Ain Shams Engineering Journal 16 (2025) 103225

Contents lists available at ScienceDirect

Ain Shams Engineering Journal

journal homepage: www.sciencedirect.com

Full Length Article

Improvements in the design of brine diffusers in shallow waters: A numerical study applied to the Canary Islands

Adrián Gil Trujillo *, J. Jaime Sadhwani Alonso

Department of Process Engineering, University of Las Palmas de Gran Canaria (ULPGC), Campus 3 de Tafira, 35017 Las Palmas, Spain

ARTICLE INFO

Keywords:
Reverse osmosis desalination
Brine disposal
Outfall design
Outfall diffuser optimisation

ABSTRACT

The desalination of seawater is a critical process for ensuring a dependable source of potable water, particularly in arid regions such as the Canary Islands. However, the disposal of brine presents considerable environmental and economic challenges. This study presents a comprehensive numerical analysis of brine diffuser design in shallow waters, with a particular focus on desalination plants in the Canary Islands. The Brine-Jet model is employed in order to evaluate the effects of key design variables, including nozzle height, discharge velocity and inclination angle, under a variety of velocity scenarios. This study presents a comprehensive analysis that, for the first time, identifies the critical importance of high nozzle height as a variable, particularly in low discharge rate scenarios. The findings of this study illustrate that even in shallow waters, elevated diffusers can confer significant benefits. Furthermore, a graphical design tool was developed to facilitate the clear visualisation of optimal diffuser configurations based on critical parameters such as dilution and plume height. The tool provides practical guidelines for improving diffuser designs, thereby ensuring more effective mitigation of the environmental impacts of brine discharge in coastal areas. Furthermore, the results emphasise the necessity for adaptable infrastructure to accommodate seasonal variations in water demand and increasingly stringent environmental regulations. This research offers a solution for optimising brine disposal, thus contributing to the development of sustainable and efficient desalination outfalls in similar marine environments.

1. Introduction

Global demand for freshwater is increasing significantly due to rapid industrial development, population growth, agriculture, and power generation. By 2050, annual water consumption is estimated to reach between 5,500 km^3 and 6,000 km^3, representing a 20 %–30 % increase from current levels [1]. This growing demand is driven by a number of factors, underscoring the necessity for enhanced water security in the context of climate change. The latter is responsible for an increase in both the intensity and duration of droughts, as well as an elevated risk of flooding affecting surface waters [2], in addition to alterations in the patterns of natural phenomena [3]. The Canary Islands, for instance, illustrate the climate vulnerability of isolated regions. The islands have recently encountered difficulties in maintaining water security due to their semi-arid climate, population growth, and rapid development, particularly in the tourism sector [4]. In response to this necessity, an urgent desalination plan is being implemented throughout the archipelago with the objective of ensuring water sovereignty. Consequently, desalination is presented as a promising solution to address the growing disparity between water availability and demand, thereby enhancing resilience and playing a pivotal role in addressing water scarcity [5].

Among the various desalination technologies, reverse osmosis (RO) is the most widely used. Due to its efficiency and scalability, RO has become the dominant method for desalination worldwide [6]. The process involves forcing seawater through a semipermeable membrane that removes salt and other impurities, producing freshwater. However, the desalination process generates a highly saline by-product known as brine, which poses a potential threat to marine ecosystems sensitive to increased salinity [7]. Benthic species, which are of high environmental value, are particularly vulnerable to brine discharges due to their sensitivity to salinity variations [8,9]. These species, such as *Posidonia oceanica* in the Mediterranean and *Caulerpa caulerpala* or *Cimodosea nodosa* in the Canary Islands [10], inhabit the seabed and are considered bioindicators of anthropogenic stress [11]. Poor management or design of brine discharge can result in serious negative impacts on marine life, making it a major concern for the desalination industry. The degradation of marine ecosystems is a consequence of anthropogenic pollution, underscoring the urgency of developing efficacious solutions [12].

* Corresponding author.
E-mail address: adrian.gil104@alu.ulpgc.es (A. Gil Trujillo).

https://doi.org/10.1016/j.asej.2024.103225
Received 10 July 2024; Received in revised form 4 December 2024; Accepted 6 December 2024
Available online 17 December 2024

At the present time, a number of strategies are being utilised with a view to the effective management of brine discharge and the reduction of its environmental impact. One common approach is to reduce the salt concentration before discharge by blending the brine with other effluents, a process known as pre-dilution. While effective, this method often requires additional infrastructure and can increase the intake flow rate, thereby raising energy consumption and operational costs [13], such as pumping costs [14]. Another strategy is to maximize dilution at the discharge point using underwater diffusers, which disperse the brine over a larger area, reducing its environmental impact. Although this method is generally more energy-efficient, its effectiveness depends on the design of the diffusers and the local hydrodynamic conditions [15]. Despite these challenges, diffusers are widely regarded as one of the most practical solutions for managing brine discharges, as they help protect marine ecosystems from the potentially harmful effects of elevated salinity [22]. The trend in modern brine management is to use submarine outfalls equipped with inclined diffusers, which do not rely on mixing with other effluents and instead focus on optimizing the dispersion and dilution of the brine in the receiving water [16]. The primary function of these diffusers is to ensure that the brine meets environmental standards for salinity concentration as it disperses [17].

The discharge of brine through submarine outfalls equipped with diffusers exhibits a distinctive behavior, particularly in seawater desalination plants using reverse osmosis (SWRO). Due to the higher density of brine compared to seawater, the brine jet follows a parabolic trajectory as it descends toward the seabed, where it spreads laterally and undergoes progressive dilution. The resulting brine plume can be divided into two distinct zones: the near-field and the far-field (Fig. 1) [18]. The near-field is the initial section where inertial and gravitational forces dominate. The jet reaches its highest point (Z_{max}) when these forces balance, with dilution effectiveness (S_i) in this area largely depending on diffuser design variables, such as nozzle height (h_o), inclination angle (α), and initial jet velocity (v_o). Following the jet's impact on the seafloor, it advances and dilutes further in the far-field, where external factors like sea current velocity, bathymetry, and density gradient play a more significant role [19]. It is therefore imperative to ensure the efficacy of underwater diffusers in the near field in order to preclude the necessity for reliance on sea currents for brine dilution. To effectively prevent and minimize the environmental impact of brine discharges, the proper design of underwater diffusers, along with the implementation of adequate monitoring and control measures, is essential [20 21].

In recent years, there has been a notable focus on the configuration of jets and the mixing process through submerged diffusers. This field of study has gained increasing significance due to its implications for sustainability and environmental protection. A number of studies have examined the impact of external factors on dilution, including the location of the discharge point, the intensity and direction of sea currents, and bathymetry. The strategic placement of the discharge point is of critical importance in the design of submarine outfalls. The high levels of hydrodynamic activity in the receiving environment have been demonstrated to significantly enhance natural mixing processes, thereby improving the dilution efficiency of diffusers. Nevertheless, in conditions of relative calm where external hydrodynamic factors are less significant, the efficiency of the dilution process is contingent upon the design of the diffuser and the operational parameters of the desalination plant. This underscores the necessity for a meticulous approach to diffuser design, with the objective of ensuring that environmental standards are consistently met.

Early studies on the optimization of diffuser design variables primarily focused on determining the optimal discharge angle. One of the foundational investigations in this area concluded that a discharge nozzle inclined at an angle of 60° relative to the seabed provided the most effective dilution results [27]. Subsequent research has expanded this discussion by employing various analytical techniques, including laboratory experiments [28] and advanced numerical models using Computational Fluid Dynamics (CFD) [29]. While these studies concentrated on identifying the angle that maximizes dilution, Jirka introduced the concept that smaller angles, ranging from 30° to 45°, may offer significant design advantages [30]. These advantages include the potential to position diffusers closer to shore in shallower waters, which is particularly beneficial when the available draft at the outfall site is limited. Placing the outfall in shallower water can reduce both construction and maintenance costs, as well as decrease the risk of pipeline failures. Furthermore, this approach can lower pumping costs depending on the specific requirements of the desalination plant. An optimal design aims to balance and minimize both capital and operational expenses.

Another important aspect of diffuser design, which has been relatively underexplored in previous studies, is the height of the nozzle relative to the seabed. Research has typically focused on establishing minimum heights, revealing that a combination of reduced discharge angles and low nozzle heights can adversely impact dilution efficiency. It is generally recommended to position the nozzle at a height between 0.5 and 1.5 m above the seabed to avoid sedimentation issues caused by variations in seabed sand levels and to prevent the intrusion of the spreading layer formed after the jet impacts the bottom [31]. Bleninger et al. further explored the relationship between nozzle inclination and seabed slope, suggesting that it is advantageous to reduce the discharge angle in regions with steep bathymetry. This is because a steep slope can

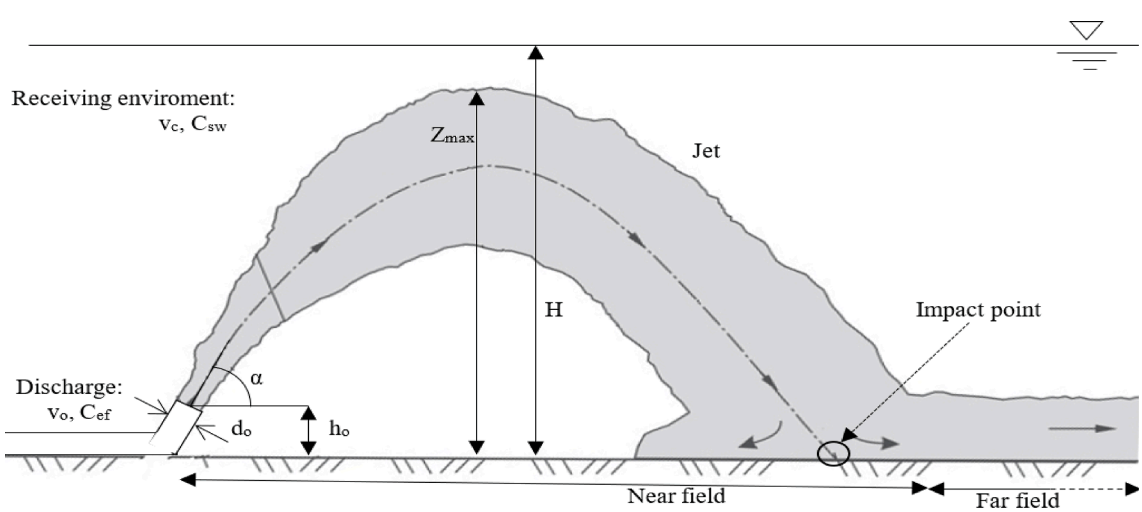

Fig. 1. Schematic representation of a hypersaline discharge.

mimic the effect of increasing the nozzle height, thereby enhancing dilution.

Additionally, the velocity of the jet plays an essential role in brine dilution, with its value contingent upon the diameter of the nozzle and the discharge flow rate. Low-velocity discharges have been shown to result in ineffective dilution [23] while excessive velocities can harm eggs, larvae, or small juvenile fish due to turbulence and shear forces [24]. However, further studies are needed to investigate the impacts of turbulence from high-velocity diffusers on vulnerable species [25]. The minimum recommended velocity value for effective dilution is that which corresponds to a densimetric Froude number of the outlet port not less than 10 [26]. With regard to the upper limits, there is a paucity of available data. For purposes of reference, the optimal Froude number values recommended by Turkish water quality regulations fall within the range of 20–25.

In summary, previous studies have shown that increasing the design variables of nozzle height, angle of inclination and jet velocity improves the dilution of the effluent. However, all of these solutions increase the maximum height of the discharge plume, which determines the draft level of the outfall design. If the discharge areas were located in areas of lower draught with shorter outfalls, this would mean savings in construction and maintenance costs [32]. The aim of this paper is to determine the dominance of the design variables of a brine diffuser. To this end, a simulation analysis was carried out for different brine diffuser configurations for the case study of reverse osmosis desalination plants in the Canary Islands. This work presents novel results that provide specific design recommendations for diffusers in shallow areas.

2. Methodology

2.1. Methodological approach

In this study, several diffuser design configurations were simulated to determine the optimal design of a shallow water brine diffuser. Following the simulations, the results obtained for maximum jet height and dilution at the point of impact were analysed to evaluate the effectiveness of the designs. The methodology employed begins with the definition of scenarios, with the Canary Islands region selected as a case study. In this context, the characteristics of the receiving environment, the properties of the brine effluent and the characteristics of the diffuser are defined. These scenarios have been designed to replicate the operational conditions of a representative desalination plant in the region, thus allowing a comprehensive evaluation of potential outfall configurations.

In order to simulate the behaviour of brine outfalls, the Brine-Jet model, an advanced tool which facilitates the analysis of effluent dispersion in aquatic environments, has been employed. This model has been employed to investigate the impact of different diffuser configurations, when operated under a range of conditions, on the efficiency of dilution and the height of the brine plume.

Following the completion of the simulations, the resulting data were subjected to processing in order to extract the dilution values at the point of impact and the maximum height reached by the plume. The results were then plotted graphically, thus facilitating a clear visualisation of the differences between the various configurations. Furthermore, the corresponding dilution and plume height gradients were calculated for each scenario and presented in tabular form for the purpose of facilitating comparison and quantitative analysis.

Subsequently, a comprehensive examination of the results was conducted, encompassing both qualitative and quantitative aspects, with the objective of identifying the most effective configurations for the design of shallow water outfalls. This analysis enabled the identification of scenarios in which optimising the dilution angle or increasing the height of the diffuser nozzle is most advantageous. The conclusions obtained provide a basis for specific recommendations to optimise the design of these outfalls, thus contributing to the sustainability and efficiency of desalination operations in similar regions. (Fig. 2).

2.2. Scenario definition

2.2.1. Receiving environment conditions

In this study, we have considered a receiving environment at rest, characterised by a current velocity (v_c) of 0.01 m/s and a flat bathymetry. These conditions represent the most unfavourable scenario for the dilution process. In consideration of the thermal stability and saline concentration of the waters in the Canary Islands, the annual mean value of temperature and saline concentration has been selected as the most appropriate for the purposes of this study. The water density has been calculated using the equation of state for seawater, which depends directly on the aforementioned mean values.

This configuration permits the evaluation of the influence of the structural variables of the outfall and the desalination plant, without the interference of external environmental conditions on the results. By isolating these factors, it is possible to ascertain that the observed changes in dilution are attributable only to modifications in the design variables of the diffuser and discharge system. This provides a clear and accurate assessment of the performance of each configuration.

2.2.2. Characteristics of the effluent

The brine or effluent discharged from reverse osmosis desalination plants is characterised by its salinity. Its concentration is determined using [Eq. (1)], knowing the inlet water concentration, which is equivalent to seawater (C_{sw}), and the efficiency (η) of the desalination plant.

$$C_{ef} = \frac{C_{sw}}{(1-\eta)} \tag{1}$$

In addition, the temperature of the brine discharged from a reverse osmosis plant is the same as that of the receiving medium. This minimises thermal differences that could otherwise affect the behaviour of the brine column in the aquatic environment. The density of the effluent is calculated in a manner analogous to that of the receiving medium, using the seawater equation of state. This approach ensures that the characterisation of the effluent is consistent with the prevailing environmental conditions, thus providing an accurate basis for assessing its dispersion and dilution in the marine environment.

2.2.3. Diffuser characteristics

The design variables of a diffuser include the inclination angle, the height above the seabed and the diameter of the diffuser nozzle. In the present study, the selected inclination angles ranged from 15 to 60 de-

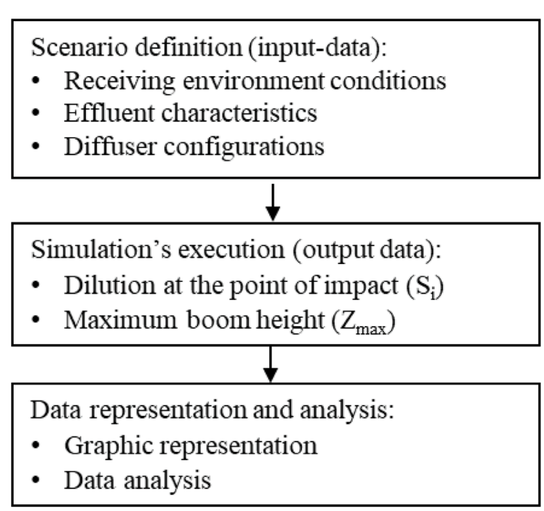

Fig. 2. Outline of the methodological approach.

grees, while the height of the diffusers was set at a range of 1 to 4 m above the seabed. Conversely, the design diameter of the diffuser nozzle was determined through an iterative process. In this process, an initial diffuser diameter of 15 cm was established in accordance with the recommended dimensions to avoid obstructions due to biofouling and a jet velocity within the range of Froude values between 10 and 25. The velocity values obtained were 1.81 and 4.54 m/s, as calculated using [Eq. (2)]. Subsequently, the velocity results were rounded to 2 and 5 m/s, respectively, for the sake of simplicity, with the diffuser diameter adjusted to 0.17 m and the Froud values as indicated in (Table 1). Furthermore, the discharge flow was estimated on the basis of an outfall with a single outlet port [Eq. (3)]. The methodology allows for the increase in the number of diffusers in cases where a greater volume of brine needs to be evacuated, as per the equation [Eq. (4)].

$$\boldsymbol{F_o} = \frac{\boldsymbol{U}_0}{\sqrt{\boldsymbol{g}' \cdot \boldsymbol{d}_0}} \tag{2}$$

Where,

Fo: is the Froude number,
Uo: is the initial velocity of the jet,
do: is the nozzle diameter, and g' is the reduced gravity.

$$Q_0 = U_o \cdot A = U_0 \cdot \pi \cdot \frac{{d_0}^2}{4} \tag{3}$$

$$Q_0 = \frac{Q_T}{n} \tag{4}$$

Where,

Q_o: represents the unit flow rate,
Q_T: represents the total flow rate discharged,
N: represents the number of ports.

The various combinations of configurations result in a total of sixty-four distinct cases, which are described in Table 2. This set of cases has been modelled in order to investigate the impact of brine dispersion in a shallow water environment for different diffuser configurations, evaluate the variables and determine the optimal design.

2.3. Simulations' execution

The process of brine and water mixing in the near field is characterised by a multitude of complex physico-chemical phenomena, which necessitates the utilisation of sophisticated modelling software. The majority of commercially available software programs, including CORMIX, VISUAL PLUMES, and VISJET, were initially developed for use with positively buoyant discharges and subsequently adapted for negatively buoyant discharges. However, these models have a number of shortcomings. For instance, some are lacking in validation for negative buoyancy or are limited to specific discharge configurations, which can result in inaccurate results in certain scenarios [33].

To address these limitations, the Centro de Estudios y Experimentación de Obras Públicas de España (CEDEX) and the Institute of Environmental Hydraulics of the University of Cantabria (IHCantabria) developed the brIHne software. The model has been recalibrated with experimental data obtained using optical techniques of laser anemometry and laser-induced fluorescence, thereby ensuring high accuracy in the simulation of brine discharges [34].

Table 1
Discharge flow characteristics.

Velocity(m/s)	Diameter(m)	Flow (m^3/s)	N° Froude
2	0.17	0.045	10.3
3	0.17	0.068	15.5
4	0.17	0.090	20.7
5	0.17	0.113	25.8

Table 2
Ranges of modelled design variables.

Variables	Range
Velocity (m/s)	[2; 3; 4; 5]
Angle (grade)	[15°; 30°; 45°; 60°]
Hight (m)	[1; 2; 3; 4]

In this study, the brIHne-Jet model, which has been specifically designed to predict the discharge of an individual jet in the near field, was employed. The brIHne model employs numerical approximations to the governing equations in order to predict the behaviour of the discharge under a variety of configurations in a quiescent or moving receiving medium. These equations encompass the conservation of mass, momentum and energy, integrated through the utilisation of advanced dimensional analysis techniques and differential methods. The recalibration with experimental data guarantees that the results of the brIHne model are accurately aligned with the actual operating conditions. Moreover, this tool is frequently employed and endorsed for brine diffuser design [35].

2.4. Data representation and analysis

Following the completion of the modelling process, the minimum dilution at the impact point (Si_{min}) and the maximum plume height (Z_{max}) were extracted from the results as key parameters. The minimum dilution at the impact point represents the most critical condition for dilution at the seabed, providing a direct measure of the efficiency of the diffuser design in the near field. Conversely, the maximum plume height, defined in the model as the isosurface with a concentration of 6 % relative to the receiving environment, serves as a fundamental criterion for determining the requisite depth limitations of the discharge.

In order to facilitate effective visualisation of the results, four graphs were constructed, each depicting the minimum dilution values for a different diffuser configuration under one of four distinct discharge velocity scenarios. In these graphs, the target variable, minimum dilution at the impact point, is plotted on the x-axis, while the nozzle height (h_o), one of the primary design variables, is represented on the y-axis. The secondary design variable, corresponding to different nozzle inclination angles, is displayed as a separate data series, fitted with polynomial regression lines. Subsequently, a secondary y-axis was incorporated to represent the maximum plume height, thus facilitating a comprehensive graphical analysis of both target variables.

This graphical approach allows for the identification of the optimal diffuser configuration in terms of both minimum dilution and plume height, thus facilitating a qualitative comparison of diffuser designs across different velocity scenarios. The analysis commenced with the calculation of the mean differences in dilution when the nozzle inclination angle was varied for each velocity scenario [Eq. (5)]. Furthermore, the impact of raising the nozzle height by one metre in each velocity scenario was evaluated and compared [Eq. (6)].

Finally, the gradients in maximum plume height resulting from changes in nozzle inclination were calculated and analysed [Eq. (7)]. The outcomes of these analyses have allowed us to discern which design variable—nozzle inclination or height—has a more significant influence on diffuser performance under various operational conditions. Furthermore, these findings provide actionable recommendations for optimising diffuser designs in shallow water environments, guiding the selection of configurations that achieve the desired balance between dilution efficiency and the necessary draft.

$$\Delta S(\alpha_{i+1}, \alpha_i) = \sum_{j=1}^{m-1} \frac{S(\alpha_{i+1})_{h_j} - S(\alpha_i)_{h_j}}{m-1} \tag{5}$$

$$\Delta S(h_{j+1}, h_j) = \sum_{i=1}^{n-1} \frac{S(h_{j+1})_{\alpha_i} - S(h_j)_{\alpha_i}}{n-1} \tag{6}$$

$$\Delta Z(\alpha_{i+1}, \alpha_i) = \sum_{j=1}^{m-1} \frac{Z(\alpha_{i+1})_{h_j} - Z(\alpha_i)_{h_j}}{m-1} \tag{7}$$

3. Results

3.1. Case study

Currently, there are over 15,900 desalination plants in operation worldwide [36]. On Gran Canaria alone, there are more than 130 desalination plants, producing 121.96 Hm3/year of desalinated water, which accounts for 52 % of the island's total water consumption [37]. Given the considerable number of desalination plants in the region, their historical development, the high level of dependency on desalinated water in the area and the region's commitment to water sustainability, the Canary Islands were selected as a case study. To this end, a standard reverse osmosis desalination plant with an underwater outfall situated in the Canary Islands was selected as a theoretical case study, employing the physico-chemical characteristics of the receiving environment, including salinity, temperature and density, which are typical of the archipelago.

The analysis concentrated on two pivotal variables: the minimum dilution at the point of impact and the maximum height of the brine plume. These variables were evaluated by combining diffuser design variables, including discharge velocity, nozzle height and angle of inclination. A series of simulations were conducted to evaluate the impact of the discharge under oceanographic and operational conditions representative of a standard desalination plant in the Canary Islands.

With regard to the physico-chemical conditions of seawater in the Canary Islands, the temperature fluctuates between 16 and 18 degrees Celsius during the winter months and between 23 and 25 degrees Celsius during the summer. The mean salinity concentration (C_{sw}) is estimated to be 36.5 practical salinity units (psu) [38]. In this case study, the mean values of temperature and salt concentration were considered, with an estimated water temperature (T_{sw}) of 20.5 °C. The density of the receiving water was calculated using the equation of state of seawater proposed by UNESCO, which relates density to temperature and salt concentration. This yielded an average seawater density (ρ_{sw}) of 1025.81 kg/m^3. In consideration of the characteristics of the effluent under examination, a conversion factor of 45 % was posited, which is representative of reverse osmosis desalination plants in the Canary Islands. This resulted in an average salt concentration (C_{ef}) of 66.36 psu, calculated according to equation [Eq. (1)].

The physicochemical values employed to delineate the attributes of both the effluent and the receiving medium align with the projections made for the case study in the Canary Islands (Table 3). The density of the effluent was calculated in a manner analogous to that employed for the receiving medium, resulting in a value of 1048.80 kg/m^3.

3.2. Minimum dilution at point of impact

The dilution results were represented in four distinct graphs, each of wich illustrated a specific discharge velocity scenario. In these graphs, the target variable, namely the minimum dilution at the point of impact, is displayed on the x-axis, while the nozzle height (h_o), which is one of the principal design variables, is plotted on the y-axis. The design variable, which corresponds to different nozzle inclination angles, is displayed as an independent data series, with polynomial regression lines fitted to it (Fig. 3).

The qualitative analysis of the data obtained shows that increasing the brine outlet velocity has a significant effect on the mixing process. The jet velocity is the variable with the greatest influence on improving the dilution of the effluent, reinforcing the dilution effect of the geometric variables of the diffuser.

Regarding the angle of inclination of the nozzle, a 60° angle gives the best results. However, the effectiveness of this variable does not follow a linear pattern, but rather an exponential one, decreasing at higher angles. This means that increasing the angle of inclination from 45° to 60° does not result in as significant an improvement in dilution as increasing the angle of inclination from 15° to 30°. As mentioned above, the velocity range influences the effectiveness of the other design parameters. It can be seen that in low velocity scenarios, the difference in dilution between different angle designs is much smaller than at higher velocities, with the improvement between 45° and 60° being almost insignificant. Furthermore, with respect to the increase in diffuser height, the results show that the dilution increases steadily regardless of the nozzle pitch or its velocity.

With regard to the results of the quantitative analysis, the difference in dilution obtained by increasing the inclination angle was calculated (Table 4). The results demonstrate that for large angles, increasing the inclination from 45° to 60° only produces a marginal improvement in dilution, reaching a maximum of 0.82 in the most favourable case. Conversely, at low angles (15° to 30°), the dilution benefit of increasing the angle is significantly higher, with a range of 1.5 to 3.55 at speeds of 5 m/s.

Concerning the effect of dilution at the point of impact when changing the height of the diffuser (Table 5), the results of the average dilution gradients generated by increasing the nozzle height by one metre show an approximate increase of 2 dilution points in all cases, regardless of the jet velocity and the height of the diffuser.

3.3. Maximum height of the plume

In this section, a secondary vertical axis is introduced to the previous graphs Fig. 3, which shows the results of the maximum plume height (Fig. 4). The results indicate that an increase in the discharge velocity, nozzle height or jet inclination angle results in a proportional increase in the maximum plume height.

The graphs demonstrate a direct correlation between the height of the diffuser nozzle and the maximum height of the plume. As an illustration, if the diffuser is elevated by one metre, the maximum height of the trajectory will be one metre higher, regardless of the speed range or the angle of inclination.

A change in the angle of inclination has a considerable impact on the speed variable, which in turn affects the trajectory and height of the discharge column. Table 6 illustrates the impact of varying the jet height by modifying the inclination angle. It can be observed that altering the angle of inclination by 15 degrees results in a change of over one metre in the maximum height of the plume, with the exception of the low speed scenario (2 m/s), where the change is less than one metre. Furthermore, for a given speed, the plume height gradients remain relatively constant across the different steps of the design inclination angle.

In order to demonstrate the utility of the generated graphs as a design tool, we have conducted an illustrative example to determine the optimal design of a discharge that requires a dilution at the point of impact of a dilution factor of 16 units. Fig. 5 illustrates the methodology employed to derive the design values for a scenario involving a discharge velocity of 3 m/s. The intersection of the vertical line marking the dilution limit with the set of lines indicates the potential design

Table 3
Effluent characteristics.

Parameters	Environmentalconditions	Effluentconditions
Salinity (psu)	36.5	66.36 (*)
Temperature (°C)	20.5	20.5
Density (Kg/m^3)	1025.81	1048.80

(*) Considering a recovery factor of 45%.

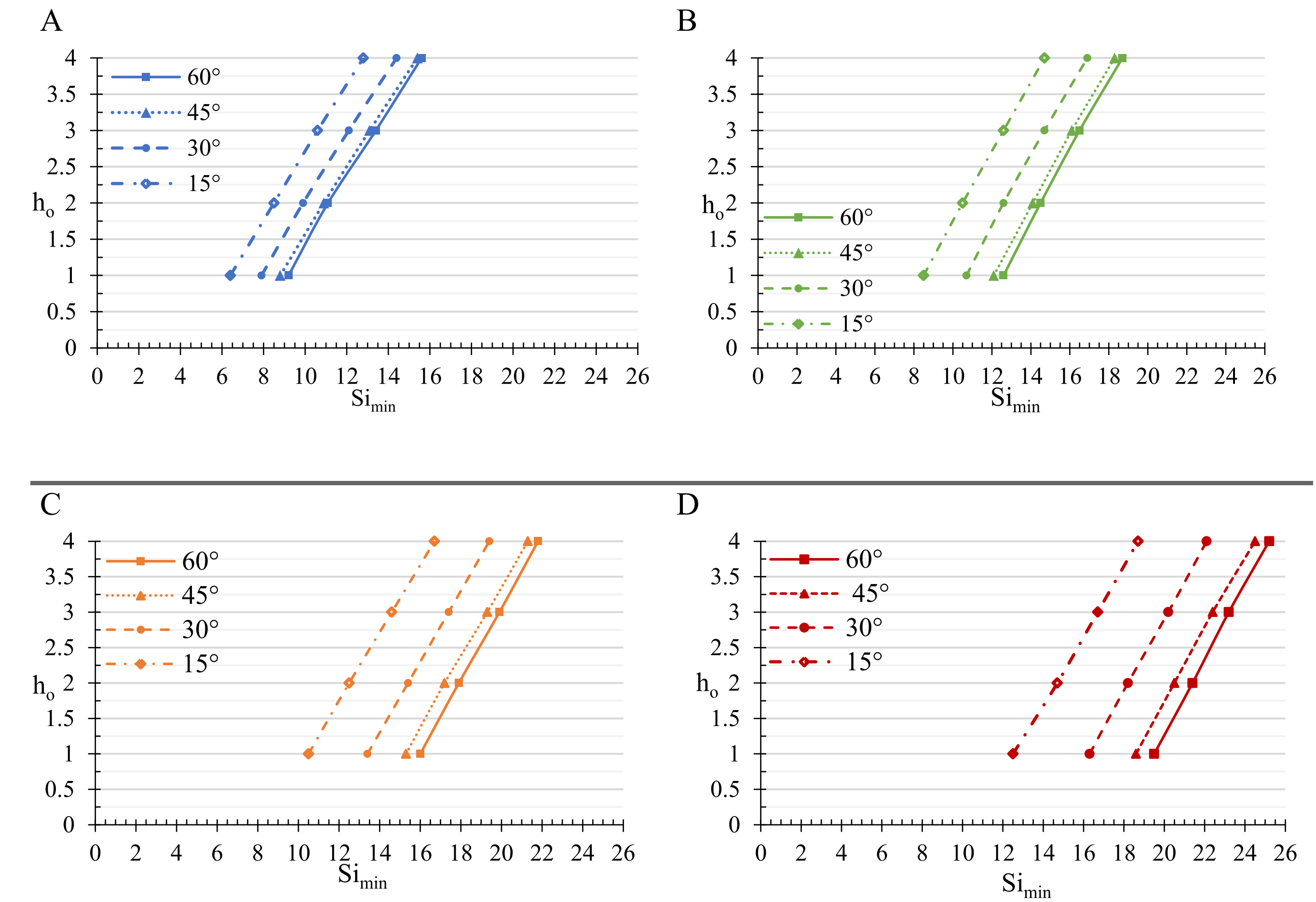

Fig. 3. Minimum dilution at impact point (Si_{min}); (A) velocity 2 m/s; (B) velocity 3 m/s; (C) velocity 4 m/s; (D) velocity 5 m/s.

Table 4
Averaged dilution gradients between inclination angles.

ΔS	2 m/s	3 m/s	4 m/s	5 m/s
$\overline{\Delta S}$ [60°; 45°]	0.27	0.42	0.62	0.82
$\overline{\Delta S}$ [45°; 30°]	0.98	1.43	1.88	2.30
$\overline{\Delta S}$ [30°; 15°]	1.50	2.15	2.83	3.55

Own elaboration.

Table 5
Averaged dilution gradients between nozzle heights.

ΔS	2 m/s	3 m/s	4 m/s	5 m/s
$\overline{\Delta S}$ [2 m; 1 m]	2.03	1.95	1.95	1.98
$\overline{\Delta S}$ [3 m; 2 m]	2.20	2.05	2.05	1.93
$\overline{\Delta S}$ [4 m; 3 m]	2.25	2.18	2.00	2.00

Own elaboration.

options and the plume height that could be achieved in each case. In this scenario, there are several potential design options, with angles between 30° and 60° and nozzle heights ranging from 2.7 m to 3.7 m.

The aforementioned procedure was repeated for each velocity scenario, with the results for the proposed case presented in Table 7. It can be observed from this exercise that the minimum dilution required cannot be achieved at velocities of 2 m/s. It can be concluded that the optimal configuration for shallow waters is a high velocity, low nozzle angle and low nozzle height design. Nevertheless, in the event that the plant or discharge conditions preclude the attainment of the

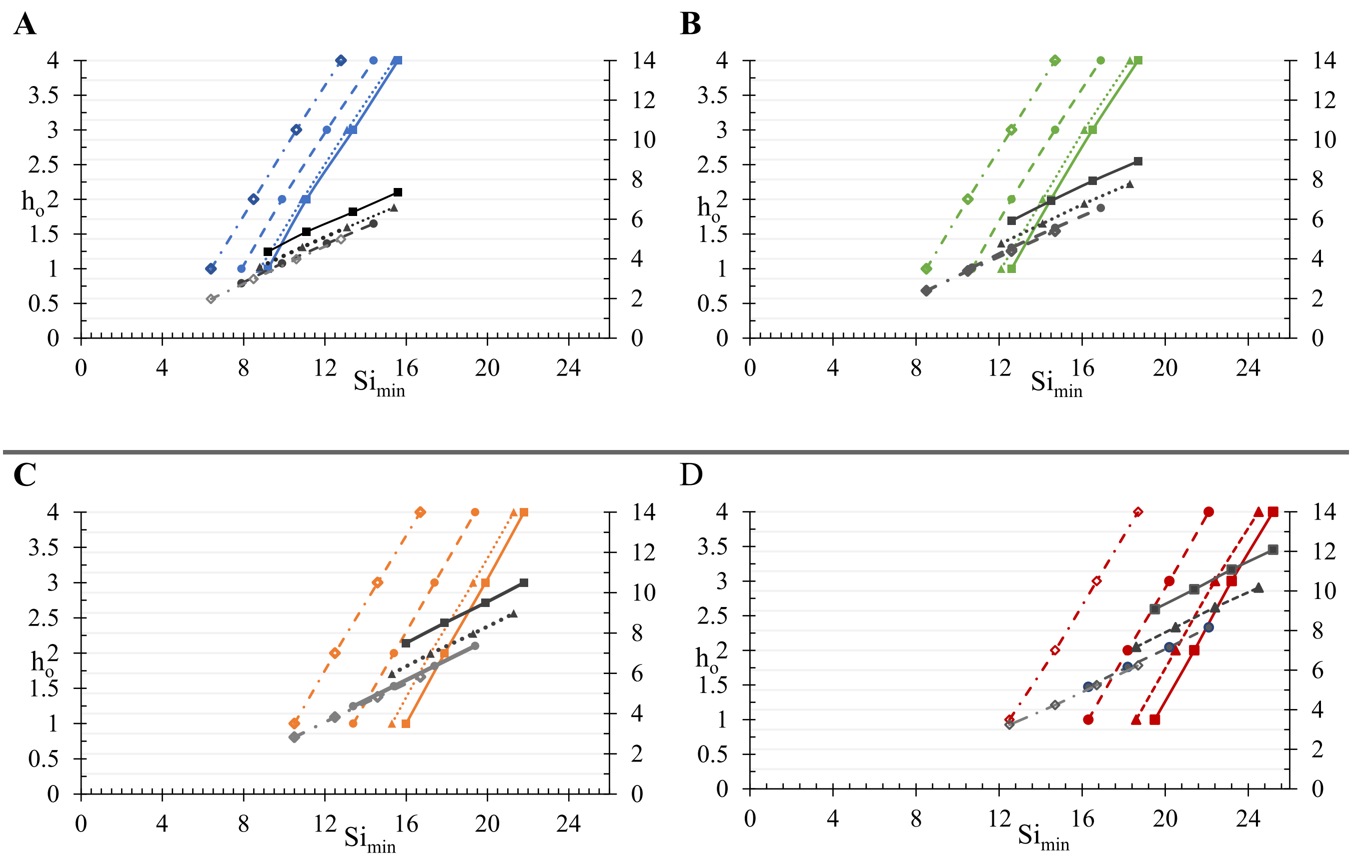

Fig. 4. Minimum dilution at impact point (Simin)- Maximum plume height (Z_t); (A) velocity 2 m/s; (B) velocity 3 m/s; (C) velocity 4 m/s; (D) velocity 5 m/s.

Table 6
Gradient of plume height between inclinate angles.

ΔZ_t	2 m/s	3 m/s	4 m/s	5 m/s
ΔZ_t [60°; 45°]	0.77	1.14	1.53	1.91
ΔZ_t [45°; 30°]	0.82	1.22	1.61	2.01
ΔZ_t [30°; 15°]	0.79	1.17	1.54	1.92

Own elaboration.

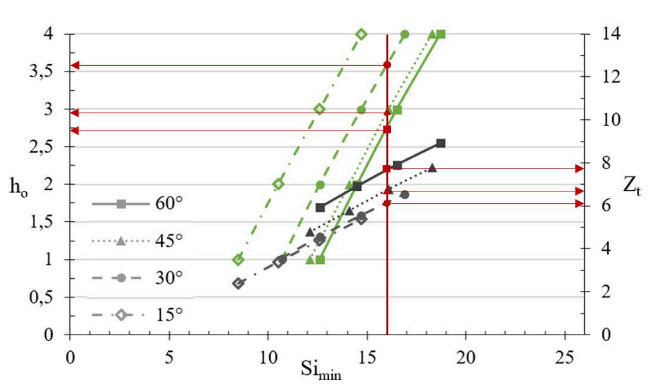

Fig. 5. Shows how to use graphs with the dilution variable as a constraint.

aforementioned velocities, it would be more prudent to augment the nozzle height and curtail the tilt angle.

4. Discussion

In recent years, there has been a growing interest in the optimal configuration of inclined brine diffusers, driven by the need to comply with environmental restrictions and reduce costs associated with submarine outfalls. The objective of this work is to determine the optimal design of a brine diffuser in shallow water environments, evaluating key design variables and their impact on dilution. The study concentrates on two principal variables: the inclination and the height of the diffuser nozzle.

This is the first comprehensive analysis of the positive effects of increasing the diffuser height according to the range of discharge velocities. The results demonstrate that, in low velocity regimes with a Froude number close to 10, increasing the diffuser height is a more effective method of improving brine dilution than the use of maximum dilution angles. This finding highlights that even in shallow waters, elevated diffusers can offer substantial benefits. This finding represents a

Table 7
Design options with a requirement of 16 dilution units for our case study.

Velocity	m/s	2	3				4				5		
Inclination angle	°	–	15°	30°	45°	60°	15°	30°	45°	60°	15°	30°	45°
Hight diffuser	m	–	–	3.7	2.9	2.7	3.7	2.3	1.4	1.0	2.6	1	>
Hight plume	m	–	–	6.1	6.8	7.8	5.5	5.7	6.3	7.5	5.0	5.1	>

Own elaboration.

significant contribution to the field, as it highlights the importance of nozzle height in low flow rate operating scenarios. This aspect has been underestimated in previous studies, underscoring the value of this research. Previous studies have primarily focused on optimising dilution by adjusting the angle and exit velocity, with the height of the diffuser being given less consideration. This is in line with the methodology proposed by Bleninger and Jirk.

By contrast, this work performs a comprehensive analysis that treats nozzle height with the same importance as inclination, thereby offering an innovative perspective. A series of 64 simulations, covering four velocity scenarios and 16 diffuser configurations, have been conducted to evaluate the specific conditions of reverse osmosis plants and the physical–chemical characteristics of water in the Canary Islands. The results confirm that a 60° angle provides the optimal dilution, in line with previous studies [40 41]. However, in cases where the recommended exit velocities correspond to Froud numbers of 25 and where draft is a limiting factor, a 45° angle is more appropriate. This is because the improvement in dilution does not justify the increase in nozzle height required to achieve higher angles.

Furthermore, the study demonstrates that scenarios with higher brine flow rates yield superior dilution outcomes, corroborating prior research that attributes this phenomenon to the elevated kinetic energy of the jet [39]. Conversely, low flow rates result in reduced dilution due to lower discharge velocities, which represents a significant environmental challenge under these conditions. Historically, low flow rates have been less of a focus, as diluted brine is often found at the boundaries of the mixing zone, where water quality criteria and environmental requirements are established [25]. The findings of this study indicate that a deeper understanding of the optimal design of diffusers and the behaviour of plumes could inform the revision of regulations associated with the mixing zone.

The paper also includes graphs that relate the geometric variables of the diffuser design to predictions of maximum plume height and dilution at the point of impact. The graphs provide invaluable insight for the design of future diffusers or the retrofitting of existing ones in shallow waters, particularly in standard reverse osmosis plants in the region under study.

While this analysis was conducted for a single port configuration, the methodology can be applied to multiport configurations, provided that it is ensured that the plumes do not interact and that there is sufficient separation between the diffusers. In scenarios with unequal flow rates, additional diffusers could be incorporated to maintain unitary flow rates similar to those observed in the study. As an alternative, the recent recommendations that suggest the use of alternating discharge angles in multiport sections could be applied [42]. It should be noted that the stream values considered were minimal in order to limit the results to the geometric variables of the diffuser. However, when applying this methodology to a specific case, it is advisable to include the speed and direction of the stream relative to the axis of the discharge jet. Furthermore, for diffuser heights exceeding four metres, alternative software such as the CORMIX model will be required. However, this also has limitations, as it does not permit the nozzle height to exceed one-third of the total depth [43].

The study aimed to identify the optimal method for achieving maximum dilution at the point of impact. It would be beneficial for future research to replicate the methodology with a specific case that includes bathymetry and current conditions. This would allow for a more detailed evaluation of the behaviour at the near-field threshold. This approach would enable a more detailed examination of the relationship between geometric variables and environmental conditions, thereby facilitating further optimisation of diffuser design.

In synthesis, this research offers a substantial contribution to the optimal design of shallow water brine diffusers. It elucidates the pivotal role of nozzle height as a critical variable, equating it in significance with the inclination angle, and presents a comprehensive methodology applicable to diverse operating conditions. A comprehensive analysis of velocity scenarios and geometric configurations reveals that an increase in diffuser height can markedly enhance dilution, even in low-velocity regimes. This challenges the conventional wisdom that minimising diffuser height is the optimal approach. Moreover, the graphs developed in this study serve as a practical tool for diffuser design, facilitating informed decision-making in future projects. This study not only expands the understanding of brine plume behaviour, but also establishes a foundation for optimising the design under specific environmental and operational constraints, marking an important advance in sustainable effluent management in desalination plants.

5. Conclusion

Seawater desalination is the cornerstone for addressing water scarcity in isolated systems or island regions. However, the environmental, social and economic challenges associated with brine discharge highlight the urgent need for sustainable solutions [44]. This study contributes to the field by investigating the optimisation of submarine diffusers for brine discharge, focusing on shallow water applications and developing a theoretical study for the case of the Canary Islands. Contrary to previous studies, this work emphasises the fundamental role of diffuser height as a design variable, especially in scenarios with low discharge rates.

Through numerical analysis, this research evaluates different diffuser configurations under different velocity scenarios, revealing the importance of factors between diffuser height and inclination angle. The results show that optimisation of these variables can significantly improve dilution performance and minimise environmental impact. For example, the study highlights that, under maximum draft restriction, increasing diffuser heights for low-velocity discharges leads to better mixing than increasing nozzle inclination angles. This not only mitigates ecological risks, but also meets economic considerations by suggesting designs in shallower waters.

The research also provides practical design guidelines, including recommended diffuser heights and a graphical configuration selection tool based on discharge jet velocity scenarios. These contributions combine theoretical knowledge with real-world applications, providing valuable resources for engineers and technicians. In addition, the study advocates adaptive designs capable of adapting to variable flow conditions, which are particularly relevant in regions with seasonal variations in water demand. Looking to the future, it calls for further research into alternative technologies, such as venturi diffusers [45], and improvements to conventional designs, paving the way for more flexible and efficient desalination operations. This work not only deepens the understanding of diffuser design variables, but also provides stakeholders with practical solutions to optimise brine management in shallow water.

CRediT authorship contribution statement

Adrián Gil Trujillo: Writing – original draft. **J. Jaime Sadhwani Alonso:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Boretti A, Rosa L. Reassessing the projections of the World Water Development Report. Npj Clean Water Jul. 2019;2(1):15. https://doi.org/10.1038/s41545-019-0039-9.
[2] Ghalehteimouri KJ, Ros FC, Rambat S. Flood risk assessment through rapid urbanization LULC change with destruction of urban green infrastructures based on NASA Landsat time series data: a case of study Kuala Lumpur between 1990–2021. Ecol Front Apr. 2024;44(2):289–306. https://doi.org/10.1016/j.chnaes.2023.06.007.
[3] Jafarpour Ghalehteimouri Kamran, Che Ros Faizah, Rambat Shuib, Nasr Tahereh. Spatial and temporal water pattern change detection through the Normalized Difference Water Index (NDWI) for Initial flood assessment: a case study of Kuala Lumpur 1990 and 2021'. J Adv Res Fluid Mech Therm Sci Feb. 2024;114(1):178–87. https://doi.org/10.37934/arfmts.114.1.178187.
[4] European Commission. Joint Research Centre., Acequia report: climate change, droughts and water uses : a LOGIC proposal for action. LU: Publications Office, 2020. Accessed: Sep. 14, 2023. [Online]. Available: https://data.europa.eu/doi/10.2760/466906.
[5] UN-Water, 'UN-Water Analytical Brief Unconventional Water Resources'. 2020. [Online]. Available: https://www.unwater.org/publications/un-water-analytical-brief-unconventional-water-resources-0.
[6] Elimelech M, Phillip WA. The future of seawater desalination: energy, technology, and the environment. Science Aug. 2011;333(6043):712–7. https://doi.org/10.1126/science.1200488.
[7] Panagopoulos A, Haralambous K-J, Loizidou M. Desalination brine disposal methods and treatment technologies - a review. Sci Total Environ Nov. 2019;693:133545. https://doi.org/10.1016/j.scitotenv.2019.07.351.
[8] Gacia E, Invers O, Manzanera M, Ballesteros E, Romero J. Impact of the brine from a desalination plant on a shallow seagrass (Posidonia oceanica) meadow. Estuar Coast Shelf Sci May 2007;72(4):579–90. https://doi.org/10.1016/j.ecss.2006.11.021.
[9] Sánchez-Lizaso JL, et al. Salinity tolerance of the Mediterranean seagrass Posidonia oceanica: recommendations to minimize the impact of brine discharges from desalination plants. Desalination Mar. 2008;221(1–3):602–7. https://doi.org/10.1016/j.desal.2007.01.119.
[10] José L, Talavera Pérez, José J, Ruiz Quesada. Identification of the mixing processes in brine discharges carried out in Barranco del Toro Beach, south of Gran Canaria (Canary Islands). Desalination 2001;139(1–3):277–86. https://doi.org/10.1016/S0011-9164(01)00320-4.
[11] Papathanasiou V, Orfanidis S, Brown MT. Cymodocea nodosa metrics as bioindicators of anthropogenic stress in N. Aegean, Greek coastal waters. Ecol Indic Apr. 2016;63:61–70. https://doi.org/10.1016/j.ecolind.2015.11.059.
[12] Mousavi SH, Kavianpour MR, Alcaraz JLG. The impacts of dumping sites on the marine environment: a system dynamics approach. Appl Water Sci May 2023;13(5):109. https://doi.org/10.1007/s13201-023-01910-9.
[13] Lattemann S, Höpner T. Environmental impact and impact assessment of seawater desalination. Desalination Mar. 2008;220(1–3):1–15. https://doi.org/10.1016/j.desal.2007.03.009.
[14] Shrivastava I, Eric Adams E. Desalination Brine Management: Effect on Outfall Design. In: . Wakil Shahzad, Dixon M, Barassi G, Bin B, Xu, Jiang Y, editors. Pathways and Challenges for Efficient Desalination, M, IntechOpen; 2022. doi: 10.5772/intechopen.99180.
[15] Voutchkov N. Overview of seawater concentrate disposal alternatives. Desalination Jun. 2011;273(1):205–19. https://doi.org/10.1016/j.desal.2010.10.018.
[16] Frank H, Fussmann KE, Rahav E, Bar Zeev E. Chronic effects of brine discharge from large-scale seawater reverse osmosis desalination facilities on benthic bacteria. Water Res Mar 2019;151:478–87. https://doi.org/10.1016/j.watres.2018.12.046.
[17] Raventos N, Macpherson E, García-Rubiés A. Effect of brine discharge from a desalination plant on macrobenthic communities in the NW Mediterranean. Mar Environ Res Jul. 2006;62(1):1–14. https://doi.org/10.1016/j.marenvres.2006.02.002.
[18] Abessi O, Roberts PJW. Multiport diffusers for dense discharges. J Hydraul Eng Aug. 2014;140(8):04014032. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000882.
[19] Bleninger T, Jirka GH. Modelling and environmentally sound management of brine discharges from desalination plants. Desalination Mar. 2008;221(1–3):585–97. https://doi.org/10.1016/j.desal.2007.02.059.
[20] Katal R, Ying Shen T, Jafari I, Masudy-Panah S, Hossein Davood Abadi Farahani M. An Overview on the Treatment and Management of the Desalination Brine Solution. In: Hossein Davood Abadi Farahani M, Vatanpour V, Hooshang Taheri A, editor. Desalination - Challenges and Opportunities, IntechOpen; 2020. doi: 10.5772/intechopen.92661.
[21] Mavukkandy MO, Chabib CM, Mustafa I, Al Ghaferi A, AlMarzooqi F. Brine management in desalination industry: from waste to resources generation. Desalination Dec 2019;472. https://doi.org/10.1016/j.desal.2019.114187.
[22] Ahmad N, Baddour RE. A review of sources, effects, disposal methods, and regulations of brine into marine environments. Ocean Coast Manag Jan. 2014;87:1–7. https://doi.org/10.1016/j.ocecoaman.2013.10.020.
[23] Zhang H, Baddour RE. Maximun penetration of vertical round dense jets at small and large Froude numbers. J Hydraul Eng May 1998;124(5):550–3.
[24] Scott A. Jenkins Consulting, Dilution Issues Related to Use of High Velocity Diffusers in Ocean Desalination Plants: Remedial Approach Applied to the West Basin Municipal Water District Master Plan for Sea Water Desalination Plants in Santa Monica Bay; May 2013.
[25] Jenkins S, Paduan J, Roberts P, Schlenk D, Weis J. Management of Brine Discharges to Coastal Waters, Recommendations of a Science Advisory Panel. Technical Report 694. California Water Resources Control Board; Mar. 2012.
[26] Maalouf S, Rosso D, Yeh W-W-G. Optimal planning and design of seawater RO brine outfalls under environmental uncertainty. Desalination Jan. 2014;333(1):134–45. https://doi.org/10.1016/j.desal.2013.11.015.
[27] Zeitoun M. Model Studies of Outfall Systems for Desalination Plants. Part III. Numerical Simulation and Design Considerations 1972.
[28] Papakonstantis IG, Christodoulou GC, Papanicolaou PN. Inclined negatively buoyant jets 2: concentration measurements. J Hydraul Res Feb. 2011;49(1):13–22. https://doi.org/10.1080/00221686.2010.542617.
[29] Taherian M, Saeidihosseini S, Mohammadian M. CFD Numerical Simulation of Submerged Dense Jets in Cross-flows. In: Proceedings of the 39th IAHR World Congress, International Association for Hydro-Environment Engineering and Research (IAHR), 2022, pp. 1981–1988. doi: 10.3850/IAHR-39WC252171192022945.
[30] Jirka GH. Improved discharge configurations for brine effluents from desalination plants. J Hydraul Eng Jan. 2008;134(1):116–20. https://doi.org/10.1061/(ASCE)0733-9429(2008)134:1(116).
[31] Palomar P, Lara JL, Losada IJ. Near field brine discharge modeling part 2: validation of commercial tools. Desalination Mar. 2012;290:28–42. https://doi.org/10.1016/j.desal.2011.10.021.
[32] Navarro R, Sánchez Lizaso JL, Sola I. Assessment of energy consumption of brine discharge from SWRO Plants. Water Feb 2023;15(4):786. https://doi.org/10.3390/w15040786.
[33] Palomar P, Lara JL, Losada Inigo J, Rodrigo M. MEDVSA: A methodology for the design of brine discharges into seawater. Brine discharge modelling. In: OCEANS 2011 IEEE - Spain, Santander, Spain: IEEE, Jun. 2011, pp. 1–10. doi: 10.1109/Oceans-Spain.2011.6003528.
[34] Palomar P, Lara JL, Losada IJ, Tarrade L. Numerical modeling of brine discharge: commercial models, MEDVSA online simulation tools and advanced computational fluid dynamics. Desalination Water Treat Jan. 2013;51(1–3):543–59. https://doi.org/10.1080/19443994.2012.714625.
[35] Pita E, Pita P, Sánchez-Barriga M, Martín L, Olalde J. Design of marine outfalls for reducing environmental impact of brine. Desalination Water Treat 2022;259:300–7. https://doi.org/10.5004/dwt.2022.28576.
[36] Jones E, Qadir M, Van Vliet MTH, Smakhtin V, Kang S. The state of desalination and brine production: a global outlook. Sci Total Environ Mar. 2019;657:1343–56. https://doi.org/10.1016/j.scitotenv.2018.12.076.
[37] Rosales-Asensio E, García-Moya FJ, González-Martínez A, Borge-Diez D, De Simón-Martín M. Stress mitigation of conventional water resources in water-scarce areas through the use of renewable energy powered desalination plants: an application to the Canary Islands. Energy Rep Feb. 2020;6:124–35. https://doi.org/10.1016/j.egyr.2019.10.031.
[38] MITECO. Marine Strategy Canarian Marine Demarcation, Part I. Ministry for the Ecological Transition and the Demographic Challenge. Madrid; 2012.
[39] Palomar P, Lara JL, Losada IJ, Rodrigo M, Alvárez A. Near field brine discharge modelling part 1: Analysis of commercial tools. Desalination Mar. 2012;290:14–27. https://doi.org/10.1016/j.desal.2011.11.037.
[40] Robinson D, Wood M, Piggott M, Gorman G. CFD modelling of marine discharge mixing and dispersion. J Appl Water Eng Res Jul. 2016;4(2):152–62. https://doi.org/10.1080/23249676.2015.1105157.
[41] Gungor E, Roberts PJW. Experimental studies on vertical dense jets in a flowing current. J Hydraul Eng Nov. 2009;135(11):935–48. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000106.
[42] Saeidi Hosseini SAR, Mohammadian A, Roberts PJW, Abessi O. Numerical study on the effect of port orientation on multiple inclined dense jets. J Mar Sci Eng Apr 2022;10(5):590. https://doi.org/10.3390/jmse10050590.
[43] Belkacem Filali M, Bessenasse M. Brine Outfall Discharges Modelling and Design: Case of a Desalination Plant in Algeria. In: Kallel A, Ksibi M, Ben Dhia H, Khélifi N, editors. Recent Advances in Environmental Science from the Euro-Mediterranean and Surrounding Regions, in Advances in Science, Technology & Innovation. Cham: Springer International Publishing, 2018, pp. 719–721. doi: 10.1007/978-3-319-70548-4_213.
[44] Sola I, Sáez CA, Sánchez-Lizaso JL. Evaluating environmental and socio-economic requirements for improving desalination development. J Clean Prod Nov. 2021;324:129296. https://doi.org/10.1016/j.jclepro.2021.129296.
[45] Amiri NS, Abessi O, Roberts PJW. Venturi nozzles for desalination brine discharges. Desalination Mar. 2024;573:117193. https://doi.org/10.1016/j.desal.2023.117193.

AdriánGil Trujillo holds a degree in Civil Engineering from the University of Granada, Spain, and a postgraduate qualification in Desalination and Renewable Energies from the University of Las Palmas de Gran Canaria (ULPGC), Spain. He is currently a pre-doctoral researcher at the ULPGC, within the PhD programme in Environmental Quality and Natural Resources. His research focuses on the sustainable management of desalination discharges to the sea and the optimisation of submarine discharge infrastructures. He has delivered presentations at numerous conferences and published articles, including an oral presentation at the biannual Conference of the European Desalination Society in 2022 and an article in the impact journal Desalination. Furthermore, he has gained experience in environmental and coastal engineering companies, where he has developed a specialisation in the marine sector. Additionally, he has been an active member of the Innovation Committee of Young Water Professionals Spain and the Association of Promoters of the Sustainable Development Goals. His dual scientific-technical and multidisciplinary profile, with expertise in environmental and engineering fields, has enabled him to conduct applied research in the area of sea discharge through submarine outfalls, addressing unresolved issues of interest to scientists and technicians.

José JaimeSadhwaniAlonso is currently a professor at the University of Las Palmas de Gran Canaria, Spain, having received three favourable research periods (sexenios). He initiated his academic career as a professor in 1989, holds a doctorate in industrial engineering, and has contributed to numerous academic publications, books, conferences, and theses in the field of environmental engineering. Additionally, he has served as Director of Sustainability and Risk Prevention at the University of Las Palmas de Gran Canaria (ULPGC) for a decade, currently directing the Chair of Water at ULPGC since 2020, and contributing to various commissions of public bodies and administrations.