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Venturi diffusers as enhancing devices for the dilution process in desalination plant brine discharges

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ABSTRACT

Brine discharges from desalination plants spread out over broad spatial scales, affecting the benthic communities encountered along the way. Because of this, it is essential to develop technology enhancement initiatives for brine discharge processes that are economically feasible and effective for both planned and existing desalination plants. The technical feasibility of using venturi diffusers rather than conventional devices to enhance dilution processes was studied at the Maspalomas II desalination plant, in the south of the island of Gran Canaria (Canary Islands-Spain). The venturi eductors needed very high exit velocities ($\geqslant$11 m/s) to reach the pressure difference required to produce the suction effect of these devices. At these velocities, the venturi eductors were more efficient than conventional diffusers, as they achieved much higher dilutions of around 39 as opposed to 27. Dilutions as high as these are not only very useful, but also necessary, as part of the island's largest and most ecologically important seagrass meadow of *Cymodocea nodosa* is found nearby.

Keywords: Brine discharges; Desalination; Diffusers; Eductor; Venturi; Dilution; Seagrasses; *Cymodocea nodosa*

1. Introduction

Brine from desalination processes is normally discharged directly into the sea, forming a very dense plume of water that spreads out over the sea floor following the steepest gradients [1]. The area around the discharge point is known as the near field. High initial dilution normally occurs in this area, as the kinetic energy of the effluent reaching the sea causes turbulence that produces rapid mixing with the water in

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the receiving environment [2]. However, at a certain distance from the discharge point, where the movement of the effluent and the associated turbulence collapse, the brine sinks due to its greater density, forming a hypersaline plume that spreads out over the sea floor virtually undiluted [3,4]. This means that the hypersaline plumes from these discharges spread over large areas [5] and can affect the benthic communities encountered along the way [4,6–12]. The impact of brine discharges on the marine ecosystem increasingly needs further attention and study, particularly in relation to seagrass meadows. Despite the high ecological importance of seagrass meadows, it is only recently that the effect of hypersaline plumes on these ecosystems has come to light. A few studies to date have revealed the high sensitivity of marine phanerogam *Posidonia oceanica* (L.) Delile to small increases in salinity [13–17] and the long-term effect on plant vitality [18]. Studies undertaken both on site and in the laboratory about the effect of increased brine on *P. oceanica* recommended that salinity should be no higher than 38.5 or 40 psu in more than 25 or 5% of observations, respectively, in any part of the seagrass meadow [16,19].

The findings of these studies have led the scientific community to take into account the effect of hypersaline discharges from industrial desalination processes on seagrass meadows and define an overall protection strategy. As a result, for desalination plants already up and running attempts are being made to assess and implement possible corrective and mitigating measures such as diluting reject water before discharge, mixing it with treated water, increasing exit diffusers and extending the outfall to deeper or more hydrodynamic zones. In terms of planning and siting new desalination plants, consideration is being given to new designs, strategies and recommendations to avoid very harmful effects on environments with the high sensitivity of seagrass meadows [6,20–22].

Thus the future of potable water production through desalination makes it essential to develop technological enhancements in the discharge processes that are economically feasible and effective for both planned and existing desalination plants.

Venturi effect technology applied to mixing processes has already been tested and is used in many different dilution processes, both in the chemical and the oil industry and more recently in the ornamental fish industry, as it efficiently mixes liquids of different densities, eliminates stratification and aids standardization in relation to pH, temperature, distribution of chemicals and dispersion of gases and solids. However, no proposals have been made to use this technology for discharge through outfall. The novelty of applying this technology to this type of discharge lies in attaching a trumpet-shaped venturi effect unit at the front of conventional diffuser nozzles to form the venturi eductor (Fig. 1). Conventional diffuser nozzles have to attain high velocities through reduction of their diameter to produce the venturi effect in the structure. After passing through the reducer nozzle (conventional diffuser nozzle), the brine enters the trumpet-shaped structure at a high velocity. The width of this structure decreases towards the neck with a smaller diameter, increasing once more after this point. The difference in the velocity of the discharge when it passes through the narrowest section of the structure in comparison with the velocity in the wider section creates a drop in pressure, causing ambient water to be suctioned through the structure. The suction zone of these structures is 360° around the narrow section and therefore this large zone could ensure dilution of as much as 1–4, depending on the pressure differential generated for it to work properly. This would enhance the mixing capacity between the brine and the seawater suctioned into the structure right at the exit of the device, enhancing near-field dilution processes at the same time.

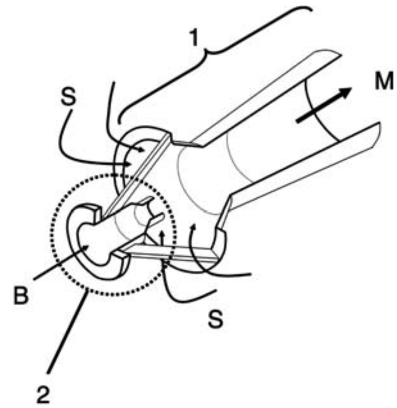


Fig. 1. Venturi eductor: Diffuser system comprising a conventional diffuser nozzle, or reducer nozzle (2), where the exit velocity of the brine discharge increases (B) after attachment of a venturi effect trumpet-shaped structure (1) through which ambient water is suctioned (S); the mixture emerges through the exit (M).

The technical feasibility of using venturi eductors rather than conventional devices to enhance dilution processes is yet to be determined. Studies designed to acquire this knowledge would therefore be of great interest for enhancing discharge processes in the desalination industry. Installing venturi eductors could help to reduce the environmental impact of brine discharges at a low cost in terms of equipment, infrastructure and maintenance.

A number of considerations and recommendations have been made in relation to appropriate exit velocities of brine jet discharge. Whereas velocities of around 4–6 m/s would ensure optimization of near-field dilution processes, velocities less than 3.5 m/s would mitigate possible effects on fish larvae and juveniles in the area [23]. The US Environmental Protection Agency (EPA) Technical Support Document For Water Quality-based Toxics Control [24] suggests using minimum discharge velocities of 3 m/s to achieve a jet flow with sufficient kinetic energy to favor rapid mixing and subsequent dilution of brine discharge, at the same time decreasing the likelihood of the diffusers becoming obstructed. The EPA [24] also recommends that if exit velocities exceed 3 m/s, the mixing zone should be no larger in any direction than 50 times the discharge length scale, defined as the square root of the cross-sectional area of any discharge pipe. Current Spanish legislation [25] recommends exceeding the minimum exit velocities of 0.6 and 0.8 m/s, but does not include criteria for maximum velocities, unlike the previous Law, which established a maximum velocity of 5 m/s. To use venturi eductors, velocities higher than these sources recommend would be required to generate the suction effect of the devices. However, these high velocities would occur inside the venturi eductor, decreasing as the diameter widens towards the exit. Therefore, both the discharge velocities right at the eductor exit and the suction velocities would be within the range of velocities normally used in conventional diffusers.

This study analyses the technical, financial and environmental feasibility of this technology for desalination plant brine discharge and its efficiency in comparison with conventional diffusers. The Maspalomas II Desalination Plant, in the south of the island of Gran Canaria (Canary Islands-Spain) was chosen for the study, given that:

- it discharges a large flow of brine;
- at quite high salinity (⩾69 psu);
- with no diffuser system of any kind; and
- over part of the island's largest and most ecologically important seagrass meadow.

2. Material and methods

2.1. Description of brine discharge and study area

The Maspalomas II reverse osmosis desalination plant, brought into service in 1988, is in the south of the island of Gran Canaria (Canary Islands-Spain) on the left side of the Barranco del Toro ravine, 500 m from the sea between the important tourism beaches of Playa de Las Burras and Playa del Cochino (Fig. 2).

The plant production is generated through six reverse osmosis racks connected to four additional concentrators that attain an average potable water capacity of around 944 m^3/h. The final conversion factor is approximately 50%, which means that a brine discharge of 944 m^3/h with an average salinity of 73.6 psu is commonly generated. The pumping station is in the southernmost part of Playa de Las Burras, very near an artificial breakwater (Fig. 2), and although the feedwater requirements are around 1,888 m^3/h, an average flow of 2,000 m^3/h is pumped. In this way, the plant operating conditions are optimized and the 188 m^3/h excess seawater is used to pre-dilute the brine to reduce discharge salinity to around 69.5 psu (habitual pre-dilution rate approximately 1:0.12) and attain a final flow of 1,062 m^3/h. 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 (Fig. 2). This seawater is stored at the plant in a 4,000 m^3 tank, from where excess intake seawater spills out and mixes with the brine in the discharge drain. The discharge mixture (brine and excess feedwater) is channeled through an underground polyvinyl chloride (PVC) pipeline with a length of 500 m and a diameter of

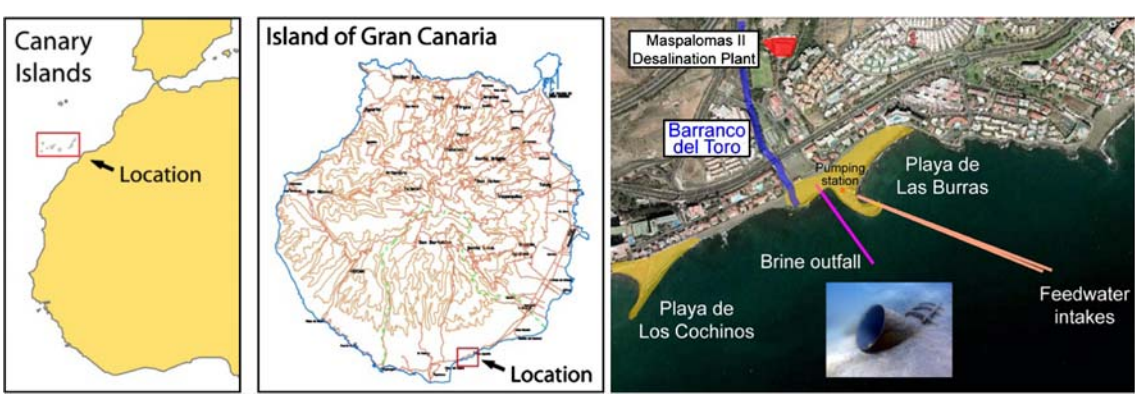


Fig. 2. Location of Maspalomas II desalination plant and underwater outfall.

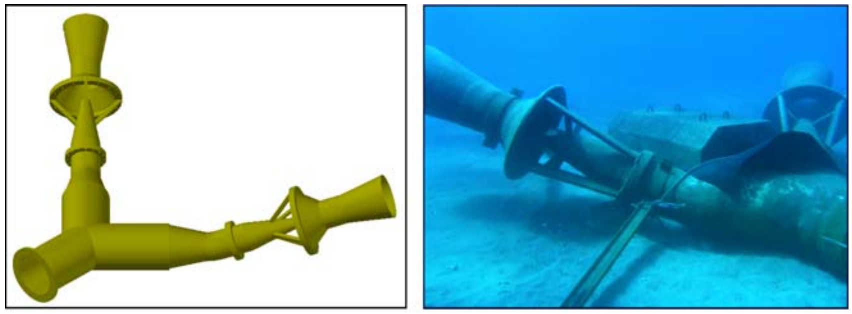


Fig. 3. Diffuser system with Y bifurcation and 90˚ aperture from where the two branches decreasing from 600/400 mm Ø lead off, where the conventional diffuser nozzles with reduced outlets of 130 mm Ø are inserted, with the venturi effect suction unit incorporating replaceable and interchangeable attachment systems: (a) image of the design, (b) photo of the device in place.

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, also with a 600 m diameter, made of cast iron. The underwater outfall has no diffuser system and discharges through a single point with the same diameter as the pipe through an outlet elbow at a vertical angle of 42.5˚ to the sea bottom (Fig. 2), at a depth of 4 m at mean low water spring tide.

The discharge area is on a wide sandy bottom with a shallow gradient of 1.6%, with a depth of 20 m 1,000 m from shore and 35 m 2,100 m from shore. This area is home to the island's largest and most ecologically important seagrass meadow of *Cymodocea nodosa* (Ucria) Asherson, which has been declared both a Site of Community Interest under the name of *Sebadales de Playa del Inglés* (Playa del Inglés Seagrass Meadows)—ES7010056—[26] and a Special Area of Conservation [27]. The underwater outfall discharges inside this large area, over a zone where one of the largest seagrass meadows is found, at Playa del Cochino. This patchy, fragmented seagrass meadow occupies an area of 15.2 ha, has a population size of 1.5 ha and occurs at depths of 4–10 m [28].

2.2. Design and construction of the venturi diffuser system

For the design of the venturi diffuser system at the Maspalomas II desalination plant the following had to be taken into account:

- optimization of the venturi eductor by attaining the differential pressure required to generate the greatest possible suction;
- determination of the manometric conditions, discharge capacity and performance curve of the plant discharge outfall, which must not require an additional pump or impulsion system;
- the maximum exit velocities must not cause drops in pressure that could lead to problems of cavitation in the eductor;
- choice of unalterable materials compatible with a custom design;
- the diffuser system must be modular, with interchangeable parts, to assess the efficiency of the dilution effect with and without the suction units;
- the characteristics of the outfall discharge area (depth, sea bottom type and swell window) must avoid impact on the sea surface or bottom; and
- earlier theory studies through mathematical models based on the technical note by Jirka [29], on the United States Environmental Protection Agency supported Cormix Modeling System [30] for near-field mixing predictions, and physical model experiments conducted by CEDEX [31] at a scale of 1:18, with various diffuser system configurations (number of diffusers, angle of inclination of the diffuser in relation to the sea bottom, exit velocity, etc.).

In line with these considerations, it was decided to use a design attached right at the exit point, with a 90˚ Y bifurcation from where the two branches with 600/400 mm diameter reductions lead off, where the reducer nozzles were inserted (conventional diffusers) (Fig. 3(a)). The angle of inclination in relation to the sea bottom finally chosen was small, at just 15˚. Although it did not reproduce the jet discharge with higher dilution capacity, it did stop the jet discharge from emerging onto the surface, even in the most adverse conditions with twice the flow and at low spring tide. This prevented the effects of the jet interacting with the surface, which would lead to lower dilution and in particular a visual impact of brine bubbling or rising above the surface close to a beach of major importance for tourism. The venturi effect suction units were joined onto the reducer nozzles through modular attachment systems so they would be replaceable and interchangeable (Fig. 3(a) and (b)). The diameter of the two conventional diffuser nozzles was decreased to 130 mm to achieve exit velocities greater than 11 m/s that would cause a differential pressure greater than 10 psi in the trumpet-shaped structure and thus ensure the suction of the venturi effect devices: 4 units of volume of ambient seawater to 1 of brine output. The venturi effect unit, however, had an aperture in the suction area with a diameter of around 810 mm, decreasing to 400 mm and then increasing again to 620 mm at the outlet. In this way the theoretical suction velocity was less than 3 m/s and the velocity of the mixture flow on exiting the narrow section of the eductor was around 6 m/s and slightly lower right at the exit, where the diameter was largest (620 mm). The system was built from fiberglass reinforced polyester and secured to the sea floor with clamps and mooring blocks (Fig. 3(b)).

2.3. Near-field sampling

Near-field sample collection to assess the dilution enhancement processes was conducted firstly without the diffuser system and then after the system had been incorporated, with the reducer nozzle (conventional diffuser) and then with the venturi effect unit.

Sampling consisted of characterizing the process of discharge, dispersion and dilution of the discharge system in the near field through three profiles taken at three very significant points representative of this behavior. These were:

- maximum height of rise;
- jet centerline position at point of impingement; and
- the start of the far field, where the brine plume begins to travel over the sea bottom without turbulence and the water column becomes a well-defined two-layer fluid.

After incorporation of the diffuser system, sampling was conducted over the discharge area of the reducer nozzle (with and without the venturi effect unit) in the northernmost area, as various sample collections and preliminary studies showed that both nozzles had the same jet discharge behavior as well as the same dispersion and dilution process.

Near-field sampling was carried out:

- when the desalination plant was operating under normal conditions, with all the osmosis racks and concentrators in optimal functioning;
- under the usual meteorological and oceanographic conditions of the area;
- with technical and human logistics support from a 5 m rigid polyethylene boat and divers for underwater work to:
  - identify the sample points by adding rhodamine (Photo 1(a), (b), (c));
  - mark sample points with marker buoys;
  - measure the distances from the discharge area to these points; and
  - lower and raise the sensors at these points (Photo 2(a) and (b)).

During each sample collection a YSI-6600-V2 multiparameter sensor was used to measure the vertical profile of the salinity and temperature, in addition to control parameters (pH and dissolved oxygen). Salinity was determined automatically from the temperature readings and sensor conductivity in accordance with the algorithms in *Standard Methods for the Examination of Water and Waste Water* [32]. Using the Practical Salinity Scale produces values without units when taking measurements in relation to the conductivity of a standard solution of 32.4356 g of KCl at 15˚C in 1 kg [33,34], although they are conventionally presented as

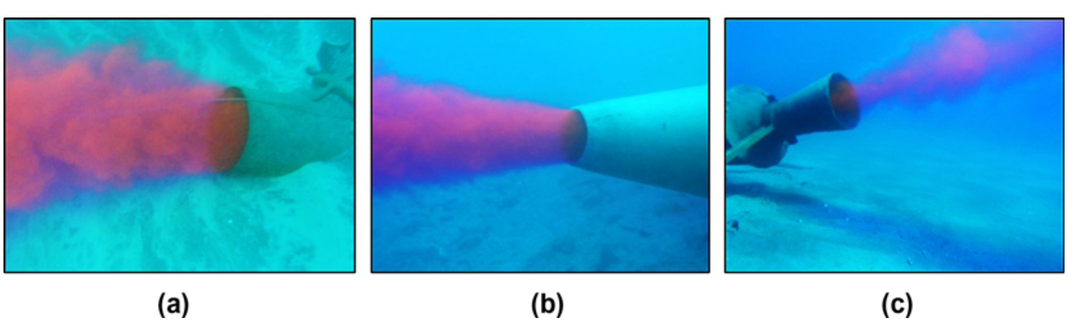


Photo 1. Addition of rhodamine during near-field sampling: (a) with no diffuser system; (b) with the reducer nozzle; and (c) with the suction unit.

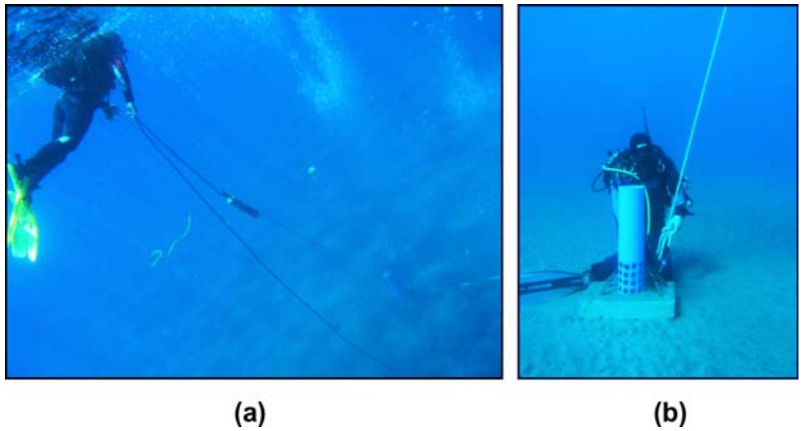


Photo 2. (a) Profile of the start of the far field, showing the diver holding the marker buoy rope tight and lowering a YSI-6600-V2 multiparameter sensor to the sea bottom, where the other sensor is anchored and taking continuous measurements; (b) Perforated cylindrical PVC tube attached to a mooring block (weighing approximately 50 kg fully loaded) to anchor a second YSI-6600-V2 multiparameter sensor in a vertical position.

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. Dissolved oxygen was determined as a percentage of dissolved oxygen saturation (ODO%). The sensor was lowered for 30 s to a depth of 0.5 m to stabilize the measuring of the various parameters and then attached to each marker buoy rope to act as a guide for the profile. With the assistance of a diver, the rope was kept as vertical and as tight as possible while the sensor was lowered and raised very slowly at a rate of 5 cm/s (Photo 2(a)). The interval between the samples was 1 s and in the profile at the start of the far field the sensor was kept on the sea floor for 10 min.

At the start of the far field, continuous recordings were made of the temporal stability of the dilution capacity of each type of discharge and its possible relation to the hydrodynamic conditions or to slight variations in discharge velocity and salinity as a way to assess these variables. The temporal recordings were obtained by anchoring another YSI-6600-V2 multiparameter sensor (Photo 2(a) and (b)) during and after the corresponding near-field sampling. The sampling period was 2–3 days while the desalination plant remained operating in optimum conditions, with a sampling interval of 60 s. The sensor was anchored using a perforated cylindrical PVC tube attached to a mooring block (weighing approximately 50 kg fully loaded). It was secured vertically to avoid sand sedimentation inside the conductivity meter over time and erroneous readings that could occur as a result (Photo 2(b)). For a better comparative study between the two diffuser systems (reducer nozzle only and with venturi eductor), the continuous reading was taken at the same distance, corresponding to the distance from the start of the far field observed in near-field sampling with the venturi eductor.

Salinity and other brine discharge variables could not be continuously recorded using a YSI-6600-V2 sensor, as it was impracticable to take readings inside the discharge point after the diffuser system had been attached due to the high dynamic pressure of the jet discharge from the reducer nozzle. Continuous recording at the desalination plant, inside the discharge drain, was not possible either, as unstable readings were obtained due to the major turbulence after draining and discharging the brine and the spillage from the excess feedwater into the drain from some height. Salinity in the receiving environment was determined by taking discharge samples every 2 min during near-field sampling and three times a day (morning, midday and afternoon) while the sensor was anchored at the start of the far field. For these samples, salinity and other physical and chemical variables were measured directly using the YSI-6600-V2 sensor. The three YSI-6600-V2 multiparametric sensors were calibrated at the same time the day before each sampling campaign in accordance with the calibration manual. Velocity fluctuations could be controlled in the near-field campaigns using the individual readings from the various flow meters, although for the study over time these could be determined only through individual readings taken three times a day (morning, midday and afternoon).

The dilution of each discharge system was calculated as ([brine discharge salinity—seawater salinity]/

[salinity at the sample point—seawater salinity]), which means it was an adimensional value.

A SONTEK ADCP Argonaut XR current profiler was lowered at the start of the far field to assess and analyze the possible effects of the hydrodynamic conditions on the dilution processes in the near field. The frequency was 0.75 MHz and the sampling interval was 20 min. To obtain weather information an anemometric station was installed on a 5 m high tower on the roof of the pumping station building, measuring wind speed and direction.

The average current speed recorded by the current profiler in the water column layers was taken as the hydrodynamic exposure the effluent was subjected to near the discharge point.

3. Results

Table 1 shows the distinguishing parameters (salinity, flow and discharge velocity) of the three discharge systems (no diffuser system, after incorporation of the reducer nozzle, and in conjunction with the venturi effect unit) during near-field sampling, the distances measured from the discharge area to the sampling points, the minimum dilutions, and the current velocity for profiling the start of the far field. Ambient seawater salinity remained practically constant, with slight variations of less than 0.2 psu, whereas the discharge salinities showed some differences, of up to 4 psu between the sampling campaigns with diffuser systems. The salinity of the venturi eductor was 70.4 psu in comparison with a lower salinity of 66.55 during sampling with reducer nozzles and 67 psu with no diffuser system. The discharge flows also showed small variations between campaigns, of less than 2%. The exit velocities with the two diffuser systems were around 10 times higher than with no diffuser system. The velocity with no diffuser system was very low, at barely 1 m/s, whereas the velocities generated through the diffuser system were much greater and almost identical, at 12.01 m/s in February 2012 with the reducer nozzles and a little lower, at 11.9 m/s, in July 2011 with the venturi eductor. The distances from the discharge area to the three sampling points also differed considerably between the system with and without the diffuser and also between the two diffuser systems (with and without the venturi effect unit). The range of the near field without the diffuser system was very limited, at less than 12 m, whereas with the venturi eductor the distance tripled even though the discharge occurred simultaneously at two outlets and therefore with half the flow. The distances from the discharge area to the point of impingement and the start of the far field varied significantly between the diffuser system without and with the venturi effect suction unit, decreasing from 18 to 16 m and increasing from 30 to 36 m, respectively, and in contrast, the distances to the maximum point of rise were similar, more than five times the distance with no diffuser system, at 10 m as opposed to 2 m. The corresponding dilutions for each discharge system and sampling point showed the inability of the original discharge system to carry out mixing. Dilution at the start of the far field was 3.3 in comparison with dilutions almost 9 or 12 times greater with the reducer nozzle and the venturi eductor, respectively. The enhanced dilution capacity of the system after the incorporation of the suction unit in comparison with the system with reducer nozzles only, both at the point of impingement and the start of the far field, was approximately 20 and 35%, respectively, even though the current velocity in the receiving environment was higher without the venturi effect suction unit. Current velocity during profiling at the start of the far field was 10.2 cm/s without the suction unit and 5.7 cm/s after it was attached.

The profiles obtained by the sounder in the water column and at the three sampling points for each discharge system are shown in Fig. 4, where the differences in variation in the profiles on coming into contact with the brine discharge can be seen. For the discharge system with no diffuser system the parameters—salinity, temperature, pH and ODO%—showed an abrupt, sudden change with depth, with much more marked variations than after incorporation of the two diffuser systems. In the profile at the sampling point of the maximum height of rise (Fig. 4(a)), salinity increased abruptly only when the bottom was reached and therefore showed no change in the middle of the water column. A maximum of 61 psu was obtained 0.9 m from the bottom and then a slight decrease occurred to 52 psu on the bottom, which means that this discharge system, with no diffuser system of any kind, produced very little parabolic motion, with discharge barely separating from the bottom and low dilution capacity. Beyond the mixing zone, the discharge still showed increased salinity compared to the receiving environment of up to 9 psu. Once the two diffuser systems had been attached, the salinity profiles (Fig. 4(b) and (c)) at this sampling point also varied rapidly, but in the middle of the water column and with less intensity. In this case, the halocline appeared at a depth of 3–5 m, making it possible to observe how the discharge jet rose around 2 m off the sea floor, with a thickness of approximately 2 m in the case of the system with the venturi eductor and a little less for the system with reducer nozzle only. The maximum salinity readings for the eductor

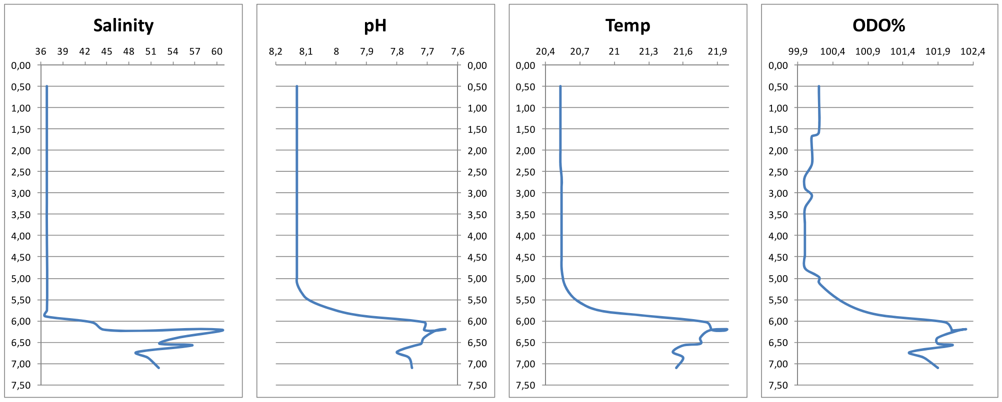
Table 1
Salinity of the brine and its receiving environment; flow and discharge velocity of the brine in the discharge systems studied and dates of sampling; measurements of the distances from the discharge area to the sampling points; respective minimum dilutions and current velocity for profiling at the start of the far field

Parameter/ discharge system	Brine salinity (psu)	Seawater salinity (psu)	Brine flow (m^3/h)	Discharg evelocity (m/s)	Xmax: distance to maximum height of rise (m)	Dilution in Xmax (Smax)	Xi: distance to point of impingement (m)	Dilution in Xi (Si)	Xff: distance to start of far field (m)	Dilution in Xff (Sff)	Current velocity (cm/s)
No diffuser 14/01/2011	67.00	36.8	1157.3	1.14	2	1.2	4.5	2.0	12	3.3	9.4
With reducer nozzle 24/02/2012	66.55	36.68	1147.8	12.01	10	13.3	18	20.2	30	28.2	10.12
Venturi eductor 27/07/2011	70.4	36.61	1137.9	11.9	10	15.4	16	24.3	36	38	5.7

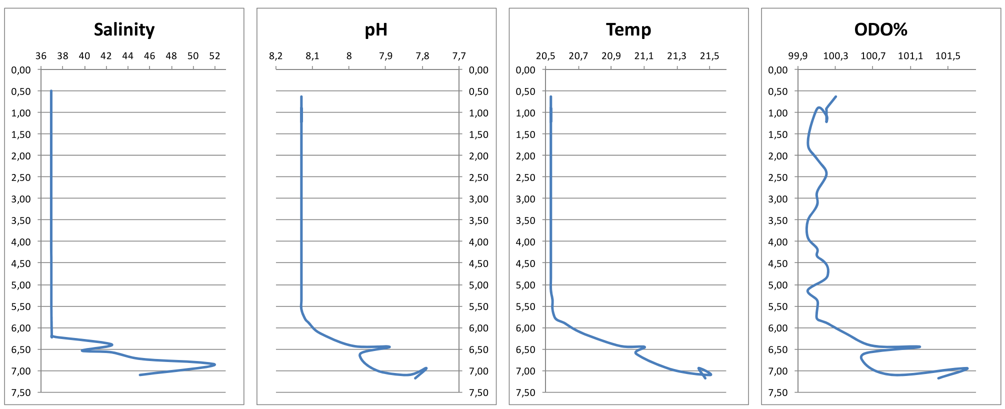
were 38.8 psu in comparison with 38.93 psu for the diffuser system with reducer nozzle only and therefore the variations in salinity were not as abrupt as they were with no diffuser system. The other variables—temperature, pH and ODO%—followed the same pattern as salinity, but with much slighter variations with the two diffuser systems. Whereas temperature, pH and ODO% varied considerably with no diffuser system, with differences of around 1.4℃, 0.5 pH units, and 2.4%, respectively, these parameters varied less with reducer nozzles only (0.15℃, 0.04 pH units and 0.6%), showing almost no variation with the venturi eductor. The profiles of the variables at the point of impingement were similar to those at the start of the far field for each discharge system, although the former showed greater irregularity and percentage variation. At this point the maximum salinities registered in the profiles with no diffuser system, with reducer nozzles only, and with the venturi eductor were 52, 38.16 and 38 psu, respectively.

The profiles obtained at the start of the far field showed the high dilution capacity of the two discharge systems with diffuser in comparison with the original system, as well as the difference between the two diffuser systems. In these profiles it was seen how the diffuser systems, with reducer nozzle only and with the venturi effect unit attached, were able to reduce the excess salinity of the discharge by 28.81 and 32.9 psu, respectively, in a distance of barely 30 m, whereas with no diffuser system the reduction was much lower, at only 21 psu. The dilutions corresponding to these decreased salinities at the three sampling points and for each system (Table 1) indicated the greater efficiency of the dilution processes with the venturi eductor in comparison with conventional diffusers, whereas dilutions were minimal with no diffuser system. The diffuser system with reducer nozzles but without the venturi effect unit attained very high dilutions of more than 28 due to the effect of the high exit velocities and in spite of such a low angle of inclination (15°) of the diffuser in relation to the sea bottom. However, the venturi eductor improved these dilutions by almost 35%, attaining minimum dilutions of around 38 in less favorable hydrodynamic conditions; i.e. with much smaller current velocities during sampling.

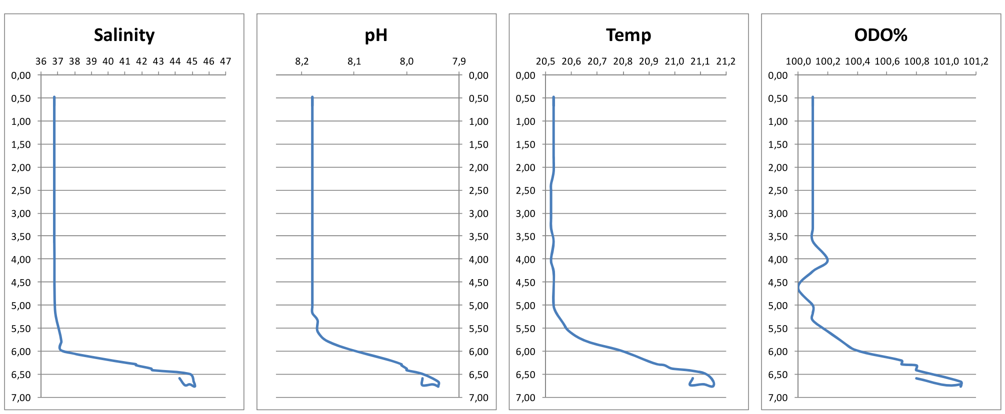
Fig. 5 is a scale representation of the longitudinal distribution of the discharge systems based on the site measurements of the distances to the sampling points and on the profiles at these points. The graphical representation shows the difference between their behavior in the discharge, dispersion and dilution process in the near field.



Profile maximum height of rise 2 m from discharge point (no diffuser)



Profile point of impingement 4.5 m from discharge point (no diffuser)

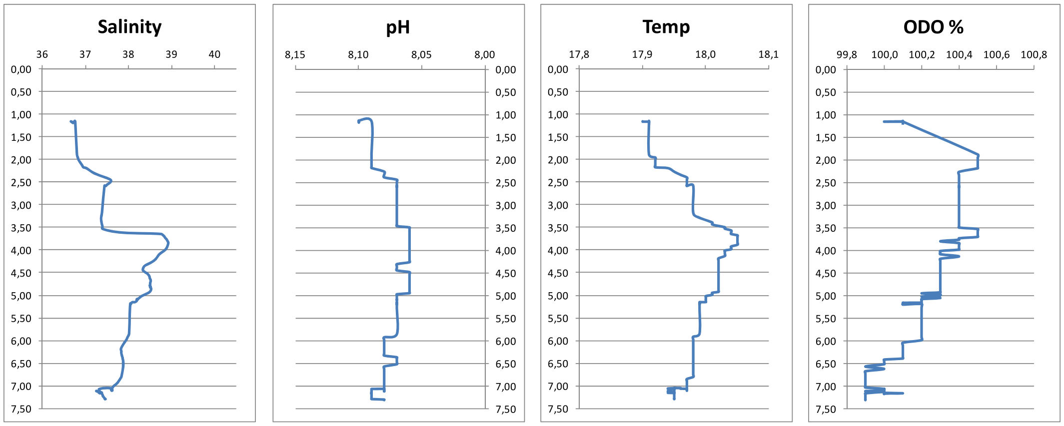


Profile start of the far field 10 m from discharge point (no diffuser)

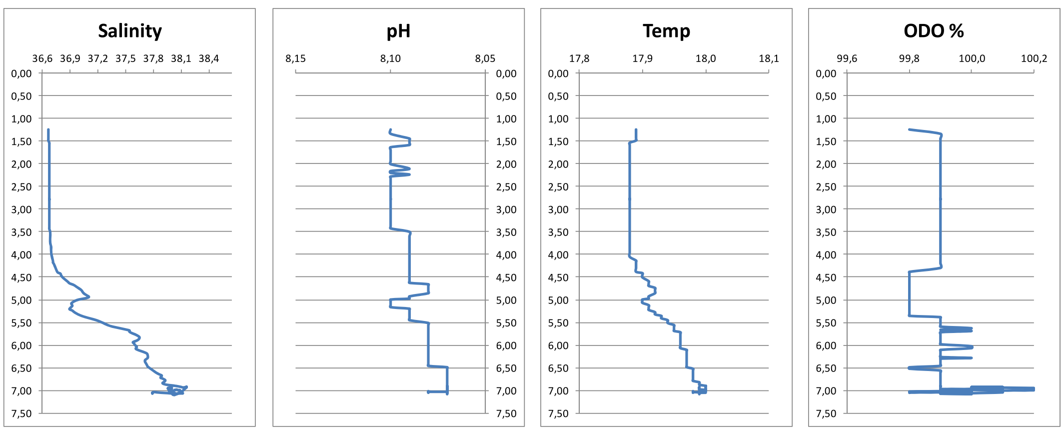
(a)

Fig. 4. (*Continued*)

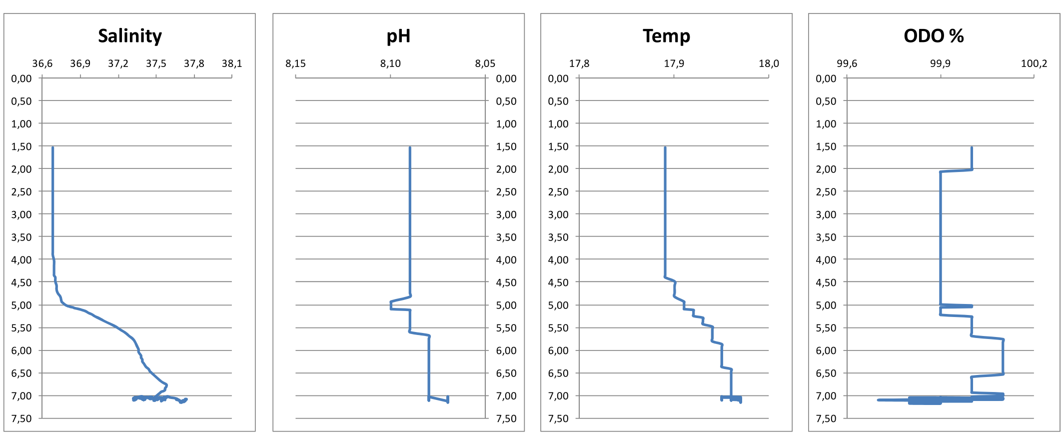
In this representation it is easier to see how the discharge system with no diffuser system did not behave as a typical jet discharge, as it did not manage to separate from the sea floor. It can also be seen how in just a few meters all the brine sank. The resulting plume was less than 1 m thick, whereas with the two



Profile maximum height of rise 10 m from discharge point (with reducer nozzle)



Profile point of impingement 18 m from discharge point (with reducer nozzle)



Profile start of the far field 30 m from discharge point (with reducer nozzle)

(b)

Fig. 4. (*Continued*)

diffuser systems the plume was almost twice as thick. Moreover, it was clear how the discharge systems with reducer nozzle and with the venturi effect unit, as a result of the high exit velocities, produced a jet

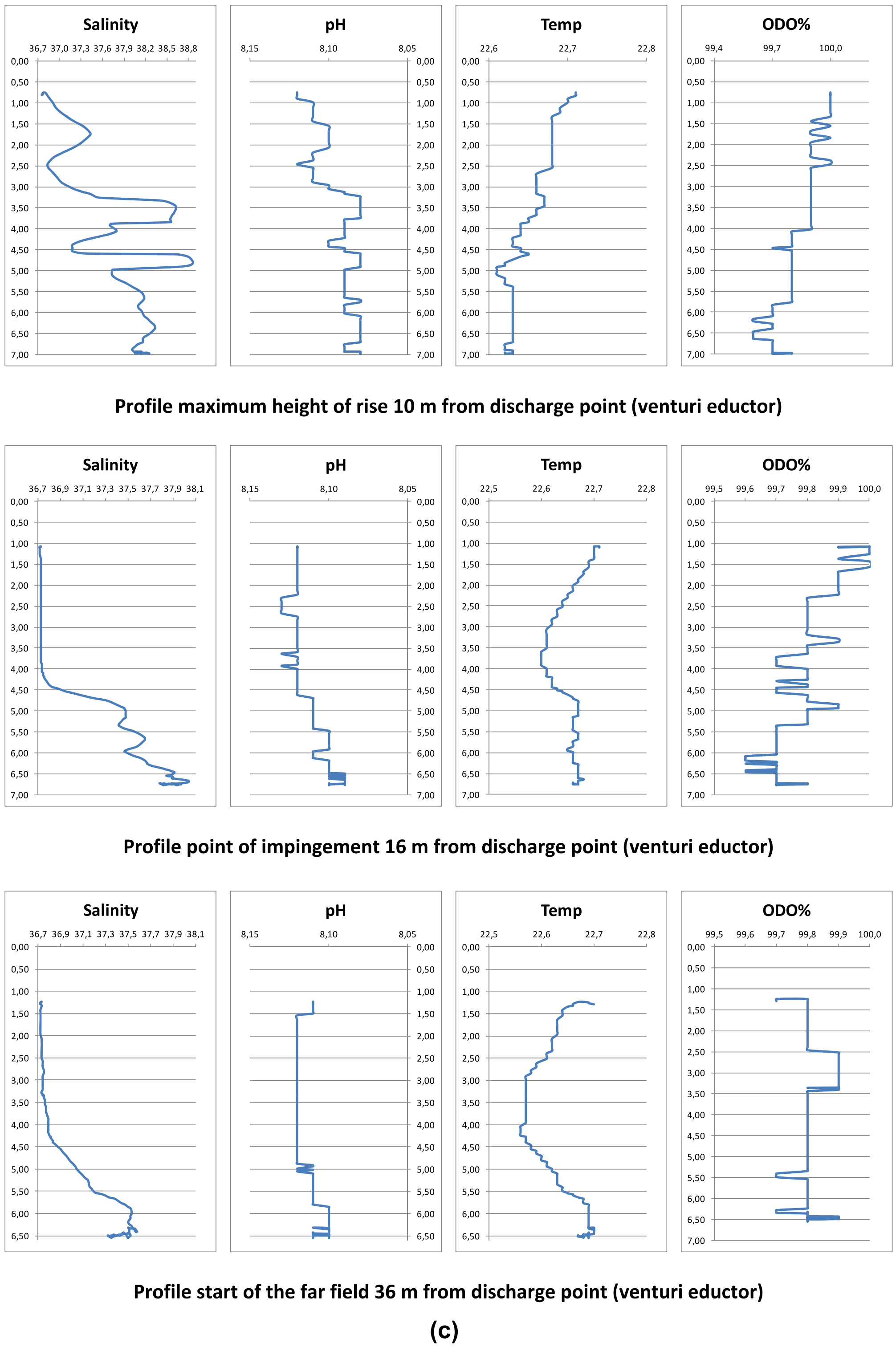


Fig. 4. Profiles in the water column of salinity, pH, temperature and percentage of dissolved oxygen saturation obtained with the YSI-6600-V2 sensor at the three sampling points (maximum height of rise, point of impingement and start of the far field) for each discharge system: (a) with no diffuser system, (b) with reducer nozzle only (c) with venturi eductor.

with a wide-ranging parabolic trajectory in both cases, even though the jets corresponded to only one of the two branches of the Y bifurcation and therefore half the flow. Jet thickness at the maximum height of rise

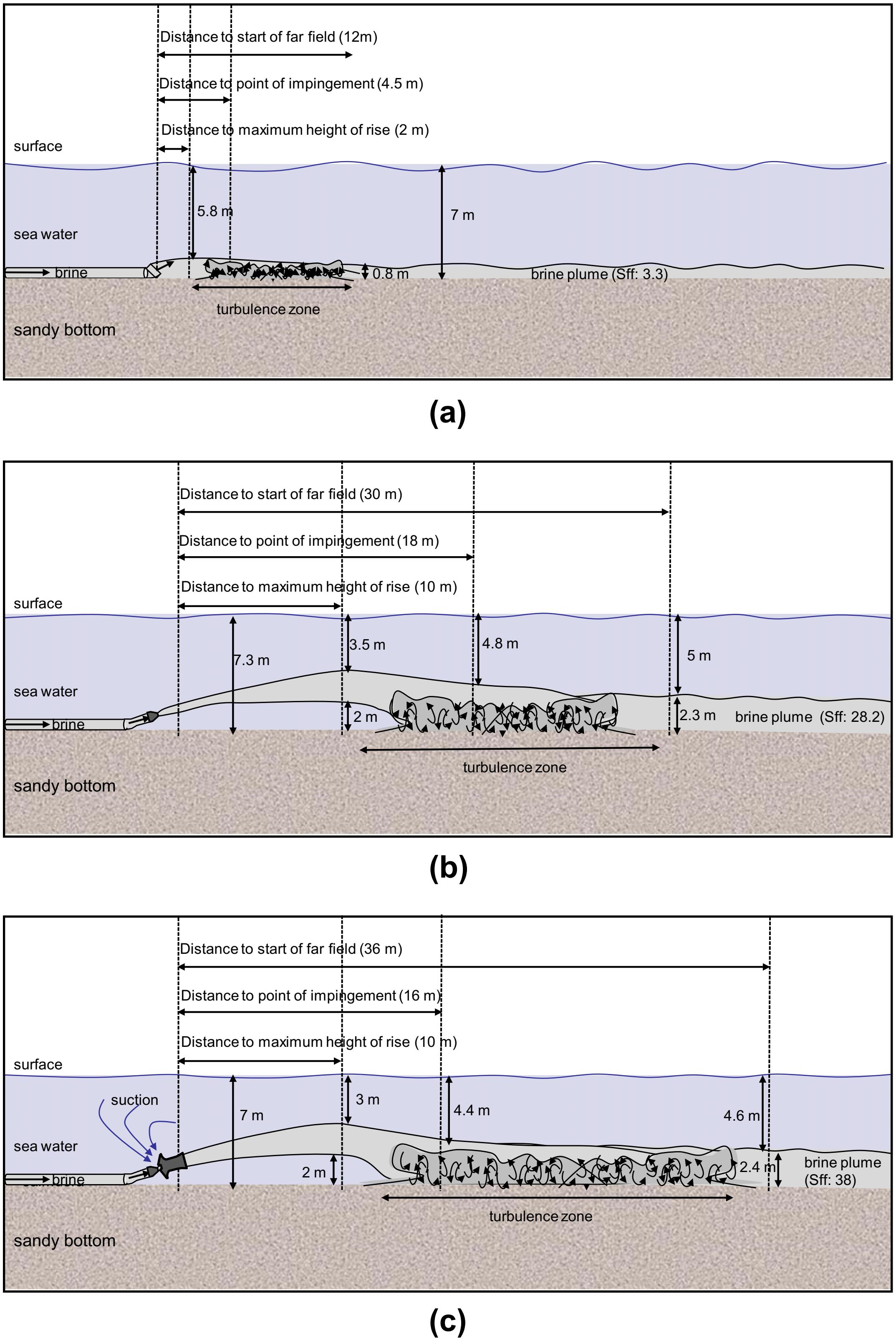
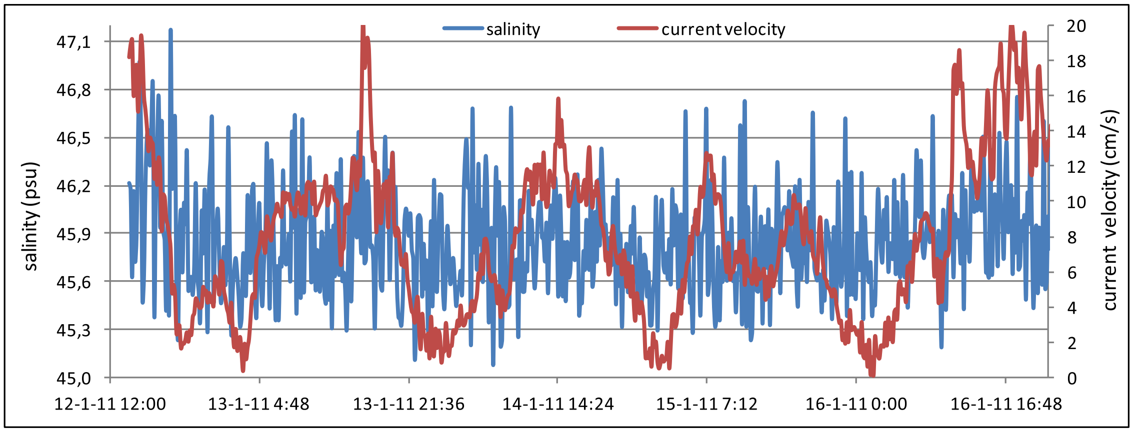
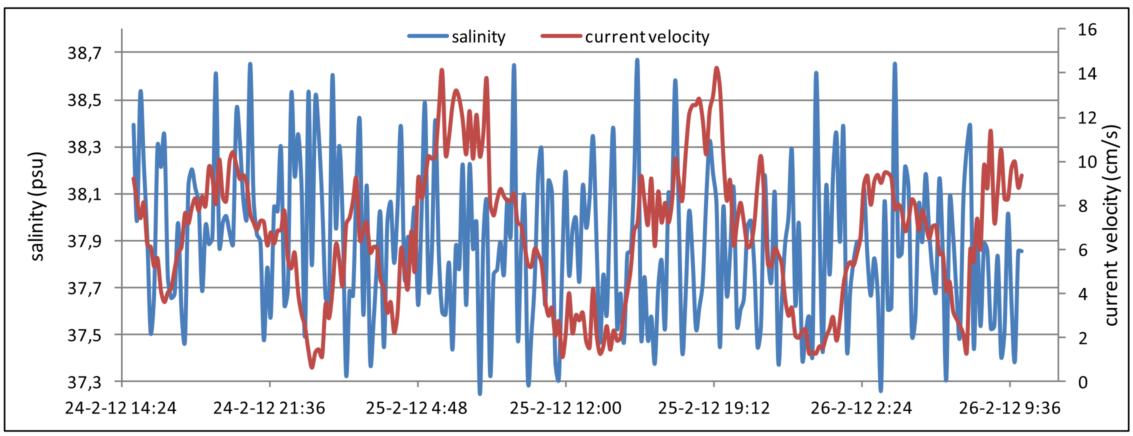


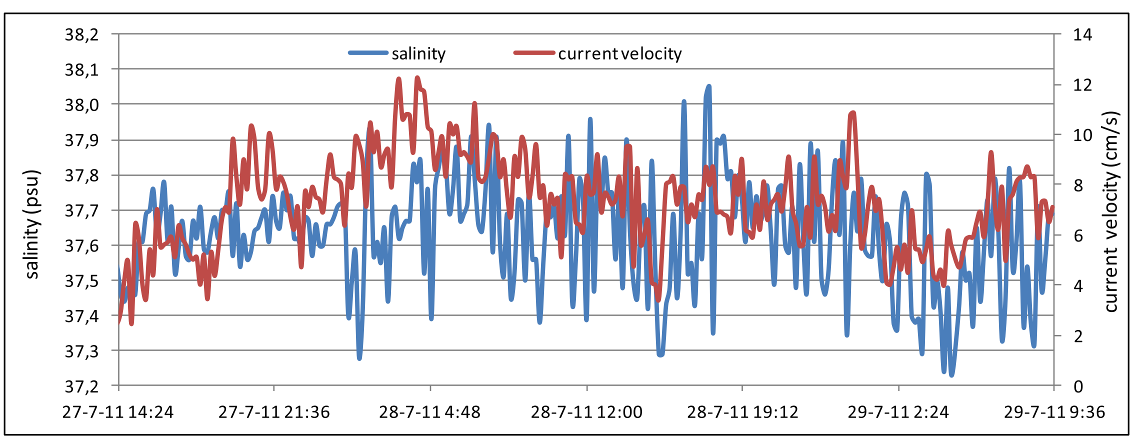
Fig. 5. Graphical representation to scale of the longitudinal distribution of the discharge system in the near field: (a) with no diffuser system (b) with reducer nozzle (conventional diffuser) (c) with venturi effect unit.



(a)



(b)



(c)

Fig. 6. Continuous salinity reading at the start of the far field by anchoring a YSI-6600-V2 multiparameter sensor, with current velocity during and after near-field sampling for each discharge system: (a) with no diffuser system (b) with reducer nozzle only (c) with venturi eductor.

was approximately 2 m. It remained around 3–3.5 m below sea level and thus avoided possible exit above the sea surface. The differences between the venturi eductors in comparison to conventional reducer nozzles without the suction unit were also noted. These were primarily in the slightly greater thickness of the jet and the resulting plume at the start of the far field, a larger area of the turbulence zone, greater range of the near field, a greater capacity to reduce the salinity of the resulting brine plume and therefore more efficient dilution capacity.

The continuous salinity readings at the start of the far field over several days, including their statistical treatment, are shown in Fig. 6 and Table 2. These dilutions, averaged on the basis of the readings over time, were for the original discharge system, at 3.6 in comparison with dilutions around 8 and 11 times higher after incorporation of the diffuser systems. They are virtually the same as the values obtained in the profiles at this point (start of the far field) in near-field sampling. Once again the lack of diffusion capacity of the original discharge system was confirmed, as well as the greater effectiveness of the venturi eductors in comparison with conventional diffusers. In this case, despite the variability of the hydrodynamic conditions (but with similar averages for current velocity) and fluctuations in exit velocities and salinities, the averaged dilution for the venturi eductors was 43% higher than with conventional reducer nozzles only.

These continuous salinity readings demonstrated the greater stability of the dilution capacity of the venturi eductors, as values very close to the mean were maintained and therefore the standard deviations were very low and the maximum and minimum values were very close to the mean for the entire measuring period, despite:

- the high variability of the hydrodynamic exposure the discharge was subjected to in the area near the outflow point; and
- minor fluctuations in exit velocity and salinity.

4. Discussion

The small differences between discharge flows and salinities in the three sampling campaigns (Table 1), when the desalination plant was operating at optimum level, were due to the slight variability in the dilution produced at the plant before discharge. This minor pre-dilution, which occurs when excess feedwater spills out of the feedwater tank into the drain and mixes with the brine, depends on the variability

Table 2
Mean, standard deviation, maximums and minimums of the continuous salinity readings at the start of the far field by anchoring a YSI-6600-V2 multiparameter sensor during and after near-field sampling for each discharge system; corresponding average dilution and average current velocity while the sensor was anchored

Discharge system	Start date	End date	Mean salinity (psu)	Standard deviation	Max. sal. (psu)	Min. sal. (psu)	Average dilution	Average current velocity (cm/s)
No diffuser	12/01/2011	16/01/2011	45.85	0.33	47.16	45.07	3.6	7.8
With reducer nozzle	24/02/2012	26/02/2012	37.88	0.32	38.74	37.21	27.4	7.1
Venturi eductor	27/07/2011	29/07/2011	37.45	0.17	37.87	37.05	39.2	7.4

and irregularity of the spillage. This causes the minor fluctuations detected in both the salinity and the flow of the discharge.

Before incorporation of the diffuser system, the system of discharging into the sea used by the plant caused very low dilutions at the start of the far field (lower than 3), as the discharge was under the velocities recommended for jet discharge systems through underwater outfall [23,24]. The discharge system with no diffuser system had no reduction of any kind, which meant that the average discharge flow inside the outfall pipe (600 mm Ø) produced an exit velocity that was too low, at approximately 1 m/s. Such a low velocity barely created parabolic motion, as the jet rose just 1.2 m and the brine sank to settle on the sea floor in less than 5 m. The discharge system at this plant therefore worked as a simple spillway, which means that it was far removed from a typical jet discharge system of the kind regarded as an efficient method for maximizing near-field dilution and to which much higher dilutions are attributed for discharge velocities greater than 3 m/s.

Despite the bifurcation of the flow into two branches, the velocities generated after incorporation of the two diffuser systems as a result of the reduction of the nozzle diameter to 130 mm were much greater than the velocities recommended for avoiding adverse effects on pelagic life in the area [35]. The venturi eductors required exit velocities greater than 11 m/s (Froude No > 65) to attain the necessary pressure difference (Ap > 10 psi) to cause the suction effect of these devices. As a result, for this study on the technical feasibility of venturi eductors it was necessary to create much greater velocities than those normally used in any conventional discharge system. However, when the venturi effect unit was added to the reducer nozzle, the resulting jet current was totally different. In this case, having passed through the reducer nozzle, the brine entered the trumpet-shaped structure and the high velocities were therefore produced inside the venturi eductor. The maximum suction velocities of the device in the suction area with a diameter of around 810 mm in the venturi effect unit were less than 3 m/s and the velocities corresponding to the mixture flow on exiting the narrow section of the eductor were around 6 m/s. This velocity decreased even further as the eductor widened to a maximum diameter of 620 mm, which meant that both the final exit velocity from the venturi eductor and the suction velocity were within the range of the velocities normally used with conventional diffusers.

The dispersion and dilution processes in the near field were related to these high exit velocities. In the mixing zone, these processes are associated with the turbulences generated, both from the rising and falling jet trajectory and after the jet impinges on the sea floor. The higher exit velocity therefore increased the range of the parabolic jet trajectory, clearly enhancing the dilution processes. The discharge system with no diffuser system clearly did not have sufficient exit velocity to behave as a typical jet discharge, whereas with the two diffuser systems, jet trajectories with a long range and high dilution capacity were produced, virtually eliminating the impact zones. These mixing processes would have been much greater with angles of inclination of the diffusers that were higher in relation to the sea floor and more in line with recommendations (45–60°), but the angle could not be increased, as a safety distance from the surface had to be maintained because of the shallow discharge area. In addition, on the odd occasion when the plant shuts down, all the feed pumps are normally turned on at once and then the various reverse osmosis racks are brought into operation sequentially and simultaneously. Because of this, the plant can sometimes discharge up to twice the normal flow through the outfall until the first osmosis rack is brought into action and therefore circumstances of this kind must be accounted for, as well as the two equinoctial spring tides each year. The differences in the jet trajectory between the two diffuser systems in terms of thickness and range were determined by the suction capacity of the eductor. The eductor had a maximum venturi effect suction capacity of 4 units of volume of ambient seawater to 1 of brine output and therefore the final flow at the eductor outlet could be multiplied by as much as five. This final mixture flow reached maximum velocity at the narrowest section of the eductor (400 mm Ø) and then slowed down as the diameter widened to 620 mm. In this way an exit flow as much as five times higher was obtained, but with lower velocity and salinity and therefore with a different jet trajectory: in this case a wider trajectory with greater range of the mixing zone than for the system with no suction unit.

The dilutions obtained with the venturi eductor achieved an average reduction of brine salinity to values of 37.45 psu, whereas with reducer nozzles only, the values reached only 37.88 psu. Although apparently slight, this difference in reduction corresponds to a significant variation in the dilution capacity, of around 39 and 27, respectively. This greater dilution could be very useful and also necessary when biological communities protected by European, state or autonomous region regulations are found in the vicinity of the discharge, or when the communities in the area are vital for ecosystems, as in the present case. The seagrass meadows in the discharge area of the Maspalomas II desalination plant are affected by the discharge and part of the island's largest and most ecologically important seagrass meadow of *C. nodosa* is found nearby. Although the impact zone currently has no plant cover [36], it was formerly colonized by seagrass meadows, as all the adjacent areas are now [28,36]. No maps exist of the area before construction of the outfall (around 1988), although oral testimony is available from local fisherman and the professional divers involved in building it, who say that a seagrass meadow was once found in the impact zone. Further witness is provided by the dead roots and rhizomes of the extinct seagrass meadow that are still preserved, buried around 20 cm under the entire area of influence of the brine discharge. Thus the use of venturi technology for discharge through underwater outfall, with greater dilution capacity than any conventional diffuser system, could mean the difference between exceeding and respecting the salinity tolerance threshold affecting seagrass meadows in a specific area. In this case, incorporating the corrective measures of the venturi eductor could encourage recovery and repopulation of the extinct seagrass meadows in the area and also comply with future criteria of any recommendations established after experimental studies of the response of *C. nodosa* to brine discharge from desalination plants (acute and chronic ecotoxicity) currently under way as part of the present study.

In the end, the effect of the hydrodynamic conditions on the outcome of the dilution processes in the discharge systems studied could not be assessed, as it was not possible to make continuous readings of exit velocity and salinity. Although in theory current velocities greater than 10 cm/s, like those recorded when the sensor was anchored, can help to increase dilution, these processes are normally conditioned by exit velocity and salinity. Due to the variability of the pre-dilution as a result of the irregular spills of excess feedwater mixing with the brine, slight fluctuations in exit velocity and salinity occur constantly. It was possible to control these fluctuations during near-field sampling with the individual readings from the flow meters and by collecting samples of outflow salinity from the drain every 2 min. However, much longer periods of study, over several hours or days, are required to evaluate the effect of current velocity on the dilution processes. In the present study this control was possible only through individual readings and collection of discharge samples three times a day (morning, midday and afternoon) while the sensor was anchored at the start of the far field and therefore the dilutions referred to averaged rather than individual values. However, the results of these continuous readings once again showed the greater effectiveness of the venturi eductor in comparison with conventional diffuser systems, despite the fluctuations in exit velocity and salinity. In these continuous readings over several days it was possible to average the variations in the dilution capacities for the various discharge systems in relation to different exit velocities and salinities, as well as current velocities. The averages of these dilutions concur with those obtained in near-field sampling, maintaining virtually the same percentage of enhanced dilution by the eductors in comparison with conventional diffusers. In addition, in both continuous readings the average current velocity in the receiving environment was practically the same.

The enhancement of around 43% in the efficiency of the dilution capacity of the venturi eductors compared with conventional diffusers is also relative, as it could be much higher. Using conventional diffusers avoids exceeding the velocities normally used (less than 6 m/s), and with venturi technology, jet velocities just after exiting from the eductor are also normally less than 6 m/s. If the two diffusion systems at the Maspalomas II desalination plant are compared in this way—the present venturi eductor in comparison with a conventional diffuser—at velocities of 6 m/s and with the same angle of inclination (15°), the capacity to enhance dilution in the impact zone, according to estimates through mathematical models based on the technical note by Jirka [29] and in the CORMIX Modeling System [30] for near-field mixing predictions, would be 131% more efficient with the eductor than with the conventional diffuser. This means that at the start of the far field, venturi eductors could achieve minimum dilutions up to 2.3 times greater than dilutions obtained with conventional diffusers, with exit velocities less than 6 m/s in both diffuser systems.

After nine months in operation, the trumpet-shaped suction structure began to be colonized by barnacles (*Megabalanus azoricus*) inside the widest areas at both ends of the suction unit, so it was cleaned by manually scraping each eductor with a sharp tool for 10 min. As cleaning is very simple and inexpensive, this action could form part of the compulsory annual inspection of the outfall. The reducer nozzle was not colonized either inside or outside.

The following conclusions can be drawn:

(1) Discharge with no diffuser system resulted in very low dilutions due to insufficient exit velocity to generate jet currents with a parabolic trajectory capable of enhancing the corresponding dilution processes.

(2) For velocities much higher than those normally used in any conventional discharge system, but necessary to ensure the suction of the venturi effect device:
 - venturi eductors were more efficient than conventional diffusers, as they increased their average dilution capacity by around 43% beyond the mixing zone;
 - in the venturi eductor the high jet current velocities at the nozzle outlet enter the eductor, whereas with the conventional diffuser they enter the receiving environment directly;
 - although they have a greater final flow, venturi eductors definitely discharge with lower exit velocity and salinity than conventional diffusers and within the range of velocities normally used;
 - the greater dilution capacity of the venturi eductors compared with conventional diffusers could, in many areas, mean the difference between exceeding the tolerance threshold of the salinity that affects seagrass meadows and respecting it, and could therefore either allow seagrass meadows to become established or inhibit them.

(3) Venturi eductors involve low costs in additional equipment and maintenance in comparison with conventional reducer nozzles and therefore discharge via underwater outfall with such high velocities could not be justified without the incorporation of venturi effect technology in the diffuser system.

(4) For final exit velocities after the respective diffuser systems and within the range of velocities normally used (less than 6 m/s), the capacity of venturi eductors to enhance dilution could, according to estimates, be more than 2.3 times the dilution obtained with conventional diffusers; and

(5) Venturi effect technology for discharge through underwater outfall is economically feasible and more effective than conventional diffusers and can be incorporated into both planned and existing desalination plants. Installing this technology could help to reduce the environmental impact of brine discharges at a low cost in terms of equipment, infrastructure and maintenance and thus help to enhance discharge processes in the desalination industry.

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