Desalination and Water Treatment
www.deswater.com

32 (2011) 329–338
August

doi: 10.5004/dwt.2011.2718

CORMIX simulations of brine discharges from Barka plants, Oman

Anton Purnama[a]*, H.H. Al-Barwani[a], T. Bleninger[b], R.L. Doneker[c]

[a]*Department of Mathematics and Statistics, College of Science, Sultan Qaboos University, PO Box 36, Al-Khod PC123, Muscat, Sultanate of Oman*
Tel. +968 2414 1428; Fax +968 2441 1435; email: antonp@squ.edu.om
[b]*Institute for Hydromechanics, Karlsruhe Institute of Technology, Kaiserstr. 12, 76131, Karlsruhe, Germany*
[c]*Department of Civil and Environmental Engineering, Portland State University, Portland, Oregon 97201, USA*

Received 1 August 2010; Accepted in revised form 14 December 2010

ABSTRACT

There are two power generation and seawater desalination plants currently operated at Barka, Oman: Barka I was commissioned in 2003, and Barka II in 2009. The cooling water from the power generation plants are mixed with reject brine (and other effluents) from desalination plants and are discharged through the same marine outfall systems. Therefore, during 2009, the brine discharge plumes changed from the previously positively buoyant from Barka I plant to a newly negatively buoyant from the combined Barka I and II plants. Consequently, instead of rising to the sea-surface, the new brine plume will now tend to sink and stay at the seabed. CORMIX simulations were carried out for two scenarios that represent the previous heated brine discharges and the new concentrated brine discharges from the Barka plants. Due to uncertainty in the input data, further simulations were carried out using salinity as a measure of the plume concentration for single port and multiport, and by varying the ambient current velocity, the effluent discharge density and flow rate. The results show that the water quality standards in the Omani coastal marine environment within the regulatory mixing zone at a 150 m radius from the discharge point have been met for both scenarios. However, the potential benthic impact due to the attachment of the new brine plume at the seabed should be monitored and investigated further.

Keywords: Barka desalination plants; Brine discharge; CORMIX; Marine outfall; Multiport; Oman

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, the annual mean rainfall for the whole country is 117 mm [1]. The mean air temperature in northern Oman varies between 32–48°C from May to September, and between 26–36°C from October to April. The mean wind speeds range between 2 and 3.5 m/s, with high winds encountered during the summer months.

Oman has been using desalinated water since 1976 when the Al-Ghubrah (co-location) power generation and seawater desalination plant was first commissioned in Muscat using thermal distillation technology

* Corresponding author.

Presented at the Third International Conference on Challenges in Environmental Science & Engineering, CESE-2010
26 September – 1 October 2010, The Sebel, Cairns, Queensland, Australia

of multi-stage flash (MSF). Due to population growth and economic development and reducing the reliance on groundwater resources, the desalinated water in the capital Muscat is supplied by Al-Ghubrah and Barka plants. Desalinated water usage in Oman is expected to increase further in the future, due to new industrial and tourism-related developments. The total demand for the desalinated water in Oman is expected to increase from 102 million m^3 in 2008 to 234 million by 2015, an average annual increase of 13% per year [2]. 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 first commissioned in 2003, the power plant with a capacity of 434 MW and the (MSF) seawater desalination plant with a capacity of 91000 m^3/d, and adjacent to Barka I plant, Barka II was recently commissioned in November 2009, the power plant with a capacity of 683 MW and the seawater desalination plant using a membrane technology of reverse osmosis (RO) with a capacity of 120000 m^3/d.

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 [3]. 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 [4], 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 (Fig. 1), that is, along the northern coast of Oman, the predominant coastal current moves southeastward from the Gulf of Oman [5], with maxima at spring tides of up to 0.22 m/s. Tides in the Gulf of Oman have a strong diurnal component with a spring-tide range of 2.6 m or more [4].

Fig. 1. Coastal currents along the coast of Oman.

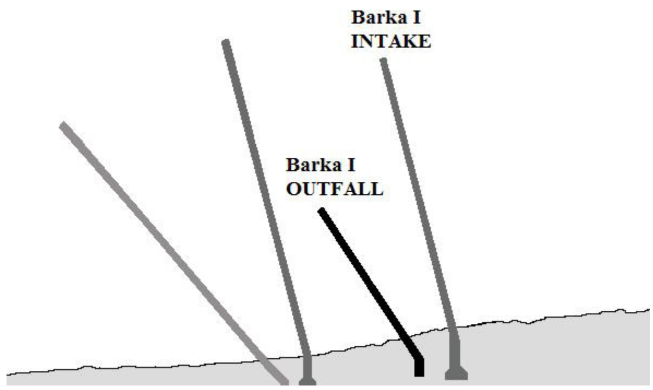

Fig. 2. Seawater intake and marine outfall systems of Barka I plant.

There are four intake and marine outfall systems constructed as part of Barka I plant facilities (Fig. 2). 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 at a rate of 67500 m^3/h, and Barka II plant at a rate of 59000 m^3/h for cooling purposes, taken from a depth of 10 m. 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 [6].

The marine outfall systems are designed to discharge the combined brine reject 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° 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° 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° above the horizontal. Barka I plant discharges at a rate of 61500 m^3/h, and Barka II plant at a rate of 60600 m^3/h.

In order to assess the compliance with the regulations for discharging effluents in the Omani marine environment [7], CORMIX simulations are carried out for two scenarios that represent brine discharges from the Barka plants: scenario I uses temperature as a measure of the positively buoyant plume concentration to simulate the previous heated brine discharges from Barka I (MSF) plant (up to November 2009), and scenario II uses salinity as a measure of the negatively buoyant plume concentration to simulate the new concentrated brine discharges from the combined Barka I (MSF) and II (RO) plants (after 2009). Due to uncertainty in the input data, sensitivity analysis were carried out for scenario II using submerged single port and multiport discharges by varying the ambient current velocity, the effluent discharge density and flow rate.

2. Cornell mixing zone model expert (CORMIX) system

CORMIX (www.cormix.info) is a US EPA approved software system for the analysis, prediction, and design of outfall mixing zones resulting from the discharge of aqueous pollutants into diverse water bodies [8–12]. It employs a rule-based expert system to screen input data and check for consistency, and select the appropriate hydrodynamic model to simulate the physical mixing processes contained 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 scheme in CORMIX system uses the length scale concept as a measure of the influence of each potential mixing process. Boundary interaction analysis and empirical knowledge from laboratory and field experiments provides 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 simulation modules which, when executed together, predict the trajectory and dilution characteristics of a complex flow. The governing equations and formulations used in CORMIX system have been reported elsewhere [9,11,13–16].

CORMIX is designed to analyze water quality criteria within regulatory mixing zones and has been successfully applied to the design and monitoring of wastewater disposal systems, and it is also recognized by regulatory authorities for environmental impact assessment [17]. 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 are reliable for the majority of cases [18–24]. CORMIX outputs include contemporary three dimensional plume and diffuser visualizations, design recommendations, flow class descriptions and reporting oriented on mixing zone analysis and regulatory compliance [25,26]. CORMIX model has also been used to simulate heated brine discharges [27,28], and the results of CORMIX simulations of concentrated brine discharges from the submerged single port and multiport diffusers are reported here.

3. CORMIX base simulations

CORMIX v6.0 simulations are carried out for two scenarios of brine discharges from the Barka plants. The input data are summarized in Table 1. 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.

3.1. Scenario I of heated brine discharges from Barka I (MSF) plant (up to November 2009)

This scenario is used to simulate the brine discharges of 9°C above ambient on an unbounded flat bed coastal environment with a surface heat loss rate of 30 W/m^2/°C. 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/m^3 is less than the surrounding ambient density 1024.4 kg/m^3, 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°C above ambient within the RMZ of 150 m radius from the outfall [7].

CORMIX system classified the motion of the brine plume from the single port as the near bottom, positively buoyant flows in a uniform density layer (flow class H2) [9,26]. 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. 3). After reaching the surface within 34 m downstream, the plume spreads laterally due to buoyant ambient spreading, and its thickness (measured vertically) is observed to be decreasing initially (Fig. 4). Further downstream, as the ambient flow is the dominating mixing mechanism, the passive brine plume grows back in thickness, and it becomes vertically fully mixed at 974.41 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 until it has reached the ROI, 1000 m downstream.

The specified WQS has been met within the RMZ, and the plume characteristics are presented in Table 2. The brine plume dilution, which is defined as the ratio of initial concentration (above ambient) at the outfall discharge point to that at a given location, is given in Fig. 5. A dilution of 507 is obtained at the ROI for the single port.

Table 1
Input data for the CORMIX base simulations

Parameter	Scenario I		Scenario II	
Marine outfall type	Single port	Multiport	Single port	Multiport
Ambient (unbounded coastal environment)				
Velocity of the currents, m/s			0.3	
Depth at discharge, m			9	
Bottom slope, °	—	—	0.8944	
Wind speed, m/s			2.5	
Temperature, °C			24	
Salinity, ppt			36	
(Uniform) density, kg/m^3			1024.4	
Effluent discharge				
Distance to shoreline, m			576.5	
Diffuser length, m	—	91	—	91
Number of ports	1	36	1	36
Port height, m			1	
Port diameter, m			0.7	
Vertical angle, °			10	
Horizontal angle, °			90	
Flow rate, m^3/s	0.474		0.942	
Temperature, °C above ambient	9		6	
Salinity, ppt above ambient	2		13	
(Uniform) density, kg/m^3	1022.91		1032.27	
Mixing zone				
WQS = water quality standard, °C	1 (above ambient)		—	—
WQS = water quality standard, ppt	—	—	2 (above ambient)	
RMZ = regulatory mixing zone, m			150	
ROI = region of interest, m			1000	

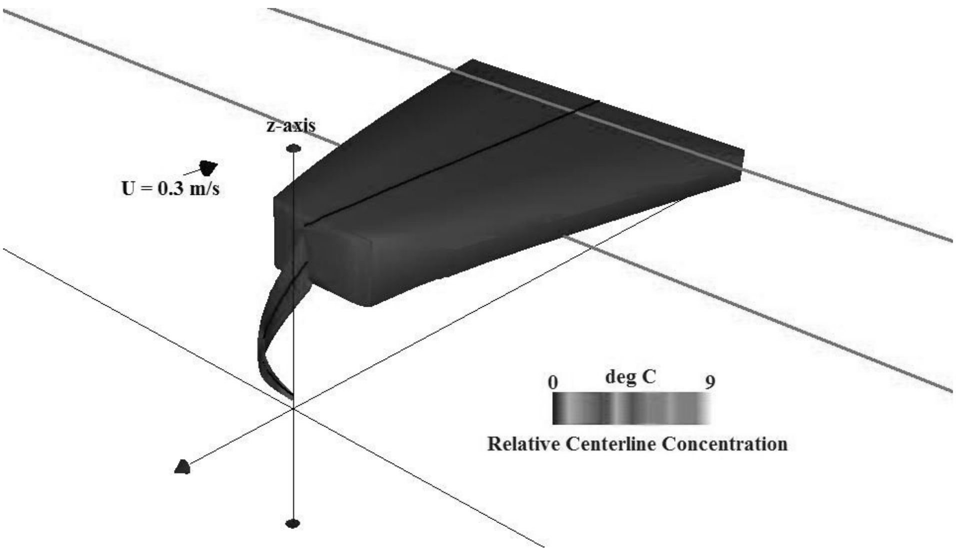

Fig. 3. The positively buoyant plume from the single port.

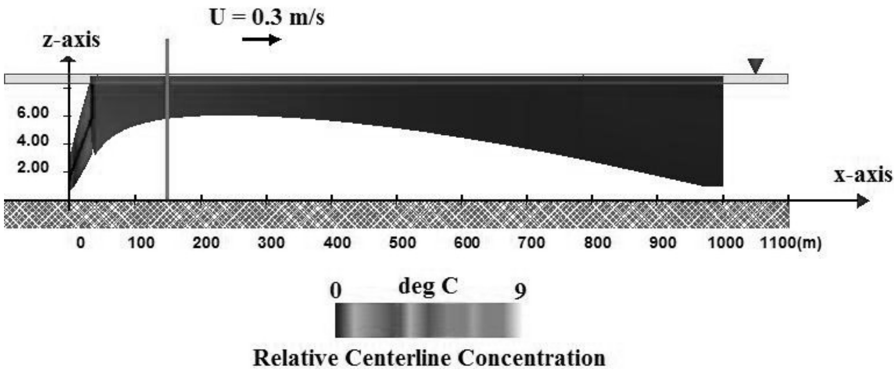

Fig. 4. Side view of the positively buoyant plume from the single port.

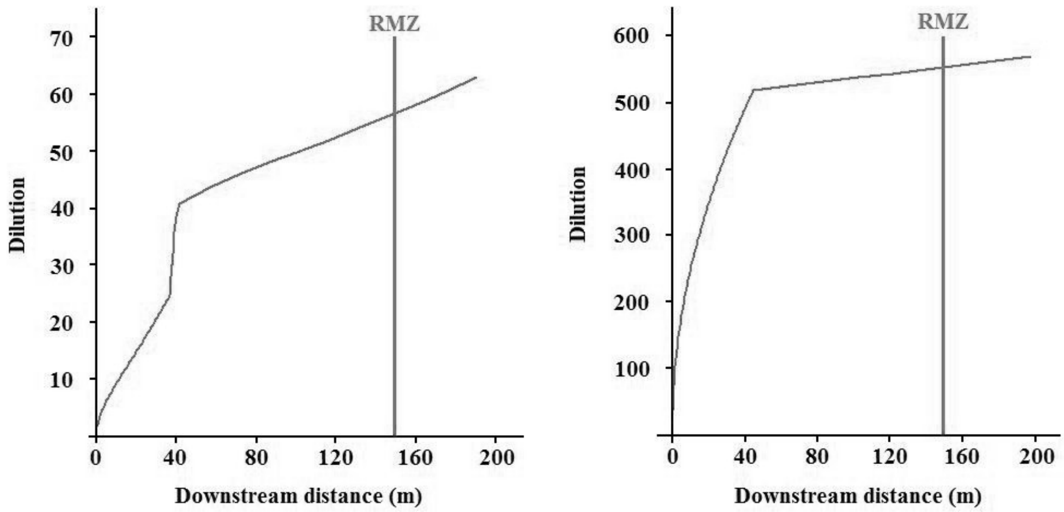

Fig. 5. The plume dilution of scenario I: single port (left) and multiport (right).

Table 2
The RMZ characteristics of scenario I

Marine outfall type	Single port	Multiport
Temperature, °C	0.16 above ambient	0.016 above ambient
Plume dilution	56.6	553.6
RMZ centerline, m	$x = 150$, $y = 8.08$, $z = 9$	$x = 150$, $y = 0$, $z = 9$
RMZ plume dimensions, m	Half-width = 14.30 Thickness = 3.13	Half-width = 48.59 Thickness = 9

The CORMIX simulation results show that the overall temperature rise is less than 0.16°C (above ambient) at the edge of the RMZ, 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 [6], and also with the heavy metals analysis of the bottom sediments sample collected [29], which is consistent with the assumption that the brine plume rises to the surface.

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, CORMIX system uses the equivalent two-dimensional slot diffuser concept to classify the motion of the brine plume from the multiport as the near bottom, positively buoyant flows in a uniform density layer (flow class MU8) [11,26]. As CORMIX assumes the merging process of the individual jets from each port as a plume rises from a long slot discharge, the merging jet-like plume is rapidly deflected by the strong ambient current inducing higher dilution, and raised towards the surface. The plume becomes vertically fully mixed as it reaches the surface within 45 m downstream, and continues to spread due to passive ambient mixing in uniform ambient until it has reached the ROI. As shown in Fig. 5, in comparison with the single port, a ten-fold dilution is achieved for the multiport discharges at the edge of the RMZ.

3.2. Scenario II of concentrated 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°. In contrast to scenario I, the effluent density 1032.27 kg/m^3 is greater 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 (or a concentration of 15.38% above ambient) within the RMZ of 150 m radius from the outfall [7].

CORMIX system classified the brine plume motion from the single port as the near bottom, negatively buoyant flows in a uniform density layer (flow class NH4) [13,26]. The jet-like plume becomes strongly deflected by the ambient current. After the top part of the plume reaches its maximum height within 1.3 m downstream, the negative buoyancy becomes the dominating factor, and the deflected plume descends toward the sloping seabed. The bent-over plume is impinged on the seabed within 26 m downstream, and the concentration distribution becomes relatively uniform across the plume width and thickness (Fig. 6). Thereafter, it continues to spread laterally due to the bottom density current while it is being advected by the ambient current. In the absence of ambient stratification, the brine plume will proceed down the slope until it has reached the ROI (Fig. 7).

Again, the specified WQS has been met within the RMZ, and the plume characteristics are presented in Table 3. The brine plume dilution is plotted in Fig. 8, and a dilution of 30.9 is obtained at the ROI for the single port. 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.

Due to the lateral interaction of adjacent jets, forming

Table 3
The RMZ characteristics of scenario II

Marine outfall type	Single port	Multiport
Plume concentration	(0.6 ppt) 4.63% above ambient	(0.056 ppt) 0.43% above ambient
Plume dilution	21.6	234
RMZ centerline, m	$x = 150$, $y = 45.50$, $z = -9.69$	$x = 150$, $y = 1.62$, $z = -9.03$
RMZ plume dimensions, m	Half-width = 14.24 Thickness = 2.99	Half-width = 47.03 Thickness = 9.01

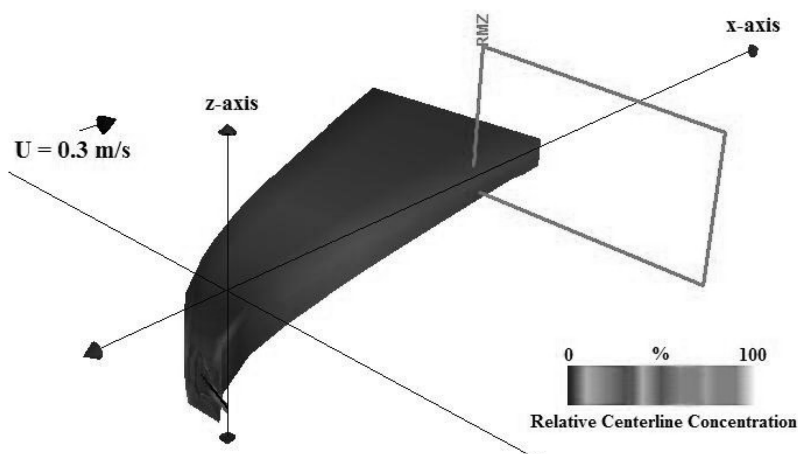

Fig. 6. The negatively buoyant plume from the single port.

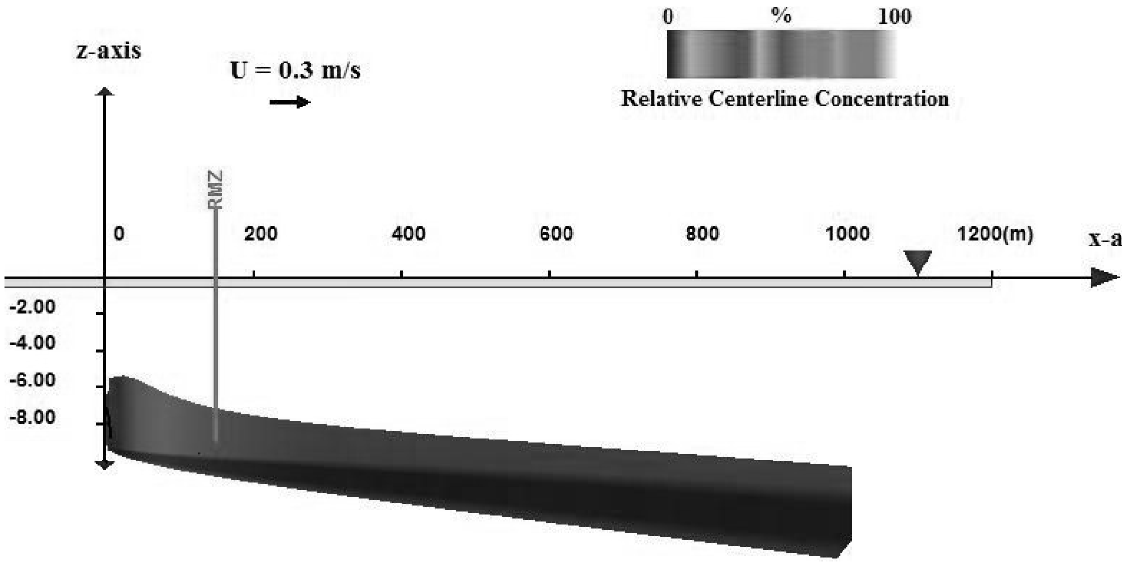

Fig. 7. Side view of the negatively buoyant plume from the single port.

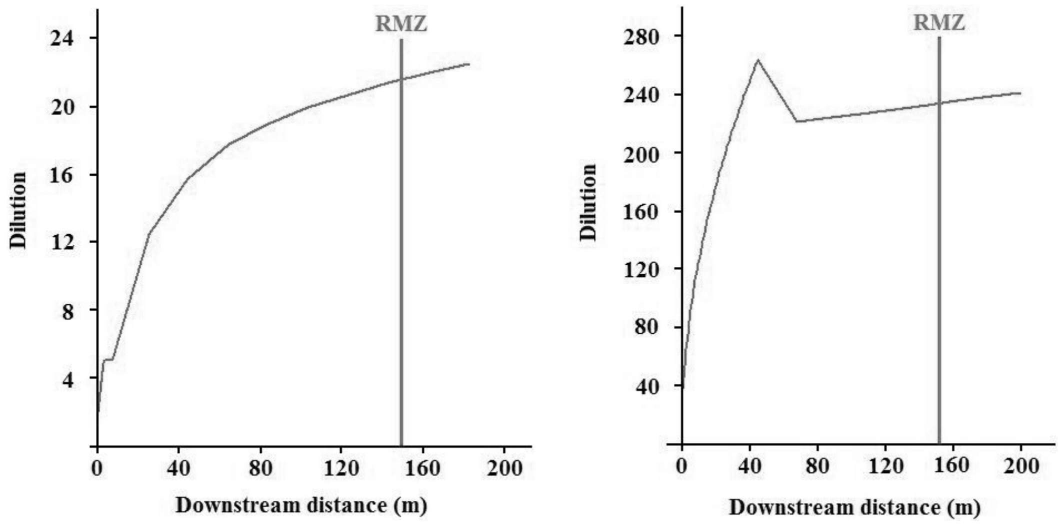

Fig. 8. The plume dilution of scenario II: single port (left) and multiport (right).

an essentially two-dimensional plume as if the discharges are made from a two-dimensional slot diffuser, CORMIX system classifies the motion of the brine plume from the multiport as the near bottom, negatively buoyant flows in a uniform density layer (flow class MNU13) [14,26]. 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. 8, in comparison with the single port, a ten-fold dilution is achieved for the multiport discharges at the edge of the RMZ.

4. CORMIX sensitivity study

CorSens is the CORMIX sensitivity analysis tool to address model performance due to inherent uncertainty in the input data [26,28]. Sensitivity studies are motivated by the fact that there are no user-adjustable parameters for model calibration within CORMIX system. The basis for this restriction is that variations in ambient conditions are likely to have greater influence on mixing zone behavior than a model parameter to obtain a desired result. Only the scenario II simulations are carried out to represent concentrated 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 (an environment parameter) while keeping the other input parameters the same as the base simulation specified in Table 1. The results summary of reducing ambient velocity from 0.5 m/s to 0.05 m/s are presented in Table 4, 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 [13,26]. For 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.

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 [14,26] 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 1025.27 kg/m^3 are given in Table 5, 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).

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 0.442 m^3/s to 1.242 m^3/s are presented in Table 6. 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 high-

Table 4
The CorSens results summary on the ambient velocity at the edge of the RMZ

Marine outfall type	Single port				Multiport			
Ambient velocity (m/s)	Flow class	Dilution	Salinity		Flow class	Dilution	Salinity	
			%	ppt			%	ppt
0.5	NH4	32.4	3.09	0.402	MNU13	387	0.26	0.034
0.45	NH4	29.7	3.37	0.438	MNU13	349	0.29	0.038
0.4	NH4	26.8	3.74	0.486	MNU13	311	0.32	0.042
0.35	NH4	23.8	4.19	0.545	MNU13	272	0.37	0.048
0.3	NH4	21.6	4.63	0.602	MNU13	234	0.43	0.056
0.25	NH5	80.9	1.24	0.161	MNU13	196	0.51	0.066
0.2	NH5	84.1	1.19	0.155	MNU13	158	0.63	0.082
0.15	NH5	82.9	1.21	0.157	MNU13	101	0.99	0.129
0.1	NH5	69.2	1.45	0.189	MNU13	72.2	1.39	0.181
0.05	NH5	62.7	1.59	0.207	MNU2	36.0	2.77	0.360

Table 5
The CorSens results summary on the discharge density at the edge of the RMZ

Marine outfall type	Single port				Multiport			
Discharge density (kg/m^3)	Flow class	Dilution	Salinity		Flow class	Dilution	Salinity	
			%	ppt			%	ppt
1034.27	NH4	20.1	4.96	0.645	MNU13	234	0.427	0.0555
1033.27	NH4	20.7	4.84	0.629	MNU13	234	0.427	0.0555
1032.27	NH4	21.6	4.63	0.602	MNU13	234	0.427	0.0555
1031.27	NH4	23.1	4.33	0.563	MNU13	234	0.428	0.0556
1030.27	NH4	25.4	3.94	0.512	MNU13	234	0.428	0.0556
1029.27	NH4	28.4	3.52	0.458	MNU13	233	0.429	0.0558
1028.27	NH4	32.6	3.07	0.399	MNU13	233	0.429	0.0558
1027.27	NH4	38.4	2.60	0.338	MNU13	233	0.430	0.0559
1026.27	NH4	46.3	2.16	0.281	MNU13	232	0.430	0.0559
1025.27	NH4	55.9	1.79	0.233	MNU13	232	0.431	0.0560

Table 6
The CorSens results summary on the discharge flow rate at the edge of the RMZ

Marine outfall type	Single port				Multiport			
Discharge flow rate (m^3/s)	Flow class	Dilution	Salinity		Flow class	Dilution	Salinity	
			%	ppt			%	ppt
0.442	NH4	14.6	6.84	0.889	MNU13	497	0.201	0.0261
0.542	NH4	16.2	6.17	0.802	MNU13	405	0.247	0.0321
0.642	NH4	17.6	5.67	0.737	MNU13	343	0.292	0.0380
0.742	NH4	19.0	5.27	0.685	MNU13	297	0.337	0.0438
0.842	NH4	20.4	4.91	0.638	MNU13	262	0.382	0.0497
0.942	NH4	21.6	4.63	0.602	MNU13	234	0.427	0.0555
1.042	NH5	23.0	4.35	0.566	MNU13	212	0.472	0.0614
1.142	NH5	49.8	2.01	0.261	MNU13	193	0.517	0.0672
1.242	NH5	51.5	1.94	0.252	MNU13	178	0.562	0.0731

er 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.

5. Conclusion

CORMIX simulations 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 [7]. 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 less than 0.2°C (above ambient) within the regulatory mixing zone of 150 m radius from the outfall. Similarly, from 2009, the overall salinity increase due to concentrated brine discharges from the combined Barka I and II plants is found to be less than 1 ppt (above ambient). These 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 brine plume 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 to and stay at the sloping seabed, and therefore the potential exposure of benthic organisms can no longer be ruled out.

Like other numerical models, 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 and its subsequent dilution in the receiving water environment. Thus, as shown in Table 4, a small change in an input parameter may result in a different flow class leading to marked discontinuities in the plume dilutions.

Acknowledgements

The authors are indebted to the late Professor G.H. Jirka for his continuous and valuable support, direction, guidance, and technical assistance. He was an exceptional mentor, colleague and friend, and a great scholar.

The authors would like to thank the Middle East Desalination Research Center (MEDRC) for its financial support of the project on the environmental planning, prediction and management of brine discharges from desalination plants (http://www.brinedis.ms).

References

[1] A.Y. Kwarteng, A.S. Dorvlo and G.T. Vijaya Kumar, Analysis of a 27-year rainfall data (1977–2003) in the Sultanate of Oman, Intl. J. Climatol., 29 (2009) 605–617.

[2] Oman Power and Water Procurement, OPWP's 7-year Statement (2010-2016), Muscat, Sultanate of Oman, 2009. (available at http://www.omanpwp.co.om/7yearstatement-1016.pdf).

[3] A. Purnama, H.H. Al-Barwani and M. Al-Lawatia, Modeling dispersion of brine waste from a coastal desalination plant, Desalination, 155 (2003) 41–47.

[4] National Hydrographic Office, Oman Maritime Book 2009, Royal Navy of Oman, Muscat, Sultanate of Oman, 2008.

[5] A. Purnama and H.H. Al-Barwani, Spreading of brine waste discharges into the Gulf of Oman, Desalination, 195 (2006) 26–31.

[6] S.A. Abdul-Wahab, Characterization of water discharges from two thermal power/desalination plants in Oman, Environ. Eng. Sci., 24 (2007) 321–337.

[7] Sultanate of Oman, Ministerial Decision No. 159/2005: Promulgating the bylaws to discharge liquid waste in the marine environment, Minister's Office, Ministry of Regional Municipalities, Environment and Water Resources, Muscat, Sultanate of Oman, 2005.

[8] R.L. Doneker and G.H. Jirka, CORMIX1: An expert system for hydrodynamic mixing zone analysis of conventional and toxic submerged single port discharges, Technical Report EPA/600/3-90/012, US EPA, Environmental Research Laboratory, Athens, Georgia, USA, 1990.

[9] G.H. Jirka and R.L. Doneker, Hydrodynamic classification of submerged single port discharges, J. Hydraul. Eng., 117 (1991) 1095–1112.

[10] P.J. Akar and G.H. Jirka, CORMIX2: An expert system for hydrodynamic mixing zone analysis of conventional and toxic submerged multiport diffuser discharges, Technical Report EPA/600/3-91/073, US EPA, Environmental Research Laboratory, Athens, Georgia, USA, 1991.

[11] G.H. Jirka and P.J. Akar, Hydrodynamic classification of submerged multiport diffuser discharges, J. Hydraul. Eng., 117 (1991) 1113–1128.

[12] G.R. Jones, J.D. Nash and G.H. Jirka, CORMIX3: An expert system for the analysis and prediction of buoyant surface discharges, Technical Report CR818527, De Frees Hydraulics Laboratory, School of Civil and Environmental Engineering, Ithaca, New York, USA, 1996.

[13] G.H. Jirka, Integral model for turbulent buoyant jets in unbounded stratified flows. Part 1: Single round jet, Environ. Fluid Mech., 4 (2004) 1–56.

[14] G.H. Jirka, Integral model for turbulent buoyant jets in unbounded stratified flows. Part 2: Plan jet dynamics resulting from multiport diffuser jets, Environ. Fluid Mech., 6 (2006) 43–100.

[15] M.M. Mendez-Diaz and G.H. Jirka, Buoyant plumes from multiport diffuser discharges in deep coflowing water, J. Hydraul. Eng., 122 (1996) 428–435.

[16] R.L. Doneker, J.D. Nash and G.H. Jirka, Pollutant transport and mixing zone simulation of sediment density currents, J. Hydraul. Eng., 130 (2004) 349–359.

[17] US EPA, Review of the D-CORMIX model, Science Advisory Board Report EPA-SAB-EC-99-011, Washington DC, USA, 1999. (available at http://www.epa.gov/science1/ec99011.pdf).

[18] P.J.W. Roberts and G. Toms, Inclined dense jets in a flowing current, J. Hydraul. Eng., 114 (1987) 323–341.

[19] P.J.W. Roberts and X. Tian, New experimental techniques for validation of marine discharge models, Environ. Model. Software, 19 (2004) 691–699.

[20] S.W. Kang, S.H. You and J.Y. Na, Near-field mixing characteristics of submerged effluent discharges into Masan Bay, Ocean Res., 22 (2000) 45–56.

[21] K.L. Pun and M.L. Davidson, On the behavior of advected plumes and thermals, J. Hydraul. Res., 37 (1999) 519–540.

[22] G.A. Kikkert, M.J. Davidson and R.I. Noakes, Inclined negatively buoyant discharges, J. Hydraul. Eng., 133 (2007) 545–554.

[23] A. Etemad-Shahidi and A.H. Azimi, Performance of CORMIX model applied to dense jet flow, Proc. XXXI IAHR Congress, Seoul, Korea, 2005, pp. 4211–4218.

[24] A.H. Azimi, F. Azizi and A. Etemad-Shahidi, A new formulation to estimate initial dilution of dense jet flow, Proc. XXXI IAHR Congress, Seoul, Korea, 2005, pp. 4241–4248.

[25] R.L. Doneker and G.H. Jirka, CORMIX-GI systems for mixing zone analysis of brine wastewater disposal, Desalination, 139 (2001) 263–274.

[26] R.L. Doneker and G.H. Jirka, CORMIX user manual: A hydrodynamic mixing zone model and decision support system for pollutant discharges into surface waters, MixZon Inc., Portland, Oregon, USA, 2007 (available at http://www.mixzon.com and http://www.cormix.info).

[27] J.V. Del Bene, G.H. Jirka and J. Largier, Ocean brine disposal, Desalination, 97 (1994) 365–372.

[28] I. Alameddine and M. El-Fadel, Brine discharge from desalination plants: a modeling approach to an optimized outfall design, Desalination, 214 (2007) 241–260.

[29] S.A. Abdul-Wahab and B.P. Jupp, Levels of heavy metals in subtidal sediments in the vicinity of thermal power/desalination plants: A case study, Desalination, 244 (2009) 261–282.