Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.933629

53 (2015) 3214–3223
March

Taylor & Francis
Taylor & Francis Group

Integrated modelling for the discharge of brine from desalination plants into coastal waters

I.K. Nikiforakis*, A.I. Stamou

School of Civil Engineering, National Technical University of Athens, Zografou 15780, Greece, Tel. +30 2107722801; Fax: +30 2107722814; email: giannisnikiforakis@gmail.com (I.K. Nikiforakis)

Received 15 October 2013; Accepted 22 January 2014

ABSTRACT

Reverse osmosis desalination plants (RODP) located in many arid or semi arid coastal areas or islands worldwide provide a solution to the problem of water scarcity by supplying fresh water to the local population. However, the constant discharge of large quantities of brine into the sea may cause harmful effects on marine flora and fauna due to excess salinities. These effects can be avoided by selecting properly the configuration and location of the water outfall system of RODP via the performance of a hydrodynamic study of the brine effluent using integrated models. This work presents (1) the mixing regions of brine effluent flow, which are the near field (NF), intermediate field (IF) and far field (FF) regions, (2) the normally used brine outfall configurations which fall into three groups: (a) the onshore surface, (b) the offshore submerged single port and (c) the offshore submerged multiport outfall, (3) the existing regulations for brine discharge salinity, (4) a comparison between the onshore surface and offshore submerged single port discharge from a typical RODP in a Greek island, through an application using the CORMIX model, showing that dilution is much greater for the second outfall type mitigating to a great extent the potential environmental adverse impacts and (5) the basic steps towards development of an integrated model for the performance of hydrodynamics studies for brine effluents from RODP which couples the NF CORMIX-CorJet model with the FF model FLOW-3DL.

Keywords: Brine; Desalination; Hydrodynamics; Environmental impact; Numerical modelling

1. Introduction

Many arid or semi arid coastal areas or islands worldwide encounter the problem of water shortage making the need for water supply from desalination plants even more imperative. Due to this need, many desalination plants, the majority of which are reverse osmosis desalination plants (RODP), have been constructed supplying fresh water to the local population.

Although sea water desalination seems to be a solution to the problem of water scarcity, the disposal of brine may cause harmful impacts on the coastal environment, especially in regions of significant ecological interest. Latteman and Hopner [1] refer that the constant discharge of brine effluents from desalination plants can be fatal for marine life and can cause

*Corresponding author.

Presented at the International Conference WIN4Life, 19–21 September 2013, Tinos Island, Greece

a lasting change in species composition and abundance in the discharge site. Laspidou et al. [2] note that benthic communities, such as Posidonia seagrass (Posidonia oceanic) habitats due to their sensitivity to high salinities, can be affected from the hyper-saline desalination plant effluents. Sánchez-Lizaso et al. [3] conducted laboratory experiments observing that an increase in salinity levels can cause lethal impacts not only on the Posidonia seagrass but also on other marine species such as mysids and sea urchins.

The aforementioned effects can be mitigated by selecting properly the location and configuration of the outfall system of the RODP. This selection should be based on a hydrodynamic study of the brine effluent aiming at avoiding relatively large excess salinities that may cause harmful environmental impacts on the benthic flora and fauna.

The scope of the present work is: (1) to present, based on literature review, the mixing processes, the types of brine discharge outfall and the existing regulations for brine discharge salinity, (2) to compare outfall configurations in a fictitious case of brine discharge from a RODP regarding the achievable mixing (dilution) in the near and intermediate field (IF) region using the CORMIX model [4,5] and (3) to present the basic steps towards development of an integrated model for the performance of hydrodynamic studies for brine effluents from RODP. It is noted that the data of the application case were selected based on the literature and correspond to a brine discharge from a typical RODP in a Greek island.

2. Brine discharge and ambient water characteristics

The discharge of brine effluents into coastal waters can be described by specific characteristics, which can be divided into three categories:

(1) Geometrical characteristics of the discharge, which are the vertical (θ_o) and horizontal (σ_o) angle of discharge, the height (h_o) of the port above the bottom, the distance of the port from the coast (DISTB), the diameter (D_o) or the area (A_o) of the port.
(2) Effluent characteristics, which are the effluent density (ρ_o), salinity (C_o), temperature (T_o), discharge velocity (U_o), volume flux (Q_o), kinematic momentum flux (M_o) and kinematic buoyancy flux (J_o).
(3) Ambient waters characteristics, which are the depth at the discharge (H_D), the bed slope (φ_o), the density (ρ_a), salinity (C_a) and temperature (T_a) of ambient waters, the speed of ambient current (u_a) and the type of vertical density distribution (stratified or unstratified ambient waters).

The aforementioned characteristics concerning a submerged round port brine discharge are shown in Fig. 1.

3. Mixing processes of brine effluents

The mixing processes of brine effluents into coastal waters can be divided into three flow regions with different spatial and time scales [4,7], shown in Fig. 2: (1) the near field (NF) region, (2) the IF region and (3) the far field (FF) region. The following analysis of these regions refers to unstratified ambient waters.

3.1. The NF region

In the NF region, the geometrical characteristics of the outfall configuration and the initial kinematic momentum flux and buoyancy flux influence the trajectory and the degree of effluent mixing. The effects of ambient conditions on the effluent trajectory are of minor importance, until any bottom interaction occurs.

3.2. The IF region

The IF region begins right after the brine effluent impinges on the bottom and starts spreading as a density current (see Fig. 1). In the IF the flow is characterised by a motion along the sea bed. The trajectory and dilution of the brine effluent is dominated by buoyant spreading motions and passive diffusion due to interfacial mixing. The source characteristics become less important.

3.3. The FF region

The FF region starts right after the IF region. In that region the ambient conditions control the brine effluent trajectory and dilution through the processes of passive diffusion due to ambient turbulence and passive advection by the ambient currents.

4. Configurations of brine effluent outfalls

Brine effluent outfalls can be classified according to their location, to onshore surface and offshore submerged outfalls. The offshore submerged outfalls can fall into two categories: single port and multiport outfalls [7].

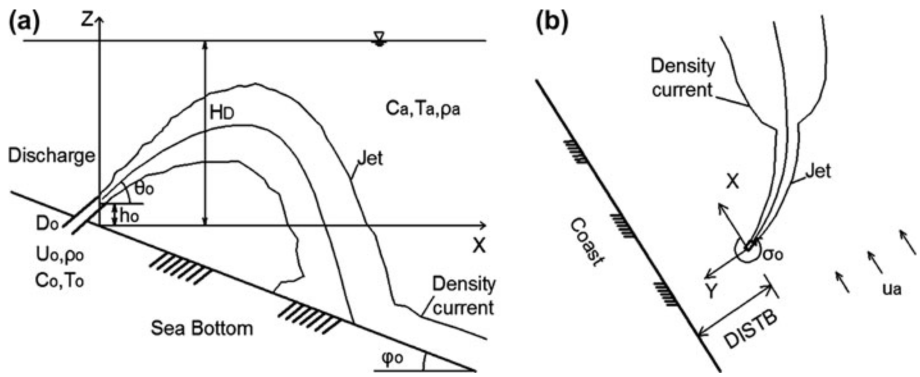

Fig. 1. Schematic representation of a brine discharge into coastal waters; (a) cross section [6], and (b) plan view.

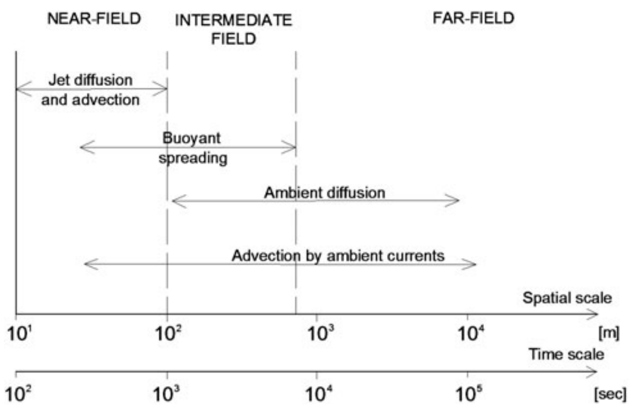

Fig. 2. Spatial and time scales of brine effluent flow regions [7].

4.1. Onshore surface outfalls

Onshore surface brine discharge outfalls range from simple rectangular channels to horizontal round pipes and can be located at or near the water surface. Three different outfall configurations relative to the bank [4] are normally used and shown in Fig. 3: (1) the flush with the bank/shore outfall, (2) the protruding from the bank outfall and (3) the co-flowing along the bank.

In Figs. 3 and 4, the geometrical characteristics of onshore brine effluent outfalls are shown: (1) distance to the coast (DISTB), (2) discharge channel width (b_o) and depth (H_o), (3) actual receiving water depth at the channel entry (H_D), (4) sea bottom slope (φ_o) and (5) horizontal angle of discharge (σ_o).

4.2. Offshore submerged single port outfalls

The geometrical characteristics of offshore submerged single port outfalls, which are depicted in Fig. 5, are the following: (1) distance to the coast (DISTB), (2) port diameter (D_o) or cross-sectional area (A_o), (3) height of the port above the bottom (h_o), (4) vertical angle of discharge (θ_o), (5) horizontal angle of discharge (σ_o), and (6) water depth at the location of discharge (H_D).

4.3. Offshore submerged multiport outfalls

An offshore submerged multiport outfall is depicted in Fig. 6. Usually, these outfalls are linear structures consisting of many ports or nozzles (diffusers) which inject a series of turbulent jets at high velocity into the ambient receiving water body [4].

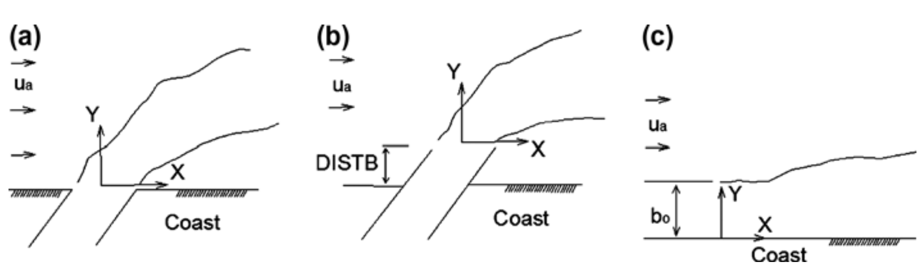

Fig. 3. Types of onshore rectangular outfalls of surface buoyant discharges [4]: (a) flush with bank/shore, (b) protruding from the bank and (c) co-flowing along the bank.

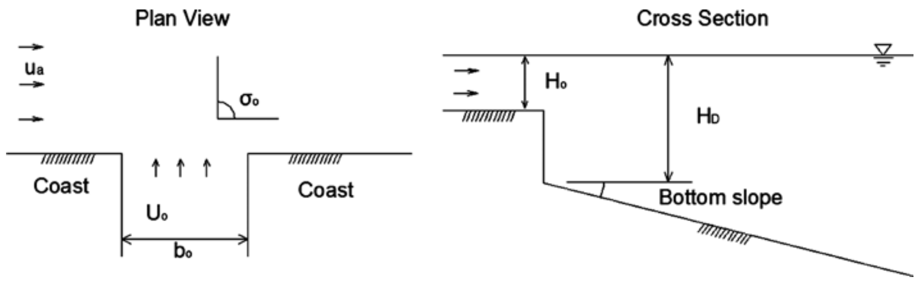

Fig. 4. Plan view and cross-section of rectangular onshore outfalls [4].

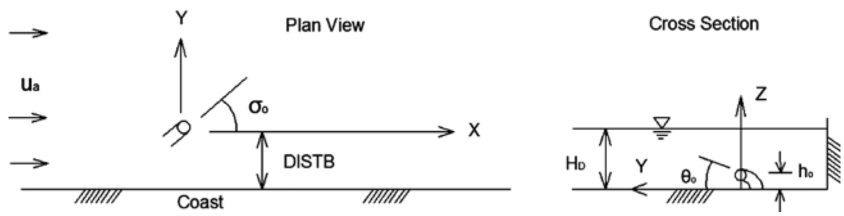

Fig. 5. Plan view and cross-section of an offshore single port outfall [4].

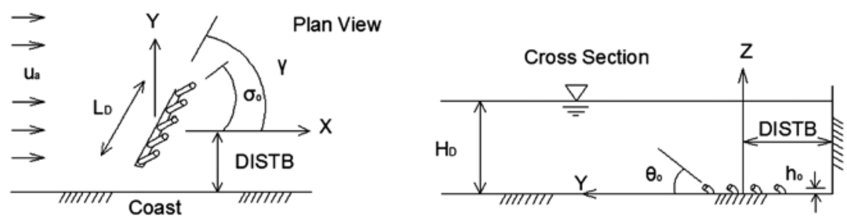

Fig. 6. Plan view and cross-section of an offshore multiport outfall [4].

The geometrical characteristics of offshore multiport brine outfalls are the following: (1) average distance to the coast (DISTB), (2) diameter of the discharge ports or nozzles (D_o), (3) height of the port centres (h_o) above the bottom, (4) vertical angle of discharge (θ_o), (5) horizontal angle of discharge (σ_o), (6) diffuser length (L_D), (7) number of ports or risers, (8) alignment angle (γ) between the diffuser and ambient current and (9) water depth at the location of discharge (H_D).

5. Length scale analysis of brine effluents

The geometric and mixing characteristics of brine effluents can be determined by using length scales. The length scales which describe the brine flow in unstratified coastal waters are [4]: (1) the discharge length scale (L_Q or l_Q), (2) the jet/plume transition length scale (L_M or l_M), (3) the jet/crossflow transition length scale (L_m or l_m) and (4) the plume/crossflow transition length scale (L_b). These length scales are listed in Table 1 for each discharge configuration [4,8]. According to Doneker and Jirka [4], Doneker and Jirka [5], Akar and Jirka [9] and Jones and Jirka [8]: the discharge length scale defines the region for which the discharge port geometry of the outfall, influences strongly the flow characteristics; the jet/plume transition length scale indicates the distance at which the transition from the jet to plume behaviour takes place; the jet/crossflow transition length scale corresponds to the distance beyond which the jet is strongly advected by the cross flow; the plume/crossflow transition length scale denotes the distance beyond which a plume is strongly advected by the crossflow. These length scales in combination with the geometric characteristics of the outfall, such as θ_o, σ_o, h_o and the geometric characteristics of the ambient receiver, such as H_D, determine the flow characteristics of brine effluents. For example, in the case of a brine effluent discharged upwards ($45^\circ < \theta_o < 90^\circ$) from a single round port, if the depth (H_D) of the receiver is smaller than the L_M scale, then the effluent is expected to impinge at the sea surface [4].

Table 1
Length scales for different types of outfall configurations

Length scales	Onshore surface outfalls/offshore single port outfalls	Offshore multiport outfalls
Discharge length scale	$L_Q = Q_o/M_o^{1/2}$ (1)	$l_Q = q_o^2/m_o$ (5)
Jet/plume transition length scale	$L_M = M_o^{3/4}/J_o^{1/2}$ (2)	$l_M = m_o/j_o^{2/3}$ (6)
Jet/crossflow transition length scale	$L_m = M_o^{1/2}/u_a$ (3)	$l_m = m_o/u_a^2$ (7)
Plume/crossflow transition length scale	$L_b = J_o/u_a^3$ (4)	–

The definitions of the brine discharge characteristics Q_o, M_o, J_o, q_o, m_o and j_o are given by Eq. (8)–(13), see Table 2, where $g'_o = g(\rho_o - \rho_a)/\rho_a$ is the initial apparent gravitational acceleration of brine effluent.

6. Brine effluent mixing zone and existing regulatory criteria for salinity

A mixing zone can be defined as a limited area or volume of water where initial dilution of a discharge takes place and where numeric water quality criteria can be exceeded [10]. Water quality standards (regulations) apply at the boundary of the mixing zone, but not within the mixing zone itself. According to Jenkins et al. [11] the boundary of this zone lies between the NF and the FF region.

Although there does not exist, despite the need of, a common regulation framework for brine effluent salinity, there are few regulations, standards, or guidelines, established only for specific desalination plants [11]. These regulations are summarised in Table 3, and share two basic characteristics: a salinity limit and a point of compliance expressed as a distance from the discharge.

7. Application

The model CORMIX [4,12] was applied for the investigation of the effect of outfall configuration on the dilution of a brine effluent discharged from a fictitious RODP located in a coastal region. CORMIX calculates the brine mixing in the NF and IF region of the flow. The data of the application were selected based on the literature and correspond to a brine discharge from a typical RODP in a Greek island. Two scenarios were investigated, (1) scenario *S*1: a flush with the shore channel discharge, and (2) scenario *S*2: a submerged single round port discharge. Table 4 lists the main characteristics of the outfall configurations, brine discharges and ambient waters used in calculations.

The ambient waters characteristics were the following: (1) $C_a = 37.87$ ppt, (2) T_a = 21.80°C, (3) ρ_a = 1,026.48 kg/m^3 and (4) u_a = 0.05 m/s.

The characteristics of the brine discharges were selected as follows:

(1) According to Canovas Cuenca [13] the fresh water capacity of RODP in Greek islands ranges from 100 to 4,500 m^3/d, so a representative value of 2,250 m^3/d = 0.026 m^3/s was selected in the calculations.
(2) According to Bleninger and Jirka [7], the recovery rate of RODP, given by the ratio of the flow rate of produced fresh water to the flow rate of sea water intake ($Q_{\text{fresh}}/Q_{\text{intake}}$), ranges from 20–50%, so a recovery rate of 50%, was used into calculations, thus Q_o = Q_{fresh} = 2,250 m^3/d.
(3) According to Bleninger and Jirka [7], T_o = T_a and the excess brine salinity, observed from several RODP worldwide, ranges from 22.0 to 52.5 ppt above ambient salinity, so a value of $C_o = C_a + 45.00$ = 82.87 ppt was used. From these values of T_o and C_o and by applying the equation of state [14] ρ_o was calculated equal to 1,061.27 kg/m^3.

Table 2
Main brine discharge characteristics

	Onshore surface outfalls/offshore single port outfalls	Offshore multiport outfalls
Initial volume flux	$Q_o = U_o A_o$ (8)	$q_o = Q_o/L_D$ (11)
Initial momentum flux	$M_o = U_o Q_o$ (9)	$m_o = M_o/L_D$ (12)
Initial buoyancy flux	$J_o = g'_o Q_o$ (10)	$j_o = J_o/L_D$ (13)

Table 3
Regulation criteria for brine discharges from specific desalination plants [11]

Region/authority	Salinity limit	Compliance point
US EPA	Excess ≤ 4ppt	
Carlsbad, CA	Absolute ≤ 40 ppt	1,000 ft
Huntington Beach, CA	Absolute ≤ 40ppt	1,000 ft
Western Australian guidelines	Excess ≤ 5%	
Oakajee Port, Western Australia	Excess ≤ 1 ppt	
Perth, Australia/Western Australia EPA	Excess ≤ 1.2 ppt at 50 m and ≤0.8ppt at 1,000 m	50 m and 1,000 m
Sydney Australia	Excess ≤ 1 ppt	50–75 m
Gold Coast, Australia	Excess ≤ 2 ppt	120 m
Okinawa, Japan	Excess ≤ 1 ppt	Mixing zone boundary[a]
Abu Dhabi	Excess ≤ 5%	Mixing zone boundary
Oman	Excess ≤ 2 ppt	300 m

[a]Defined as the location where the brine effluent reaches the sea bed [7].

Table 4
Characteristics of the brine discharge and ambient waters

Discharge and ambient waters characteristics	Symbol (units)	Scenario $S1$	Scenario $S2$
Specific volume flux	Q_o (m^3/s)	0.026	0.026
Specific momentum flux	M_o (m^4/s^2)	0.017	0.086
Apparent gravitational acceleration	g'_o (m/s^2)	0.3324	0.3324
Specific buoyancy flux	J_o (m^4/s^3)	0.0086	0.0086
Discharge velocity	U_o (m/s)	0.65	3.31
Distance from the coast	DISTB (m)	0.00	220.00
Port diameter	D_o (m)	–	0.10
Discharge channel depth	H_o (m)	0.40	–
Discharge channel width	b_o (m)	0.10	–
Cross sectional port area	A_o (m^2)	0.04	0.008
Height of the port centre above the bottom	h_o (m)	–	1.00[a]
Water depth at the location of discharge	H_D (m)	0.80	11.00
Vertical angle of discharge	θ_o (°)	–	45[a]
Horizontal angle of discharge	σ_o (°)	90[b]	270[b]
Bottom slope	φ_o (°)	5	5
Ambient current speed	u_a (m/s)	0.05	0.05

[a]The selection of $\theta_o = 45^\circ$ and $h_o = 1.00$ m was based on the design procedure for brine effluents proposed by Jirka [6], for bottom slopes with $\varphi_o \leq 15^\circ$.
[b]both effluents are discharged transversally to the coastline.

(4) According to Jirka [6], the initial densimetric Froude number, $F_o = U_o/(g'_o D_o)^{1/2} = 4Q_o/(\pi (g'_o D_o^5)^{1/2})$, for single round port discharges should be in the recommended range F_o = 20–25. Also D_o should not be less than 0.10 m to avoid possible problems of blockage (Bleninger and Jirka [15]). Therefore a value close to 20 (F_o = 18.2) was selected in combination with D_o = 0.1 m.

(5) By applying Eq. 14, U_o of the effluent discharge were calculated to 3.31 m/s. This calculated value of U_o is in accordance with the proposed design rules for submerged outfalls reported by Bleninger and Jirka [15]. Bleninger and Jirka [15] report that U_o should be greater than 0.5 m/s and less than 12 m/s.

$$U_o = 4Q_o/(D_o^2\pi) \tag{1}$$

(6) Suh [16] reports in his work F_o values of onshore surface discharges into coastal waters. These values range between 1.98 and 6.45; therefore a value of F_o = 2.52 was selected in the calculations of scenario $S1$, which gives $U_o = F_o(g'_o(H_o b_o)^{1/2})^{1/2}$ = 0.65 m/s.

CORMIX calculations were performed with the following assumptions: (1) the flow and concentration fields are steady state, (2) the coastal current flows parallel to the shore, (3) the ambient waters are not stratified and (4) the effect of tide is negligible.

Fig. 7 depicts the brine effluent trajectory for the two investigated scenarios. As observed in Fig. 7, in both scenarios the flow of the brine effluent can be described by its (1) trajectory deflection due to the presence of the ambient current and (2) downslope motion along the bottom due to presence of buoyancy. Comparing Fig. 7(a) and (b), it is noticed that the lateral spreading of the density current in scenario S2 is greater than that in S1. This may be explained by the fact that in scenario S1 the vertical mixing of the effluent is performed over the entire depth, resulting in greater vertical dilution and reduced lateral spreading. Also it is observed that the deflection due to ambient current is approximately the same after the distance of $L_b = 69.13$ m, as the numeric value of this length scale is the same for both scenarios.

Table 5 lists the average excess salinity (ΔC) and dilution (S), $S = (C_o - C_a)/\Delta C$, of the brine effluent according to the distance from the source for both scenarios. As shown in Table 5, S values for scenario S2 are much greater than those of S1, resulting in greater mitigation of potential environmental impacts especially near shore.

8. Discussion on the development of an integrated model for brine discharges and future work

The calculated values of S for scenarios S1 and S2 lie in the range of values reported by Bleninger and Jirka [17]. According to Bleninger and Jirka [17], S ranges (a) for onshore surface discharges, from 1 to 6, near shore, and (b) for offshore submerged discharges, from 10 to 20 or more, at the end of NF. The respective calculated values of S are (a) S = 3.0–3.4 for scenario S1 and (b) S = 15.5 for scenario S2. Jenkins et al. [11] refer that the lower values of S in the case of surface discharges can be attributed to the lower values of U_o, resulting in lower entrainment of ambient fluid into the brine effluent and therefore lower mixing and dilution. A conclusion, therefore, that can be drawn is that the use of offshore submerged single port outfalls mitigates much further the adverse environmental impacts than the use of surface outfalls.

It is noted that the performed calculations with CORMIX and the derived conclusions were based on simplifications, which do not take into account the effects of spatial and temporal variations of hydrodynamics (flow field) of the coastal region, the morphology of the coastline-geometry of the water body [18] and the existence and (subsequently) the effect of the abstraction structure of an RODP. All these effects belong to the FF flow region and thus CORMIX cannot consider them. Moreover, in brine effluents there exists a wide range of space and time scales in the main regions of flow (NF, IF and FF), so the transport processes cannot effectively be simulated by a single model [19] e.g. by using only CORMIX or a FF model. For these reasons, an integrated model for brine discharges should be developed coupling CORMIX with a FF model.

The development of such an integrated model for brine effluents discharged through submerged single port outfalls, can be based on the procedure proposed by Stamou et al. [20] and may employ the NF model CORMIX-CorJet [21] and the FF model FLOW-3DL

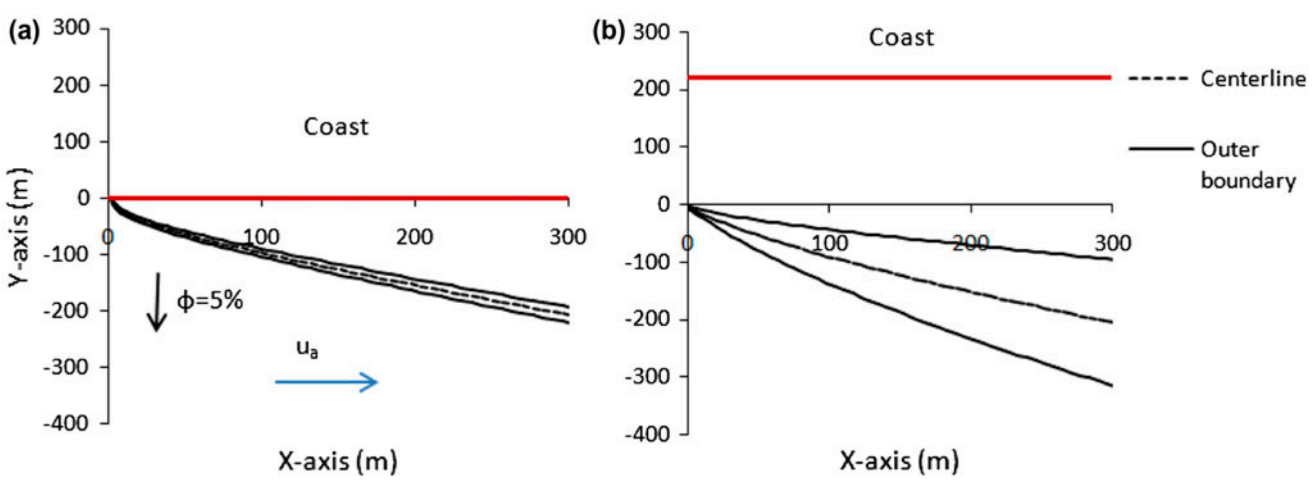

Fig. 7. Plan views of the brine effluent trajectories for scenarios (a) S1 and (b) S2.

Table 5
Calculated excess salinity (ΔC) and dilution (S) values at specific distances from the outfall

Distance from the outfall along effluent's centreline trajectory (m)	Scenario $S1$		Scenario $S2$	
	ΔC (ppt)	S (–)	ΔC (ppt)	S (–)
8.06[a]	15.2	3.0	2.9	15.5
10	13.4	3.4	1.6	28.1
30	3.6	12.5	0.7	64.3
50	1.8	25.0	0.5	90.0
100	0.7	64.3	0.3	150.0
200	0.3	150.0	0.1	450.0

[a]Distance between the impingement point of the brine effluent and the source (scenario $S2$).

[22,23]. Implementing the procedure of Stamou et al. [20] 5 steps should be followed, (1) definition of the characteristics of brine discharge and ambient waters, (2) estimation of the NF region characteristics using preliminary length scale analysis, (3) modelling of the NF region using CORMIX-CorJet model, (4) coupling the FF region model FLOW-3DL with the NF region model and (5) application of the model in the FF region.

In the following text, an analysis of the basic steps (3–5) of this procedure is performed, mentioning as future work any necessary modification of the employed models and their coupling method in order to become applicable in the case of brine discharges.

8.1. Modelling the NF region

The model CORMIX-CorJet can be used to simulate the mixing of brine effluents into the NF region, similar to the work of Stamou and Nikiforakis [24]. The simulation in this region with CORMIX-CorJet ends when the brine jet impinges on the sea bottom.

8.2. Modelling the FF region

The model FLOW-3DL can be used to model the brine effluent flow in the FF region (the IF region is considered here as part of the FF region). FLOW-3DL consists of a hydrodynamic sub-model and a water quality sub-model [25]. The hydrodynamic sub-model involves the 3-D unsteady state shallow water, continuity and momentum equations, expressed in layer formulation, while the water quality sub-model involves the unsteady convection-diffusion equation for the layer averaged salinity (C). Using fixed permeable interfaces between layers, the equations of the model are vertically integrated over a depth range h_i, corresponding to the computational layer i of that thickness. The shallow water equations and convection-diffusion equation are solved explicitly in a staggered orthogonal grid (velocities are determined at the faces of the volumes, while C is determined at their centres) using the upwind scheme for the discretisation of the transport terms and the central differencing scheme for the diffusion terms.

FLOW-3DL should be modified (according to Stamou et al. [20]) to take into account the effect of sea bottom inclination on the development of the density current.

8.3. Coupling the NF and the FF region

Stamou and Nikiforakis [24] developed an algorithm for the coupling of the NF model CORMIX-CorJet and the FF model FLOW-3DL for the case of thermal discharges. This algorithm can be modified properly to become applicable in the case of brine discharges. This modified algorithm should consist of the following steps (analytical description of the steps can be found in Stamou and Nikiforakis [24]):

(1) via the solution of CorJet equations, the coordinates (X_{jet}, Y_{jet}, Z_{jet}) of the trajectory of the brine jet axis in the CORMIX coordinate system and the values of the NF variables of the jet along its trajectory are determined. These NF variables are the jet flow rate (Q_{jet}), axial momentum fluxes M_X, M_Y and M_Z in directions X, Y and Z, respectively, excess salinity (ΔC_{jet}), and vertical and horizontal angles of trajectory (θ and σ).
(2) The jet trajectory coordinates are transformed into FLOW-3DL x, y and z coordinates.
(3) The faces of the control volumes for scalar quantities (C) that are intersected with jet axis trajectory (Fig. 8) are identified and the corresponding control volumes are named "jet control volumes". At these faces the values of the

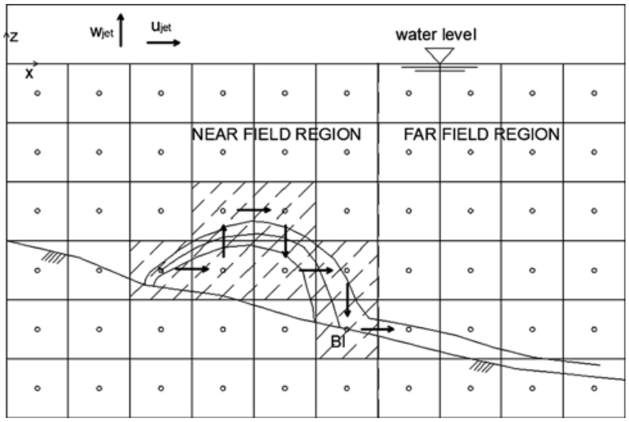

Fig. 8. Schematic representation of the intersected control volumes (dashed lines) of FLOW-3DL with jet axis.

horizontal (u_{jet}, v_{jet}) and/or vertical (w_{jet}) velocities are calculated by dividing the jet flow rate Q_{jet} by the corresponding face area. ΔC_{jet} is determined in each control volume by dividing the source effluent flux $Q_{jeto}x\Delta C_{jeto}$ with Q_{jet}. The values of u_{jet}, v_{jet}, w_{jet} and ΔC_{jet} are given as "fixed" in the solution procedure of the integrated model.

(4) When the jet impinges on the bottom, the jet control volume (BI) is located at the last layer (bottom layer) at which the values of the horizontal velocities and salinity should be calculated. This should be performed by distributing properly the impinging on the bottom flow rate Q_b in the directions x and y based on horizontal and vertical angles formed between the jet axis and the bottom plane.

(5) For each jet control volume at which the vertical velocity of the jet (w_{jet}) is determined, a correction is performed to the rest horizontal velocities of this jet control volume to satisfy continuity. The correction that will be implemented should be based on specific correction types according to the distribution of velocities. These correction types will be similar to those reported in Stamou and Nikiforakis [24]; however, the downwards direction of the vertical velocities should be considered.

9. Conclusions

The main conclusions that can be drawn from the present work are the following:

- No common regulation framework for brine effluents exists, apart from few regulations, standards, or guidelines, established only for specific desalination plants. These regulations vary in the specifics but almost all share two basic characteristics: a salinity limit and a point of compliance expressed as a distance from the discharge.
- There are three normally used brine outfall configurations: (a) the onshore surface, (b) the offshore submerged single port and (c) the offshore submerged multiport outfall.
- The mixing processes of brine effluents into coastal waters can be divided into three flow regions: (a) the NF, (b) the IF and (c) the FF region.
- The use of offshore submerged single port outfalls results in greater dilution values than the use of onshore surface outfalls mitigating much further the adverse environmental impacts caused by excess salinities.
- The harmful environmental effects from brine discharge can be avoided to a great extent by selecting properly the configuration and location of the water outfall system of RODP via the performance of a hydrodynamic study of the brine effluent using integrated models.
- The development of such an integrated model can be based on the employment and coupling of the NF CORMIX-CorJet model with the FF model FLOW-3DL.

Acknowledgements

This research has been co-financed by the European Union (European Social Fund—ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF)—Research Funding Program: Heracleitus II. Investing in knowledge society through the European Social Fund.

Symbols

A_o — cross section area of the outfall port
D_o — outfall diameter
F_o — initial densimetric Froude number
g'_o — initial apparent acceleration of gravity
J_o — initial specific buoyancy flux
j_o — initial specific buoyancy flux per unit diffuser length
L_b — plume/crossflow transition length scale
L_D — length of the diffuser
l_m — diffuser jet/crossflow transition length scale
l_M — diffuser jet/plume transition length scale

L_m — jet/crossflow transition length scale
L_M — jet/plume transition length scale
l_Q — diffuser discharge length scale
L_Q — discharge length scale
M_o — initial specific momentum flux
m_o — initial specific momentum flux per unit diffuser length
Q_o — initial volume flux
q_o — initial volume flux per unit diffuser length
u_a — ambient current velocity
U_o — discharge velocity

References

[1] S. Lattemann, T. Höpner, Environmental impact and impact assessment of seawater desalination, Desalination 220(1–3) (2008) 1–15.
[2] C. Laspidou, K. Hadjibiros, S. Gialis, Minimizing the environmental impact of sea brine disposal by coupling desalination plants with solar saltworks: A case study for Greece, Water 2 (2010) 75–84.
[3] J. Sánchez-Lizaso, J. Romero, J. Ruiz, E. Gacia, J. Buceta, O. Invers, Y. Torquemada, J. Mas, A. Ruiz-Mateo, M. Manzanera, Salinity tolerance of the Mediterranean seagrass Posidonia oceanica: Recommendations to minimize the impact of brine discharges from desalination plants, Desalination 221 (2008) 602–607.
[4] R.L. Doneker, G.H. Jirka, CORMIX User Manual: A hydrodynamic Mixing Zone Model and Decision Support System for Pollutant Discharges into Surface Waters, EPA-823-K-07-001, 2007.
[5] R.L. Doneker, G.H. Jirka, Expert System for Hydrodynamic Mixing Zone Analysis of Conventional and Toxic Submerged Single Port Discharges (CORMIX1), Technical Report EPA/600/3-90/012, 1990.
[6] G.H. Jirka, Improved discharge configurations for brine effluents from desalination plants, J. Hydraul. Eng. 134(1) (2008) 116–120.
[7] T. Bleninger, G.H. Jirka, Environmental planning, prediction and management of brine discharges from desalination plants, Middle East Desalination Research Center Muscat, Sultanate of Oman, 2010, http://www.ifh.unikarlsruhe.de/science/envflu/research/brinedis/brinedis-finalreport.pdf, Accessed 15th of July 2013.
[8] G.R. Jones, G.H. Jirka, CORMIX3: An Expert System for the Analysis and Prediction of Buoyant Surface Discharges, Tech. Rep., DeFrees Hydraulics Laboratory, Cornell University, 1991.
[9] P.J. Akar, 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, U.S. Environmental Research Laboratory, Athens, Georgia, 1991.
[10] US EPA, Water Quality Standards Handbook, second ed., EPA 823-B-94-005a, Washington, DC, 1994.
[11] S. Jenkins, J. Paduan, P. Roberts, D. Schlenk, J. Weis, Management of brine discharges to coastal waters recommmendations of a science advisory panel, Technical Report 694, Southern California Coastal Water Research Project, Costa Mesa, 2012.
[12] G.H. Jirka, R.L. Doneker, S.W. Hinton, User's Manual for CORMIX: A Hydrodynamic Mixing Zone Model and Decision Support System for Pollutant Discharges into Surface Waters, US Environmental Protection Agency, Tech Rep, Environmental Research Lab, Athens, 1996.
[13] J. Canovas-Cuenca, Report on Water Desalination Status in the Mediterranean Countries, Instintuto Murciano de Investigacion y Desarrollo Agrario y Alimentario, Murcia, Spain, 2012.
[14] S.C. McCutcheon, J.L. Martin, T.O. Barnwell Jr, in: Water quality, D.R. Maidment (Ed.), *Handbook of Hydrology*, McGraw-Hill, New York, NY, 1993, pp. 11.1–11.73.
[15] T. Bleninger, G.H. Jirka, User's Manual for CORHYD: An Internal Diffuser Hydraulics Model, Universität Karlsruhe, Institut für Hydromechanik, 2005.
[16] S.W. Suh, A hybrid near-field/far-field thermal discharge model for coastal areas, Mar. Pollut. Bull. 43 (7–12) (2001) 225–233.
[17] T. Bleninger, G.H. Jirka, Mixing zone regulation for effluent discharges into EU waters, Proc. ICE – Water Manage. 164 (2011) 387–396.
[18] V. Maderych, R. Heling, V. Koshebutskyy, Application of 3D numerical model THREETOX to the prediction of cooling water transport and mixing, J. Environ. Sci. Eng. 7 (2005) 53–60.
[19] X.Y. Zhang, E.E. Adams, Prediction of near field plume characteristics using far field circulation model, J. Hydraul. Eng. 125(3) (1999) 233–241.
[20] A.I. Stamou, E. Douka, I. Nikiforakis, P. Dimitriadis, G.H. Jirka, T. Bleninger, Towards an integrated model for the discharge of brine from reverse osmosis desalination plants into coastal waters, Proceedings of the 11th International Conference on Environmental Science and Technology, Chania, Crete, Greece, 2009.
[21] G.H. Jirka, Integral model for turbulent buoyant jets in unbounded stratified flows: Part I: Single round jet, Environ. Fluid Mech. 4 (2004) 1–56.
[22] A.I. Stamou, C.D. Memos, M.E. Kapetanaki, Modeling water renewal in a coastal embayment, Proc. ICE – Mar. Eng. 160(3) (2007) 93–104.
[23] A.I. Stamou, C. Noutsopoulos, K.G. Pipilis, E. Gavalaki, A. Andreadakis, Hydrodynamic and water quality modeling of Southern Evoikos Gulf-Greece, Global Nest. Int. J. 1(2) (1999) 5–15.
[24] A.I. Stamou, I. Nikiforakis, Integrated modelling of single port, steady-state thermal discharges in unstratified coastal waters, Environ. Fluid Mech. 13(4) (2013) 309–336.
[25] A.I. Stamou, K. Memos, K. Pipilis, Mathematical Modelling of Thermal Discharges in Coastal Regions, 28th IAHR Congress, Graz, Austria, 1999.