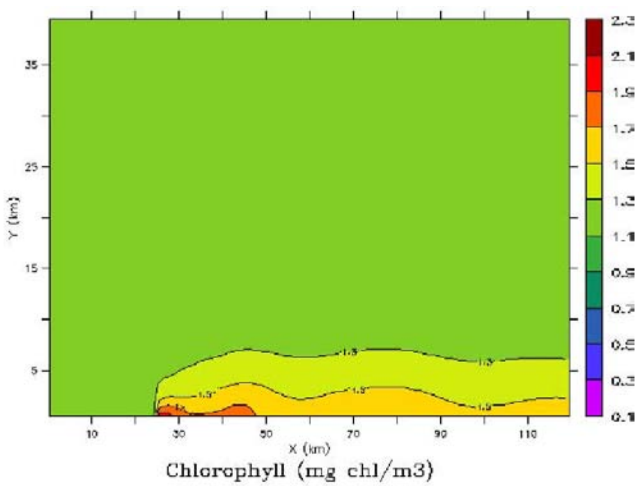

Fig. 10— Chlorophyll variations in spring

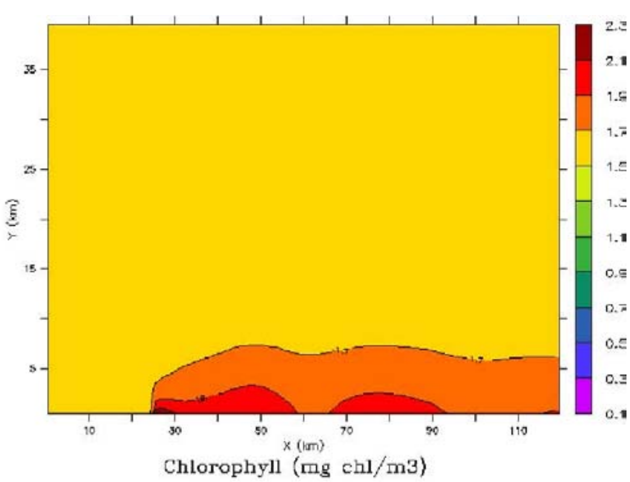

Fig. 11— Chlorophyll variations in summer

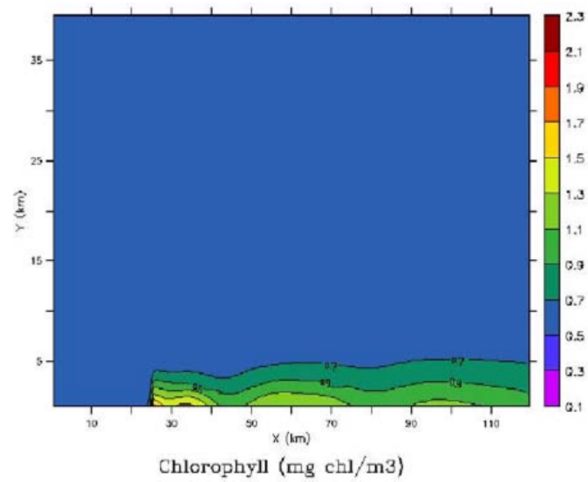

Fig. 12— Chlorophyll variations in autumn

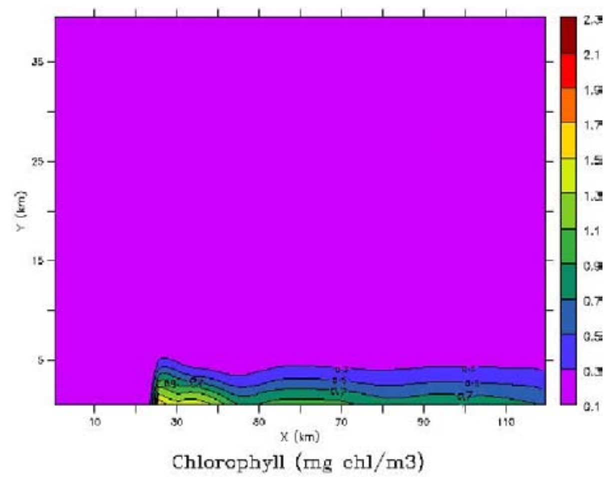

Fig. 13— Chlorophyll variations in winter

Fig. 10 indicates that in spring, chlorophyll concentration in the discharge site was 2 mg/m^3. At this time, this concentration for the domain was equal to 1.3 mg/m^3. Chlorophyll concentration in the domain was 1.7 mg/m^3 and in the discharge site it was 2.2 mg/m^3 in summer (Fig. 11). These values in autumn were 0.6 mg/m^3 and 1.8 mg/m^3 (Fig. 12). Lastly, Fig.13 shows that these concentrations during winter were 0.2 mg/m^3 and 1.7 mg/m^3. It should be noted that in this study, just the effect of temperature on chlorophyll concentration has been modeled.

Discussion and Conclusion

In order to consider the thermal discharge effects on the environment and coolant water system efficiency, deliberation of the temperature field is necessary. Temperature variations in the water body due to thermal discharge are shown in Fig. 2 to Fig. 5. These results of the model are in agreement with those of Sehgal et al. (1982), wherein they obtained the temperature field as isotherm by analytical solving of dominant equations[4].

Thermal plume turned to the right as shown in Fig. 2 to Fig. 5. This is due to the Coriolis force that affects large scale phenomena and turns them to the right (left) in the north (south) hemisphere. We use the non-dimensional number (Rossby number) to indicate whether this phenomenon is considered as a large scale. Large scale flows are defined as those with a Rossby number in the order of one or less[14]. In our study, the Rossby number was 0.04; hence, this thermal plume was a large scale one, affected by the Coriolis force. Since most industries discharge heated wastewater in large water domains that continues for a long time, usually these phenomena are large scale. So, it is suggested that cold water intake should be localized on the left (right) side of the discharge site in the north (south) hemisphere to decrease the probability of adverse effects on the coolant water system efficiency. In this condition, the study of environmental factors on the right in north hemisphere and in south hemisphere, left side of the discharge site is necessary.

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