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A Computational Model Study of Brine Discharges from Seawater Desalination Plants at Barka, Oman

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1. Introduction

Oman is situated at the south-east of the Arabian Peninsula at the entrance to the Arabian Gulf, and its coastline stretches 1700 km along the Gulf of Oman in the north to the Arabian Sea in the south. Most of the population lives in the north-eastern coastal areas and in the capital area of Muscat. The climate of Oman is typically described as a tropical hyper-arid, with two distinct seasons: winter and summer. The winter period extends from late November to April, during which rains at irregular intervals occur. However, based on 27 years of rainfall data from 1977 (Kwarteng et al., 2009), the annual mean rainfall for the whole country is 117 mm. Hot weather with high humidity is experienced in the coastal areas during the summer months. The mean air temperature in northern Oman varies between 32 ºC to 48 ºC from May to September, and between 26 ºC to 36 ºC from October to April. The mean wind speeds range between 2 and 3.5 m/s, with high winds encountered during the summer months.

Desalinated water has been used in Oman since 1976 when the Al-Ghubrah (co-location) power and seawater desalination plant using a thermal technology of multi-stage flash (MSF) was first commissioned in Muscat. To meet continuously growing water demand due to population growth and economic and social development and to reduce the reliance on groundwater resources, by 1999 the Al-Ghubrah plant had seven MSF desalination units installed. The first seawater desalination unit installed had a capacity of 22,750 m^3/d, and the other six MSF units each have a capacity of 27,000 m^3/d. Desalinated water usage in Oman is expected to increase further in the future, due to new industrial and tourism-related developments.

Desalination plants extract large volumes of seawater and discharge hot, hypersaline brine back into the marine environment. Therefore, the main concern of continuous brine discharges has been the potential impact upon the salinity of seawater (and possible thermal stress for discharges from MSF plants), and the resultant effects to marine communities around discharge outlets. Other occasional discharges from the plants include corrosion products, toxic antifoulants and antiscalants used in maintaining plant infrastructure (Roberts et al., 2010). As brine discharges are often denser and heavier than receiving marine waters, the brine streams tend to sink and spread further along the seabed than at the

surface, and thus it has a greater exposure to benthic organisms than that of pelagic and planktonic organisms.

In order to demonstrate the compliance with the regulations for discharging brines from modern and recently operated Barka desalination plants in the Omani marine environment (MRMEWR, 2005), CORMIX simulations are carried out for two scenarios: scenario I uses temperature as a measure of the positively buoyant plume concentration to simulate the previous heated brine discharges from Barka I plant (up to November 2009), and scenario II uses salinity as a measure of the negatively buoyant plume concentration to simulate the new dense brine discharges from the combined Barka I and II plants (after 2009). In contrast to scenario I, where the simulated plume rises towards the surface, the simulated brine plume for scenario II should sink and stay at the seabed. Due to inherent uncertainty in the input data, sensitivity analysis were also carried out for scenario II using both submerged single port and multiport discharges by varying the ambient current velocity (to evaluate the effect of uncertainty in sea conditions), the brine discharge density (to evaluate the effect of uncertainty on the brine characteristic) and the brine flow rate (to evaluate the effect of uncertainty on the desalination plant's operation).

Fig. 1. Seawater desalination plants in the Gulf of Oman

2. Outlook for seawater desalination in Oman

To manage the future water demands in Oman, the Oman Power and Water Procurement (OPWP) company was established in 2005, and one of its responsibilities is to procure the production of desalinated water in conjunction with electricity and to ensure the adequacy

of generation of resources for new desalination capacity. Based on the annual report issued by OPWP in 2009, the forecasted total demand for the desalinated water is expected to increase from 259.5 million m^3 in 2010 to 405.2 million by 2016, an average annual increase of 13% per year. OPWP has forecasted also that by 2016 (Table 1), the additional 32,000 m^3/d of water desalination capacity is needed.

The desalinated water in the capital Muscat area is supplied mainly by Al-Ghubrah and Barka plants (Fig. 1). Due to proximity to demand, availability of land and infrastructure, both Al-Ghubrah and Barka plants sites are the preferred locations for additional power and seawater desalination capacity. The site for the Barka plants has been designated as the location for the construction of up to four (co-location) power generation and seawater desalination plants. Barka I was the first plant to be built, operated in 2003 and owned by the private sector, AES Barka. The power plant has a capacity of 427 MW and the (MSF) seawater desalination plant has a capacity of 91000 m^3/d. Adjacent to Barka I, Barka II plant was recently commissioned in November 2009, and owned by the private sector, SMN Barka Power company; the power plant with a capacity of 685 MW and the seawater desalination plant using a membrane technology of reverse osmosis (RO) with a capacity of 120000 m^3/d.

	2010	2011	2012	2013	2014	2015	2016
Forecasted water demand (in thousand m^3/d)	**711**	**782**	**850**	**925**	**1020**	**1094**	**1110**
Al-Ghubrah East plant	205	205	205	161	138	138	138
Al-Ghubrah West plant				135	135	135	135
Barka I + II plants	211	211	211	211	211	211	211
Barka III plant					180	180	180
Sohar plant	150	150	150	150	150	150	150
Sohar II plant					135	135	135
Sur I + II plants	80	80	80	80	80	80	80
Sur III plant						23	23
Other smaller plants	14	16	19	22	22	22	22
Salalah (MSF) plant		68	68	68	68	68	68
Total desalination capacity (in thousand m^3/d)	**660**	**730**	**733**	**827**	**1119**	**1142**	**1142**

Table 1. Projected water demand and total seawater desalination capacity in Oman

From 2012 onward, the reduction in desalination capacity is mainly due to the retirement of old MSF desalination units at the Al-Ghubrah plant. In order to meet the future water demands, OPWP has launched a new scheme to expand/redevelop the Al-Ghubrah plant by splitting the existing plant site into two parts. The existing plant will be called Al-Ghubrah East, and the new independent water and power project Al-Ghubrah West with a total desalination capacity of 135,000 m^3/d will be built and operated by a private sector by 2013. A new additional of independent water and power project at Barka with a total desalination capacity of 180,000 m^3/d will also be built and operated by a private sector by 2014.

Sohar (co-location) power and seawater desalination plant was the second plant to be built, operated in 2007 using MSF technology and owned by the private sector, Sohar Power company. To meet the additional water desalination requirements, a new independent power and water project at Sohar with a total desalination capacity of 135,000 m³/d will be built and operated by a private sector by 2014.

Neither of the RO seawater desalination plants at Sur are co-generation plants and they are owned by Public Authority for Electricity and Water. The first plant with a capacity of 12,000 m³/d was built in 1993, and the second plant with a capacity of 68,000 m³/d was built in 2009. A new desalination plant at Sur with a total capacity of 23,000 m³/d will need to be built by 2015 in order to meet the future water demand.

Finally, the first Salalah (co-location) power and seawater desalination plant with a total desalination capacity of 68,000 m³/d will be built, and operated by a private sector by 2011. However, to meet the future water demands, a new additional seawater desalination plant with a capacity of 80,000 m³/d will need to be built by 2016.

3. Environmental standards for effluent discharges into Omani coastal waters

Brine discharges from coastal seawater desalination plants in Oman are regulated according to the Omani ministerial decision No. 159/2005 (MRMEWR, 2005) on "promulgating the bylaws to discharge liquid waste in the marine environment", where the term liquid waste is defined as "any liquid containing environmental pollutants discharged into the marine environment from land or sea sources". To regulate such discharges, Article 5 states that "no liquid waste shall be directly or indirectly discharged in the marine environment without obtaining prior license". The license is issued by the Department of Inspection and Environment Control and depends on the following conditions as further measures to reduce the potential environmental impacts. Firstly, as stated in Article 7, the desalination plant operators must undertake to reuse or recycle the liquid waste, or destroy hazardous contents of such waste, or mitigate it by using proper environmental treatment.

Secondly, the plant operators have to provide a detailed description and the description of the characteristics of the liquid waste (Article 8) and the quality of liquid waste has to conform to the discharge limits specified in Annex 1 (Article 9). Besides the discharge limits, a circular mixing zone of 300 m in diameter around the outfall is specified as the initial mitigating area. Within the mixing zone, no marine life at the seabed may be destroyed (Article 14). Beyond the mixing zone, the ambient water temperature must not be increased by more than 1 °C (weekly average), and the average ambient salinity must not be changed by more than 2 ppt (daily average). A mixing zone can conceptually be defined as a limited area or volume of water where initial dilution of a discharge takes place.

Thirdly, the plant operators have to also provide information about the discharge location, such as physical, chemical and biological characteristics of seawater and recreational areas or other usages of the concerned shoreline (Article 10). The outfall pipes must not be installed less than one meter from the lowest tide line (Article 11). The temperature of liquid waste at the discharge point should not exceed 10 °C over the temperature of the water surrounding the seawater intake, if any (Article 2). The discharge pipes must be located in a place where it is impossible for the waste plume to hit corals and seaweed at the bottom (Article 3).

For the selection of the discharge site and the construction of the outfall, information about wind speed and direction for one month, low and high tide currents in an area of 1 km

around the outfall and the average sea depth in the same area should be included (Article 13). Multiport diffuser pipes are recommended to be installed in order to improve the brine dilution. Finally, for those violating any of these regulations, the penalties of the Environment Protection and Pollution Control Law shall be applied (Article 17).

4. Cornell mixing zone model expert (CORMIX) system

CORMIX (www.cormix.info) is a United States Environmental Protection Agency (US EPA) approved software system for the analysis, prediction, and design of marine outfall mixing zones resulting from continuous point source discharge of aqueous pollutants into diverse water bodies (Doneker & Jirka, 1990; Akar & Jirka, 1991; Jirka & Akar, 1991; Jirka & Doneker, 1991; Del Bene et al., 1994; Jones et al., 1996). It employs an easy-to-use rule-based expert system to screen input data and check for consistency, analyze regulatory requirements, and select the appropriate hydrodynamic computational model to simulate the physical mixing processes likely to be present for flow within a given discharge-environment interaction, ranging from internally trapped plumes, buoyant plumes in uniform density layers, and sinking of negatively-buoyant plumes. Boundary interaction, upstream intrusion, buoyant spreading, and passive diffusion in the far field are also considered.

The hydrodynamic classification schemes in CORMIX system use the length scale concepts, as a measure of the influence of each potential mixing process due to momentum flux and buoyancy of the discharge in relation to boundary interactions, to predict steady-state mixing zone characteristics and plume geometry. Boundary interaction analysis on mixing processes from laboratory and field experiments provide a rigorous and robust expert knowledge base that distinguishes among the many hydrodynamic flow patterns that may occur. For every flow class, CORMIX assembles and executes a sequence of appropriate hydrodynamic computational modules to predict the trajectory and dilution characteristics of a complex flow. Efficient computational algorithms provide simulation results in seconds for mixing zone problems with space scales of meters to kilometers and time scales of seconds to hours. The governing equations and formulations used in CORMIX system have been reported elsewhere (Jirka & Akar, 1991; Jirka & Doneker, 1991; Mendez-Diaz & Jirka, 1996; Doneker et al., 2004; Jirka, 2004; Jirka, 2006).

CORMIX is designed to analyze water quality criteria within regulatory mixing zones and has been successfully applied by engineers and environmental scientists to the design and monitoring of wastewater disposal systems in ocean, rivers, lakes, and estuaries, and it is also recognized by regulatory authorities for environmental impact assessment (US EPA, 1999). Extensive comparison with available field and laboratory data (including the negatively buoyant discharges) has shown that the CORMIX system predictions on plume dilutions and concentrations (with associated plume geometries) are reliable for the majority of cases (Roberts & Toms, 1987; Pun & Davidson, 1999; Kang et al., 2000; Roberts & Tian, 2004; Etemad-Shahidi & Azimi, 2005; Azimi et al., 2005; Kikkert et al., 2007). CORMIX simulation outputs include contemporary three dimensional plume and diffuser visualizations, design recommendations, flow class descriptions and reporting oriented on mixing zone analysis and regulatory compliance (Doneker & Jirka, 2001; Doneker & Jirka, 2007). CORMIX model has also been used to simulate heated brine discharges (Del Bene et al., 1994; Alameddine & El-Fadel, 2007), and the results of CORMIX simulations of dense brine discharges from the submerged single port and multiport diffusers are reported here.

Parameter	Scenario I	Scenario II	
Outfall type	Single	Single	Multiport
Ambient (unbounded coastal environmental)			
Velocity of the currents (m/s)	0.2	0.3	
Depth at discharge (m)	9	9	
Bottom slope (degree)	-	0.8944	
Wind speed (m/s)	2.5	2.5	
Temperature (°C)	24	24	
Salinity (ppt)	36	36	
(Uniform) Density (kg/m³)	1024.4	1024.4	
Brine discharge			
Distance to shoreline (m)	576.5	576.5	
Diffuser length (m)	-	-	91
Number of ports	1	1	36
Port height (m)	1	1	
Port diameter (m)	0.7	0.7	
Vertical angle (degree)	10	10	
Horizontal angle (degree)	90	90	
Flow rate (m³/s)	0.474	0.942	
Temperature (°C above ambient)	9	6	
Salinity (ppt above ambient)	2	13	
(Uniform) Density (kg/m³)	1022.91	1032.27	
Mixing zone			
WQS = Water quality standard (°C)	1	-	
WQS = Water quality standard (ppt)	-	2	
RMZ = Regulatory mixing zone (m)	150	150	
ROI = Region of interest (m)	1000	1000	

Table 2. Input data for the CORMIX simulations

5. Model simulations of brine discharges from Barka plants

Barka is situated on the coastal plain near to the Gulf of Oman, an agricultural area that has been suffering from seawater intrusion due to excessively pumped out groundwater usage for irrigation (Purnama et al., 2003). The surface land features can be described as flat with a sandy strip parallel to the coastline approximately 300 m inland. Ground surface elevations vary typically from 1.5 to 5 m above mean sea level. From the regional bathymetry of the Barka coastline (National Hydrographic Office, 2008), the gradient is about 1:140 up to the 10 m depth contour and about 1:220 between the 10 m and 30 m depth contours. Near the plant site, the water depth reaches 5 m at about 500 m offshore and 10 m at about 2000 m offshore. The general flow in the ocean currents in the Gulf of Oman is in the anticlockwise direction, that is, along the northern coast of Oman, the predominant coastal current moves southeastward from the Gulf of Oman (Purnama & Al-Barwani, 2006), with maxima at spring tides of up to 0.42 m/s. Tides in the Gulf of Oman have a strong diurnal component with a spring-tide range of 2.6 m or more (National Hydrographic Office, 2008).

There are two power generation and seawater desalination plants currently operated at Barka: Barka I was commissioned in 2003, and Barka II in 2009. There are four intake and

marine outfall systems constructed as part of Barka I plant facilities. So far, only two seawater intake and marine outfall systems are used for both Barka I and Barka II plants. The intake system consists of four parallel pipes of 1.2 km in length and a diameter of 2.2 m. The pipes are spaced 2 m apart, buried under the seabed (not visible on the surface) and the intake structure opens at 1.5 m above the seabed. Barka I plant withdraws seawater from a depth of 10 m up to a maximum rate of 67500 m³/h, and Barka II plant at a rate of 59000 m³/h for cooling purposes. To avoid the circulation of concentrated brine discharges to the intake system, the outfall discharge point is constructed at a distance of 800 m from the intake point (Abdul-Wahab, 2007).

The marine outfall systems are designed to discharge the combined brine reject (and other effluents) from the desalination plants and the once through condenser cooling water system from the power plant. It also comprises of four parallel pipes angled at 62 degrees to the beach, each with a diameter of 2.5 m, buried at 5 m below the seabed and spaced equally at 4.8 m apart. The 62.4 m long staged multiport diffuser, consisting of nine ports, are installed at the end of each outfall pipe. The diffusers are arranged in two nested V shapes, and each pair diverges at an angle of 30 degrees on either side of the outfall pipelines. The two internal pipes of length 653 m have its end at a depth of 9 m, while the other two shorter external pipes of length 582 m end at a depth of 8.4 m. Each port with a diameter 0.7 m opens up at 1 m above the seabed, and the jet brine stream is discharged up at an angle of 10 degrees above the horizontal. Barka I plant discharges up to a maximum flow rate of 61500 m³/h, and Barka II plant discharges up to a maximum flow rate of 60600 m³/h.
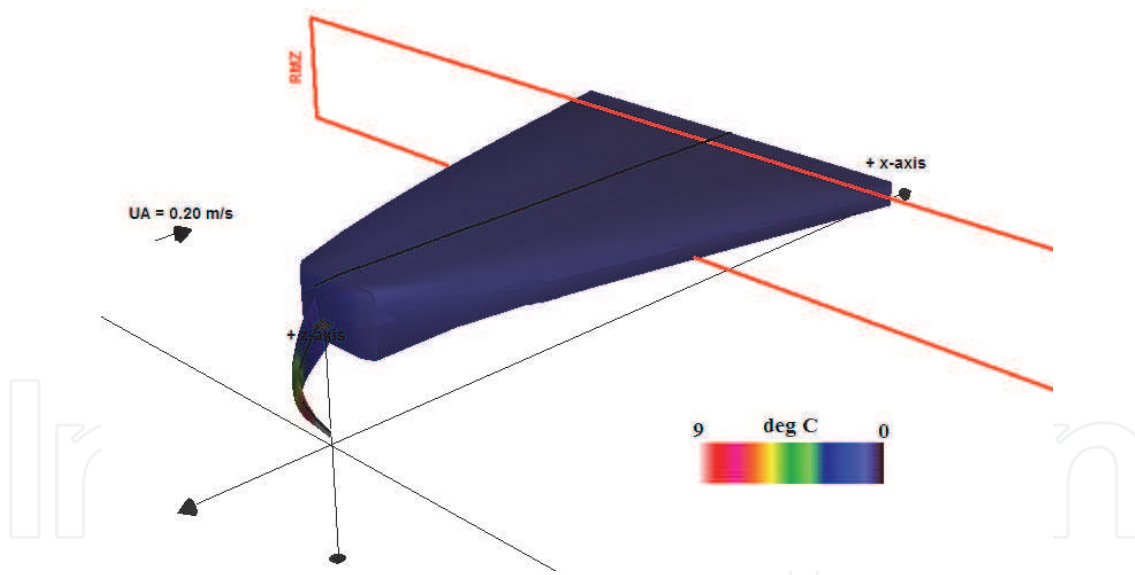

Fig. 2. Scenario I brine plume from the single port discharge

The mixing processes of brine discharges into marine coastal waters are significantly influenced by the effluent density, which is controlled by salinity and temperature of the effluent (Bleninger & Jirka, 2008). The brine of MSF desalination plants is extremely hot, and must be diluted with cooling water from the power generation plants. As a result, the brine discharges are lighter than the receiving seawater. In contrast, the brine of RO desalination plants is higher in salinity, and such discharges are heavier than the receiving waters. During 2009, the physical properties of brine discharge from Barka plants are changing from the previously positively buoyant plume (from Barka I only) to a negatively buoyant plume

(from combined Barka I and II). In order to assess the compliance with the regulations for discharging effluents in the Omani marine environment, CORMIX v6.0 simulations are carried out for two scenarios of brine discharges from the Barka plants. The input data are summarized in Table 2. The outfall discharge point for the single port and the midpoint of diffuser line for the multiport are located at 576.5 m offshore, and 9 m below the sea surface. Since the height of the ports is 1 m above the seabed, according to CORMIX, this is a deeply submerged discharge.

Outfall type	Single port
Temperature (in ºC)	0.2
Plume dilution	43.9
RMZ centerline (in m)	$x = 150$, $y = 10.85$, $z = 9$
RMZ plume dimensions (in m)	Half-width = 21.60 Thickness = 2.41

Table 3. The RMZ characteristics of scenario I

5.1 Scenario I : Heated brine discharges from Barka I plant (up to November 2009)

This scenario is used to simulate the brine discharges of 9 ºC above ambient on an unbounded flat bed coastal environment with a surface heat loss rate of 30 W/m²/ºC. The origin is located at the seabed, directly below the outfall, and 576.5 m offshore. The x-axis points downstream, the y-axis points to left (in the flow direction), and the z-axis points upward. As the effluent density 1022.91 kg/m³ is less than the surrounding ambient density 1024.4 kg/m³, the effluent plume is positively buoyant and will rise to the surface. The maximum permissible temperature limits set by the Omani government is WQS = 1 ºC above ambient within the RMZ of 150 m radius from the outfall (MRMEWR, 2005).
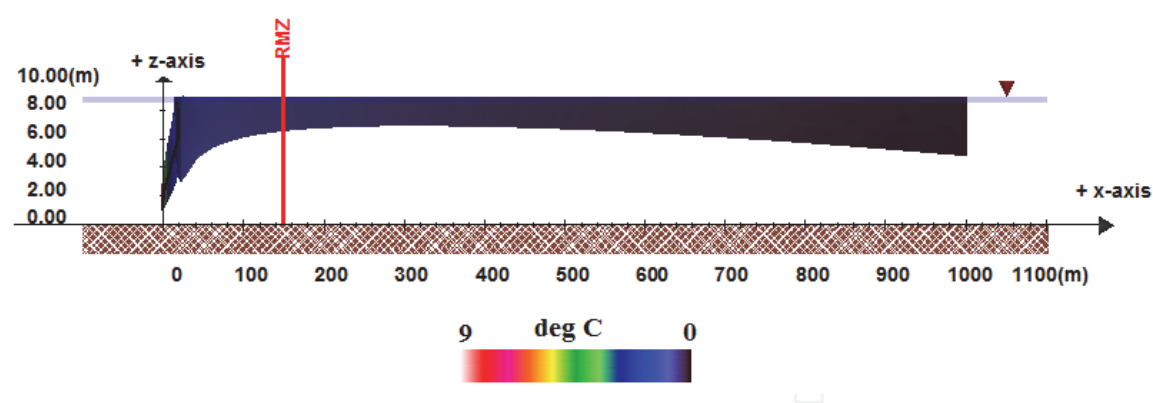

Fig. 3. Side view of scenario I brine plume from the single port discharge

CORMIX system classified the motion of the brine plume from the single port discharge as the flow class H2 near bottom (horizontal), positively buoyant flows in a uniform density layer (Jirka & Doneker, 1991; Doneker & Jirka, 2007). The jet-like plume is weakly deflected by the ambient current into the flow direction, and the bent-over brine plume rises towards the surface (Fig. 2). After reaching the surface within 17 m downstream, the plume spreads laterally due to buoyant ambient spreading, and its thickness (measured vertically) is observed to be decreasing initially (Fig. 3), the lower part of the plume reaches its maximum height within 300 m downstream. Further downstream, as the ambient flow is the

dominating mixing mechanism, the passive brine plume grows back in thickness, and it eventually becomes vertically fully mixed beyond the ROI, 1000 m downstream as the bottom plume attaches to the seabed; after that the plume collapses and continues to spread due to passive ambient mixing in uniform ambient.
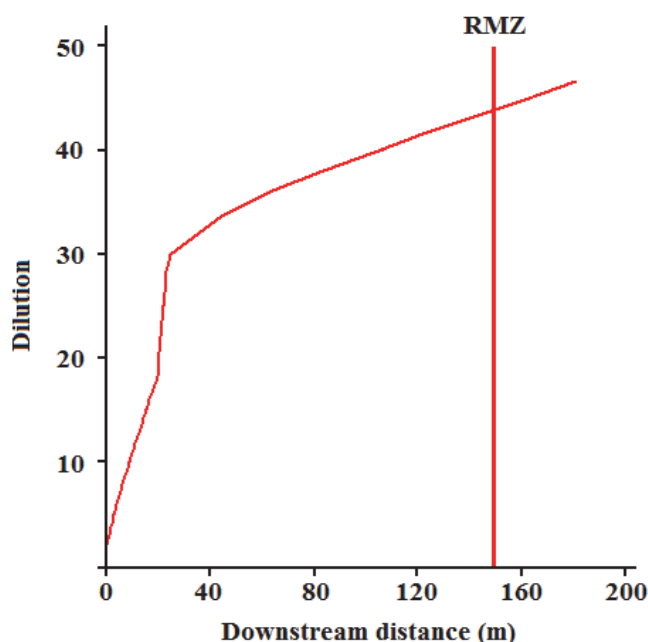

Fig. 4. Brine plume dilution of scenario I

The specified WQS has been met within 8 m downstream, and the plume characteristics at the edge of the RMZ are presented in Table 3. The mixing performance (concentration reduction) is measured in the CORMIX system as brine plume dilution, which is defined as the ratio of initial brine concentration (above ambient) at the outfall discharge point to that at a given location. The increasing values of hydrodynamic brine plume dilution within the RMZ are shown in Fig. 4, and a dilution of 271 is obtained at the end of the ROI. The CORMIX simulation results show that the overall temperature rise at the edge of the RMZ is slightly more than 0.2 °C (above ambient), which is well below the maximum permissible limits by the Omani government. This appears to be in agreement with the field survey conducted in the vicinity of Barka I plant (Abdul-Wahab, 2007), and also with the heavy metals analysis of the bottom sediments sample collected (Abdul-Wahab & Jupp, 2009), which is consistent with the assumption that the brine plume rises to the surface.

5.2 Scenario II : Dense brine discharges from Barka plants (after 2009)

This scenario is used to simulate the brine discharges of salinity 13 ppt above ambient (set to a concentration of 100% above ambient) on the uniformly sloping beach coastal environment with slope 0.9 degree. In contrast to scenario I, the effluent density 1032.27 kg/m^3 is denser and heavier than the surrounding ambient density 1024.4 kg/m^3, the effluent plume is negatively buoyant and it will tend to sink at the seabed. The origin is located at the sea surface directly above the submerged outfall, and 576.5 m offshore. The maximum permissible salinity limits set by the Omani government is WQS = 2 ppt above ambient within the RMZ of 150 m radius from the outfall (MRMEWR, 2005).
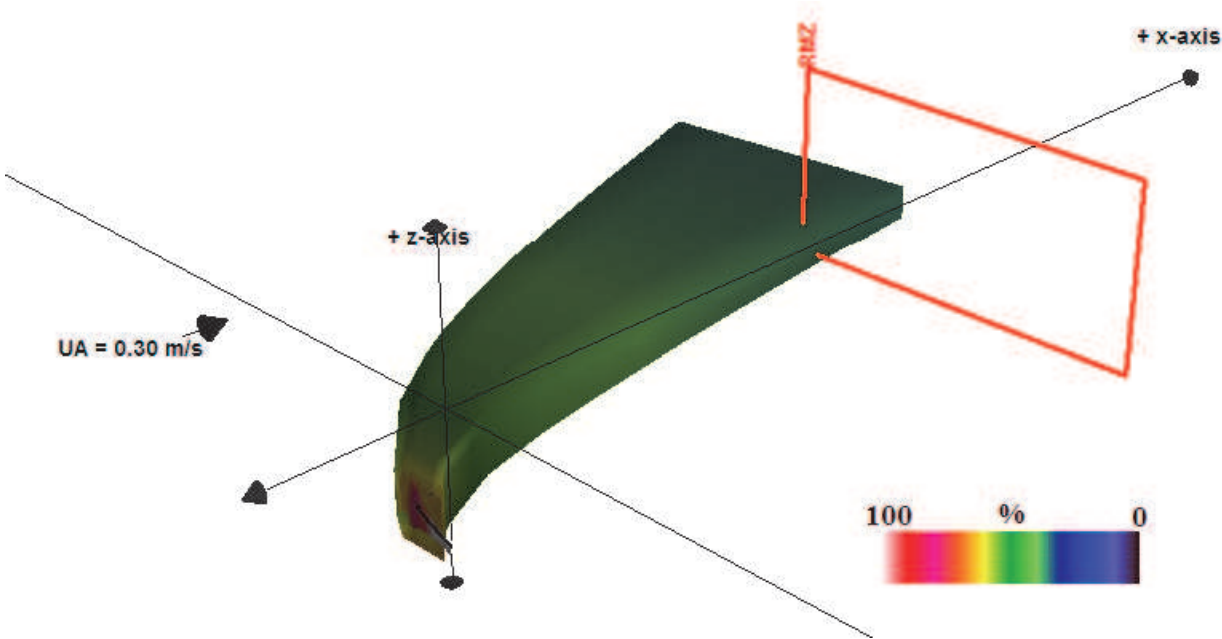
Fig. 5. Scenario II brine plume from the single port discharge

CORMIX system classified the brine plume motion from the single port discharge as the flow class NH4 near bottom (horizontal), negatively buoyant flows in a uniform density layer (Jirka, 2004; Doneker & Jirka, 2007). As the brine stream is released from the outfall, the ambient current strongly deflects the jet-like plume trajectory into the current direction, inducing higher dilution. The bent-over brine plume slowly descends toward the sloping bed, it impinges on the seabed within 1.3 m downstream, and the plume remains at the seabed due to its negative buoyancy. Impingement is a complex three-dimensional process, with forward, lateral, and partially reverses spreading, until a bottom density current is formed. The height of the top part of the plume slowly rises and reaches its maximum within 26 m downstream, and the concentration distribution becomes relatively uniform across the plume width and thickness (Fig. 5). Thereafter, it continues to spread laterally due to bottom density current while it is being advected by the ambient current (Bleninger & Jirka, 2008). In the absence of ambient stratification, the brine plume will propagate down the slope until it reaches the ROI (Fig. 6), and thus, the potential benthic impact due to brine plume should be of concern.

Outfall type	Single port	Multiport
Plume concentration	0.6 ppt	0.056 ppt
Plume dilution	21.6	234
RMZ centerline (in m)	$x = 150$, $y = 45.50$, $z = -9.69$	$x = 150$, $y = 1.62$, $z = -9.03$
RMZ plume dimensions (in m)	Half-width = 14.24 Thickness = 2.99	Half-width = 47.03 Thickness = 9.01

Table 4. The RMZ characteristics of scenario II

Again, the specified WQS has been met within 7 m downstream, and the plume characteristics are presented in Table 4. The increasing values of brine plume dilution with the RMZ are plotted in Fig. 7, and a dilution of 30.9 is obtained at the edge of the ROI for the single port discharge. The CORMIX simulation results show that the overall salinity increase

is less than 0.6 ppt (above ambient) at the edge of the RMZ, which is well below the maximum permissible limits by the Oman government.

For the submerged multiport, the brine discharge volume is distributed over 36 ports, which are placed in the alternating arrangement perpendicular to the diffuser line, and the average spacing between the individual ports is 2.6 m. Due to the lateral merging and interactions of adjacent brine plumes, forming a dynamically equivalent two-dimensional plume as if the discharges are made from a two-dimensional slot diffuser and that the downstream plume behaviour after merging is independent of the port arrangement. CORMIX system classifies the motion of the brine plume from the multiport discharge as the flow class MNU13 near bottom, negatively buoyant flows in a uniform density layer (Jirka, 2006; Doneker & Jirka, 2007). As CORMIX assumes the complex merging process of the individual jets from each port as a plume releases from a long slot discharge, the merging jet-like plume is rapidly deflected by the strong ambient current, and due to instability, it immediately becomes vertically fully mixed as it leaves the multiport, descending toward the sloping bottom. After it is attached to the seabed, it continues to spread laterally due to the bottom density current and in the absence of ambient stratification will proceed down the slope until it has reached the ROI. As shown in Fig. 7, in comparison with the single port, a ten-fold brine plume dilution is achieved for the multiport discharges at the edge of the RMZ.
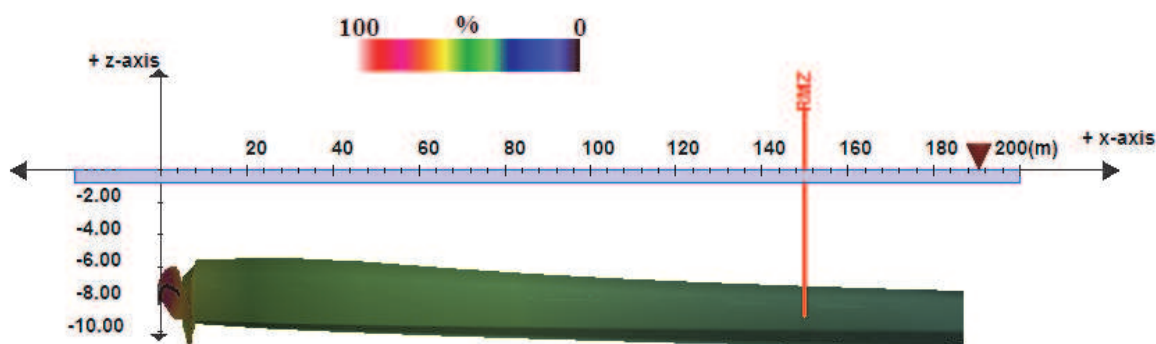

Fig. 6. Side view of scenario II brine plume from the single port discharge

6. CORMIX iterative simulations

CorSens is the CORMIX sensitivity analysis tool that generates a sensitivity study case to address model performance due to inherent uncertainty in the input data (Doneker & Jirka, 2007; Alameddine & El-Fadel, 2007). Therefore, instead of the tedious repetition of manual data entry, it automatically increments input data to analyze mixing zone conditions. Sensitivity studies are also motivated by the fact that there are no user-adjustable parameters for model calibration within CORMIX system. The basis for this restriction is that normal variations in ambient conditions are likely to have greater influence over mixing zone behavior than a model parameter to obtain a desired result. Only the scenario II simulations are carried out to represent dense brine discharges from Barka plants after 2009. Firstly, to evaluate the effect of uncertainty in sea conditions, simulations were conducted by varying the ambient current velocity (a coastal environment parameter) while keeping the other input parameters the same as the base (Section 5.2) simulation specified in Table 2. The results summary of reducing ambient velocity from 0.45 m/s to 0.05 m/s are presented in Table 5, and for the single port discharges, it is observed that flow class changes from

NH4 to a new class NH5: momentum dominated bottom-attached jet motion (Jirka, 2004; Doneker & Jirka, 2007). For calm sea conditions, i.e. the ambient velocity smaller than 0.25 m/s, the discharge induced momentum flux dominates the flow, and due to instability, the brine plume becomes attached to the sloping seabed and vertically fully mixed as it leaves the port. The ambient stratification also occurs when the ambient velocity is less than 0.1 m/s, and for the smallest value of 0.05 m/s, the stratification occurs within 29 m downstream. CORMIX also predicts the occurrence of localized recirculation into the jet-plume like regions, thus blocking the ambient current and reducing the plume dilution.
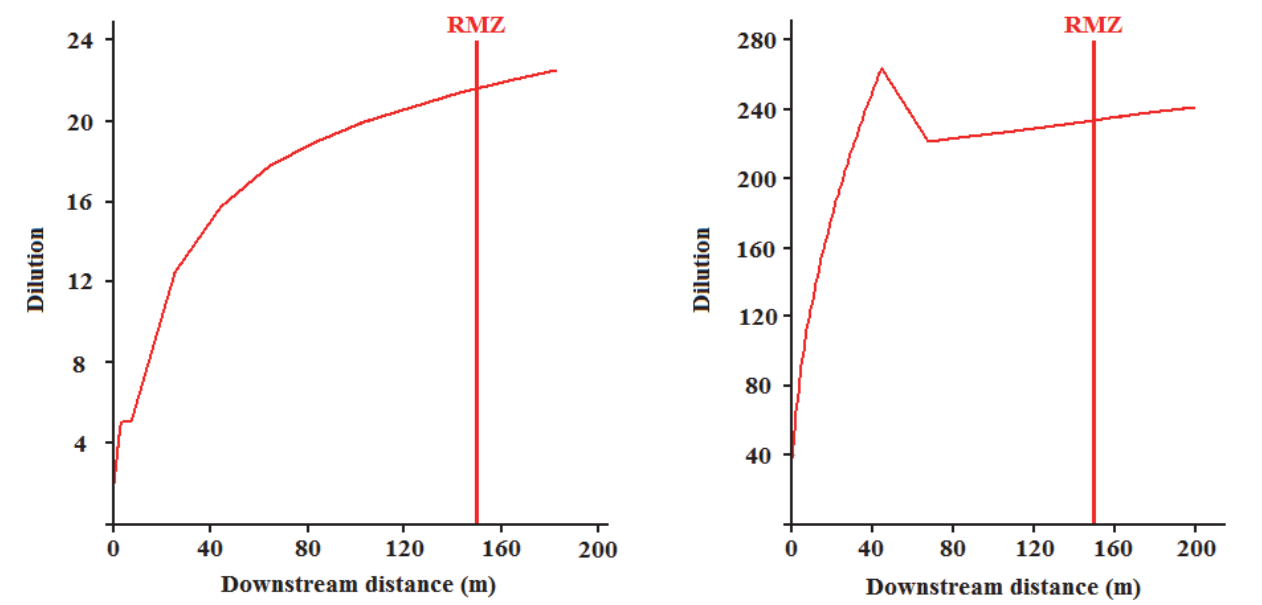
Fig. 7. Brine plume dilution of scenario II: single port (left) and multiport (right) discharges

At the edge of the RMZ, plume dilution values are much greater than the base dilution for the single port discharges, and for the ambient velocity 0.01 m/s, dilution is more than three times the base value. Therefore, the uncertainty in sea conditions may result in the overall salinity increase to be less than the base value of 0.6 ppt (above ambient).

For the multiport discharges, it is observed that by reducing the ambient velocity, the plume dilution decreases. The bottom density current develops along the diffuser line due to the continuous inflow of mixed buoyant water becoming stronger, reducing the mixing rate and thus the plume dilution. The flow class changes from MNU13 to MNU2 (Jirka, 2006; Doneker & Jirka, 2007) occur when the velocity value equals to 0.05 m/s, where the momentum flux is now weak relative to the buoyancy flux. The ambient stratification also occurs when the ambient velocity is less than 0.1 m/s, and for the smallest value of 0.05 m/s, the bottom stratification occurs within 23.44 m downstream. It is found that the uncertainty in sea conditions may result in the overall salinity increase of 0.4 ppt (above ambient) at the edge of the RMZ.

Next, the simulations were conducted by varying the discharge density (an effluent parameter), which reflect the uncertainty on the brine characteristic. Salinity and temperature directly influence the density of the effluent. The results summary of reducing discharge density from 1034.27 kg/m^3 to 1026.27 kg/m^3 are given in Table 6, showing that there are no flow class changes for the single and multiport discharges. At the edge of the

RMZ, plume dilution increases to more than double for the single port discharges since the stronger momentum with relatively weak buoyancy controls the flow class NH4, but the same effect is minor for the multiport discharges. Thus, the uncertainty on the brine characteristic may result in the overall salinity increase being less than 0.65 ppt (above ambient).

Outfall type	Single port			Multiport		
Ambient velocity (m/s)	Flow Class	Dilution	Salinity (ppt)	Flow Class	Dilution	Salinity (ppt)
0.45	NH4	29.7	0.438	MNU13	349	0.038
0.4	NH4	26.8	0.486	MNU13	311	0.042
0.35	NH4	23.8	0.545	MNU13	272	0.048
0.3	NH4	21.6	0.602	MNU13	234	0.056
0.25	NH5	80.9	0.161	MNU13	196	0.066
0.2	NH5	84.1	0.155	MNU13	158	0.082
0.15	NH5	82.9	0.157	MNU13	101	0.129
0.1	NH5	69.2	0.189	MNU13	72.2	0.181
0.05	NH5	62.7	0.207	MNU2	36.0	0.360

Table 5. CorSens results summary on the ambient velocity at the edge of the RMZ

Outfall type	Single port			Multiport		
Discharge density (kg/m^3)	Flow Class	Dilution	Salinity (ppt)	Flow Class	Dilution	Salinity (ppt)
1034.27	NH4	20.1	0.645	MNU13	234	0.0555
1032.27	NH4	21.6	0.602	MNU13	234	0.0555
1030.27	NH4	25.4	0.512	MNU13	234	0.0556
1028.27	NH4	32.6	0.399	MNU13	233	0.0558
1026.27	NH4	46.3	0.281	MNU13	232	0.0559

Table 6. CorSens results summary on the discharge density at the edge of the RMZ

Lastly, the simulations were carried out by varying the brine flow rate (a discharge parameter), which reflect the uncertainty on the plant's operation. During the winter months, Barka I plant operates with 60% load by shutting down one of the three desalination units for maintenance. The results summary of increasing discharge rate from 0.542 m^3/s to 1.242 m^3/s are presented in Table 7. For the single port discharges, the brine flow rates lower than the base rate lead to smaller plume dilution due to less momentum flux controlling the flow class NH4. The flow class changes to NH5 occur at higher flow rates than the base rate, and thus, larger momentum flux produces higher plume dilution. However in contrast, for the multiport discharges there are no flow class changes, and plume dilution decreases. It is found that the uncertainty in the brine discharge rate may result in the overall salinity increase of 0.9 ppt (above ambient) at the edge of the RMZ.

Outfall type	Single port			Multiport		
Discharge flow rate (m³/s)	Flow Class	Dilution	Salinity (ppt)	Flow Class	Dilution	Salinity (ppt)
0.542	NH4	16.2	0.802	MNU13	405	0.0321
0.642	NH4	17.6	0.737	MNU13	343	0.0380
0.742	NH4	19.0	0.685	MNU13	297	0.0438
0.842	NH4	20.4	0.638	MNU13	262	0.0497
0.942	NH4	21.6	0.602	MNU13	234	0.0555
1.042	NH5	23.0	0.566	MNU13	212	0.0614
1.142	NH5	49.8	0.261	MNU13	193	0.0672
1.242	NH5	51.5	0.252	MNU13	178	0.0731

Table 7. CorSens results summary on the discharge flow rate at the edge of the RMZ

7. Conclusion

CORMIX simulations for submerged single port and multiport discharges were carried out for two scenarios to assess the compliance of brine discharge from Barka plants within the regulations for discharging effluents in the Omani marine environment (MRMEWR, 2005). The results show that, up to November 2009, the overall temperature rise due to heated brine discharges from Barka I plant is found to be around 0.2 °C (above ambient) within the regulatory mixing zone of 150 m radius from the outfall. Similarly, since November 2009, the overall salinity increase due to dense brine discharges from the combined Barka I and II plants is found to be less than 1 ppt (above ambient). These values are well below the maximum permissible limits set by the Omani government, which are respectively 1 °C and 2 ppt above ambient.

It is also observed that there is a change in the Barka brine discharge characteristic, from a positively buoyant plume to a negatively buoyant plume. In contrast to the positively buoyant plume that will rise towards the surface, the new negatively buoyant plume will sink and attach to the sloping seabed and then spreads due to the bottom density current downslope, and therefore the potential exposure of benthic organisms should also be monitored and investigated further.

Like other numerical models, the CORMIX system has several inherent limitations. One major limitation results from the representation of the coastal environment as the unbounded rectangular channel, and as a uniformly sloping cross-section channel for concentrated brine discharges, where the current velocity is assumed to be uniform. Another limitation is the flow classification system (without even starting a numerical computation) based on hydrodynamic criteria using significant length scale analysis to predict mixing processes and its subsequent dilution in the receiving water environment. Thus, as shown in Table 5, a small change in an input parameter may result in a different CORMIX flow class leading to marked discontinuities in the plume dilutions.

8. Acknowledgements

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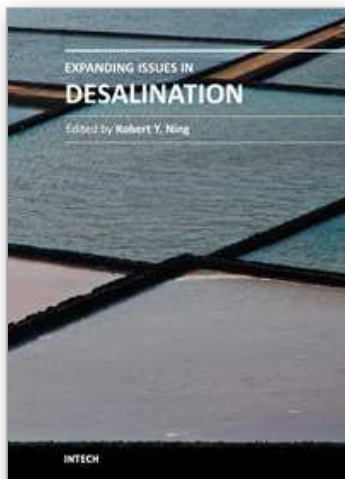
For this book, the term â€œdesalinationâ€ is used in the broadest sense of the removal of dissolved, suspended, visible and invisible impurities in seawater, brackish water and wastewater, to make them drinkable, or pure enough for industrial applications like in the processes for the production of steam, power, pharmaceuticals and microelectronics, or simply for discharge back into the environment. This book is a companion volume to â€œDesalination, Trends and Technologiesâ€, INTECH, 2011, expanding on the extension of seawater desalination to brackish and wastewater desalination applications, and associated technical issues. For students and workers in the field of desalination, this book provides a summary of key concepts and keywords with which detailed information may be gathered through internet search engines. Papers and reviews collected in this volume covers the spectrum of topics on the desalination of water, too broad to delve into in depth. The literature citations in these papers serve to fill in gaps in the coverage of this book. Contributions to the knowledge-base of desalination is expected to continue to grow exponentially in the coming years.

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