Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2013.795349

52 (2014) 164–177
January

Taylor & Francis
Taylor & Francis Group

Dispersion of desalination plant brine discharge under varied hydrodynamic conditions in the south of Gran Canaria

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Received 15 March 2012; Accepted 11 March 2013

ABSTRACT

Brine discharged directly into the sea from desalination processes, forms a very dense plume that spreads out over the sea floor following the steepest slope due to its greater density than ambient sea water. Because the large difference in density slows down brine dilution processes in ambient sea water, hypersaline plumes spread out over broad areas and affect the benthic communities in their path. The Maspalomas II desalination plant, in the south of the island of Gran Canaria (Canary Islands-Spain), discharges brine through an underwater outfall over a wide sandy bottom with a mild slope. The behavior of this brine discharge was characterized under various hydrodynamic conditions. A higher degree of hydrodynamic exposure favored dilution of the outer edges of the plume, helping to reduce the area of influence.

Keywords: Desalination; Brine; Discharge; Outfall; Plume; Hydrodynamic conditions; Dilution; Dispersion

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1. Introduction

Seawater desalination is currently the most viable technological method of satisfying the growing demand for potable water in the Mediterranean basin along the Spanish coast [1,2], and in the Canary Islands it has become the most important source of artificial water [3,4]. In these coastal areas, the climate conditions (low annual rainfall, periods of drought, and scarcity of other water resources) and the sociodemographic context (population increase and rise of tourism) have dictated that the supply of potable water must be met by seawater desalination, both now and in the future. In the case of the Canary Islands, the growth of tourism has made desalination in some islands, such as Lanzarote and Fuerteventura, the only available source of potable water [5].

This need and subsequent demand for potable water has led to a spectacular rise in the number of desalination plants in the Canary Islands and on much of the Spanish mainland coast, bringing with it

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a boost in research and development of desalination technologies. The two desalination processes in use in coastal areas are reverse osmosis and distillation. Reverse osmosis is the most widespread because of the lower investment cost, lower energy consumption, and smaller space requirements [6,7]. Reverse osmosis usually has outputs [(product water/feed water) × 100] of around 50%, which means it can produce hypersaline reject water, or brine, with more than twice the salt concentration of sea water [8]. Most desalination plants discharge this brine directly into the sea through a variety of discharge systems (underwater outfall with or without diffuser systems, surface discharge, cliff outfall, discharge over breakwaters, etc.). The area around the discharge point, known as the near field, is where the brine discharge dilution processes normally occur, as the kinetic energy the effluent usually has on entering the sea produces turbulence that aids rapid, efficient mixing processes with the water in the receiving environment [9]. However, at a certain distance from the discharge point, where the forward momentum of the effluent and the associated turbulence cease, the brine sinks because of its greater density. This brine becomes a hypersaline plume that spreads out over the sea floor virtually undiluted [10], following the steepest gradients [11]. This area, known as the far field, is where the water column occurs, in the form of a two-layer fluid in which the sea water occupies the upper layer and the brine occupies the lower layer. As the brine advances, it increases in width due to lateral spreading and decreases in thickness at the same time [9], but the degree of stratification between the two layers is so great that it slows down the exchange and dilution processes even when a certain degree of hydrodynamism occurs [12]. Brine discharges through systems with limited initial dilution capacity therefore become plumes with very high salinities that spread out over broad areas [13] and affect the benthic communities encountered along the way [14–20]. Because of this, large capacity desalination plants require appropriate exit velocities of brine jet discharges as well as flatter discharge angles of around 30°–45°, to ensure optimization of near-field dilution processes and minimize the environmental impact [21–23]. In addition to the characteristics of the discharge system, the discharge flow and salinity, and the byproducts from chemical treatments, the impact will depend on the ecosystem in the discharge zone, the bathymetry and bottom roughness, and the prevalent meteorological and oceanographic conditions in the area [14,24]. These two conditions are largely responsible for determining the degree of hydrodynamic exposure of the receiving environment, and in certain cases, may even condition the dispersion processes of the brine discharge. The impact of brine discharges began to require attention when their effect on seagrass meadows, one of the most ecologically important ecosystems in coastal areas, was detected. The earliest studies in the Mediterranean showed that short-term exposure of the dominant, endemic species *Posidonia oceanica* (L.) Delile to small increases in salinity in the receiving environment was capable of producing a series of toxic effects that could compromise plant vitality [25,26] and physiological functions [27]. Using a different type of estimate *in situ*, Gacia et al. [28] and Ruiz et al. [29] obtained experimental evidence to show that these effects can be responsible for the decline in the vitality and the structure of seagrass meadows over a longer period of time (months or years).

In 2003, a study was conducted both in the laboratory and *in situ* on the effect of increased brine on *P. oceanica* by the University of Alicante Department of Environmental Sciences, the Spanish Institute of Oceanography's Oceanographic Centre in Murcia, the University of Barcelona Department of Ecology and the Spanish National Research Council Centre of Advanced Studies, in Blanes, coordinated by the Public Works Study and Experimentation Centre (CEDEX—Ministry of Development). This study made a number of recommendations to protect seagrass meadows from brine discharges [30,31]. The most important were:

- salinity should be no higher than 38.5 psu in more than 25% of observations in any part of the seagrass meadow;
- salinity should be no higher than 40 psu in more than 5% of observations in any part of the seagrass meadow.

The results of these studies, in turn, led to further research into the behavior of brine discharges and their effects and to studies on designs, strategies, and recommendations for their release into the marine environment. At desalination plants already operating, corrective, and mitigating measures began to be developed and tested, such as increasing diffusers at the outfall, extending the outfall to deeper or more hydrodynamic areas, diluting reject water before discharge, and mixing it with treated water. For planned desalination plants, designs, and recommendations to minimize harmful effects on seagrass meadows are being taken into consideration [14,32–34].

This study characterizes the dispersion process of brine discharge under various hydrodynamic conditions. It was designed to analyze the usual behavior of the brine plume dispersion process, the effect of variations in the degree of hydrodynamic exposure of the receiving environment on this process. The study was conducted at the Maspalomas II desalination plant, in the south of the island of Gran Canaria (Canary Islands-Spain), which discharges brine over a wide sandy bottom with a mild slope.

2. Materials and methods

2.1. Description of brine discharge and study area

The Maspalomas II reverse osmosis desalination plant is in the south of the island of Gran Canaria (Canary Islands-Spain), in the Barranco del Toro ravine, around 500 m from the sea between the important tourism beaches of Playa de Las Burras and Playa del Cochino (Fig. 1). The plant began operating in 1988 and today, after renovations and enlargements, average production is around 944 m^3/h potable water (Table 1).

The desalination plant has six reverse osmosis racks connected to four additional concentrators with a final conversion factor of approximately 50% that normally produces a brine ~~discharge~~ of 944 m^3/h with an average salinity of 73.6 psu. Feedwater intake is through two pipes with a length of 1,000 m and a diameter of 600 mm north of the underwater outfall of the brine discharge, and the pumping station is at Playa de Las Burras, near an artificial breakwater (Fig. 1). Feedwater requirements are around 1,888 m^3/h, although to optimize plant operation a slightly larger average flow of around 2,000 m^3/h is pumped into a 4,000 m^3 storage tank at the desalination plant. The 118 m^3/h excess feed water spills out of the tank and mixes with the brine in a drain, where it is diluted. Discharge salinity is reduced to approximately 69.5 psu (habitual pre-dilution rate of 0.13) with a final mixture flow of 1,062 m^3/h. The final discharge is channeled through an underground PVC pipeline with a length of 500 m and a diameter of 600 mm on one side of the Barranco del Toro ravine. At the mouth of the ravine, at a pebble beach between Playa de Las Burras and Playa del Cochino, the pipe joins onto a 300 m underwater outfall made of cast iron, also with a 600 mm diameter. The discharge system is a simple outlet elbow with the same diameter as the outfall, at a vertical angle of 42.5° to the sea bottom (Fig. 1). The discharge point is at a depth of 4 m at mean low water spring tide (MLWS) and brine is discharged over a wide sandy bottom with a mild slope of 1.6% and a depth of 20 m 1,000 m from the discharge outlet and 30 m 2,100 m from the outlet. This sandy bottom is home to the island's largest and

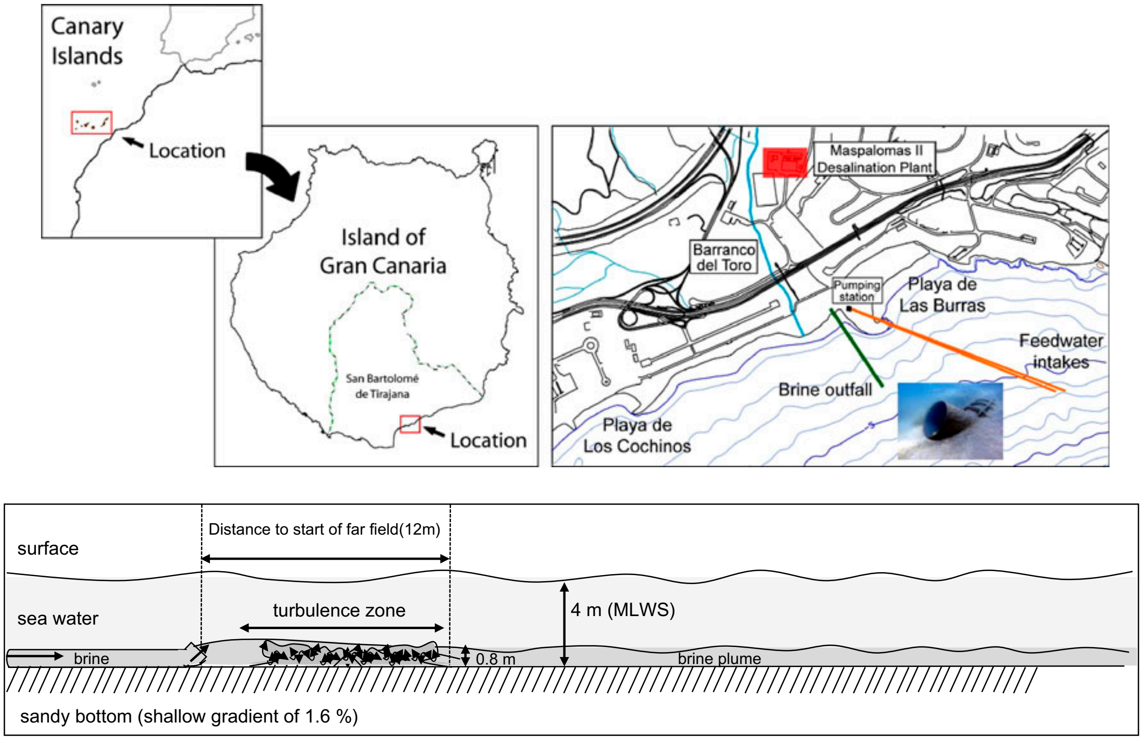


Fig. 1. Location of Maspalomas II desalination plant, underwater outfall, and brine discharge scheme.

Table 1
Characteristics of Maspalomas II desalination plant

Average feedwater intake (m^3/h)	Average conversion factor (%)	Average production (m^3/h)	Average seawater salinity (psu)	Average brine salinity (psu)	Average discharge final flow (m^3/h)	Average discharge final salinity (psu)
2.000	50	944	36.8	73.6	1.062	69.5

most ecologically important seagrass meadow of *Cymodocea nodosa* and has been declared both a Site of Community Interest under the name of *Sebadales de Playa del Inglés* (Playa del Inglés Seagrass Meadows)—ES7010056—[35] and a Special Area of Conservation [36]. The discharge emerges onto an area with a smaller seagrass meadow at Playa del Cochino, which is patchy and fragmented and occupies an area of 15.2 ha. Its population size is 1.5 ha and plants occur at depths of 4–10 m [37].

2.2. Sampling and data gathering.

Eight sampling campaigns were conducted of the salinity field in the influence zone when the desalination plant was operating under normal conditions with all the osmosis racks and most of the concentrators in optimal functioning. Sampling days were chosen with the habitual meteorological and oceanographic conditions of the area, but with some differentiation in terms of prevalent wave, wind, and tide conditions so as to have a certain amount of variability in the hydrodynamic conditions between campaigns.

A sampling grid was installed over the influence zone of the discharge to monitor the brine dispersion process. The study area size, and grid spacing and resolution depended on the plant discharge system, the brine flow and salinity, the characteristics of the receiving environment (bathymetry and bottom roughness), and the meteorological and oceanographic conditions at the time. To estimate the size of the area of influence, a MIKE3 model (comprehensive water

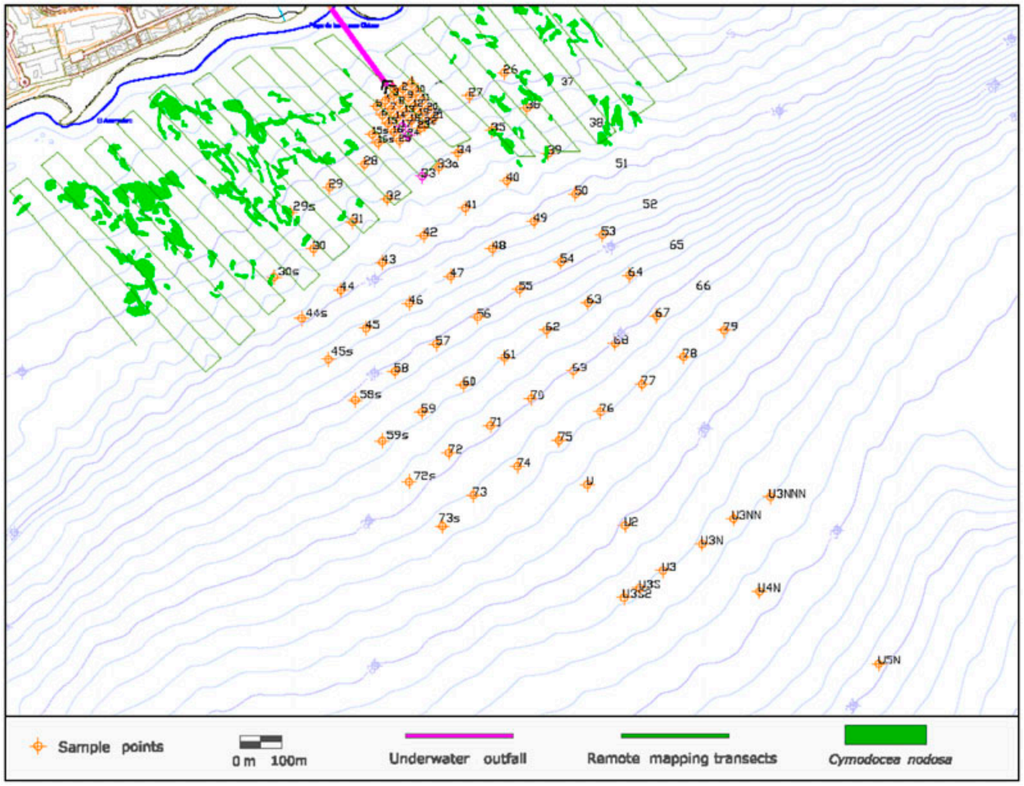


Fig. 2. Sampling points and bathymetry map.

modeling system developed by DHI Water & Environment—www.dhigroup.com/Software/) was established using the least favorable parameters (those that do not aid the mixing and dilution processes) as a way to estimate the dimension of the maximum area of influence on which the sampling campaigns should be planned. Developing a MIKE3 model beforehand made it possible:

- to estimate the maximum area of influence of the discharge, on the one hand;
- and, on the other hand, to determine certain characteristics of the discharge before sampling (e.g. start and extent of the far field; shape, arrangement, and spatial distribution of the plume throughout its trajectory; and plume velocity).

Once the area of influence of the brine discharge under these very poor dilution conditions had been delimited, an initial point grid was defined to take in this entire region. Through this first estimate of the sampling point grid, several preliminary campaigns were carried out with these conditions of low-hydrodynamic exposure to compare discharge variability and fluctuations, the degree of spatial distribution of the salinity field and so on. This information, gathered from the MIKE3 model estimate and preliminary sampling, aided better organization, planning and focus of sampling campaigns, and also helped to define an optimum, reliable sampling point grid (Fig. 2). The grid covered the maximum area of influence of the discharge in such a way that the grid transects roughly followed the bathymetry of the zone, which is virtually parallel to the coast. The hypersaline plume sank entirely 12 m from the discharge point, where the depth was 4 m (MLWS), corresponding to the depth at the start of the settlement of the neighboring Playa del Cochino seagrass meadow, so this distance was taken as the start of the grid transects. Although preliminary campaigns still detected salinity increases of 1.2 psu at 2,000 m, the grid boundary was established as a distance of 1,150 m, as the depth at this distance was 22 m and therefore the point grid circumscribed the most frequent bathymetric distribution of the seagrass meadows in the Canary Islands [38,39], particularly that of the neighboring seagrass meadow [34]. The point grid was divided into two zones and an intermediate area (Fig. 2) with:

- A smaller grid with higher resolution for the zone near the discharge, with 25 equidistant points (25 × 25 m). This area, where the width of the plume was less than 60 m, had the highest salinities, which remained practically invariable over the entire section. On each side of the transect furthest from the discharge point (points 21, 22, 23, 24 and 25) and in line with it, two points were added: one at a distance of 125 m and the other at a distance of 250 m;
- Another wider, larger grid for the zone furthest from the discharge point, with 42 equidistant points (150 × 150 m). In this zone, the plume slowly widened due to lateral spreading and the salinity field gradually decreased as the plume moved away from the discharge point;
- A transect of eight points between the two zones (points 30, 31, 32, 33, 34, 35, 36, and 37), equidistant at 125 m apart and 125 m from the smallest grid and 150 m from the widest.

This 75-point grid covered an area of 145 ha. The grid transects at a distance of 25, 125, 250, 400, 550, 700, 850, 1,000, and 1,150 m from the discharge point corresponded to depths of 4, 5, 7, 9, 12, 15, 18, 20, and 22 m, respectively (Fig. 2). The U points, also shown in Fig. 2, were points of reference used to find the maximum range of the plume.

Campaigns were conducted in numerical order of the grid points, with logistics support from a 5 m rigid polyethylene boat. Each measuring station was positioned by a Garmin Lowrance LCX 27C GPS (precision ± 5 m) with GPS + WAAS antenna and 50/200 kHz dual-frequency sensor. At each sampling point a YSI-6600-V2 multi-parameter sonde was used to measure the vertical profile of salinity and temperature, in addition to control parameters: pH, turbidity, dissolved oxygen, and chlorophyll. The sonde had a cylindrical body with a diameter of 10 cm. The sensors were inserted into the bulkhead at one end of the sonde, arranged concentrically. A probe guard protected the sensors during calibration and measurement. A field cable connector at the other end of the sonde was connected to a display system to enable the data recorded to be viewed from the boat in real time. Salinity was determined automatically from the temperature and conductivity readings in accordance with the algorithms in Standard Methods for the Examination of Water and WasteWater [40]. Using the Practical Salinity Scale produced values without units when measurements were taken in relation to the conductivity of a standard solution of 32.4356 g of KCl at 15°C in 1 kg [41,42], although following convention, they were presented as practical salinity units (psu). The measuring interval for salinity was 0–70 psu, with a precision of ±1% of the reading or 0.1 psu, whichever was greater, and a resolution of 0.01 psu. The sonde was lowered to a depth of 0.5 m for 30 s to stabilize parameter measuring before each sample was

Table 2
Salinity of the receiving environment, discharge salinity and velocity, flow and Froude number, maximum salinities recorded on the bottom, and mean near-bottom current velocity (cm/s) recorded by the SONTEK ADCP current profiler during sampling and total area of the affected zone (ha) corresponding to the salinity field greater than 38 psu

Date/parameter	7/22/2009	7/23/2009	9/29/2009	9/30/2009	3/30/2010	10/09/2010a	10/09/2010b	1/17/2011
Brine salinity (psu)	73.2	72.2	68.4	73.0	69.3	72.7	71.1	67.0
Seawater salinity (psu)	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8
Brine flow (m^3/h)	1.025	1.041	1.107	1.014	1.055	996	1.043	1.157
Froude number	2.68	2.72	2.90	2.65	2.76	2.60	2.73	3.03
Discharge velocity (m/s)	1.00	1.02	1.08	0.99	1.04	0.98	1.02	1.14
Max. sal. (psu)	47.0	46.5	42.3	45.2	46.9	47.4	45.9	45.3
Near-bottom current velocity (cm/s)	7.4	11	4.2	2.2	2.7	6.2	3.9	4.8
38 psu (ha)	12.35	8.9	22.5	33.7	25.6	17.3	21.6	14.8

taken. The sampling interval was 4 s and data were recorded only while the sensor was being lowered. The sonde was lowered slowly by hand at a rate of 0.25 m/s and when it reached the bottom it was held in position until parameter measuring stabilized, as the sonde caused disturbances when it came into contact with the plume or the bottom. A weight was attached to the sonde on the side of the conductivity sensor to keep it as close as possible to the bottom, as the thickness on the outer edges or central area of the plume could be less than 10 cm beyond the furthest distances. This avoided erroneous salinity measurements when the plume was less than 10 cm thick and also helped to prevent the sonde being spun around by the bottom currents or the effect of the waves. The boat was anchored at each sampling point to prevent drift and stop the sonde being dragged off position, which would have given erroneous readings as a result of the turbulence created. Two YSI-6600-V2 sondes were lowered for each campaign, one inside the discharge point and the other at a distance of approximately 250 m at a variable point centered in the plume, to control possible variations in the characteristics of the discharge on exit and the difference in the discharge after a certain distance. The position of this variable point was determined at the beginning of every campaign by laying a transect parallel to the coast at this distance, shown from points 30–37, and choosing the point where the highest bottom salinity value was found. The two YSI-6600-V2 sondes measured salinity, temperature, pH, turbidity, and dissolved oxygen with a sampling interval of 60 s. They were calibrated at the same time the day before each campaign in conjunction with the sonde used to measure the water column profiles. A SONTEK ADCP Argonaut XR current profiler, with a frequency of 0.75 MHz and a sampling interval of 20 min, was also lowered at the variable point to measure near-bottom current and other oceanographic parameters: significant wave height (Hs), peak period (Tp), and tide amplitude. An anemometric station was installed on a 5 m high tower on the roof of the pumping station to obtain weather information, measuring wind speed, and direction.

Near-bottom current velocity was taken as the reference parameter for the degree of hydrodynamic exposure of the receiving environment, as it is the result of the prevailing hydrodynamic and geomorphological conditions and variation in its intensity could affect and influence the dispersion process of the plume over the sea floor.

2.3. *Spatial representation of salinity data*

The horizontal spatial distribution of the salinity was shown only on the bottom, as all the brine discharge had settled on the sea floor barely 12 m from the discharge point. The Surfer Program (V.8) was used to map the salinity obtained in the point grid, as it uses the interpolation technique known as kriging, and to obtain a graphical representation of the bottom salinity field. These maps were superimposed onto the bathymetry of the area. The affected zone was defined as the spatial distribution of salinity field greater than 38 psu, as any measure above this would have toxic effects on seagrass meadows.

3. Results

Table 2 shows the salinity of the receiving environment, the salinity and flow of discharge during far-field sampling, mean velocity of the near-bottom current during sampling, and total area of the affected zone. The total area of the affected zone was the area corresponding to a salinity field greater than 38 psu, as beyond this value the brine could harm the seagrass meadows. Ambient seawater salinity remained constant, with values of 36.8 psu for all sampling campaigns, whereas discharge salinity showed some differences, with maximum values of up to 73.2 psu on 22 July 2009 and minimums as low as 67 psu on 17 January 2011. Discharge flows also showed slight variations between campaigns, of up to 14%, due to spillage of excess feedwater and subsequent mixing with the brine discharge, even though the desalination plant was operating under normal and similar conditions. The varied meteorological and oceanographic conditions between campaigns in terms of wave, wind, and tidal intensity caused the expected variations in near-bottom current velocity intensity between campaigns. Mean near-bottom current velocities during sampling differed substantially, with very-high mean velocities of up to 11 cm/s during sampling on 23 July 2009, mean velocities around 4–7 cm/s on 22 July 2009, 29 September 2009, and campaigns in September 2010, and mean velocities on 30 September 2009 and 30 March 2010, at 2.2 and 2.7 cm/s, respectively.

These brine discharges with varied hydrodynamic conditions and slight variations in exit flows and salinities formed areas corresponding to affected zones (ha) that were very large but also dissimilar. Extensive impact zones of almost 34 ha were determined during sampling on 30 September 2009, whereas on 23 July 2009 the impact zones were much smaller, at less than 9 ha. This largest impact zone (>33 ha) corresponded to characterization of discharge during sampling with less hydrodynamism and a mean near-bottom current velocity of 2.2 cm/s, and the smallest zone (<9 ha) corresponded to the highest current velocity, at 11 cm/s. In addition, discharge for these two campaigns in the far field had similar exit salinity and flow. For the mean current velocities of 3.9 and 4.2 cm/s on 10 September 2010 (b) and 29 September 2009, respectively, the impact zones of the discharges were around 22 ha.

The horizontal spatial distribution of the salinity field recorded on the bottom (Fig. 3) shows how all the brine discharges characterized formed elongated hypersaline plumes that spread out over the bottom due to their greater density, perpendicular to the coast, and following the direction with maximum slope. In the first 125 m of these hypersaline plumes, the salinity fields were reduced to a narrow effluent barely 60 m wide, where salinities greater than 42 psu were concentrated and, with the exception of 29 September 2009, areas larger than 3,000 m^2 with salinities greater than 44 psu appeared. The salinity fields greater than 42 psu continued to spread out over the bottom, increasing in width to 150 m, and in length to distances of up to 400 m from the discharge point. Depths at these distances were 8–9 m, which are within the most common bathymetric distribution of seagrass meadows in the Canary Islands [38,39]. On 29 September 2009, the day with the lowest discharge salinity and the largest flow, the hypersaline plume formed had different characteristics from the others in terms of the high salinity fields (>42 psu). Although in this case the affected zones corresponding to these high salinities were smaller, the area of influence of the salinity fields greater than 38 psu were also considerable and in proportion to the other characterizations. Beyond this distance (400 m) and with increased distance from the discharge point, the high salinity fields (>42 psu) began to diminish, although the fields corresponding to salinities greater than 38 psu did not. These salinity fields extended in length to depths of more than 20 m and the distance from the discharge point increased to more than 1,000 m, whereas in terms of width they grew slowly and expanded but with considerable differences in spreading between sampling campaigns. Characterizations where greater lateral spreading was observed were on days with less hydrodynamism, and less lateral spreading was observed when the greatest near-bottom current velocities were recorded (Table 2). It was also observed that these hydrodynamic conditions affected only the range of the affected zone, without affecting the direction of the discharge, which always followed the maximum gradient. The hypersaline plumes maintained the same elongated form and followed the same direction, although they narrowed or widened depending on the degree of hydrodynamic exposure in the receiving environment. On 30 September 2009, during the campaign with the lowest degree of hydrodynamism, the maximum range of the affected zone corresponding to the salinity field greater than 38 psu in relation to the discharge point was a distance of 2,100 m, at a depth of 35 m. At such a long distance, the brine plume still maintained increased salinity of 1.2 psu in comparison with the receiving environment.

This variation in the size of affected zones corresponding and relative to the spatial distribution of salinity fields greater than 38 psu was associated with the mean near-bottom current velocities recorded during characterization of the discharge in Fig. 4. The trend type and equation that best fitted this relation was the potential form, with a determination coefficient greater than 0.9. This type of relation indicated

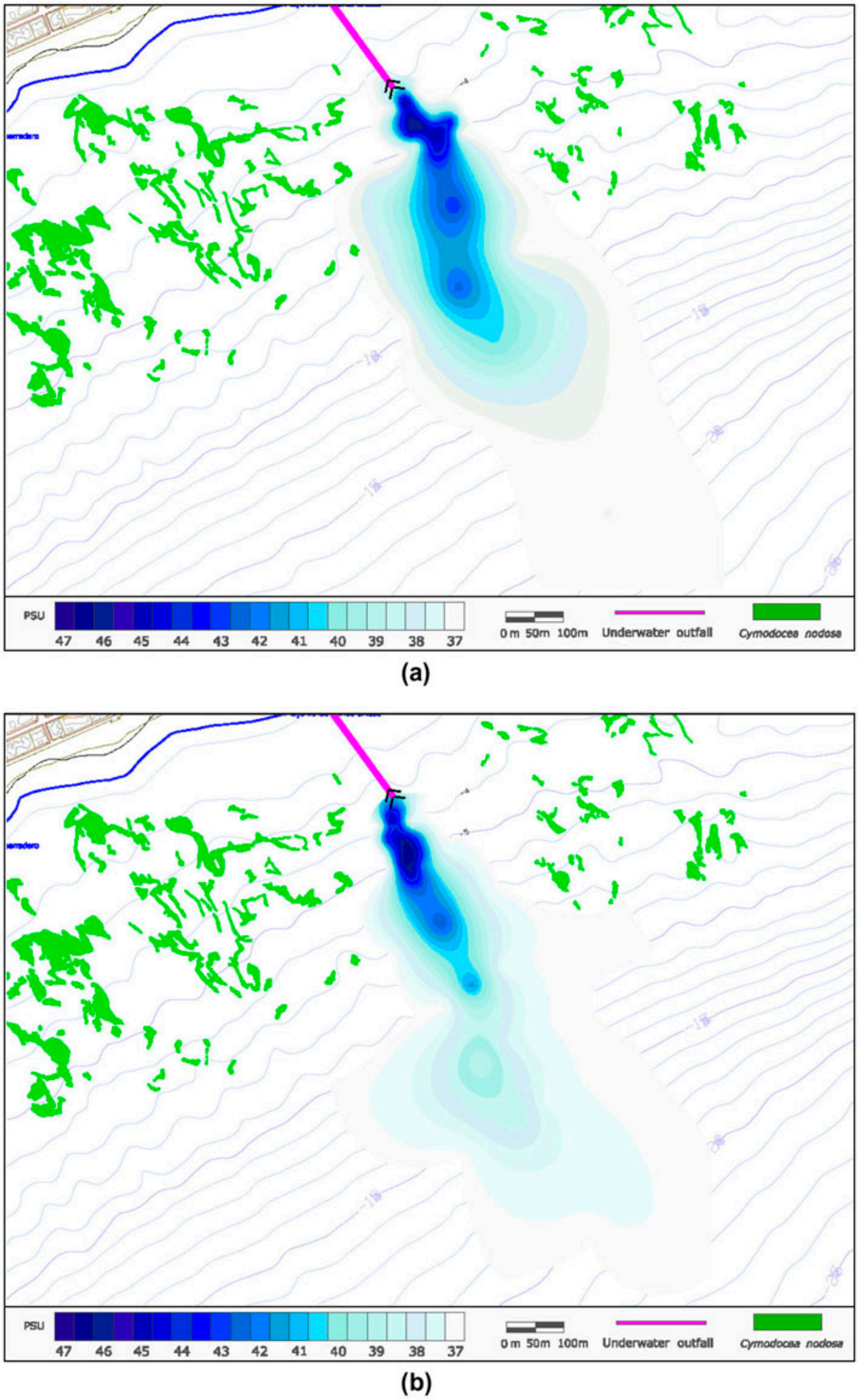


Fig. 3. Horizontal spatial distribution of the maximum salinities recorded on the bottom during sampling on: 22 July 2009 (a), 23 July 2009 (b), 29 September 2009 (c), 30 September 2009 (d), 30 March 2010 (e), 10 September 2010-a morning (f), 10 September 2010-b afternoon (g), and 17 January 2011 (h).

that a slight increase in low near-bottom current velocities has a greater repercussion on the percentage decrease of the areas of the affected zones than a slight increase in high velocities.

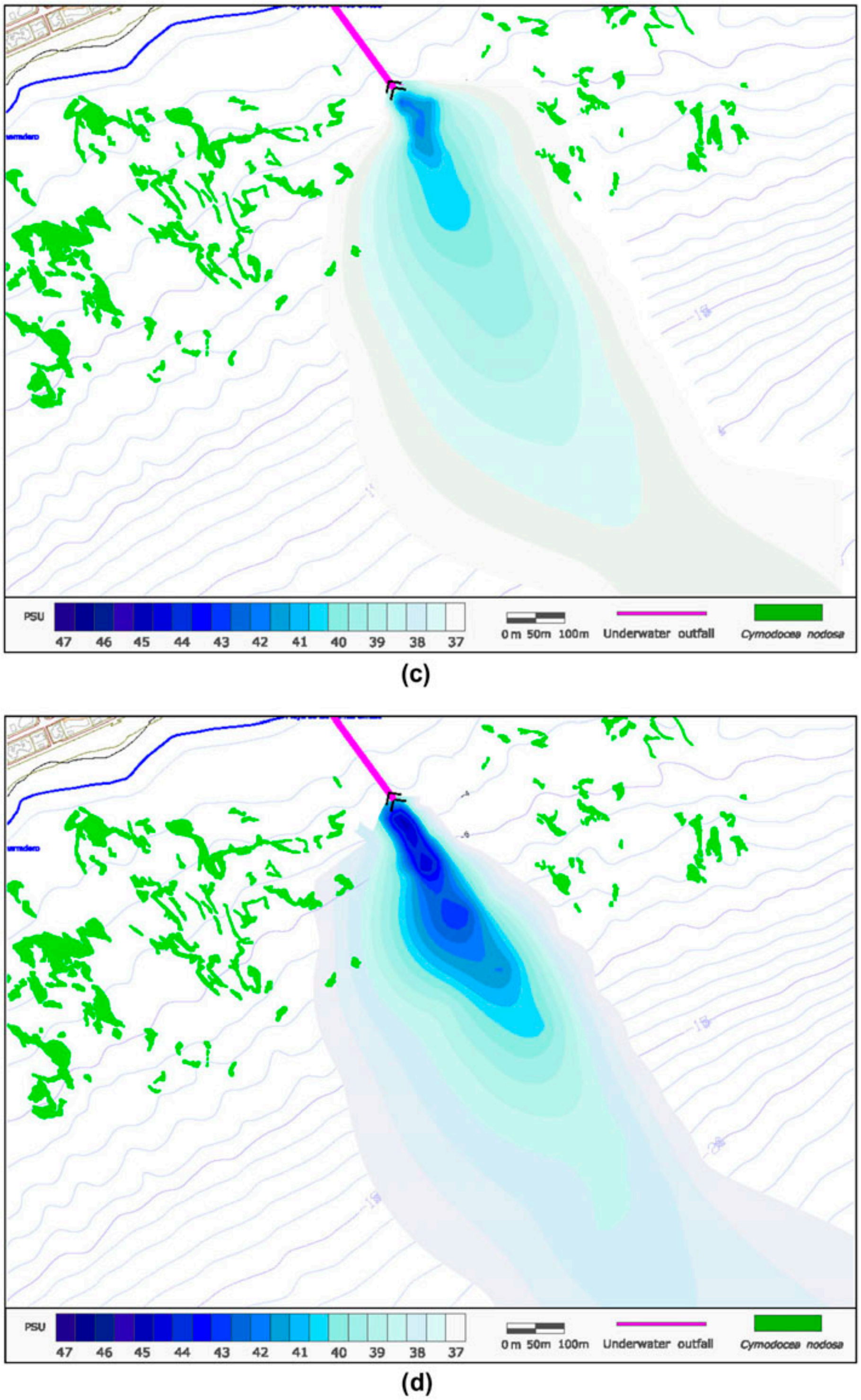


Fig. 3. (*Continued*)

4. Discussion

The small differences between discharge flows and salinities between sampling campaigns (Table 2), when the Maspalomas II desalination plant was operating at optimum level, were due to the slight variability in dilution occurring at the plant before discharge. This minor pre-dilution, which occurs when excess feed-water spills out of the feed tank into the drain and

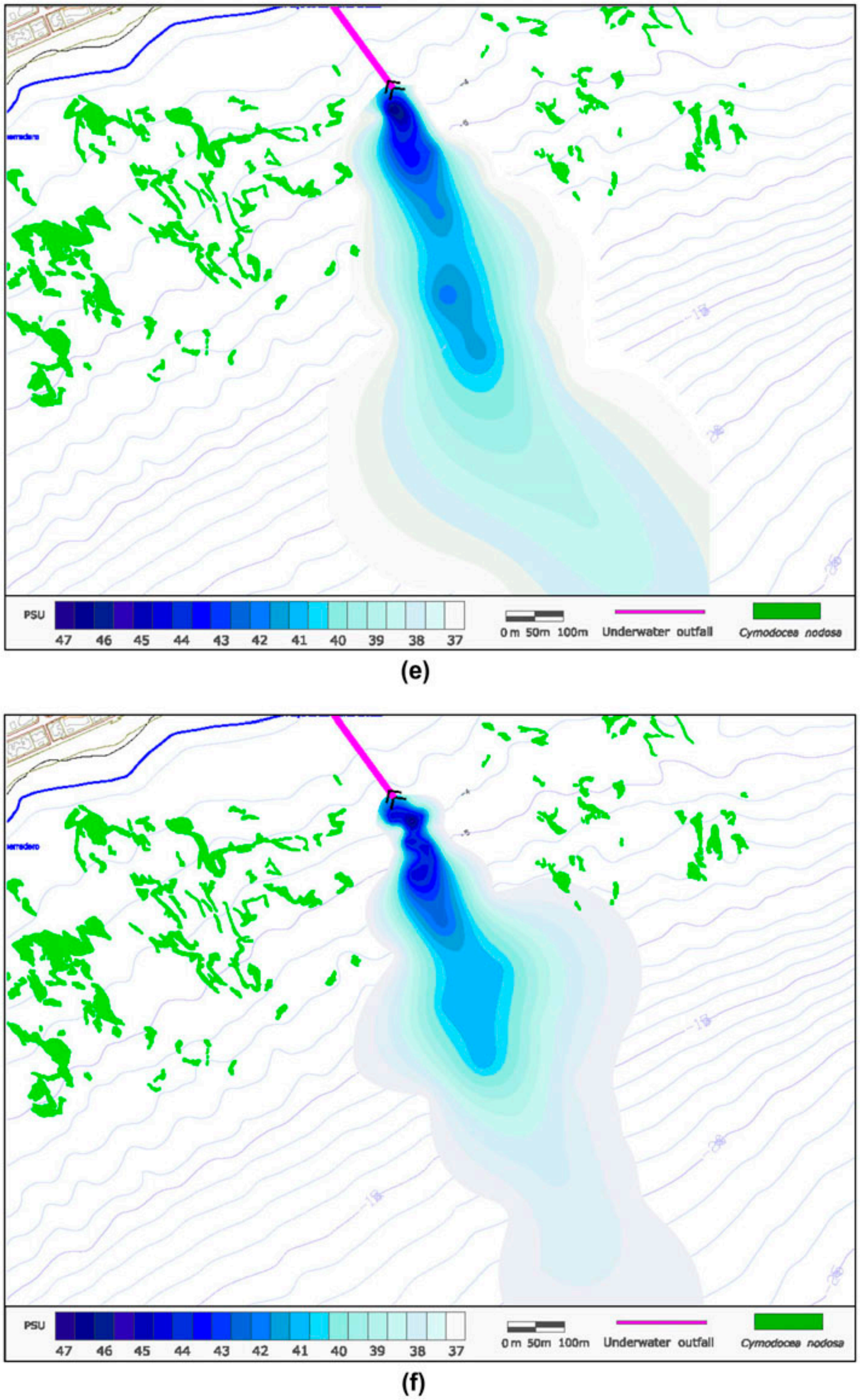
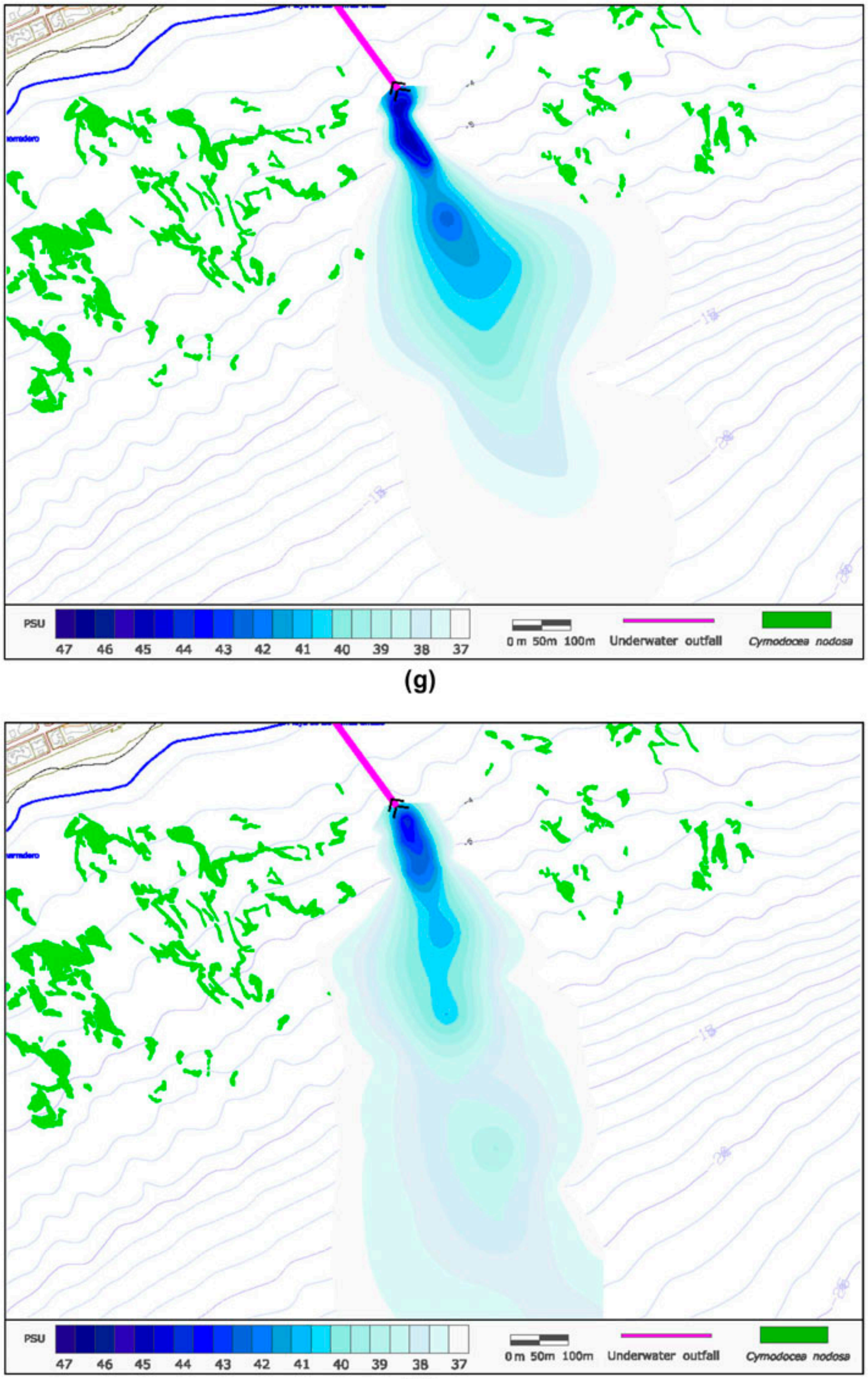


Fig. 3. (*Continued*)

mixes with the brine, depends on the variability and irregularity of the spillage and is responsible for the minor fluctuations detected in both the salinity and the flow of the discharge. As a result, the largest flows corresponded to the lowest salinities, as on 29 September 2009 and 17 January 2011, whereas in the campaigns with lower flows, the highest salinities were recorded (22 July and 30 September 2009).



(g)

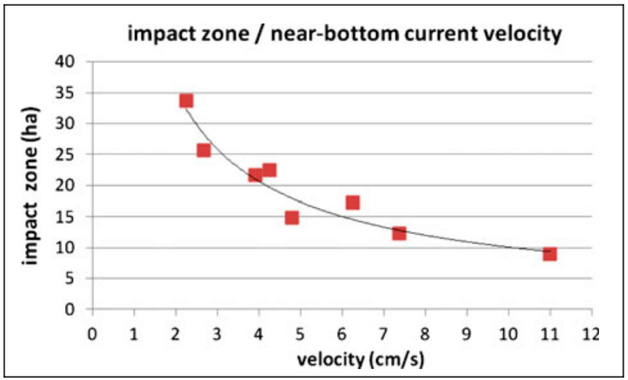
(h)

Fig. 3. (*Continued*)

Sampling was conducted under the usual meteorological and oceanographic conditions of the area, but with slight differences in waves, wind, and tides. These differences in hydrodynamic conditions were responsible for the variability of near-bottom current intensity between campaigns (Table 2), and near-bottom current, in turn, influenced the dispersion process of the plume over the sea bottom. Thus, near-bottom current velocity provided a reference parameter for the degree of hydrodynamic exposure of the receiving environment to assess the effect on the brine plume that spreads out over the sea floor.

The system of discharging into the sea used by this plant produced very low dilutions at the start of the far field, as salinities greater than 44 psu were recorded in the area near the discharge. This low dilution capacity of the plant discharge system was the result of the lack of a diffuser or reducer to produce the velocities recommended to generate a jet current with sufficient kinetic energy to favor rapid mixing and therefore dilution of the effluent [21–23,43–45]. The underwater outfall of the Maspalomas II desalination plant, with discharge through an outlet elbow at a single point with the same diameter as the outfall (600 mm), releases an average discharge flow of approximately 1,062 m^3/h, producing very low velocities of around 1 m/s at the outlet. In 2012, the technical feasibility of using venturi diffusers to enhance dilution processes at this desalination plant was studied [45]. Near-field sample collection to assess the dilution enhancement processes was conducted firstly with no diffuser system and then with diffuser systems in place. Discharge without a diffuser system did not behave as a typical jet discharge, as it did not manage to separate from the sea floor. The very low velocity formed almost no parabolic jet and therefore the brine discharge barely rose after emerging from the outfall, settling on the bottom in less than 5 m. This falls well short of a typical jet discharge system regarded as an efficient method for maximizing near-field dilution. Thus the discharge system of this plant worked as a simple spillway, producing very low dilutions and, as a result, a hypersaline plume with a high degree of stratification. The exchange and dilution processes after the hypersaline plume spreads out over the sea floor are very limited and slow and therefore this brine discharge spreads out over large areas and may affect the benthic communities present. However, in the study by Portillo et al. [45], incorporation of venturi eductors at the underwater outfall was sufficiently effective to eliminate the affected zones in the marine environment.

The hydrodynamic conditions had an effect on the differences in the range of the large affected zones formed. The brine discharges characterized during campaigns when near-bottom current velocities were low had much larger salinity fields than the plumes for campaigns when larger current velocities were recorded. The range of the salinity fields greater than 38 psu was in accordance with the progress of the near-bottom current velocities, maintaining a reasonable potential regression (determination coefficients > 0.9) that could explain their cause-effect relation (Fig. 4). According to this trend, the decrease of the area of influence corresponding to the spatial distribution of the salinity fields greater than 38 psu when near-bottom current velocity increases from 1 to 3 cm/s would be around 60%, whereas when it increases from 9 to 11 cm/s, the decrease would be only 7%. This potential trend type, which indicates how a slight increase in the low near-bottom current velocities had a greater repercussion on the percentage decrease of the areas of the affected zones than a slight increase in high velocities, could be explained through the dispersion process of the plume over the sea floor. As the hypersaline plume advances it widens and consequently its thickness and salinity field decrease [9]. This means that the outer edges of the hypersaline plume are less thick, on the one hand, and have less stratification because of their lower salinities, on the other hand. Situations of low hydrodynamism, where near-bottom current velocities were low, did not favor dilution of the outer edges of the plume and therefore the areas of influence corresponding to the horizontal spatial distribution of the salinity field greater than 38 psu attained much larger ranges. However, a slightly greater degree of hydrodynamic exposure, corresponding to slightly higher near-bottom current velocities, could have helped to enhance the mixing and dilution process at the edges of the plume, where less stratification occurred. Because of this, a higher degree of hydrodynamic exposure favored dilution of the outer edges of the plume and, as a result, reduction of the area of influence corresponding to salinity fields greater than 38 psu. In the central part of the plume or in areas with higher salinity fields (>42 psu), the thickness and degree of stratification



Total area impact zone (ha) = 61.24*(mean nearv-bottom current velocity (cm/s))$^{-0.78}$

($R^2 = 0.92$, n=8)

Fig. 4. Relation between mean near-bottom current velocity (cm/s) for each campaign and total area (ha) of the impact zone corresponding to the salinity field greater than 38 psu.

between the two layers is much greater and therefore in these areas much lower exchange and dilution processes are achieved even when a certain degree of hydrodynamic exposure occurs.

The few existing studies on the characterization of brine discharges from desalination plants have not estimated the effect of the hydrodynamic conditions on the dispersion processes, apart from the study by Payo et al. [11], which estimated the effect of waves on the dilution of brine discharge, but at a fixed point of observation of bottom salinity. This point was located inside the area of influence of the discharge from the Alicante I and II desalination plants on the southeast coast of Spain and it was observed how wave action increased near-bottom current velocities and dilution processes at this point. This effect of enhanced dilution processes when the near-bottom current velocity increased after significant wave episodes, although at only one point, concurs with the observations of the present study, where an increase in near-bottom current velocities favored the dilution processes on the outer edges of the impact zones and thus helped to reduce the impact zones. In the study by Fernández-Torquemada et al. [13], on the areas of influence of discharges from desalination plants in the southeast of Spain (Jávea, Alicante I and II and San Pedro del Pinatar), significant variation was observed depending on the varying production levels of the plants, the pre-dilution achieved and the characteristics of the discharge system (through outfall or channel, outfall length and discharge depth, with or without diffusers, etc.). Characterizations of these hypersaline plumes [13] could not be compared with those of the present study due to differences in the flows and salinities of the discharges and in the discharge systems. However, brine discharge behavior was similar in terms of dispersion over the sea floor in the direction, where bathymetry increased and in relation to the large ranges they achieve without appropriate management or action plans for the discharge system (diffuser system, pre-dilution, etc.).

5. Conclusion

This study shows how brine discharges from desalination plants form hypersaline plumes that spread out over the sea floor following the steepest gradients and extending over areas of influence that can vary considerably in size and range depending on the hydrodynamic conditions in the area. Affected zones were defined with salinity fields greater than 38 psu ranging in size from approximately 9–34 ha, corresponding to a maximum difference in size of almost four times. A higher near-bottom current velocity favored dilution of the outer edges of the plume and therefore helped to reduce the affected zone.

Acknowledgments

This study was conducted as part of the project "Technical feasibility study of venturi diffusers in desalination plant brine discharges to enhance the dilution process and reduce the environmental impact on marine ecosystems", under the Spanish National Programme for Experimental Development Projects, within the Ministry of the Environment and Rural and Marine Affairs, Environment and Eco-Innovation Sector, Management and Sustainable Uses of Natural Resources Subsection. The authors are grateful to A. Arencibia and F. Roch, from General Electrics, for their support, M. Antequera and A. Ruiz, from CEDEX, and J. McGrath, for translation of the manuscript from Spanish.

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