We are IntechOpen,
the world's leading publisher of
Open Access books
Built by scientists, for scientists

4,800
Open access books available

122,000
International authors and editors

135M
Downloads

Our authors are among the

154
Countries delivered to

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

CLARIVATE ANALYTICS
BOOK CITATION INDEX
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Impacts of Brine Discharge on the Marine Environment. Modelling as a Predictive Tool

Pilar Palomar and Iñigo. J. Losada
Environmental Hydraulics Institute "IH Cantabria", (Universidad de Cantabria)
Spain

1. Introduction

Desalination is a rainfall independent source of water for security long term water supplies. Is is expected that in the medium term desalination would be an optimum to apply to different uses of human consumption, such as irrigation.

Desalination is any of the several processes involved in removing dissolved minerals (especially salt) from seawater, brackish water, or treated wastewater. A number of technologies have been developed for desalination, including thermal processes and membrane technologies. In the present chapter we will focus on seawater desalination, with the aim of obtaining fresh water for human supply, irrigation or industrial facilities.

Seawater desalination has gained importance in coastal countries where conventional water sources are insufficient or overexploited. It can be considered an inexhaustible natural source that generates a high quality product and guarantees demand supply. On the other hand, desalinated water is expensive (due to high energy consumption) and the brine discharged into the sea has negative effects on some important marine ecosystems.

1.1 Environmental Impact by type of desalination project.

The main environmental impacts of desalination projects are associated with construction, marine structures, waste water disposal and energy consumption. The importance of these impacts depends on the type of technology used in salt separation.

MSF thermal plants work with small conversion rates (10% - 20%), so they need greater amounts of feedwater to produce the same volume of fresh desalinated water. The consequences are: a higher water intake, pipes and outfall structures, increased energy losses in pipes and more concentration of chemical additives required. Energy consumption with this technology is very high, which means a higher fuel consumption (Afgan et al, 1998), and thus, emissions of greenhouse gases. The waste water effluent has a slight hypersalinity with respect to the seawater receiving body. However, it has a significant thermal and chemical pollution capability, thus affecting water quality. In general, MSF brine is less dense than seawater, so it floats and rises to the surface, reducing impact risk on benthic ecosystems, but increasing the risk of contamination of recreational or commercial fishing areas. The combustion processes that take place in the plant generate emissions of air pollutants. Finally, visual impact is also significant because of the large amount of piping, tanks and chimneys associated with such plants.

RO plants work with conversion rates of 40 - 50%, so that the need of feedwater is smaller, as are the environmental impacts associated to it. Energy consumption is high but much lower than in MSF plants. The waste effluent or brine has no chemical or thermal pollution, but the salt concentration is very high, making it denser than seawater and thus increasing the risk of negative effects on stenohaline benthic ecosystems. RO plants do not include combustion processes resulting in no air pollution. Its visual impact is less because the plants are usually compact. However, an additional solid waste is generated by RO plants compared to those of MSF, since membranes need to be changed at a certain frequency and at the moment they are not reusable (Hoepner, 1999).

1.2 Desalination impacts on the marine environment.

Among the most important and significant **impacts of seawater desalination projects** are those associated with marine structures construction, as the water intake and outlet:

- Impacts on the water quality and on the benthic organisms present in the receiving water body, due to dredging of trenches and placement of new infrastructures.
- Impacts on navigation and fishing because of the presence of new infrastructures.
- Impacts on the coastal dynamics of beaches by the presence of structures in the active beach profile zone, which may affect longshore and cross-shore sediment transport.

The second and third impacts can be avoided by locating the marine structures in zones with no interference with other applications or processes, and informing the competent authorities of these activities. The following pages are dedicated to impacts and prevention and mitigation measures related to marine dredging and location of pipes.

To place underwater pipelines (associated with water intake and outfall), seabed dredging and trenching are conducted. The **impacts associated with dredging** are:

- Occupation and physical destruction of benthic ecosystems located in the dredging area.
- Effects on water quality_due to increase in suspended particles and turbidity (suspended solid concentration in the water column).
- Reduction in the percentage of light passing through the water column and reaching the seabed Gacía et al, (1999). This reduction can affect benthic primary producers. Some scientific studies carried out with *Posidonia oceanica* seagrasses show that suspended solid concentrations higher than 20mg/l adversely affect their growth.
- Burial of benthic organisms by suspended solids sedimentation. These particles may be transported by ambient currents and therefore affect benthic organisms even far away from the dredging area.

Regarding **marine water intakes**, the main impacts include:

- The risk of saltwater intrusion into nearby fresh groundwater aquifers, in case of subsurface water intakes.
- Regarding, open seawater intakes, the main impacts include:
  - Needs for more concentration of chemical additives in the pre-treatment phase, due to lower quality of feedwater.
  - Negative impacts on habitats which are in the vicinity of the intake due to the extraction of large quantities of water.
  - Impingement: Pinning of larger organisms on screen mesh by the withdrawn water flow, causing physical damage (peeling) and disorientation, due to the extraction of huge seawater flows through the screens.

- Entrainment: Passage of smaller organisms (often passive life stages, but also small fishes) living in the vicinity of the intake, through the screen mesh (Hogan, 2008).

The impacts associated with brine discharges into seawaters are related to:

- Effects on Water Quality due to potentital chemical pollution, anoxia at the sea bottoms and turbidity because of the presence os hipersaline effluent.
- Impacts on plankton by causing a drop in osmotic pressure (breaking the osmotic equilibrium between plankton organisms and seawater) and hence causing negative effects in primary production.
- Impacts on fish fauna. These communities, thanks to their mobility can swim far away from the turbidity and emissions associated with the brine and cleaning water discharges. However, extinction of the larvae and younger individuals (Einav & Lokiec, 2003) has been detected near MSF brine discharges. In the case of discharges by high velocity jets, a significant alteration of local hydrodynamics in the environment can affect sensitive fish species, especially the smaller individuals, creating confusion and increasing their vulnerability to predators. To reduce this impact, a jet discharge velocity of 3 -3.5 m/s should not be exceeded.
- Effects on coral reefs, which are very sensitive to changes in environmental conditions (chemical pollution, hydrodynamic alterations, temperature, salinity, etc.), and thus, brine disposal may have significant negative effects.
- Impacs on seagrasses and algae due to turbidity of the brine presence, which affects seagrasses by reducing the percentage of light filtered through the water column that reaches the seabed, thus affecting seagrass photosynthesis (Gacía et al, 2007).
- Impacts on seagrasses due to the presence of the hypersaline brine effluent, depending on the sensitivity of the species. Studies on marine angiosperms have detected a low tolerance to salinity and temperature changes in the conditions of the receiving environment. As an example, in the Mediterranean Sea there are ecologically important angiosperms (Gacía et al, 2007), as is the case of *Posidonia oceanica*, *Cymodocea nodosa*, *Zostera noltii*, with high ecological value, which are stenohaline species, and hence sensitive to salinity variations.

At the moment, there are no regulations limiting the physical parameters and chemical concentrations of brine effluents resulting from desalination processes (Palomar & Losada, 2009). The lack of legislation and the vulnerability and ecological importance of marine ecosystems justify the diverse studies carried out over the last years regarding the impact of hypersaline discharges in the marine environment.

Table 1 shows salinity thresholds, established by different authors, for some of the main Mediterranean Sea ecosystems and species.

In order to minimize the impacts of brine discharges on water quality and marine ecosystems, the following prevention and **mitigation measures** are proposed:

- Brine disposal should be placed in non-protected areas or in areas under anthropic influence.
- The brine discharge system should be placed in areas of high turbulence (Hoepnet & Windelberg, 1996), where ambient currents and waves facilitate brine dilution into the receiving water body. Ambient conditions, including slope, water column stratification and bottom currents are essential in far field dilution. If the discharge zone is deeper than the area to be protected, the latter should not be affected, since brine flows down slope to the bottom.

ECOSYSTEMS / SPECIES	CRITICAL SALINITY LIMITS	SOURCE
Posidonia oceanica seagrasses	Should not exceed 38.5psu in more than 25% of measurements: $S_{25,lim}$=38.5 Should not exceed 40psu in more than 5% of measurements: $S_{25,lim}$=40	(Sánchez Lizaso et al, 2008)
Cymodocea nodosa seagrasses	Should not exceed 39.5psu in more than 25% of measurements: $S_{25,lim}$=39.5 Should not exceed 41psu in more than 5% of measurements: $S_{25,lim}$=41	Spanish Ministry of the Environment
Caulerpa prolifera algae	Threshold established around 50-60psu	(Terrados & Ros, 1992)
Zostera noltii seagrasses	Threshold established around 41psu	(Fernández &Sánchez, 2006)
Mussels	Threshold established around 50-70psu	(Iso et al, 1994)

Table 1. Suggested limits in saline concentration for different ecosystems and species present in the Mediterranean Sea. Salinity in "psu", practical salinity units.

- The brine discharge configuration should consider the particular characteristics of the discharge area and the degree of dilution necessary to guarantee compliance with environmental quality standards and the protection of marine ecosystems located in the area affected by the discharge.
- If there are any protected ecosystems along the seabed in the area surrounding the discharge zone, it is recommended to avoid direct surface brine discharge systems because the degree of dilution and mixing is very weak.
- To maximize brine dilution, multiport jet diffuser discharge systems are recommended.

The following sections are focused on brine discharge, as one of the most important environmental impacts of desalination plant projects. Descriptions of the behaviour of brine in the near and far field regions, disposal systems and experimental and numerical modelling are included.

2. Brine discharge into seawaters

2.1 Behaviour of the brine: near and far field regiones.

Two regions with a different effluent behaviour should be considered when studying the discharge of brine into receiving water body: the near and the far field regions.

The **Near field region** is located in the vicinity of the discharge point and is characterised by initial mixing, which mainly depends on the brine discharge configuration design and the effluent and ambient properties. Higher dilution rates are reached at the near field, due to the turbulence effects created by the shear layer because of the differences of velocity between the jet and the ambient body. Flow and mixing characteristics are dominated by small scales (~metres and ~minutes). Normally, the brine discharge system is designed to maximize dilution in the near field region.

The **Far field region** is located further away from the discharge point, where the brine turns into a gravity current that flows down the seabed. Mixing depends on the ambient

conditions (bathymetry, currents, waves, etc.) and the differences in density between the hypersaline plume and receiving waters. The water column appears stratified and the pycnocline difficults mixing between the hypersaline plume and seawater. The brine dilution ratio is very small in this region and tends to take an almost constant value. Flow and mixing characteristics are dominated by large scales (~kilometers and ~hours).

Figure 1 shows a diagram of the different behaviour areas of a brine jet discharge: ① jet ascending trajectory: the inclined jet is discharged with a certain velocity, so momentum (impulse) significantly influences its, ascending trajectory opposite to gravity force. At some distance from the discharge point, the buoyant force (weight) equals the momentum and the jet reaches its maximum height. From this point buoyancy is the dominant force and the jet descends ② to impact the bottom, where it undergoes an additional dilution due to turbulence phenomena and flow expansion. The region between the bottom impact zone and the far field region ③ is a transition zone, where flow behaves as a "spreading layer". In the far field region, brine behaves as a gravity current ④
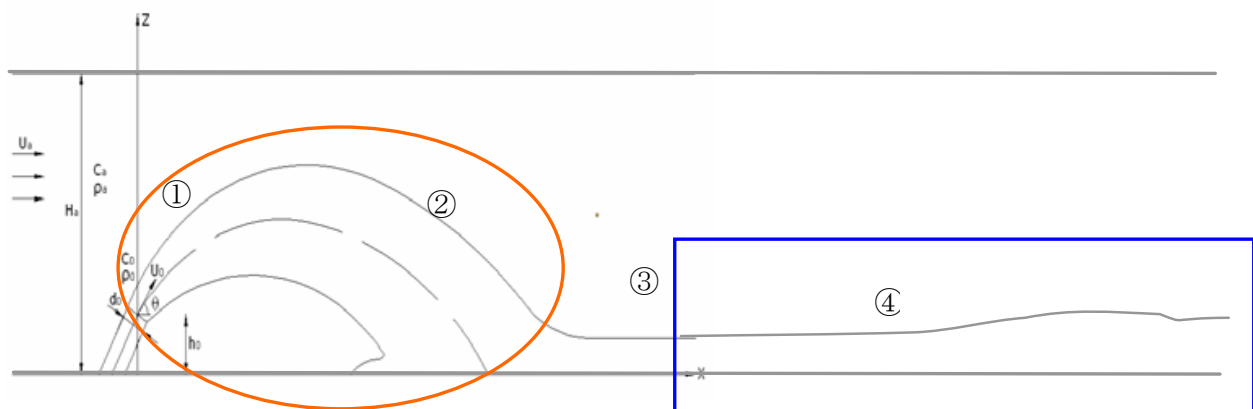

Fig. 1. Near and far field regions in a jet discharge, comparing brine and waste water effluents.

Figure 2 shows photographs of a brine single jet discharged from the SWRO Maspalomas desalination plant, located in Gran Canaria Island (Spain). Brine is coloured with rhodamine in order to study *ad hoc* the behaviour of the effluent discharged, in the near and far field regions. Pictures belong to the Instituto Canario del Agua, S.A. and area related to a Venturi research project (Portillo, 2009).

2.2 Brine discharge systems.

There are different management possibilities for the brine waste effluent generated in the desalination process:

- Discharge directly into the sea through some discharge configuration
- Discharge combined with other effluents (e.g., power plant cooling water or sewage treatment effluent).
- Dry out.

In most cases, especially in large desalination plants, the brine is discharged into seawater, because other alternatives are technically, socially, economically or environmentally not feasible.

There are different discharge configurations for brine discharges, the optimal one depending on the brine physical and chemical properties, the discharge location, the
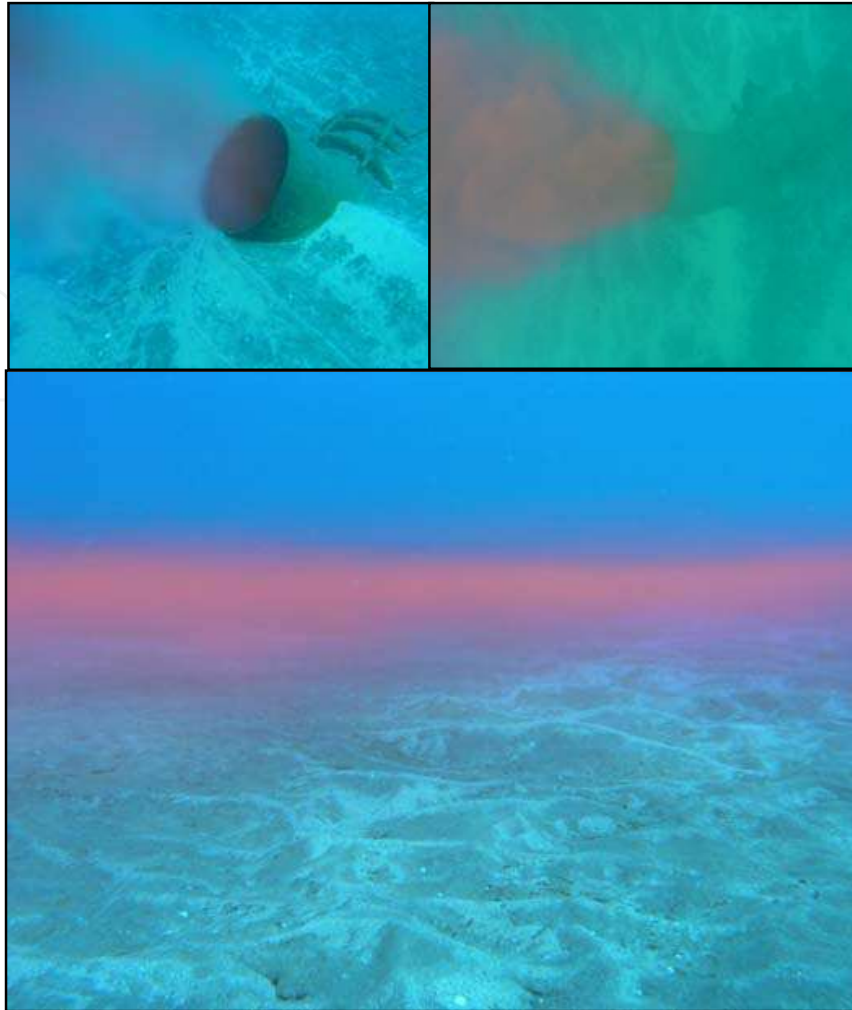
Fig. 2. Pictures from an ad hoc brine discharge dyed by rhodamine in Maspalomas beach. Near (upper panel) and Far field (lower panel) regions can be observed.

ambient conditions and the presence of stenohaline protected species that can be particularly vulnerable to brine. Among others, the most common discharge systems are: direct surface disposal through gravel beaches, through watercourses, etc., overflow spill in a cliff, submerged single or multiple jets by outfalls, and discharge on a breakwater.
Figure 3 shows pictures of some types of brine discharge configurations:
The design of the discharge system determines the degree of brine dilution in the near field region, where density differences (between brine and seawater) and momentum (depending on the discharge system) control the geometry and mixing processes of the brine effluent. This dilution influences the salinity of the gravity current in the far field region and, consequently increasing risk of impact on benthic communities located far away from the discharging point.
Faced with the expected increase in flow rate of brine discharged into the Mediterranean Sea and the negative impact on the marine environment, the Spanish Center of Studies and Experimentation of Publish Works (CEDEX) carried out an experimental investigation on scaled physical models to determine the most effective dilution brine discharge systems in the near field region. Several systems were tested (Ruiz Mateo, 2007). According to previous studies, CEDEX concluded that the system generating the greatest dilution is the submerged

Fig. 3. Photographs of brine discharge configurations located in Spain. .A) Dicharge trough a submerged outfall. B) Surfce discharge .C) Discharge trough multiple jets (CEDEX).

multiport diffuser outfall with an angle of discharge of approximately 65°. In contrast, physical model tests simulating a surface discharge directly on a watercourse flowing into the sea revealed that, except in the collapse zone, mixing and dilution are very weak. According to this, the brine effluent rapidly turns into a negatively buoyant plume with a very high salt concentration that flows down the seabed, as a gravity current, in the far field region. Surface discharge tests indicate a dilution degree of about 4 at the end of the near field under stagnant ambient conditions.

3. Brine discharge modelling.

3.1 Introduction

Water quality modelling can simulate the behaviour of brine discharges, thus it is an essential prediction tool in the environmental assessment of desalination projects.

Regarding the goal of polluted effluent discharge models: considering the properties of the brine effluent and the discharge configuration, the model predicts brine disposal evolution under ambient conditions in the receiving water body. Simulation leads to prediction of the performance of quality standards (EQS) in the receiving waters and to guarantee that critical salinity limits will not be exceeded.

There are two types of modelling techniques:

- Experimental modelling: scaled physical models.
- Numerical modelling.

The following sections describe the main characteristics of these techniques. We will focus especially on numerical modelling since it is less expensive and, if correctly calibrated, can be generalized and used on any type of discharge configuration or ambient scenarios.

3.2 Experimental physical modelling.

Experimental modelling consists in performing laboratory experiments using scale physical models, which are a copy of the real case being tested, i.e.: the prototype, but normally at a smaller scale. Experimental tests can be carried out on any effluent, discharge configuration and ambient conditions.

The model and the prototype maintain the relative proportions (the scale factor) and they are scaled in terms of both geometry and forces. In order to guarantee the correspondence between the model and the prototype behaviour, the following conditions must be achieved:

1. **Geometric similarity** exists between model and prototype if the ratio of all corresponding dimensions in the model and prototype are equal. Dimension scales are defined by the formulas: $n_L = \dfrac{L_{model}}{L_{prototype}} = \dfrac{L_m}{L_p}$ where n_L is the scale factor for length and $n_L^2 = \dfrac{A_{model}}{A_{prototype}} = \dfrac{L_m^2}{L_p^2}$. All corresponding angles are the same.

2. **Kinematic similarity** is the similarity of time and geometry. It exists between model and prototype if the paths of moving particles are geometrically similar and if the ratio of the particles velocities are similar. Scales include ratios of discharge, acceleration: $n_a = \dfrac{a_{model}}{a_{prototype}} = \dfrac{L_m / T_m^2}{L_p / T_p^2}$, velocity: $n_v = \dfrac{v_m}{v_p} = \dfrac{L_m / T_m}{L_p / T_p}$ and time: $n_t = \dfrac{t_m}{t_p}$, with the relations: $n_v = (n_L)^{0.5}$ y $n_v = (n_t)^{0.5}$

3. **Dynamic similarity** includes geometrically and kinematically similar systems, if the ratios of all forces in the model and prototype are the same. The force ratio: $\dfrac{F_m}{F_p} = \dfrac{M_m a_m}{M_p a_p} = \dfrac{\rho_m L_m^3}{\rho_p L_p^3} * \dfrac{n_L}{n_T^2}$.

The forces acting on the fluid are: inertial gravity, viscosity, surface tension, elasticity and pressure, with different scales. In order to achieve dynamic similarity, the most influential forces are identified and secondary forces are neglected. Deviations between the model and the prototype are called "scale effects." In the case of moving fluids, the inertial ones are the predominant forces. The relationship of inertial forces and others leads to dimensionless numbers. The ratio between inertia and viscous forces is defined by the dimensionless Reynolds number. If its value is sufficiently high, the viscous forces can be neglected, thus the brine effluent behaviour depends mainly on the Densimetric Froude number, which is defined as the ratio between the inertial and the gravity forces: $F_{rd} = \dfrac{u}{\sqrt{g\dfrac{\Delta\rho}{\rho}D}} = \dfrac{u}{\sqrt{g_o' D}}$,

being u:: velocity; D: diameter of the orifice and $g_o' = g\dfrac{\rho_o - \rho_A}{\rho_{ref}}$: reduced gravitational buoyancy acceleration. ρ_o, ρ_a: effluent and ambient fluid density.

Traditionally, measures taken in laboratory experiments have been done with conventional techniques such as video, photography, conductivity meters, peristaltic pumps, etc., in order to typify the main characteristics of the effluents being discharged. In experimental tests, brine is usually dyed with rhodamine to distinguish its presence easily and describe its behaviour qualitatively. Geometric and kinematic similarities are guaranteed by scaling

magnitudes in the model and the prototype, and dynamic similarity is considered to be achieved when the Densimetric Froude number remains the same. A high Reynolds number: Re> 1500 (Jirka, 2004) is required for the assumption of fully turbulent flow and neglected viscous forces.

Figure 4 shows photographs of physical model tests of a brine single jet discharge (Portillo, CEDEX). Rhodamine colouring makes it possible to observe the brine, which is denser than the receiving water and thus sinks to the bottom.
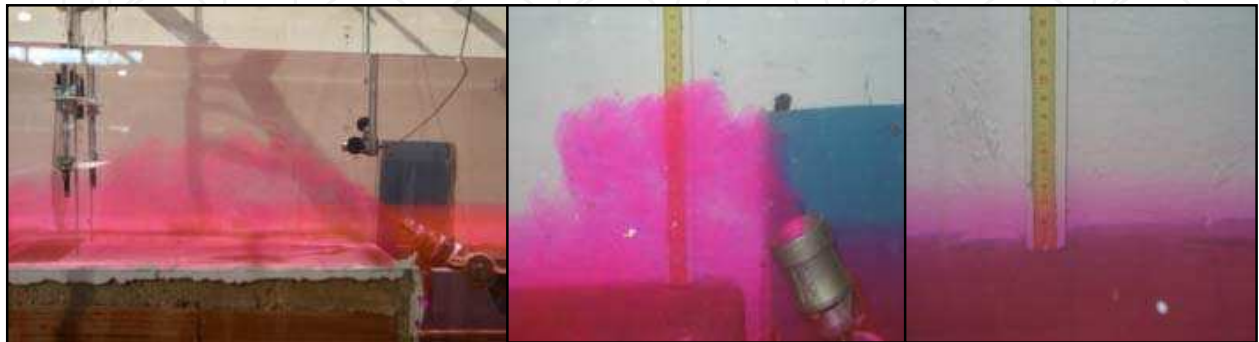

Fig. 4. Physical model test of a brine single jet discharge. Figure 4A shows the jet flow path in the near field region. Figure 4B) shows a detail of the jet orifice and flux exit. Figure 4.C) shows the brine hypersaline plume which is typical of the far field region.

Figure 5 shows a tank and precision conductivity meters to measure salinity at the bottom layer of the water column in the receiving body. Tank walls are white in order to correctly observe the rhodamine coloured brine.
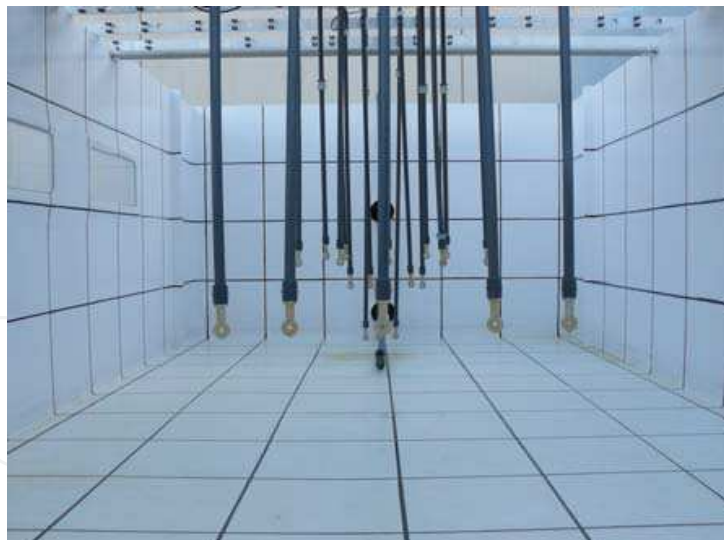

Fig. 5. Tank and gauges for brine discharge physical experiments.

Scaled physical models with conventional measurement techniques are generally used for a qualitative description of the effluent being discharged, and for determining the approximate geometry, dimensions and dilution degree of the effluent. Typically, quantitative measures are taken at control points (e.g. maximum rise height, impingement point distance and centerline dilution, in the case of jet discharges). Table 2 (Ruiz Mateo, 2007) shows, as an example, the approximate dilution rates obtained at the end of the near field region. Tests were carried out at the CEDEX Laboratory, in Spain.

APPROXIMATE VALUES OF DILUTION IN THE NEAR FIELD AREA Hypersaline effluent discharge		
BRINE DISCHARGE SYSTEM		DILUTION IN THE NEAR FIELD REGION
Discharge on gravel beaches		2,5
Discharge on mouth of channels flowing to seawaters		4
Discharge on a breakwater of a sheltered dock		6
Discharge by and horizontal submerged jet		10
Overflow spillway in a cliff discharge (influenced by the discharge height and depth available)		18
Discharge by single jet outfalls (Minimum dilution at the impact point)	Submerged 65º inclined jet, on the bottom.	30
	Submerged vertical jet, at surface level	8,7
	Submerged horizontal jet, at surface level.	10
	Above surface vertical jet	9
	Above surface horizontal jet.	23
Discharge by multiple jets diffuser outfalls	One orifices per diffuser	24
	Two orifices in opposite directions	30

Table 2. Estimated dilutions of the brine effluent in the near field region under different discharge configurations. Results obtained by scaled physical laboratory tests (Ruiz Mateo, 2007).

The experimental results obtained from conventional techniques are generally used to calibrate simple formulas based on dimensional analysis which describe the flux approximately. Some of the main dimensional analysis formulas for a single jet discharge characterization are (Pincince & List, 1973):

$$\frac{y_t}{DF} = C_1 ; \quad \frac{X_i}{DF} = C_2 ; \quad \frac{S_i}{F} = C_3$$

Being:

y_t : maximum rise height (maximum height of the top boundary or upper edge of the jet).

X_i : horizontal distance of the centerline peak at the impact (impingement) point

S_i : minimum centerline dilution at the impact point.

D: diameter of the orifice.

F: Densimetric Froude number.

$C_1, C_2. C_3$: experimental constants or coefficients obtained from laboratory physical scale models.

New and more sophisticated measuring techniques for laboratory experiments have been developed in the last years using advanced optical technology as Laser Induced Fluorescence (LIF) and Particle Image Velocimeter (PIV). With these techniques the concentration and velocity fields can be completely characterized. Results can also be used to calibrate and validate complex CFD (Computational Fluid Dynamics) numerical models. Table 3 shows the experimental coefficient values obtained by experimental research, focused on negatively buoyant jet discharges into stagnant environment:

NEGATIVELY BOUYANT SINGLE JET IN STAGNANT ENVIRONMENT.					
RESEARCH	α	Nº Froude	$\dfrac{y_t}{D}$	$\dfrac{x_i}{D}$	S_i
Zeitoun et al (1970) *Conventional techniques*	30º	25-60	1.04F	3.48	-
	45º	25-60	1.56F	3.33	-
	60º	25-60	2.13F	3.19	1.12F
Roberts et al, (1997) *Optical techniques*	60º	18-36	2.2F	2.4F	1.6F+/-12%
Cipollina et al (2009) *Convencional techniques*	30º	18-32	1.08	3.03	-
	45º	18-32	1.61	2.82	-
	60º	18-32	2.32	2.25	-
Kikkert et al (2007) (LA) *Optical techniques*	30º	27-50	1.07	3.18	1.51
	45º	27-50	1.71	3.332	1.71
	60º	27-50	2.2	2.79	1.81
Shao et al (2010) *Optical Techniques*	30º	18-36	1.05	3	1.45
	45º	18-36	1.47	2.83	1.26

Table 3. Experimental coefficients for dimensional analysis formulas for single port hyperdense jets (α : discharge angle).

3.3 Numerical modelling.

Water quality modelling is a mathematical representation of the physical and chemical mechanisms determining the development of pollutant concentrations discharged into the seawater receiving body. It involves the prediction of water pollution using mathematical simulation techniques and determines the position and momentum of pollutants in a water body taking into account ambient conditions.

Water quality modelling applied to brine discharges solves the hydrodynamics and transport equations adapted to a negatively buoyant effluent. The equations can be set up by a Lagrangian or Eulerian system. In the first case, the effluent brine is represented by a collection of particles moving in time and changing their properties. In the second case, the space is represented by a mesh of fixed points defined by their spatial coordinates, on which differential equations are solved.

Figure 6 shows the modelling scheme for designing brine discharges (Palomar et al, 2010).
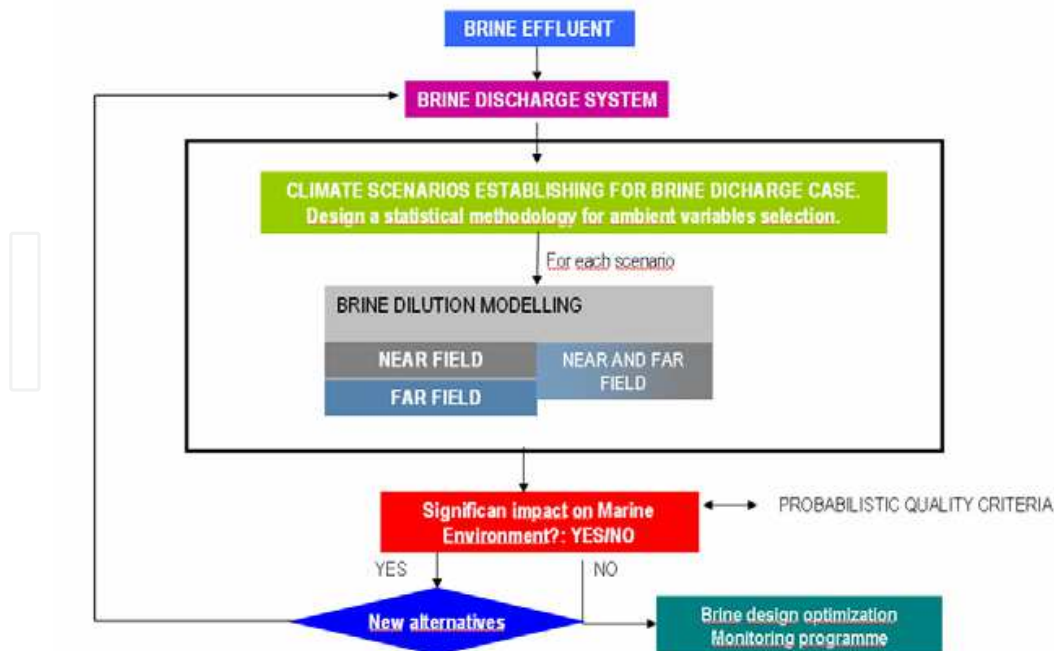
Fig. 6. Scheme of brine discharge modelling.

3.3.1 Symplifying assumptions within modelling.

Simplifying assumptions which are generally taken in the modelling of brine discharges are (Doneker & Jirka, 2001):

1. <u>Incompressible fluid</u> (pressure does not affect density of the fluid).
2. <u>Reynolds decomposition</u>: $f(t) = \overline{f}(t) + f'(t)$ the instantaneous value of a magnitude is the sum of a time-averaged component and a random (instant, turbulent) component.
3. <u>Boussinesq approximation</u>: density differences between effluent discharges and the water receiving environment are small and are important only in terms of the buoyancy force.
4. Turbulence closure model based on <u>Boussinesq turbulent viscosity theory</u>, $\rho \overline{u'_i u'_j} = \rho \mu_{ei} \dfrac{d\overline{U_i}}{dx_j}$. Turbulent terms are proportional to the average value of the magnitude, with an experimental proportionality coefficient (eddy viscosity). In recent years, more rigorous and sophisticated closure models, such as the k-ε model, are being applied.
5. Molecular diffusion is negligible compared to turbulent diffusion in the effluent.
6. There are no fluid sources or drain.

3.3.2 Governing equations.

Once the simplifying assumptions have been applied, the partial differential equations to be solved in brine discharge modelling are:

Equation of Continuity (Mass Conservation)

It is a statement of mass conservation. For a control volume that has a single inlet and a single outlet, the principle of mass conservation states that, for steady-state flow, the mass

flow rate into the volume must equal the mass flow rate out of it. It relates velocity and density of the fluid.

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \quad \text{Cartesian coordintes:} \quad \left(\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{v}}{\partial y} + \frac{\partial \overline{w}}{\partial z} \right) = 0$$

Equation of momentum conservation

The momentum equation is a statement of Newton's Second Law and relates the sum of the forces acting on a fluid element (incompressible) to its acceleration or momentum change rate: $\sum \overline{F} = \dfrac{d\overline{p}}{dt}$. Total force is the sum of surface forces (viscous stresses) acting by direct contact, and volume forces (inertial) acting without contact

$$\frac{D\overrightarrow{u_i}}{Dt} = -\frac{1}{\rho_o}\overrightarrow{\nabla} p - g\delta_{i3} + \mu_{ei}\nabla^2 \overrightarrow{u_i} \quad \text{Cartesian coordinates:}$$

$$\text{X Axis:} \rightarrow \rho_o \left(\frac{\partial \overline{u}}{\partial t} + \overline{u}\frac{\partial \overline{u}}{\partial x} + \overline{v}\frac{\partial \overline{u}}{\partial y} + \overline{w}\frac{\partial \overline{u}}{\partial z} \right) = -\frac{\partial p}{\partial x} + \mu_{ex} \left(\frac{\partial^2 \overline{u}}{\partial x^2} + \frac{\partial^2 \overline{u}}{\partial y^2} + \frac{\partial^2 \overline{u}}{\partial z^2} \right)$$

$$\text{Y Axis} \rightarrow \rho_o \left(\frac{\partial \overline{v}}{\partial t} + \overline{u}\frac{\partial \overline{v}}{\partial x} + \overline{v}\frac{\partial \overline{v}}{\partial y} + \overline{w}\frac{\partial \overline{v}}{\partial z} \right) = -\frac{\partial p}{\partial y} + \mu_{ey} \left(\frac{\partial^2 \overline{v}}{\partial x^2} + \frac{\partial^2 \overline{v}}{\partial y^2} + \frac{\partial^2 \overline{v}}{\partial z^2} \right)$$

$$\text{Z Axis} \rightarrow \rho_o \left(\frac{\partial \overline{w}}{\partial t} + \overline{u}\frac{\partial \overline{w}}{\partial x} + \overline{v}\frac{\partial \overline{w}}{\partial y} + \overline{w}\frac{\partial \overline{w}}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu_{ez} \left(\frac{\partial^2 \overline{w}}{\partial x^2} + \frac{\partial^2 \overline{w}}{\partial y^2} + \frac{\partial^2 \overline{w}}{\partial z^2} \right) - g\rho$$

Transport equation (Conservation of Solute mass)

For a control volume, changes in concentration (salinity) are due to: advective transport of fluid containing the substance, solute mass flow by diffusion, and destruction or incorporation of the substance in the fluid.

$$\text{Cartesian coordinates:} \quad \frac{\partial \overline{c}}{\partial t} + \overline{u}\frac{\partial \overline{c}}{\partial x} + \overline{v}\frac{\partial \overline{c}}{\partial y} + \overline{w}\frac{\partial \overline{c}}{\partial z} = \frac{\partial}{\partial x}\left(\varepsilon_x \frac{\partial \overline{c}}{\partial x} \right) + \frac{\partial}{\partial y}\left(\varepsilon_y \frac{\partial \overline{c}}{\partial y} \right) + \frac{\partial}{\partial z}\left(\varepsilon_z \frac{\partial \overline{c}}{\partial z} \right)$$

Equation of State.

For an incompressible fluid, relates temperature, salinity and density. Normally the empirical equation of the UNESCO is used. Salinity is expressed in "psu (practical salinity units) and is calculated through fluid conductivity:

$$\rho(T,S) = 999.842594 + 6.793952 \cdot 10^{-2}T - 9.09529 \cdot 10^{-3}T^2 + 1.001685 \cdot 10^{-4}T^3 - 1.120083 \cdot 10^{-6}T^4 +$$
$$+6.536332 \cdot 10^{-9}T^5 + (0.824493 - 4.0899 \cdot 10^{-3}T + 7.6438 \cdot 10^{-5}T^2 - 8.2467 \cdot 10^{-7}T^3 + 5.3875 \cdot 10^{-9}T^4)S +$$
$$+(-5.72466 \cdot 10^{-3} + 1.0227 \cdot 10^{-4}T - 1.6546 \cdot 10^{-6}T^2)S^{1.5} + 4.8314 \cdot 10^{-4}S^2$$

Variables in the equations are:

p : Fluid pressure at position (x, y, z).

(u, v, w) : Time averaged velocity components.

ρ : Effluent density at position (x,y,z).

μ_{ei} : Fluid dynamic viscosity of the fluid.

ν : Eddy viscosity

ε_i : Turbulent diffusion coefficient.

c : Pollutant concentration, in this case: salinity, at position (x,y,z).

U_o ; V_o ; Q_o ; ρ_o : velocity, volume, flow and density of the effluent at discharge.

U_A ; V_A ; Q_A ; ρ_A : velocity, volume, flow and density of the receiving seawater body.

D : diameter of the orifice.

$g_o' = g \dfrac{\rho_o - \rho_A}{\rho_{ref}}$: reduced gravitational buoyancy acceleration.

The variables "x" time averaged are expressed through an upper dash.

3.3 Model types according to mathematical approach.

There are three basic approaches for solving the equations according to the hypothesis and simplifications assumed, resulting in three types of physical and mathematical models to describe the behaviour of a discharge (Doneker &Jirka, 2001):

- Models based on a dimensional analysis of the phenomenon.
- Models based on integration of differential equations along the cross section of flow.
- Hydrodynamics models.

A) Models based on a dimensional analysis of the phenomenon.

The length scale models, derived from a dimensional analysis of the phenomenon, are the simplest models because they accept important simplifying assumptions.

Dimensional analysis is used to form reasonable hypotheses about complex physical situations that can be tested experimentally and to categorize types of physical quantities and units based on their relations to or dependence on other units, or their dimensions if any.

In dimensional analysis, variables with a higher influence in the phenomenon are considered, setting up the value of the ones with less influence, to reduce the independent variables under consideration. Selected independent variables are related through "flux" magnitudes, which represent the major forces determining effluent behaviour. For the discharging phenomenon, the main fluxes are:

- **Kinematic flux of mass**: $Q_0 = \dfrac{\pi}{4} D^2 U$. Dimension $\left[L^3 / T \right]$. Represents effluent flow discharged into the receiving environment.

- **Kinematic flux of momentum**: $M = UQ$. Dimension: $\left[L^4 / T^2 \right]$. It represents the energy transmitted during the discharge of the effluent.

- **Kinematic flux of buoyancy**: $J = g'Q$ in dimension $\left[L^4 / T^3 \right]$. Represents the effect of gravity on the effluent discharge.

Fluxes are combined with each other and with other parameters that influence discharge behaviour (ambient currents, density stratification, jet vertical angle, etc.) to generate length

scale magnitudes that characterise effluent behaviour. The value of the length scales depends, anyhow, on the role of the forces acting on the effluent and varies along the trajectory of the effluent. The main length scales for a round buoyant jet are (Roberts et al, 1997):

Flux-momentum length scale. $l_Q = \dfrac{Q}{M^{1/2}}$: a measure of the distance over which the volume flux of the entrained ambient fluid becomes approximately equal to the initial volume flux.

Momentum-Buoyancy length scale. $l_M = \dfrac{M^{3/4}}{J^{1/2}}$: a measure of the distance over which the buoyancy generated *momentum* is approximately equal to the initial volume flux.

Assuming full turbulent flow (thus neglecting viscous forces), any dependent variable will be a function of the fluxes: Q, M, J. The dependent variables of interest may be expressed in terms of length scales, with a proportionality coefficient, which is obtained from laboratory experiments.

$$y_t, X_i, S_i = f_1(Q, M, J) = f_2(l_Q, l_M)$$

Considering $l_Q \ll l_M$, assuming Boussinesq hypothesis for gravity terms and using the equivalent expression obtained by substituying the values of M and J in the l_M expression: $l_M = \left(\dfrac{\pi}{4}\right)^{1/4} \bullet DF$, the variables of interest will depend on the diameter orifice and the Densimetric Froude number:

$$\frac{y_t}{DF} = C_1 \,; \quad \frac{X_i}{DF} = C_2 \,; \quad \frac{S_i}{F} = C_3$$

Being:

y_t : maximum rise height (maximum height of the top boundary or upper edge of the jet).

X_i : horizontal distance of centerline peak at the impact (impingement) point

S_i : minimum centerline dilution at the impact point.

U: discharge velocity.

D: diameter of the orifice.

F: Densimetric Froude number.

$C_1, C_2. C_3$: experimental constants or coefficients obtained from laboratory physical scale models (for a stagnant environment, different discharge angles, etc.).

As already explained, the dimensional analysis derives from highly simplified formulas for the characterization of the flow because governing equations are reduced to semi-empirical expressions of length scales. Since this method does not solve rigorous equations of the phenomenon, its reliability would depend on the range and quality of the experimental tests performed.

Some examples of the length scale models for brine discharge modelling are those showed in section 3.2, with the experimental coefficients obtained by several authors and showed in Table 3. Dimensional analysis formulas are also those used for CORMIX1 (Doneker & Jirka,

2000), and CORMIX2 (Akar & Jirka, 1991) subsystems of the CORMIX software (Doneker & Jirka, 2001).

B) Models based on the integration of differential equations.

Governing equations of flow are in this case integrated over the cross section, transforming them into simple ordinary differential equations which are easily solved with numerical methods, as Runge Kutta formula. These integration models are mainly used for jets and gravity current modelling.

Integration of the equation requires assumption of an unlimited receiving water body and consequently boundary effects cannot be modelled. Because of this, even if these models give detailed descriptions of the jet effluent, results are valid only in the effluent trajectory prior to the impact of the jet on the bottom, and whenever the effluent does not previously reach the surface or impact with obstacles or lateral boundaries. Since the results of the integrated equation refer to magnitudes in the brine effluent axis, calculations of these values in cross-sections require assuming a distribution function, generally Gaussian, and experimentally determining the basic parameters. Effluent diffusion is controlled in these models through simple "entrainment" formulas with coefficients obtained experimentally.

Commercial models of this type are: CORJET (Jirka, 2004, 2006) of CORMIX software; JetLag of VISJET software (Lee & Cheung, 1990) and UM3 of VISUAL PLUMES (Frick, 2004), all of them available for negatively buoyant discharges.

Some of the advantages of integration models are (Palomar & Losada, 2008): equation solving and calibration are quite easy and need few input data for modelling. Among the disadvantages is the unlimited receiving water, which limits brine discharges modelling to the near field region.

C) Hydrodynamic models

Hydrodynamics three-dimensional models are the most general and rigorous models for effluent discharge simulation. They solve differential hydrodynamics and transport equations with complete partial derivates. These models require a great number of initial data but can consider more processes and variables such as: boundary effects, bathymetry, salinity/ temperature (density) water columns stratification, ambient currents at different depths, waves, tides, etc.

Among their advantages are: more rigorous and complex phenomena modelling, possibility of continuous simulation of the near and far field region, simulation of any discharge configuration and ambient conditions.

At present, these models are not completely developed and have some limitations such as: coupling between the near and far field regions, because of the different spatial and time scales; need of a large amount of initial data; difficulty in calibration of the model and long computational time.

Hydrodynamics three dimensional models are: COHERENS software (Luyten et al, 1999), DELFT3D], etc.

3.4 Commercial tools for brine discharge modelling.

Nowadays there are many commercial tools for discharge modelling and some of them are adapted to simulate negatively buoyant effluents, as that of brine. These tools solve the numerical equations with approaches such as those explained in the previous section, considering the most relevant processes and determining the geometry and saline concentration evolution of the effluent.

CORMIX, VISUAL PLUMES and VISJET are some of the most notable commercial software for brine discharge modelling. The models predict brine behaviour, including trajectory, dimensions and dilution degrees, considering the effluent properties (e.g., flow rate, temperature, salinity, etc.), the disposal configuration and the ambient conditions (e.g., local water depth, stratification, currents, etc.). Commercial models are often used by promoters to design the discharge and by environmental authorities to predict potential marine impacts. Figure 7 shows images and schemes of numerical results obtained by commercial software:
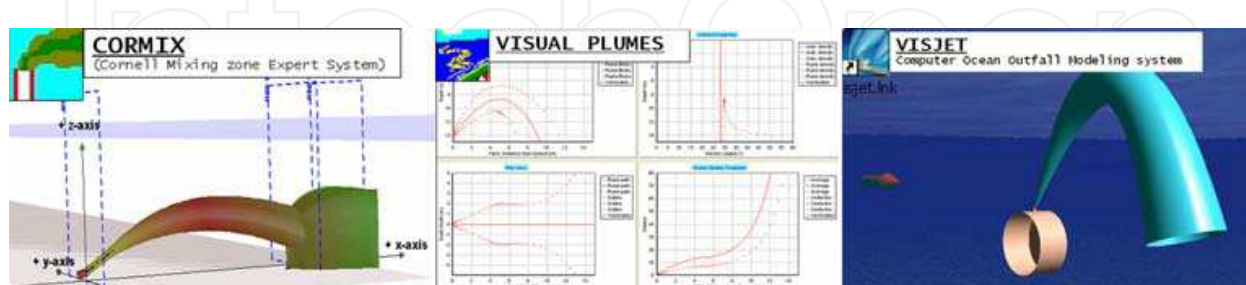
CORMIX, VISUAL PLUMES and VISJET include several models to simulate brine discharges through different types of discharge configuration. Table 4 shows the software models adapted to negatively buoyant effluents modelling:

CORMIX software	VISUAL PLUMES software	VISJET software
CORMIX 1: submerged and emerged single port jet. CORMIX 2: submerged multiport jets D-CORMIX: Direct surface discharge CORJET: submerged single and multi-port jets	UM3: submerged jets single and multi-port	JetLag; submerged jets single and multi-port
OTHER MODELS OF THE COMMERCIAL SOFTWARE		
CORMIX3: for positively buoyant effluents	DKHW, RSB: only positively buoyant effluents	

Table 4. Software models for brine discharge modelling.

3.4.1 CORMIX software.

CORMIX software (Cornell Mixing Zone Expert System) (Doneker & Jirka, 2001) was developed in the 1980s at Cornell University as a project subsidized by the Environmental Protection Agency (EPA). Since it was supported by EPA, it has become one of the most popular programs for discharge modelling.

CORMIX is defined as a Hydrodynamic Mixing Zone Model and Decision Support System for the analysis, prediction, and design of aqueous toxic or conventional pollutant discharges into diverse water bodies. It is an expert system, which also includes various subsystems for simulating the discharge phenomenon.

The subsystems: CORMIX 1, 2 and 3 are based on dimensional analyses of the phenomenon while the model CORJET is based on the integration of differential equations. CORMIX can simulate disposals of effluents with positive, negative and neutral buoyancy, under different types of discharge (single port and multiple port diffusers, emerged and submerged jets,

surface discharges, etc.) and ambient conditions (temperature/salinity, currents direction and intensity, etc.).

CORMIX is a steady state model, therefore time series data and statistical analyses cannot be considered.

CORMIX1: SUBMERGED SINGLE PORT DISCHARGES.

CORMIX1 (Doneker & Jirka, 1990) is the CORMIX subsystem applicable to single port discharges. Regarding negatively buoyant effluents, CORMIX1 can simulate submerged and emerged jets.

The model is based on a dimensional analysis of the phenomenon. The subsystem calculates flows, length scales and dimensionless relationships, and identifies and classifies the flow of study in one of the 35 flux classes included in its database. Once the flow has been classified, simplified semi-empirical formulas are applied in order to calculate the main features of the brine effluent behaviour.

CORMIX1 can make a roughly approximation of the brine effluent's behaviour in the near and the far field regions. CORMIX1 simulates the interaction of the flow with the contours and if no interaction is detected, it applies the model CORJET. CORMIX1 includes some terms to consider the COANDA attachment effect.

The main assumptions of CORMIX1 are:

- Since calculation formulas are mainly empirical, reliability depends on the quality and approach of the case study to the experiments used to calibrate the formulas.
- Unrealistically sharp transitions in the development of flow behaviour, for example: from the near to the far field region.
- "Black box" formula based on volume control for the characterization of some flux regions.
- Water body geometry restrictions: rectangular, horizontal and flat channel receiving water bodies. Limitations related to the port elevation with respect to the position of the pycnocline in a stratified water column.
- Unidirectional and steady ambient currents
- If flow impacts the surface, depending on water depth, CORMIX1 makes the simplification of flow homogenized in the water column, etc.

The initial data for CORMIX1 are: temperature, salinity or density of the effluent, pollutant concentration, jet discharge velocity or brine flow, diameter of the orifice, discharge angle, local water depth, port elevation, ambient salinity and temperature or ambient density, ambient current velocity and direction, among others.

One of the main limitations of CORMIX1 is the lack of validation studies for negatively buoyant effluents. Studies presented in the CORMIX1 manual only include the case of a vertical submerged jet discharged in a dynamic receiving water body, and the validation is restricted to trajectories, but not dilution rates. Other shortcoming is that in many cases the flux classification assumed by CORMIX1 does not match with the type of flow observed in the laboratory experiments. It is also important to be careful when using CORMIX1 since it is very sensitive to changes of input data and occasionally small changes in the data values lead to a misclassification of the flow in another flux class, resulting a completely different behaviour.

Some recommendations for using CORMIX1 in brine discharge modelling are: if a single jet with no interaction with the contours is to be designed, it is recommended to utilize the CORJET module instead of CORMIX1, or utilize both and compare the results to ensure that

the classification of the flow is correct and the results are consistent. Given the strong simplifying assumptions imposed and the lack of validation data, CORMIX1 should be avoided for simulations of single port brine discharges impacting the surface.

CORMIX 2: SUBMERGED MULTI-PORT DISCHARGES

CORMIX2 (Akar & JIrka, 1991) is the CORMIX subsystem applicable to submerged multiport discharges.

The model is based on a dimensional analysis of the phenomenon. The subsystem calculates flows, length scales and dimensionless relationships, and identifies and classifies the flow of study in one of the 31 flux classes included in its database. Once, the flow has been classified, simplified semi-empirical formulas are applied to characterize brine behaviour.

CORMIX2 can make a rough approximation of the brine effluent behaviour in the near and far field regions. CORMIX2 simulates the interaction of the flow with the contours and if no interaction is detected, it applies the model CORJET. CORMIX1 includes some terms to consider the COANDA attachment effect. One of the most important advantages of CORMIX2 is the possibility of modelling merging phenomena when contiguous jets interact. The main assumptions of CORMIX2 are:

- If CORMIX2 detects merging between contiguous jets, it assumes the hypothesis of a equivalent slot diffuser, in which the discharge from the diffuser of equally spaced ports is assumed to be the same as a line slot discharge with the same length, brine flow rate and momentum as the set of ports. This assumption makes the model to consider a two-dimensional flow, with a uniform distribution across the section.
- As CORMIX1: since the calculation formulas are mainly empirical, reliability depends on the quality and the approach of the case studies of the experiments used to calibrate the formulas. Unrealistically sharp transitions in the evolution of flow behaviour and simplified receiving water body and "Black box" formulas are applied.
- Although CORMIX2 supposedly simulates a large variety of diffuser multi-port configurations (unidirectional, staged, alternating diffusers; same direction and fanned out jets), important assumptions are made, all cases leading to two types: a unidirectional diffuser with perpendicular jets and a diffuser with vertical jets. This fact causes important errors in the case of negatively buoyant effluents.

CORMIX2 initial data are: temperature, salinity or density of effluent, pollutant concentration, jet discharge velocity or brine flow, discharge angle, diameter of the orifices, port elevation, diffuser length, port spacing, number of ports, local water depth, ambient salinity and temperature and current velocity and direction, among others. An important shortcoming of CORMIX2 is the assumption applied to bilateral or rosette discharges, in which CORMIX2 considers the jets merging in a unique vertical single jet. This assumption is roughly correct for positively buoyant effluents whereas it is not valid for negatively buoyant effluents, leading to completely wrong results. The equivalent slot diffuser hypothesis leads in some cases to unrealistic results.

The limitations are similar to those of CORMIX1 in relation to receiving water body geometry simplifications, lack of validation studies for hyperdense effluents, or sensitivity to initial data variations.

Some recommendations for using CORMIX2 in brine discharge modelling are: given the strong simplifying assumptions imposed and the lack of validation data, CORMIX2 subsystem should be avoided in the case of flux interacting with contours. Due to the invalid hypotheses assumed, CORMIX2 cannot be used with bidirectional and alternating

diffusers, rosettes and unidirectional diffuser with jets forming less than 60°. The typical diffuser configuration with bidirectional jets forming 180° should be modelled by CORMIX2 considering separately each diffuser side.

CORJET: CORNELL BUOYANT JET INTEGRAL MODEL

CORJET is a model of CORMIX applicable to submerged single port (Jirka, 2004) and multi port discharges (Jirka, 2006).

It is a three dimensional eulerian model based on the integration of the differential equations of motion and transport through the cross section, obtaining the evolution of the jet axis variables. The integration of the differential equations transforms them into an ordinary equation system, which is solved with a four order Runge Kutta numerical method. Integration requires assuming an unlimited receiving water body and sections self similarity. Regarding the variables distribution in the jet cross section, CORJET assumes Gaussian profiles since it has been experimentally observed in round jets.

Since the model assumes unlimited environment, it cannot simulate the interaction of the jet with the contours, thus the scope is limited to the near field zone, before the impingement of the jet with the bottom. The COANDA effect and intrusion are not modelled by CORJET. As CORMIX1 and CORMIX2, CORJET validation studies are very scarce and limited to the jet path with few dilution data (Jirka, 2008). Regarding the diffuser configuration, CORJET can only model unidirectional jets perpendicular to the diffuser direction, with the same diameter orifices, equal spaces, and with the same port elevation and discharge angle.

CORJET initial data are similar to those indicated for CORMIX1 and CORMIX2, with the advantage of a more detailed description of the flux, with the evolution of the variables of interest (axis trajectory (x,y,z), velocity, concentration, etc.)

For calculating the jet upper edge position it is recommended to add to the maximum height axis (zmax), the radius, calculated with the formulas $r = \sqrt{2}b$ or $r = 2b$, "b" being the radial distance in which the concentration is 50% and velocity amounts to 37% of axis concentration and velocity respectively. The $r = \sqrt{2}b$ value stands for the radial distance in which the concentration is 25% and velocity is 14% of that in the jet axis. The value $r = 2b$ stands for the radial distance in which the concentration is 6% and velocity is 2% of that in the jet axis. The user must verify that the jet does not impact the surface by calculating this addition.

Since CORJET cannot simulate COANDA effects it is recommended not to simulate jets with a discharge angle smaller than 30° and zero port height. Since it does not either model reintrusion phenomena, discharge angles larger than 70° should not be simulated with CORJET.

3.4.2 VISUAL PLUMES software.

VISUAL PLUMES (Frick, 2004) is a software developed by the Environment Protection Agency (EPA), which includes several models to simulate positively, negatively and neutrally buoyant effluents discharged into water receiving bodies.

VISUAL PLUMES considers the effluent properties, the discharge configuration and the ambient conditions (temperature, salinity and currents whose intensity and direction can be variable through the water column). It is limited to the near field region modelling and does not simulate the interaction of the flow with the contours. VISUAL PLUMES can consider time series data, simulating discharges under scenarios which change over time.

"UM3" MODEL (UPDATED MERGE 3D): SINGLE AND MULTI-PORT DIFFUSER.

UM3 is the only model of VISUAL PLUMES applicable to negatively buoyant effluents. It is a three dimensional lagrangian model which simulates the behaviour of submerged single or multi port jet discharges into stagnant or dynamic environments. It is based on the integration of motion and transport differential equations, and shows the evolution of the variables along the jet axis. As CORJET, UM3 also assumes an unlimited receiving water body and sections self similarity, but it considers a uniform ("top hat") distribution of the variables across the section.

UM3 includes the possibility of simulating a tide effect on the behaviour of the discharge. The water column can be separated into layers with different temperature and salinity values, and velocity or intensity of currents.

As a model based on the integration of differential equations, it cannot simulate COANDA effects, reintrusion phenomena or interaction of the flow with the contours, so its scope is limited to the point before jets impinge with the bottom. Regarding the diffuser configuration, UM3 can only model unidirectional jets perpendicular to the diffuser's direction, with the same diameter orifices, equal spaces, and with the same port elevation and discharge angle.

No validation data have been found in the literature for negatively buoyant effluents modelled with UM3.

Some recommendations are: the user must enter at least two levels (surface and depth) to run the model; UM3 does not break when the jet impacts the bottom so the user must be careful to reject results beyond this point. UM3 considers a uniform distribution of magnitudes in the cross section, thus if UM3 dilutions are compared with CORJET axis dilutions, the following formula must be applied: $D_{axis} = D_{Top-Hat} / 1.7$.

3.4.3 VISJET Software.

VISJET software (Innovative Modeling and Visualization Technology for Environmental Impact Assessment) has been developed by the University of Hong Kong.

JETLAG MODEL (LAGRANGIAN JET MODEL): SINGLE AND MULTI-PORT DIFFUSERS.

JetLag is a three dimensional lagrangian model which simulates single and multi-port submerged jet discharges. It can simulate positively, negatively and neutrally buoyant effluents, considering stagnant or dynamic water environments.

JetLag does not strictly resolve the mathematical governing equations, but makes an approximation of the physical processes, considering entrainment phenomena, in each slice in which the jet has been previously discretized. It assumes section self similarity and considers a uniform ("Top Hat") distribution of the variables in the cross section.

Among its possibilities, it can consider tidal effects on the effluent behaviour. Water column can be discretized into layers, with different temperature or salinity values, and ambient currents. JetLag allows different designs for each jet, i.e.: a different diameter in each orifice, different port elevations, angles of discharge, velocity, etc., in each jet. This fact is due to the fact that JetLag calculates each jet independently.

JetLag cannot simulate the COANDA effect, the intrusion phenomenon or the interaction of the flow with the contours. Because of this, JetLag is limited to the point before the jet impacts the bottom. An important shortcoming of Jetlag, which the users should take into

account, is that the model does not consider the merging between jets although it seems to do that. Thus, the choice of diffuser type is not relevant since JetLag always calculates each jet individually as a single port. JetLag cannot consider time series.

Some recommendations for using JETLAG in brine discharge modelling are: the user must enter at least two vertical levels in the discretization of the vertical column. Because Jetlag only simulates single individual jets and cannot calculate merging between jets, it should not be used for multi-port diffuser modelling. The user must calculate the upper edge of the jet and calculate if it impacts the surface (invalidating the model) since JetLag only fails when the axis impacts the surface. JetLag results can be directly compared with UM3 since both assume a uniform distribution.

3.5 Research related to brine discharge behaviour and modelling: State of art.

The first research related to brine discharge behaviour started in the 1940s in the United States, and increased radically during the 1960 and 1970 decades.

Regarding the description of the near field region, Turner, 1996, carried out a dimensional analysis of the phenomenon and established length scales for jet characterization, considering those variables with strongest influence. Some years later, Turner conducted physical (scale) laboratory tests to determine experimental coefficient values for the maximum rise height of a negatively buoyant vertical jet in stagnant waters. Other authors, such as Holly et al, 1972, followed this line, but extended the studies to other geometrical jet characteristics. Zeitoun et al, 1970, studied the influence of the discharge angle on jet behaviour for 30º, 45º, 60º and 90º angles, obtaining the highest dilution with 60º angles. Since then 60º has been established as the optimum angle for hyperdense jet discharges. Gaussian profiles along jet cross sections were also observed by Zeitoun. Pincince & List, 1973, based on Zeitoun´s results, studied the effect of dynamic environments in a 60º jet, concluding that they increase dilution. Chu, 1975, proposed a theoretical model. Fisher et al, 1979, described the three fluxes which are the base of dimensional analysis in relation to round buoyant jets. Roberts & Toms, 1987, studied the behaviour of vertical and 60º jets into stagnant and dynamic receiving environments. A significant quantity of laboratory tests were carried out obtaining experimental coefficients for dimensional analysis formulas. Roberts et al, 1997, developed new experiments using optical Laser Fluorescence induced (LIF) techniques for a more rigorous study of a 60º hyperdense jet, discharged on a stagnant environment.

Cipollina et al, 2005, developed a numerical model for hyperdense jets discharged into a stagnant environment, based on the integration of differential equations. Jirka, 2004, proposed a more complex eulerian three dimensional integration model for stagnant and dynamic environments. This same author (Jirka, 2006) extended his model to multiport discharges, considering the interaction or merging of jets. Jirka, 2008, introduced the effect of the bottom slope on jet behaviour. Cipollina et al, 2009, presented new experimental coefficients for dimensional analysis formulas.

During the last decade, several authors have performed experimental research using advanced optical techniques, as LIF and PIV, in order to acquire a better knowledge of jet velocity and concentration fields. Ferrari, 2008, studied 60º and 90º jets in stagnant and wavy environments. Chen et al, 2008, also considered the effect of waves on jets.

Kikkert & Davidson, 2007, proposed an analytical model for single jet modelling and calibrated it with experimental coefficients obtained from physical scale tests, using LIF and

LA techniques. Kikkert compared his results with those of other authors. Papanicolaou et al, 2008, reviewed the entrainment state of the art and proposed new values for negatively buoyant effluents. Gungor & Roberts, 2009, studied the behaviour of a vertical jet in a dynamic environment. Recently, Shao, 2010, carried out physical scale experiments with 30° and 60° jets, taking measurements with PIV and LIF optical techniques, and obtained experimental coefficients for dimensional analysis formulas. Plum, 2008, applied the commercial CFD software FLUENT for brine modelling, analysing different turbulence models.

Regarding the far field region, where brine forms a gravity current, the first important research was carried out by Ellison & Turner, 1959, who developed a two dimensional integration model with a simple entrainment formula. The authors experimentally proved that, at some distance from the discharge point, the plume takes a Richardson number constant value. Fietz & Wood, 1967, considered a three dimensional plume and analyzed the influence of the discharge. Alavian, 1986, proposed a three-dimensional integration model and distinguished between supercritical and subcritical behaviours. Garcia, 1996, presented an interesting two dimensional integration model based on the eddy viscosity formula for entrainment. Raithby et al, 1988, applied a more complex turbulence model in a three-dimensional hydrodynamic model, calibrating it with experimental results.

Regarding entrainment phenomena research, Turner, 1986, studied the mixing associated to turbulence movement and the effect of viscosity in effluent mixing and behaviour. Kaminski et al, 2005, experimentally and theoretically studied turbulent entrainment in jets with arbitrary buoyancy. Papanicolau et al, 2008, studied the entrainment phenomenon in negatively buoyant jets.

Alavian at al, 1992, expanded their study to a three-dimensional flow moving in a stratified environment. Tsihrintzis & Alavian, 1986, experimentally obtained an equation for calculating the plume width in a laminar regime. Christodoulou & Tzachou, 1979, simulated the behaviour of three-dimensional gravity currents in scaled tanks and obtained formulas for calculating the velocity, the width and the thickness of the gravity current. Cheong & Han, 1997, studied the influence of the bottom slope in plume behaviour. Bournet et al, 1999, applied different turbulence closure models, performing laboratory experiments and obtaining coefficients for dimensional analysis formulas.

Ross et al, 2001, presented a model based on integration equations to simulate a gravity current on a sloping bottom, and supported it with laboratory data, including geometry and dilution. Özgökmen & Chassignet, 2002, studied the behaviour of a plume, varying the parameters of interest and considering small-scale turbulence.

Bombardelli et al., 2004, studied three-dimensional gravity currents using CFDs (Computational Fluid Mechanics) models, capturing small-scale turbulent phenomena, and comparing the results obtained using different commercial software. Oliver et al, 2008, discussed the mixing of a hypersaline plume with ambient fluid using a closure model for turbulent terms. Joongcheol Paik et al, 2009, used a three dimensional RANS equations model to simulate a two-dimensional plume, comparing experimental data with numerical results using different turbulence closure models.

Dallimore et al, 2003. used an underflow model coupled to a three dimensional hydrodynamic model, comparing numerical results with field data. Martin & García, 2008, conducted an experimental research combining optical PIV/LIF measurements to study gravity currents. Recently, Hodges et al, 2010, modelled a real case of a brine discharge gravity current from a desalination plant in Texas (U.S).

3.6 Shortcomings and research line proposal.

The following paragraphs illustrate the main shortcomings detected in the different fields related with brine discharge modelling and the knowledge of impact on the marine environment, proposing some research lines.

As regards the **effects on the marine environment**, it is necessary to establish critical salinity limits, in statistical terms, for ecologically important species which are sensitive to hyper-salinity and are located in areas of frequent brine discharges. It is also important to carry out additional studies regarding the synergistic effects of different effluent discharges, as is the case of brine mixed with cooling water or seawater waste effluents.

Regarding **regulations,** a new legislation regulating brine discharges, which includes emission limit values and quality standards in the environment is still necessary. Regulation defining dimensions of the mixing zone would be also interesting.

Regarding **brine discharge systems,** some discharge configurations such as direct surface disposal, discharge on gravel beaches, on the mouth of channels flowing to seawaters, discharge on a breakwater sheltered dock or overflow spillway in a cliff discharge, among others, are in need of further investigations. Research must be focused on quantitative descriptions, including dilution rates and modelling.

As regards **methodologies,** new ones are needed for brine discharge systems design and marine impact assessment, that describe all the aspects that need to be taken into account.

Regarding **brine discharge modelling,** the following research is proposed to improve current knowledge on the matter (Palomar & Losada, 2010):

-    Methodology to describe the marine climate and selection of the ambient scenarios in statistical terms, including the most frequent and unfavourable conditions.
-    Further investigation of the entrainment phenomenon for negatively buoyant effluents.
-    Recalibration of numerical models with experimental coefficients obtained from experimental measurements carried out with the most rigorous and precise optical techniques developed in the last years.
-    To improve the knowledge of the gravity currents behaviour and to develop tools for three dimensional numerical modelling, considering the effect of bathymetry, waves, bottom currents, environment stratification, etc.
-    To study the possibility of coupling near and far field processes modelling.

To improve the knowledge in some of these areas, several investigation projects are being developed. One of the most important in the Mediterranean area is the project "Horizon 2020 initiative" which aims to eliminate pollution in the Mediterranean by the year 2020 by tackling the sources of pollution, including brine from desalination plants. In Spain, the following projects, financed by the Ministry of Environment, are being developed to improve brine discharge knowledge and methodologies:

-    **ASDECO project** (Automated control system for Desalination dilution), the objectives of which are: to design, develop and validate a prototype of the Automatic Control of Toxic Desalination; analyzing real-time ocean-meteorological data of the receiving environment and effluent data (all recorded by the system itself ASDECO), focusing on its application in brine discharge environmental monitoring plans.
-    **VENTURI project** (Portillo, 2010), , which aims to test the efficiency in the dilution degree of Venturi systems as compared to conventional broadcasters, for single port submerged jet discharges, while "ad hoc" studying the near and far field regions of a brine discharge in the Canary Islands (Atlantic Ocean).

- **MEDVSA project** (Palomar et al, 2010) which aims to develop a methodology in order to improve brine discharge system design to reduce the impacts of brine discharges on the marine environment. The objective is to make compatible the use of desalination as an important water resource in some Spanish coastal areas, with the protection of marine areas, while following Sustainable Development principles. Two important Spanish Research Centres: IH Cantabria and CEDEX are collaborating in the R&D project "MEDVSA" development. It includes the following tasks: experimental research (Scale physical models), numerical research for near and far field simulations (including commercial tool analysis, online MEDVSA tools, using CFDs for near field modelling and ROMS application for far field simulation, etc.); climate scenario research; numerical tool validation (field works and experimental tests); a methodological guide and dissemination and training. Regarding commercial tools analysis, CORMIX, VISUAL PLUMES and VISJET, focused on negatively buoyant effluents, have been analyzed in detail. As a result, Technical Specification Cards have been developed, including: theoretical basis, simplifying assumptions, modelling options, possibilities and limitations and recommendations for implementation and management. After having analyzed in detail the brine discharge commercial simulation tools and having reviewed the existing literature on the matter, different codes are being programmed in order to have freely accessible tools, with codes similar to those of the commercial software. These tools will be calibrated and validated with the results of new laboratory tests. Technical Specification Cards and MEDVSA online tools are available and can be downloaded from the Web Page of the MEDVSA project.

4. Recommendations on the design and modelling of brine discharges into the sea.

In order to improve design of brine discharge systems, the following paragraphs propose some recommendation for reducing marine environment impacts faced to these disposals (Palomar & Losada, 2010):

- Brine disposal should be placed in non-protected areas or in areas under anthropic influence.
- The brine discharge system should be placed in areas of high turbulence, where ambient currents and waves facilitate brine dilution into the receiving water body. Ambient conditions, including slope, water column stratification and bottom currents are essential in far field dilution. If the discharge zone is deeper than the area to be protected, the latter should not be affected, since brine flows down slope to the bottom.
- The brine discharge configuration should consider the particular characteristics of the discharge area and the degree of dilution necessary to guarantee compliance with environmental quality standards and the protection of marine ecosystems located in the area affected by the discharge.
- If there are any protected ecosystems along the seabed in the area surrounding the discharge zone, it is recommended to avoid direct surface brine discharge systems because the degree of dilution and mixing is very weak.
- To maximize brine dilution, jet discharge configurations, through outfall structures, are recommended to be installed. It can be a solution when there are ecologically important stenohaline species near the discharge area. The following requirements are recommended to optimize jet discharges:

- The densimetric Froude number at the discharge must always be higher than 1, even so the installation of valves is recommended.
- Jet discharge velocity should be maximized to increase mixing and dilution with seawater in the near field region. The optimum ratio between the diameter of the port and brine flow rate per port is set so that the effluent velocity at discharge is about 4 – 5 m/s.
- Nozzle diameters are recommended to be bigger than 20cm, to prevent their clogging due to biofouling.
- To maximize mixing and dilution with submerged outfall discharges, a jet discharge angle between 45° and 60° with respect to the seabed is advisable, under stagnant or co-flowing ambient conditions. In case of cross-flow, vertical jets (90°) reach higher dilution rates (Roberts et el, 1987)- Avoid angles exceeding 75° and below 30°.
- Diffusers (ports) should be located at a certain height (elevation) above the seabed, avoiding the brine jet interaction with the hypersaline spreading layer formed after the jet impacts the bottom. This port height can be set up between 0.5 and 1.5 m.
- The discharge zone is recommended to be deep enough to avoid the jet from impacting the surface under any ambient conditions.
- Avoid designs with several jets in a rosette.
- Riser spacing is recommended to be large enough to avoid merging between contiguous jets along the trajectory, because this interaction will reduce the dilution obtained in the near field region and also because the modelling tools to simulate this merging are less feasible.

- If it is necessary to build a submarine outfall, and it passes through interesting benthic ecosystems, a microtunnel to locate the pipeline should be constructed.
- As a prevention measure, modelling tools should be used for modelling discharge and brine behaviour into seawaters, under different ambient scenarios.
- An interesting alternative is to discharge brine into closed areas with a low water renovation rate, or areas receiving wastewater disposals. This mixture is favourable since it reduces chemicals concentration and anoxia in receiving waters.
- An environmental monitoring plan must be established, including the following controls: feedwater and brine flow variables, surroundings of the discharge zone, receiving seawater bodies and marine ecosystems under protection located in the area affected by the brine discharge.

Regarding **brine discharge modelling** (Palomar & Losada, 2010):
- Modelling data must be reliable and representative of the real brine and ambient conditions. Their collection should be carried out by direct measurements in the field. The most important data in the near field region are: 1) brine effluent properties: flow rate, temperature and salinity, or density, and 2) discharge system parameters. In the far field region, mixing is dominated by ambient conditions: bathymetry, density stratification in the water column, ambient currents on the bottom, etc.
- In the case of using CORMIX1 or CORMIX2 for brine discharge modelling, it must be taken into account that both are based on dimensional analysis and thus reliability depends on the quality of the laboratory experiments on which they are based, and on the degree of assimilation to the real case to be modelled. The scarcity of validation studies for negatively buoyant effluents in CORMIX1 and CORMIX2, is one of the main shortcomings of these commercial tools.

- For each simulation case, it is recommended to use different models and to compare the results to ensure that jet dimensions and dilution are being correctly modelled. It is also recommended to run the case under different scenarios, always within the range of realistic values of the ambient parameters.
- With respect to brine surface discharges, most of the commercial codes: RSB and PSD of VISUAL PLUMES or CORMIX 3 of CORMIX focus on positively buoyant discharges. D-CORMIX is designed for hyperdense effluent surface discharges but has not yet been sufficiently validated and therefore cannot be considered feasible at the moment.
- For far field region behaviour modelling, hydrodynamics three-dimensional or quasi-three dimensional models are recommended. At present, these models have errors linked to numerical solutions of differential equations, especially in the boundaries of large gradient areas, such as the pycnocline between brine and seawater in the far field region. These errors can be partially solved if enough small cells are used in the areas where large gradients may arise, but it significantly increases the modelling computation time.
- It is necessary to generate hindcast databases of ambient conditions in the coastal waters which are the receiving big volumes of brine discharges, considering those variables with a higher influence in brine behaviour. Analysis of this database by means of statistical and classification tools will allow establishing scenarios to be used in the assessment of brine discharge impact.

5. Conclusion

Desalination projects cause negative effects on the environment. Some of the most significant impacts are those associated with the construction of marine structures, energy consumption, seawater intake and brine disposal.

This chapter focuses on brine disposal impacts, describing the most important aspects related to brine behaviour and environmental assessment, especially from seawater desalination plants (SWRO). Brine is, in these cases, a hypersaline effluent which is denser than the seawater receiving body, and thus behaves as a negatively buoyant effluent, sinking to the bottom and affecting water quality and stenohaline benthic marine ecosystems.

The present chapter describes the main aspects related to brine disposal behaviour into the seawater, discharge configuration devices and experimental and numerical modelling. Since numerical modelling is currently and is expected to be in the future, a very important predictive tool for brine behaviour and marine impact studies, it is described in detail, including: simplifying assumptions, governing equations and model types according to mathematical approaches. The most used commercial software for brine discharge modelling: CORMIX, VISUAL PLUMES y VISJET are also analyzed including all modules applicable to hyperdense effluent disposal. New modelling tools, as MEDVSA online models, are also introduced.

The chapter reviews the state of the art related to negatively buoyant effluents, outlining the main research being carried out for both the near and far field regions. To overcome the shortcomings detected in the analysis, some research lines are proposed, related to important aspects such as: marine environment effects, regulation, disposal systems, numerical modelling, etc. Finally, some recommendations are proposed in order to improve the design of brine discharge systems in order to reduce impacts on the marine environment. These recommendations may be useful to promoters and environmental authorities.

6. References

Afgan, N.H; Al Gobaisi, D; Carvalho, M.G. & Cumo, M. (1998). Sustainable energy management. *Renewable and Sustainable Energy Review, vol 2*, pp. 235–286.

Akar, P.J. & Jirka, G.H. (1991). CORMIX2: An Expert System for Hydrodynamic Mixing Zone Analysis of Conventional and Toxic Submerged Multiport Diffuser Discharges, *U.S. Environmental Protection Agency (EPA), Office of Research and Development..*

Alavian, V. (1986). Behaviour of density current on an incline. *Journal of Hydraulic Engineering, vol 112*, No 1.

Alavian, V; Jirka, G.H; Denton, R.A; Jhonson, M.C; Stefan, G.C (1992). Density currents Entering lakes and reservoirs. *Journal of Hydraulic Engineering, vol 118*, No 11.

ASDECO project: Automated System for desalination dilution control: http://www.proyectoasdeco.com/

Bombardelli, F.A; Cantero, M.I; Buscaglia, G.C & García, M.H. (2004). Comparative study of convergence of CFD commercial codes when simulating dense underflows. Mecánica *computacional. Vol 23*, pp.1187 -1199.

Bournet, P.E; Dartus, D; Tassin.B & VinÇon-Leite.B. (1999). Numerical investigation of plunging density current. *Journal of Hydraulic Engineering. Vol. 125*, No. 6, pp. 584-594.

CEDEX: Spanish Center of Studies and Experimentation of Publish Works www.cedex.es

Chen, Y.P; Lia, C.W & Zhang, C.K. (2008). Numerical modelling o a Round Jet discharged into random waves. *Ocean Engineering, vol. 35*, pp.77-89.

Christodoulou, G.C & Tzachou, F.E, (1997). Experiments on 3-D Turbulent density currents. *4th Annual Int. Symp. on Stratified Flows, Grenoble, France.*

Chu, V.H. (1975). Turbulent dense plumes in a laminar crossflow. *Journal of Hydraulic research*, pp. 253-279.

Cipollina, A; Brucato, A; Grisafi, F; Nicosia, S. (2005). "Bench-Scale Investigation of Inclined Dense Jets". *Journal of Hydraulic Engineering, vol 131, n 11*, pp. 1017-1022.

Cipollina, A; Brucato,A & Micale, G. (2009). A mathematical tool for describing the behaviour of a dense effluent discharge. *Desalination and Water Treatment, vol 2,* pp. 295-309.

Dallimore, C.J, Hodges, B.R & Imberger, J. (2003). Coupled an underflow model to a three dimensional Hydrodinamic models. *Journal of Hydraulic Engineering, vol 129, nº10,* pp. 748-757

Delft Hydraulics Software. Delft Hydraulics part of Deltares. Available from: http://delftsoftware.wldelft.nl/.

Doneker, R.L. & Jirka, G.H. (1990). Expert System for Hydrodynamic Mixing Zone Analysis of Conventional and Toxic Submerged Single Port Discharges (CORMIX1). *Technical Report EPA 600-3-90-012. U.S. Environmental Protection Agency (EPA).*

Doneker, R.L & Jirka, G.H. (2001). CORMIX-GI systems for mixing zone analysis of brine wastewater disposal. Desalination *(ELSEVIER), vol 139*, pp. 263–274. www.cormix.info/.

Einav, R & Lokiec, F. (2003). Environmental aspects of a desalination plant in Ashkelon. Desalination (ELSEVIER), vol 156, pp. 79-85.

Ellison, T.H& Turner, J.S. (1959). Turbulent entraintment in stratified flows. *Journal of Fluids Mechanics, vol 6, part 3*, pp.423-448.

Environmental Hydraulics Institute "IH Cantabria" & Centre of Studies and Experimentation of Public Works (CEDEX). Project MEDVSA (A methodology for the design of brine discharges into the seawater), *funded by the National Programme for Experimental Development of the Spanish Ministry of the Environment and Rural and Marine Affairs (2008-2010). Available from:* www.mevsa.es. *Technical specification cards*

Environmental Hydraulics Institute: IH Cantabria. University of Cantabria, Spain. www.ihcantabria.com

Fernández Torquemada, Y & Sánchez Lisazo, J.L. (2006). Effects of salinity on growth and survival of Cymodocea *nodosa* (Ucria) *Aschernon* and *Zostera noltii Hornemann"*. *Biology Marine Mediterranean, vol 13 (4)*, pp 46-47.

Ferrari, S & Querzoli, G. (2004). Sea discharge of brine from desalination plants: a laboratory model of negatively buoyant jets. *MWWD 2004, 3th International Conference on Marine Waste Water Disposal and Marine Environment.* Ferrari, S;

Fietz, T.R & Wood, I. (1967). Three-dimensional density currents. *Journal of Hydraulics Division.* Proceedings of the American Society of Civil Engineers.

Frick, W.E. (2004). Visual Plumes mixing zone modelling software. *Environmental & Modelling Software (ELSEVIER),* vol 19, pp 645-654. http://www.epa.gov/ceampubl/swater/vplume/

Gacia, E.; Granata, T.C. & Duarte, C.M. (1999). An approach to measurements of particle flux and sediment retention within seagrass *Posidonia oceanica* meadows. *Aquatic Botany, vol 65*, pp. 255–268.

Gacia, E.; Invers, O.; Ballesteros, E.; Manzanera M. & Romero, J. (2007). The impact of the brine from a desalination plant on a shallow seagrass *(Posidonia oceanica)* meadow. *Estuarine, Coastal and Shelf Science, vol 72, Issue 4,* pp.579-590.

García, Marcelo. (1996). Environmental Hydrodynamics. Sante Fe, Argentina: Publications Center, Universidad Nacional del Litoral.

Gungor, E & Roberts, P.J. (2009). Experimental Studies on Vertical Dense Jets in a Flowing Current. *Journal of* Hydraulic *Enginnering, vol 135, No11*, pp.935-948.

Hauenstein, W & Dracos, TH. (1984). Investigation of plunging currents lacustres generated by inflows. *Journal of* Hydraulic *Research, vol 22*, No 3.

Hodges, B.R; Furnans, J.E & Kulis, P.S. (2010). Case study: A thin-layer gravity current with implications for desalination brine disposal. *Journal of Hydraulic Engineering (in press).*

Hogan, T. (2008). Impingement and Entrainment: Biological Efficacy of Intake Alternatives. *Desalination Intake Solutions Workshop Alden Research Laboratory.*

Holly, Forrest M., Jr., & Grace, John L., Jr. (1972). Model Study of Dense Jet in Flowing Fluid. *Journal of the Hydraulics* Division, *ASCE, vol. 98*, pp. 1921-1933.

Höpner, T & Windelberg, J. (1996). Elements of environmental impact studies on the coastal desalination plants. *Desalination (ELSEVIER), vol 108*, pp. 11-18.

Hópner, T. (1999). A procedure for environmental impact assessment (EIA) for seawater desalination plants. *Desalination (ELSEVIER), vol 124*, pp. 1-12.

Hyeong-Bin Cheong & Young-Ho Han (1997). Numerical Study of Two-Dimensional Gravity Currents on a Slope. *Journal of Oceanography, vol. 53*, pp. 179 - 192.

Iso, S; Suizu, S & Maejima, A. (1994). The Lethal Effect of Hypertonic Solutions and Avoidance of Marine Organisms in relation to discharged brine from a Desalination Plant. *Desalination (ELSEVIER), vol 97*, pp. 389-399.

Jirka, G-H. (2004). Integral model for turbulent buoyant jets in unbounded stratified flows. Part I: The single round jet. *Environmental Fluid Mechanics (ASCE), vol 4*, pp.1–56.

Jirka, G. H. (2006). Integral model for turbulent buoyant jets in unbounded stratified flows. Part II: Plane jet dynamics resulting from multiport diffuser jets. *Environmental Fluid Mechanics, vol. 6*, pp.43–100.

Jirka, G.H. (2008). Improved Discharge Configurations for Brine Effluents from Desalination Plants. *Journal of Hydraulic Enginnering,* vol 134, nº1, pp 116-120.

Joongcheol Paik, Eghbalzadeh, A; Sotiropoulos, F. (2009). Three-Dimensional Unsteady RANS Modeling of Discontinous Gravity Currents in rectangular Domains. *Journal of Hydraulic Engineering, vol 135*, n 6, pp. 505-521.

Kaminski, E; Tait, S & Carzzo, G. (2005). Turbulent entrainment in jets with arbitrary buoyancy. *Journal of Fluid Mechanics, vol. 526*, pp. 361-376.

Kikkert, G.A; Davidson, M.J; Nokes, R.I (2007). "Inclined Negatively Buoyant Discharges". *Journal of Hydraulic* engineering, *vol 133, pp.545 – 554.*

Lee, J.H.W. & Cheung, V. (1990). Generalized Lagrangian model for buoyant jets in current. *Journal of* Environmental *Engineering (ASCE), vol 116 (6)*, pp. 1085-1105.

Luyten P.J., Jones J.E., Proctor R., Tabor A., Tett P. & Wild-Allen K. (1999). COHERENS: A Coupled Hydrodynamical-Ecological Model for Regional and Shelf Seas: User Documentation. *MUMM Report, Management Unit of the Mathematical Models of the North Sea, 914.* www.mumm.ac.be/coherens/.

Martin, J.E; García, M.H. (2008). Combined PIV/LIF measurements of a steady density current front. *Exp Fluids, 46*, pp.265-276

Oliver, C.J; Davidson, M.J & Nokes, R.I. (2008). K-ε Predictions of the initial mixing of desalination discharges. Environmental *Fluid Mechanics, vol 8*: pp.617-625

Özgökmen, T.M. & E.P. Chassignet (2002). Dynamics of two-dimensional turbulent bottom gravity currents. Journal *of Physical Oceanography, vol 32/5*, pp.1460-1478.

Palomar, P & Losada, I.J. (2008). Desalinización de agua marina en España: aspectos a considerar en el diseño del sistema de vertido para protección del medio marino. *Public civil works Magazine (Revista de Obras Públicas). Nº 3486, pp. 37-52.*

Palomar, P & Losada, I.J. (2009). Desalination in Spain: Recent developments and Recommendations. *Desalination (ELSEVIER), vol 255*, pp. 97-106.

Palomar, P; Ruiz-Mateo, A; Losada, IJ; Lara, J L; Lloret, A; Castanedo, S; Álvarez, A; Méndez, F; Rodrigo, M; Camus, P; Vila, F; Lomónaco, P & Antequera, M. (2010). *"MEDVSA: a methodology for design of brine discharges into seawater" Desalination and Water Reuse, vol. 20/1*, pp. 21-25.

Palomar, P & Losada, I.J. (2010). "Desalination Impacts on the marine environment". *Book. The Marine Environment: ecology, management and conservation". Edit. NOVA Publishers.* Submitted.

Papanicolau, P, Papakonstantis, I.G; & Christodoulou, G.C.(2008). On the entrainment coefficients in negatively buoyant jets. *Journal of Fluid Mechanics, vol. 614,* pp. 447-470.

Pincice, A.B., & List, E.J. (1973). Disposal of brine into an estuary. *Journal Water Pollution, vol 45 (11),* pp. 2335-2344.

Plum, B.R. (2008). Modelling desalination plant outfalls. *Final Thesis Report. University of New South Wales at the Australia Defence Force Academy.*

Portillo, 2009. Instituto Tecnológico de Canarias. S.A. "Venturi Projects" , funded by the National Programme for Experimental Development of the Spanish Ministry of the Environment and Rural and Marine Affairs (2008-2010).

Querzoli, G. (2006) An experimental investigation of interaction between dense sea discharges and wave motion. *MWWD 2006, 4th International Conference on Marine Waste Water Disposal and Marine Environment.*

Raithby, G.D; Elliott, R.V; Hutchinson, B.R (1988). Prediction of three-dimensional thermal Discharge flows. *Journal of Hydraulic Division, ASCE 114(7),* 720–737

Roberts, P.J.W & Toms, G. (1987). Inclined dense jets in a flowing current. *Journal of Hydraulic Engineering, vol 113*, nº 3.

Roberts, P.J.; Ferrier, A & Daviero, G. (1997). Mixing in inclined dense jets. *Journal of Hydraulic Engineering (ASCE), vol. 123, No 8*, pp. 693-699.

Ross, A; Linden, F y Dalziel S.B. (2001). A study os three-dimensional gravity currents on a uniform slope. *Journal of Fluid Mechanics, vol 453*, pp.239-261.

Ruiz Mateo, A. (2007). Los vertidos al mar de las plantas desaladoras" (Brine discharges into seawaters). *AMBIENTA magazine, vol .51*, pp. 51-57.

Sánchez-Lizaso, J.L.; Romero, J.; Ruiz, J.; Gacia, E.; Buceta, J.L.; Invers, O.; Fernández Torquemada, Y.; Mas, J.; Ruiz-Mateo, A. & Manzanera, M. (2008). Salinity tolerance of the Mediterranean seagrass *Posidonia oceanica*: recommendations to minimize the impact of brine discharges from desalination plants. *Desalination (ELSEVIER), vol 221*, pp. 602-607.

Shao, D & Wing-Keung Lao. (2010). "Mixing and boundary interactions of 30º and 45º inclined dense jets". *Environmental Fluid Mechanics, vol 10, nº5*, pp. 521-553.

Terrados, J & Ros, J.D. (1992). Growth and primary production of *Cymodocea nodosa* (Ucria) Ascherson in a Mediterranean coastal lagoon: the Mar Menor (SE Spain). *Aquatic Botany, vol 43*, pp 63-74.

Tsihrintzis, V.A. and Alavian, V. (1986). Mathematical modeling of boundary attached gravity plumes. *Proceedings Intern. Symposium on Buoyant Flows, G. Noutsopoulos (ed), Athens, Greece,* pp.289-300.

Turner, J.S. (1966). Jets and plumes with negative or reversing buoyancy. *Journal of Fluid Mechanics,* vol. 26, pp 779-792.

Turner, J.S (1986). Turbulent entraintment: the development of the entraintment assumption, and its application to geophysical flows. *Journal of Fluid Mechanics, vol 173,* pp.431-471

VISJET: Innovative Modeling and Visualization Technology for Environmental Impact Assessment. http://www.aoe-water.hku.hk/visjet/visjet.htm

Zeitoun, M.A & McIlhenny, W.F. (1970). Conceptual designs of outfall systems for desalination plants. *Research and Development Progress Rept. No 550. Office of Saline Water, U.S. Dept, of Interior.*

Desalination, Trends and Technologies

Edited by Michael Schorr

The book comprises 14 chapters covering all the issues related to water desalination. These chapters emphasize the relationship between problems encountered with the use of feed water, the processes developed to address them, the operation of the required plants and solutions actually implemented. This compendium will assist designers, engineers and investigators to select the process and plant configuration that are most appropriate for the particular feed water to be used, for the geographic region considered, as well as for the characteristics required of the treated water produced. This survey offers a comprehensive, hierarchical and logical assessment of the entire desalination industry. It starts with the worldwide scarcity of water and energy, continues with the thermal - and membrane-based processes and, finally, presents the design and operation of large and small desalination plants. As such, it covers all the scientific, technological and economical aspects of this critical industry, not disregarding its environmental and social points of view. One of InTech's books has received widespread praise across a number of key publications. Desalination, Trends and Technologies (Ed. Schorr, M. 2011) has been reviewed in Corrosion Engineering, Science & Technology – the official magazine for the Institute of Materials, Minerals & Mining, and Taylor & Francis's Desalination Publications. Praised for its "multi-faceted content [which] contributes to enrich it," and described as "an essential companion...[that] enables the reader to gain a deeper understanding of the desalination industry," this book is testament to the quality improvements we have been striving towards over the last twelve months.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

INTECH
open science | open minds

Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

Phone: +86-21-62489820
Fax: +86-21-62489821