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Dispersal of Thermal and Saline Pollution in Coastal Waters, Red Sea: A Theoretical Study

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Abstract. The dispersion of the hot-salty wastewater from Jeddah desalination plant is investigated by using a three-dimensional circulation model. Firstly, the model was used to predict the distribution of the temperature and the salinity in the baseline situation when no wastewater is discharged. Secondly, the model is used to predict the dispersion of the wastewater from the desalination plant when it is discharged at the surface. Finally, the effects of a subsurface discharge at 30 m are investigated. Accordingly, the model results show that, the seasonal changes and the discharge depth influences the dispersion of the discharge. In winter, because of increased vertical mixing, the saline discharge sinks to about 50 m depth and then moves horizontally towards the open sea. In summer the water column is strongly stratified and when the waste is discharged at the surface the plume disperses horizontally with little sinking. In contrast, the surface waters are not affected by the wastewater when a subsurface discharge is taking place. It is evident that the baseline water circulation is modified by the addition of hot saline wastewater. During the winter, an eddy caused by sinking wastewater is formed in the vicinity of the discharge point. This eddy disappears in the summer season when horizontal dispersion is dominant.

Introduction

Saudi Arabia is located in an arid region and the accumulation of substantial ground water reserves is not very common. As a consequence the desalination plants have become a necessary source of fresh water.

Large-scale seawater desalination was first introduced to Saudi Arabia in 1907. In 1928 the first multistage flash desalination plant (MSF) with capacity of 227 m^3 day^{-1} was built in Doba and Al-Wajh. The Saline Water Conversion Corporation (SWCC) was established in 1978 to carry out the necessary feasibility and preliminary studies for installing future desalination plants and to maintain the operating ones. SWCC planned to supply the coastal and inland cities and towns with desalted seawater. Within the last 25 years the number of desalination plants has increased rapidly and means at present Saudi Arabia is the world's largest producer of desalted water. It is noteworthy that about 50% of the world desalination capacity is in Saudi Arabia. That is, there are twenty two desalination plants in operation with a combined capacity of 1.854 Mm^3 d^{-1} (Al-Mutaz, 1994).

Along the Red Sea coast there are 15 desalination plants in operation and other three are under construction. Table 1 shows the major operating and the under construction desalination plants along the Red Sea coast and Fig. 1 shows their locations on the map.

Table 1. Major desalination plants, including those under construction, along the Red Sea coast (SWCC, annual report, Riyadh, 1991).

Desalination Plant	Start-up Year	Capacity (m^3 day^{-1})
Haql II	1989	3785
Duba III	1989	3785
Al-Wajh II	1979	473
Al-Wajh ext. 1	1986	825
Al-Wajh ext. 2	1989	1032
Umlujj II	1986	3785
Madinah-Yanbu I	1980	95000
Jeddah RO(1)	1989	48827
Jeddah II	1978	10000
Jeddah III	1979	75700
Jeddah IV	1982	189250
Shoaibah I	1989	181800
Assir I	1989	75700
Farasan I	1979	430
Farasan ext. 2	1984	1075

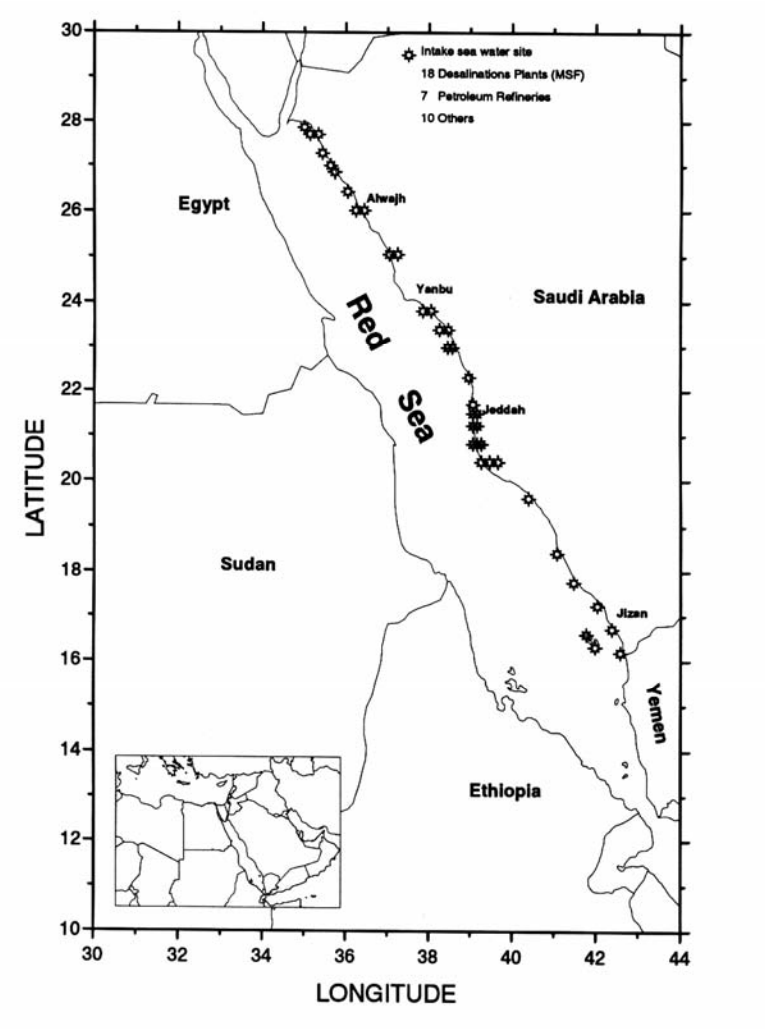

Fig. 1. Red Sea map showing the locations of the desalination plants along the Saudi Coast.

Thermal and Saline Pollution

Pollution has been defined as the presence of one or more contaminants for such duration that may damage the environment (Al-Mutaz, 1991). Desalination plants cause different types of pollution, such as, air pollution and water pollution. The daily inputs of heat and dissolved substances to the oceans from desalination plants is 3.86×10^{7} kcal and 4.5×10^{16} tons of minerals (Al-Mutaz, 1994). The aim of this work is to understand and predict the spread of water pollutants and, in particular, both thermal and saline pollution caused by hyper-saline wastewater from desalination plants.

The effects of the thermal and saline pollution are becoming more serious as the demand for the desalinated water increases. The temperature and the salinity of the discharged wastewater are always higher than the ambient water. Typically, the discharged water temperature is between 2-6 °C higher than the ambient seawater temperature, while the salinity of the discharged water is about 1.5-2 times higher than that of ambient seawater salinity (Dow, 1968; Mandelli & McLlenny, 1971). Evidently, the magnitude of the thermal and saline pollution varies with the temperature and salinity of the discharged wastewater, the topography and the dispersion rate of the receiving water (Jensen *et al.,* 1969, Coutant, 1970 and Davies & Jensen, 1974).

It has been suggested that all marine life will be affected by the increase in the temperature and salinity of seawater. Based on laboratory tests, Zeitoun *et al.,* (1969) showed that, most of the inter-tidal animals are killed when the water temperature increases from 30 to 39 °C. Therefore, thermal and saline pollutions may cause major changes in the natural ecosystem. This is because both saline and thermal pollutions change the thermal enrichment of the receiving water, the chemical make-up of the water and the biotic structure (GESAMP, 1984). Because of these changes many of the properties of seawater are changed and, in particular, the absorption coefficient for dissolved gases, the density, the viscosity and the osmotic pressure are affected (Zeitoun *et al.,* 1969 and Winter *et al.,* 1979).

The effects of the thermal and saline pollutions on the marine environment depend on the dispersion rate. As the dispersion rate increases the thermal and saline pollutions decrease (Eloranta, 1983). Field results from Sitra Power and Desalination Plant in Bahrain indicate that, wastewater is directly discharged into shallow coastal waters at temperature of 10-15 °C above the seawater. The discharged wastewater spreads over the sea surface into regions where the mixing rate is minimal. As a result, because of the increase in the water temperature and salinity, the water circulation is affected. Accordingly, the high temperature and salinity of discharged wastewater will affect the intake water. The best solution was to increase the depth of the wastewater discharge and increase the distance between the coast and the discharge outflow (Altayaran & Madany, 1992).

In the Jeddah area, the various desalination plants are located on the Red Sea coast close to the main recreational beach. The desalination plants were originally established to supply water to Jeddah city and the other nearby cities (*e. g.* Makkah and Taif). The production capacity of the desalination plants is about 382000 $m^3\ d^{-1}$. To produce this amount of fresh water, the plants require an intake of about 3.07 $Mm^3\ d^{-1}$. Approximately 2.65 $Mm^3\ d^{-1}$ of seawater with salinity 39 PSU is used for cooling and desalination purposes, after which it is discharged to the sea. The average salinity of this discharged wastewater is about 45.6 PSU, *i.e.,* higher by about 17 % than the seawater salinity. Accordingly, about 1400 $kg\ s^{-1}$ of salt is added to the local area of the sea. This may seem to be small compared to the total content of the salt in the Red Sea is 8.4×10^{15} kg, with an exchange rate of $13.5\times10^{6}\ kg\ s^{-1}$ at the Strait of Bab Al-Mandab (Al-Mutaz, 1991), but the discharge may cause the accumulation of salt in a small area unless it is dispersed efficiently.

In the light of the above explanation, the Red Sea environment is affected by the wastewater discharges from the desalination plants. Therefore, one of the objectives of this work is an attempt to predict the water circulation and determine the dispersion of the discharged wastewater. Also the optimum depth for the wastewater release from the desalination plant is considered, so that the pollution in the environment can be reduced.

The main objective of this study is to investigate the dispersion of the hot hyper-saline wastewater discharged from the Jeddah desalination plants. In order to achieve this objective, it was necessary to introduce several subordinate aims and objectives. These include the prediction of the temperature and salinity distribution in the Red Sea and the prediction of the water circulation in the Red Sea. Al-Barakati *et al.* (2002) applied three dimensional circulation model to the Red Sea and the results were used as boundary condition in this study.

The water circulation and the temperature-salinity distributions in the coastal region around the Jeddah Desalination Plants were obtained using the computer model. The results are presented for three different cases. These are:

1- Natural environment;

2- when wastewater is discharged to the surface waters; and

3- when wastewater is discharged into the subsurface waters.

Theoretical Model

$$\frac{\partial u}{\partial t} + \Gamma\,(u) - \frac{u\,v\,\tan\phi}{a} - f\ v = -\frac{1}{a\,\rho_0\,\cos\phi}\frac{\partial p}{\partial \lambda} + \frac{\partial}{\partial z}(\,K_m\frac{\partial u}{\partial z}) + F(\lambda)$$

$$\frac{\partial v}{\partial t} + \Gamma\,(v) - \frac{u^2\,\tan\phi}{a} + f\ u = -\frac{1}{a\,\rho_o\,\cos\phi}\frac{\partial p}{\partial \phi} + \frac{\partial}{\partial z}(\,K_m\frac{\partial v}{\partial z}) + F(\phi)$$

$$\frac{\partial T}{\partial t} + \Gamma\,(T) = \frac{\partial}{\partial z}(K_h\,\frac{\partial T}{\partial z}) + \nabla(\,A_h\,\nabla T)$$

$$\frac{\partial S}{\partial t} + \Gamma\,(S) = \frac{\partial}{\partial z}(K_h\,\frac{\partial S}{\partial z}) + \nabla(\,A_h\,\nabla S)$$

$$\frac{\partial w}{\partial z} = -\frac{1}{a\cos\phi}\left\{\frac{\partial u}{\partial \lambda} + \frac{\partial}{\partial \phi}(\,v\cos\phi\,)\right\}$$

$$\frac{\partial p}{\partial z} = -\,\rho\,g$$

$$\rho = \rho\,(T, S, P)$$

where,

u, v and w	: Zonal, meridional and vertical velocities.
a	: Mean radius of the earth (6370 x 10^5 cm).
g	: Mean gravitational acceleration (980.6 cm / sec^2).
ρ_o	: Mean ocean density profile (1.035 gm / cm^3).
ρ	: Potential density.
p	: Pressure.
K_m	: Vertical viscosity coefficient (cm^2 / sec).
K_h	: Vertical diffusion coefficient (cm^2 / sec).
A_h	: Lateral diffusion coefficient (cm^2 / sec).

T : Potential temperature.

S : Potential salinity.

Γ : Advection and diffusion terms are given as follow:

$$\Gamma(\alpha) = \frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}(v\alpha\cos\phi) + \frac{\partial}{\partial z}(w\alpha)$$

α : An arbitrary variable.

$F(\lambda)$ and $F(\phi)$ are the horizontal friction terms varying with longitude and latitude respectively and given by:

$$F(\lambda) = \nabla(A_m \nabla u) + A_m\left\{\frac{(1-\tan^2\phi)\,u}{a^2} - \frac{2\sin\phi}{a^2\cos^2\phi}\frac{\partial v}{\partial\lambda}\right\}$$

$$F(\phi) = \nabla(A_m \nabla v) + A_m\left\{\frac{(1-\tan^2\phi)\,v}{a^2} - \frac{2\sin\phi}{a^2\cos^2\phi}\frac{\partial u}{\partial\lambda}\right\}$$

A_m : Lateral viscosity coefficient (cm^2 / sec).

f : Coriolis parameter given by: $f = 2\,\Omega\sin\phi$

Ω : Angular speed of rotation of the earth

Results

Results for January and July (representing winter and summer seasons) are shown in three-dimensional volume plots. The water column is divided into a maximum of nine layers. Therefore, there are up to nine horizontal planes (x-y). However, only the first three layers are presented (20 m layer thickness) because there are no significant changes in the lower layers.

For the purpose of comparison, it is necessary to differentiate between the conditions that prevailed in the Red Sea before the desalination plants were built from those afterwards when a discharge is made. The term 'natural environment' refers to the conditions prevailing before any discharge was made.

Case 1: Natural Environment

The predicted temperature and salinity for January and July (representing winter and summer seasons) are shown in Fig. 2. The predicted temperatures and salinities represent the monthly averaged distribution, and scales of the colour contours have been set so that they are constant. This allows comparison of the variations in temperature and salinity. The layer by layer water circulation inferred from the calculated velocity distribution is shown in Fig. 3.

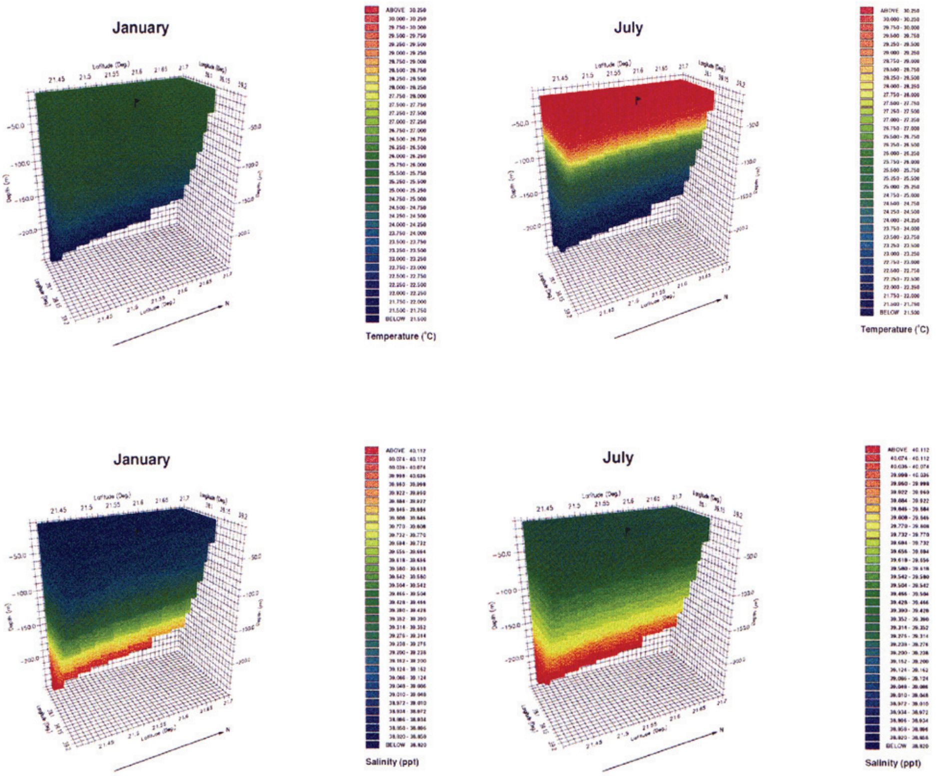

Fig. 2. Natural environment temperature and salinity distribution during January and July.

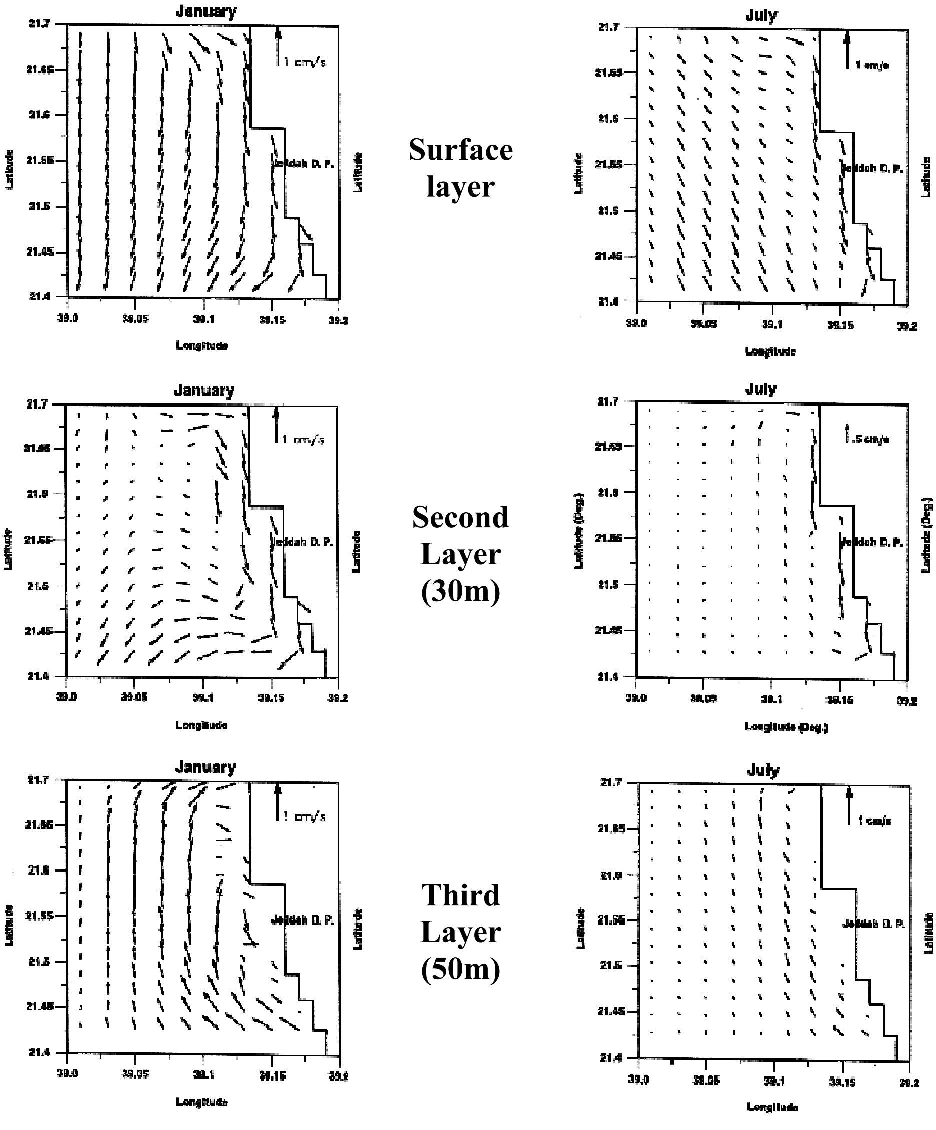

Fig. 3. Water circulation pattern for natural environment conditions during January and July.

Case 2: Surface Waters Discharge

Taking the predicted temperatures and salinities for a grid box that is representative of the location of the desalination plant from the natural condition, the Jeddah Desalination Plants wastewater was introduced to the model after local mixing. Firstly, the discharged wastewater from the Jeddah Desalination Plant was introduced in the first layer of the model. The temperature and salinity of the discharged wastewater were 40 ^{o}C and 45.6 PSU respectively. Predicted water temperature and salinity distributions for January and July representing winter and summer seasons are shown in Fig. 4. The first three layers of the horizontal water circulation are shown in Fig. 5.

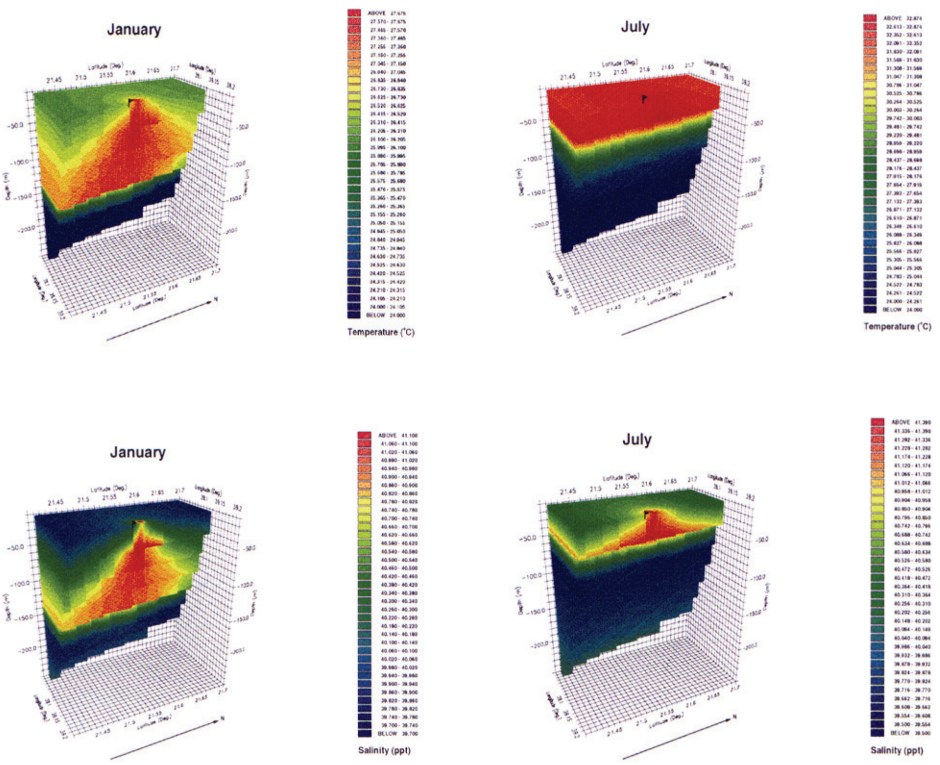

Fig. 4. Temperature and salinity distribution during January and July, due to surface water discharge.

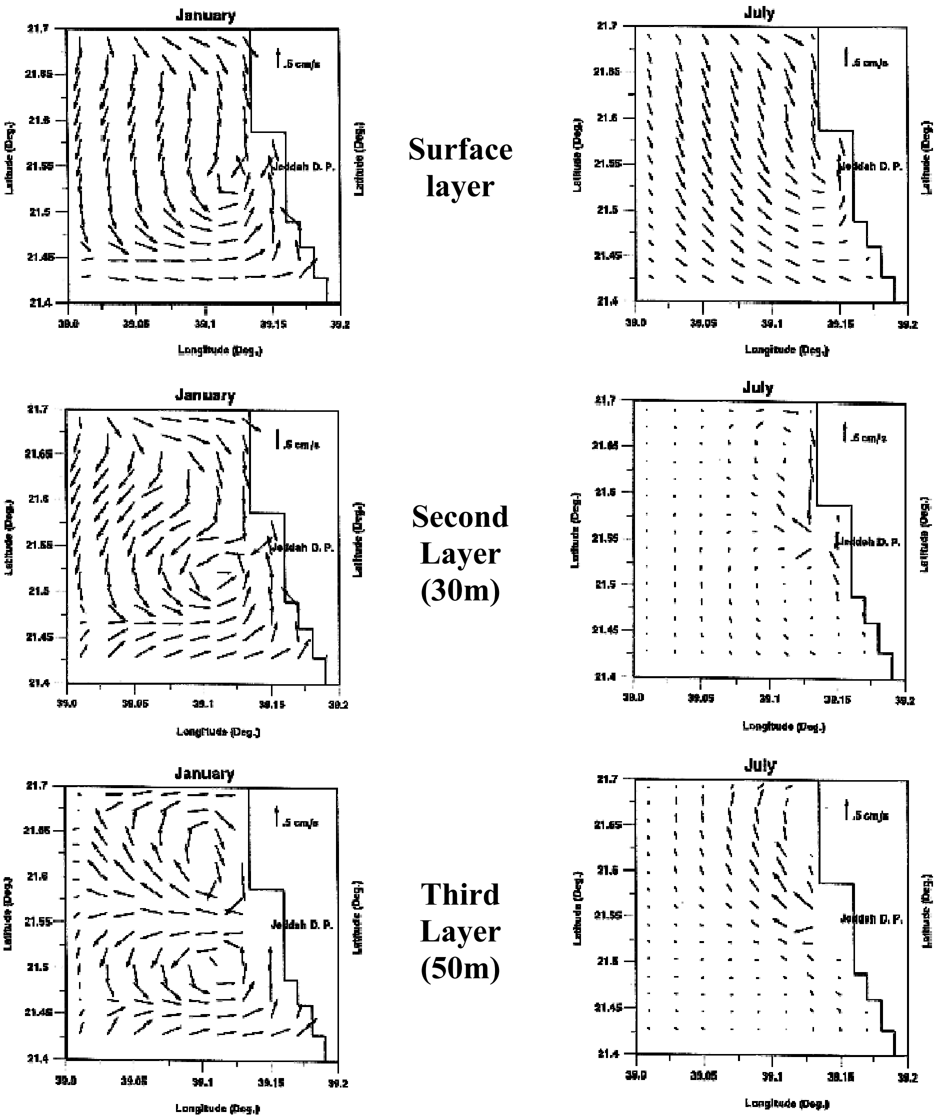

Fig. 5. Water circulation pattern for surface water discharge during January and July.

Case 3: Sub-Surface Waters Discharge

The model is used now to examine the dispersion patterns that would occur, if the Jeddah Desalination Plants wastewater was discharged in the sub-surface, at a depth of 30 m (*i.e.,* layer two). The methodology used is the same as that for a surface discharge. The method assumes a complete local mixing between the discharged wastewater and the natural seawater. A second layer grid box at the location of Jeddah Desalination Plant is chosen for the wastewater release.

The predicted temperature and salinity distributions for January and July are shown in Fig. 6 and 7, the water circulation pattern obtained from the model.

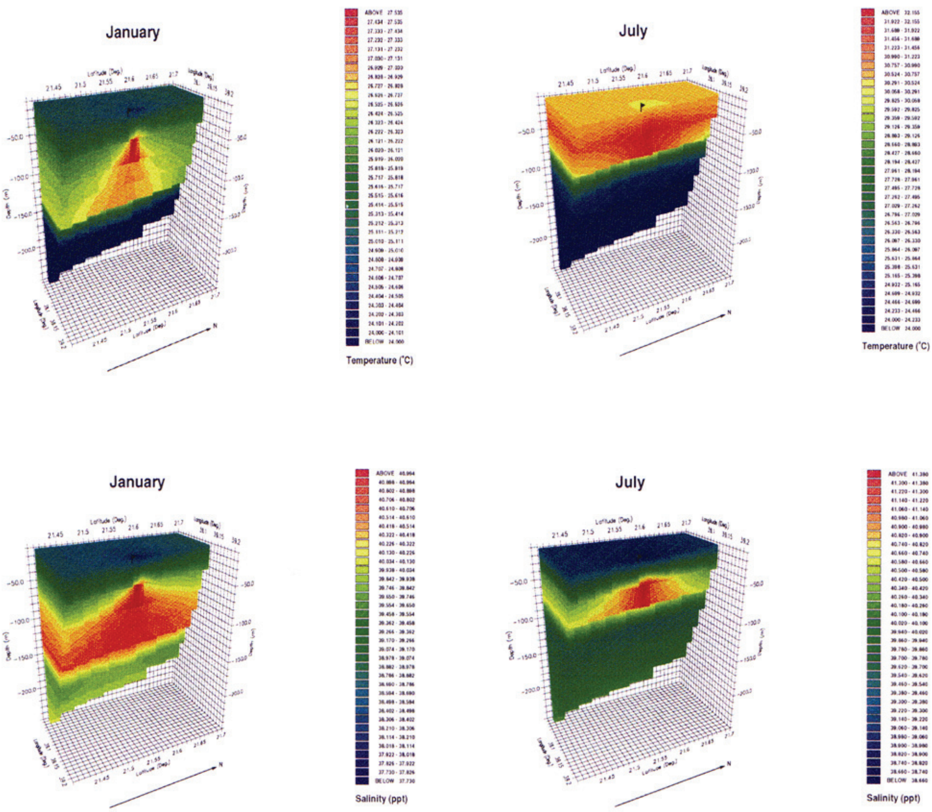

Fig. 6. Sub-surface water discharge temperature and salinity distributions during January and July.

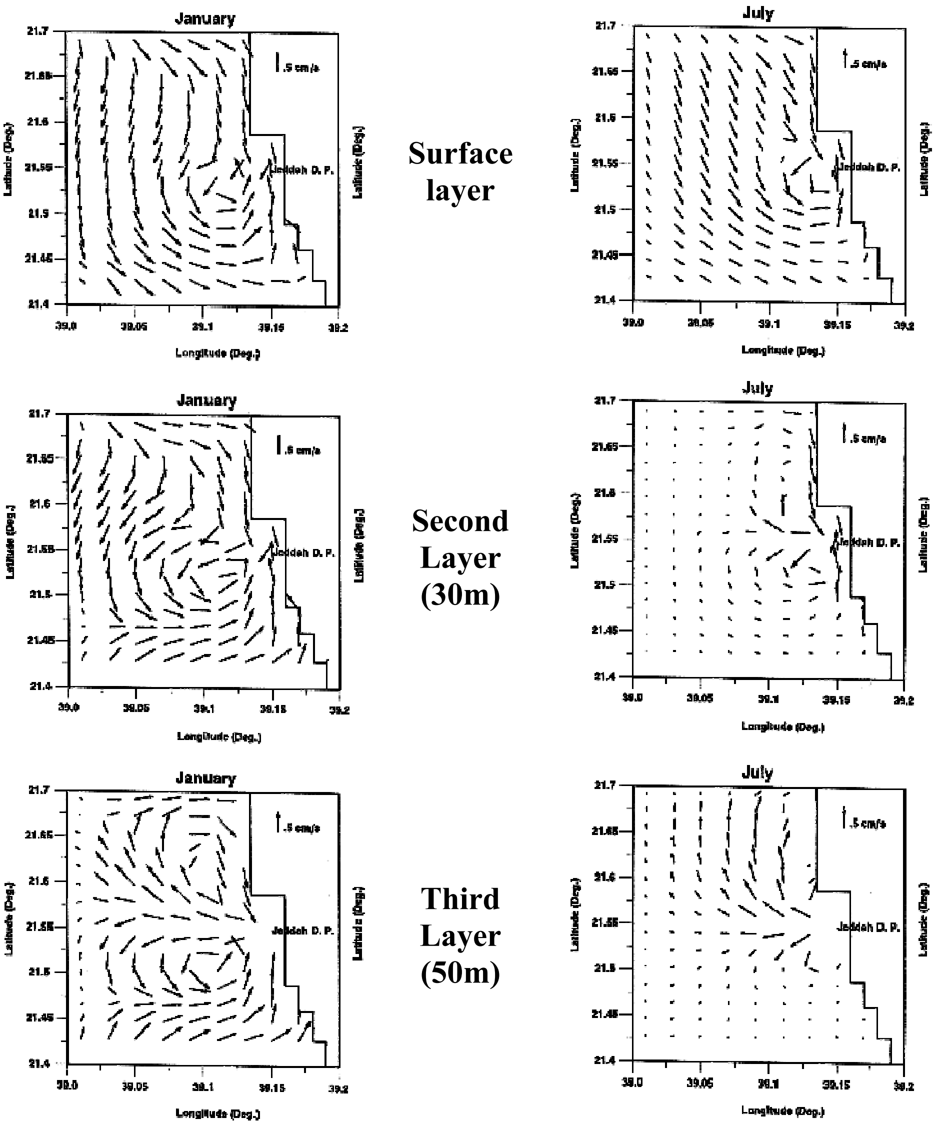

Fig. 7. Water circulation pattern for sub-surface water discharge during January and July.

Discussion

Case 1: Natural Environment

During winter the mixed layer is deeper than that during summer, when the water column is more stratified. During winter and summer seasons the salinity increases with depth. At the surface layer the currents are mainly southward due to the wind stress force. Currents are directed northward at the second and third layers because of the continuity.

***Case 2:* Surface Discharge**

Discharging the wastewater at the surface layer shows that, in the winter the area of high temperature and salinity is spreading downward at the discharging region. As going away from the discharge region the area of high temperature and salinity is confined between 50 m and 90m depth. From the sea surface down to about 50m depth and also from 125m depth downward, the seawater temperature and salinity are not much affected by the discharged wastewater.

In summer the area of high temperature and salinity is only found at the surface layer (30m). However, within this layer the temperature and salinity is decreasing as moving away from the discharge region. Beneath 50m depth the seawater temperature and salinity are not affected by the discharged wastewater.

The water circulation is modified after introducing wastewater to the system. At the surface layer, the currents are directed toward the discharge region where sinking occurs. This is more obvious in winter than in summer. At the second layer, the currents close to the discharge region start to flow westward. A strong westward jet occurs at the third layer. During summer the water circulation at the second and the third layer does not show significant differences relative to natural case.

***Case 3:* Sub-Surface Discharge**

In both winter and summer seasons the surface water is not affected by the discharged wastewater. In winter the area of high temperature and salinity is spread downward from the wastewater discharge region and then it spreads horizontally. On the other hand, in summer the region of high temperature and salinity is confined between 30 to 50m depths. Water circulation in winter is similar to that in case two. However, during summer the currents at the surface layer are directed toward the discharge region and the westward currents, at the second and third layers are more clear compared to case two.

Overall, the dispersion of the discharged wastewater varies according to two factors: a) the seasonal changes and b) the discharge depth. High vertical mixing in winter causes the discharged wastewater to sink to about 50 m depth. From this depth it starts to move horizontally as well as vertically. On the other hand, during summer, where the water column is stratified the discharged wastewater mainly moves horizontally. Water characteristic of the surface layer is not affected when the wastewater is discharged from the sub-surface layer.

During winter, water circulation is modified by the wastewater introduced to the sea. In the surface layer, due to the sinking of the wastewater, and is formed in the region close to the discharge point. At depth between 50 to 70 m (third layer) there is a jet directed towards the open sea with two eddies around it. These two eddies are formed due to the velocity sheer produced by the jet. These eddies are not found during the summer where there is no significant change in the water circulation pattern compared to the natural condition.

Conclusion

In conclusion the optimum discharge depth to reduce marine pollution varies seasonally. During winter, the discharged wastewater sinks and it is reasonable to discharge the wastewater at the surface because it disperses rapidly in the seawater. It is reasonable to discharge the wastewater to the sub-surface during summer where the spread of the wastewater is mainly at the same discharged depth.

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تشتت الملوثات الملحرارية في المياه الشاطئية، البحر الأحمر: دراسة نظرية

علاء محمد عون البركاتـــي

كلية علوم البحار– جامعة الملك عبدالعزيز– جدة

المملكة العربية السعودية

المستخلص. تم استعمال نموذج رياضي ثلاثي الأبعاد لدراسة انتشار مياه الرجيع من محطات تحلية المياه بجدة، في الحالة الأولى تم تطبيق النموذج الرياضي مع افتراض عدم وجود مياه الرجيع من التحلية، وفي الحالة الثانية افترض تصريف مياه الرجيع من التحلية في السطح مباشرة، وأخيرًا، في حالة تصريف مياه الرجيع من التحلية في الطبقة تحت السطحية (٣٠م)، وبناءً على نتائج النموذج الرياضي فإن العمق الذي تصرف فيه مياه الرجيع من التحلية وتتشتت في البحر المفتوح يختلف مع فصول السنة.

ففي الشتاء وبسبب الزيادة في عمليات الخلط الرأسية، فإن مياه الرجيع من التحلية تهبط إلى عمق ٥٠ مترًا، ومن ثم تتحرك أفقيًا إلى البحر المفتوح، وفي الصيف حيث عمود الماء مستقر ومتراصف، فإنه عند تصريف مياه الرجيع من التحلية على السطح فإنها تتحرك أفقيًا، ولكن عند تصريفها في الطبقة تحت السطحية فإنها لا تؤثر على المياه السطحية. كما أوضحت نتائج النموذج الرياضي أن حركة المياه تتغير بسبب تصريف مياه الرجيع من

التحلية، ففي فصل الشتاء تحدث بعض الحركات الدوامية عند منطقة الصرف، بسبب هبوط المياه السطحية، وتختفي هذه الحركات في فصل الصيف، حيث لا تهبط المياه السطحية بسبب تراصف عمود الماء.