TESIS DOCTORAL

DILUTION AND DISPERSION OF GRAN CANARIA DESALINATION PLANT BRINE DISCHARGE: INFLUENCE ON SEAGRASS MEADOWS AND POTENTIAL CORRECTIVE MEASURES.

Eduardo Portillo Hahnefeld

UNIVERSIDAD DE LAS PALMAS DE GRAN CANARIA

Departamento de Biología

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D/Dª José Manuel Vergara Martín SECRETARIO/A DEL DEPARTAMENTO DE BIOLOGÍA DE LA UNIVERSIDAD DE LAS PALMAS DE GRAN CANARIA,

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Que el Consejo de Doctores del Departamento en sesión extraordinaria tomó el acuerdo de dar el consentimiento para su tramitación, a la Tesis doctoral titulada "*Dilution and dispersion of Gran Canaria desalination plant brine discharge: influence on seagrass meadows and potential corrective measures*.**"** presentada por el/la doctorando/a D/Dª. Eduardo Portillo Hahnefeld y dirigida por la Dra. María M. Gómez Cabrera, el Dr. Héctor Mendoza y el Dr. Juan Manuel Ruiz Fernández.

Y para que así conste, y a efectos de lo previsto en el Artº 73.2 del Reglamento de Estudios de Doctorado de esta Universidad, firmo la presente en Las Palmas de Gran Canaria, a de Mayo de 2014.

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Título de la Tesis:

Dilution and dispersion of Gran Canaria desalination plant brine discharge: influence on seagrass meadows and potential corrective measures**.**

(Dilución y dispersión de un vertido de salmuera de una planta desaladora en Gran Canaria: su influencia en las praderas marinas y posibles medidas correctoras.)

Tesis doctoral presentada por D. Eduardo Portillo Hahnefeld para obtener el grado de Doctor por la Universidad de Las Palmas de Gran Canaria.

Dirigida por Dra. María M. Gómez Cabrera
Dr. Héctor Mendoza (codirector)
Dr. Juan Manuel Ruiz Fernández (codirector)

El/la Director/a **El/la Co-Director/a** **El/la Co-Director/a** **El/la Doctorando**

Dilution and dispersion of Gran Canaria desalination plant brine discharge: influence on seagrass meadows and potential corrective measures.

TESIS DOCTORAL

Eduardo Portillo Hahnefeld

Doctorado en Oceanografía
Facultad de Ciencias del Mar
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A mi gran familia

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Mamá, Papá,

y Rubito!

Mi ilusión y mi rumbo, mi hogar y mi apoyo, mi locura y mi calma, mi vida y mi todo!

"Research is to ***see*** *what everybody else has seen, and to* ***think*** *what nobody else has thought"*

Albert Szent-Györgi (1893-1986)

A pesar de la elevada importancia ecológica de las praderas marinas, no hace mucho que se ha empezado a conocer el efecto dañino de los vertidos de salmuera procedentes de los procesos de desalación sobre estos ecosistemas, verificándose a largo plazo una afección en la vitalidad de la fanerógama marina *Posidonia oceanica* (L.) Delile a incrementos pequeños de salinidad. Sin embargo, en el caso de las praderas de *Cymodocea nodosa* (Ucria) Asherson (conocidas como sebadales en las Islas Canarias) no existía mucha información sobre su tolerancia a este tipo de vertido. Además, en el sur de Gran Canaria se había detectado una significativa reducción de los arribazones de sebas en los últimos 30 años que podría estar relacionado con un posible estado de regresión de estas praderas marinas debido a este tipo de vertidos o de los provenientes de plantas depuradoras, así como de construcciones de muelles, dragados, encauzamientos de los barrancos, etc. Por estos motivos, esta Tesis ha pretendido contribuir a una mayor comprensión sobre el comportamiento de dilución y dispersión del vertido de salmuera de plantas desaladoras al mar, su efecto sobre los sebadales, así como evaluar e implementar posibles medidas correctoras que consigan minimizar su impacto.

La planta desaladora Maspalomas II al sur de la isla de Gran Canaria (Islas Canarias) vierte la salmuera a través de un emisario submarino sobre parte del sebadal más extenso de la isla. Los procesos de dilución y dispersión de este vertido de salmuera fueron caracterizados bajo diferentes condiciones hidrodinámicas, así como el estudio del asentamiento de las praderas marinas en la zona de afección e inmediaciones. Por un lado, el sistema de vertido producía diluciones muy bajas, ya que se vertía sin sistema difusor y por debajo de las velocidades recomendadas para sistemas de vertido en chorro a través de emisario submarino. Por consiguiente el vertido de salmuera evolucionaba en plumas con salinidades muy altas que se ensanchaban sobre amplias extensiones. Por otro lado, un mayor grado de exposición hidrodinámica favoreció la dilución de los márgenes laterales de estas extensas plumas hipersalinas y por tanto una ligera reducción de la zona de afección o impacto. Los recorridos de estas plumas de salmuera coincidieron con un auténtico pasillo de ausencia de cobertura vegetal. Los sebadales se distribuyeron a partir de los márgenes externos de las zonas de afección del vertido de salmuera indicando la sensibilidad de *C. nodosa* a estos vertidos. La relación causa-efecto entre la presencia o ausencia de sebadales y la salmuera se estableció a través de ensayos experimentales in situ de trasplantes de *C. nodosa* en las zonas impactadas. Los resultados de los trasplantes determinaron el efecto tóxico de la salmuera a partir del segundo mes de exposición y a partir de pequeños incrementos salinos ($\geq$ 2,2 psu). Por otra parte, en esta planta desaladora la desinfección de las membranas de ósmosis inversa se realizaba mediante tratamientos periódicos de choque de metabisulfito sódico, por lo que también se evaluó el efecto de este tratamiento químico en la disminución del pH y de la concentración de oxígeno disuelto durante el proceso de dispersión del vertido de la salmuera

por el fondo marino, así como su posible repercusión en la flora y fauna bentónica. Tras este tratamiento de choque de desinfección de las membranas con metabisulfito sódico, el vertido de salmuera se conformó en una pluma hipersalina con un alto grado de acidificación y desoxigenación abarcando un área de influencia bastante amplia. A través de test de tolerancia, se determinó una alta sensibilidad de *C. nodosa* a exposiciones con bajas concentraciones de metabisulfito sódico. Por esta razón, se determinó que estos tratamientos químicos incrementan los efectos tóxicos de la salmuera debido a su incremento de salinidad.

El sistema difusor con eductores venturi se reveló como una medida correctora idónea, tanto por su bajo coste de fabricación, instalación y mantenimiento, así como por su altísima eficacia. Los eductores venturi requirieron de velocidades de salida muy elevadas, mayores del doble de las recomendadas en dispositivos convencionales (≥ 12 m/s), para poder alcanzar una diferencia de presión necesaria para generar el efecto de succión propio del dispositivo. A estas velocidades, se consiguen diluciones del orden del doble que un dispositivo convencional, sin embargo, cuando se incorpora la estructura de succión, la capacidad de dilución incrementa en un 40 % a la vez que se consigue reducir la velocidad de salida del chorro hasta el rango de velocidades recomendadas (≤ 3 m/s). Tras su incorporación los nuevos trasplantes se mantuvieron en un buen estado durante el mismo tiempo de ensayo y es que se consiguió alcanzar prácticamente la salinidad del medio receptor. Por tanto se redujo casi en su totalidad la pluma hipersalina, así como las zonas de influencia tras el tratamiento químico con metabisulfito sódico y por consiguiente se eliminó prácticamente dicho impacto.

ABSTRACT

Despite the high ecological importance of seagrass meadows, the harmful effect on these ecosystems caused by brine discharges from desalination processes has only recently come to light after demonstration of the long-term effect of small salinity increases on the vitality of marine phanerogam *Posidonia oceanica* (L.) Delile. The tolerance of seagrass meadows of *Cymodocea nodosa* (Ucria) Ascherson (known as sebadales in the Canary Islands) to this type of discharge is little documented. At the same time, a significant reduction has been detected in beach cast material of this species in the south of Gran Canaria in the last 30 years. This could be associated with a potential state of regression of *C. nodosa* seagrass meadows caused by discharges from desalination and water treatment plants or as the result of dock building, dredging, and channelling of ravine mouths. In view of this situation, this thesis aims to increase understanding of the behaviour of the dilution and dispersion of brine discharges from desalination plants into the sea and their effect on seagrass meadows, and to assess and implement potential corrective measures to minimise their impact.

The Maspalomas II desalination plant, in the south of the island of Gran Canaria (Canary Islands-Spain), discharges brine via an underwater outfall over part of the island's largest *C. nodosa* seagrass meadow. The dilution and dispersion processes of the brine discharge were described under various hydrodynamic conditions and the settlement process of seagrass meadows in the area of influence and the vicinity of the discharge was also studied. On the one hand, the discharge system produced very low dilutions, as it had no diffuser system and discharged below the velocities recommended for jet discharge systems through underwater outfall. As a result, the brine discharge emerged in plumes with very high salinities that spread out over large areas. On the other hand, a higher degree of hydrodynamic exposure favoured dilution of the outer edges of these extensive hypersaline plumes, achieving a slight reduction in the area of influence. The trajectories of the brine plumes coincided with a corridor completely lacking in plant cover. The seagrass meadows occurred beyond the outer edges of the areas of influence of the brine discharge, indicating the sensitivity of *C. nodosa* to these discharges. The cause-effect relation between the presence or absence of seagrass meadows and brine was established through experimental in situ testing of *C. nodosa* transplants in the affected areas. The transplant results showed the toxic effect of the brine from the second month of exposure after small salinity increases (≥ 2.2 psu). In addition, the reverse osmosis membranes at the Maspalomas II plant were disinfected by regular shock treatments with sodium metabisulphite. A study was also conducted on the effect of this chemical treatment on the decreased pH and dissolved oxygen concentration during the dispersion process of the brine discharge over the sea floor and the repercussions it could have on the benthic flora and fauna. After shock disinfection treatment of the membranes with sodium metabisulphite, the brine discharge became a hypersaline plume with a high level of acidification and deoxygenation that spread out over a large area of influence. Tolerance tests revealed the high sensitivity of *C. nodosa* to exposures with low sodium metabisulphite concentrations, demonstrating that chemical treatments increase the toxic effects of the brine because of the increased salinity.

The diffuser system with venturi eductors proved to be an ideal corrective measure, both in terms of its low production, installation and maintenance costs and its very high efficiency. The venturi eductors needed very high exit velocities - more than twice the recommendations for conventional devices (≥ 12 m/s) - to reach the pressure difference required to produce the suction effect of the eductor. At these velocities, the dilutions achieved are around twice the dilutions of a conventional device, but when the suction unit is added, the dilution capacity increases 40 % and the exit velocity of the jet is also reduced to the range of recommended velocities (≤ 3 m/s). After the venturi eductors were added, the newly transplanted seagrasses remained in good condition during the time of the test and the salinity achieved was practically the same as in the receiving environment. As a result, the hypersaline plume was reduced to a minimum. The areas of influence after chemical treatment with sodium metabisulphite were similarly greatly reduced and thus the impact of the disinfectant was virtually eliminated.

PRESENTACIÓN DE LA TESIS

La presentación de la Tesis titulada *"Dilución y dispersión de un vertido de salmuera de una planta desaladora en Gran Canaria: su influencia en las praderas marinas y posibles medidas correctoras."* surge de los trabajos realizados dentro del proyecto de cooperación interregional INTERREG III C "Regional cycle development through coastal cooperation seagrass and algae focus / CosCo – Project" y del proyecto de desarrollo experimental del Plan Nacional de I+D+i 2008-2011 "*Estudio de viabilidad técnica de los difusores venturi en vertidos de salmuera procedentes de desaladoras como mejora del proceso de dilución y reducción del impacto ambiental en los ecosistemas marinos*" del Ministerio de Medio Ambiente y Medio Rural y Marino del Sector de Medio Ambiente y Ecoinnovación (NºExpdte:004/RN08/0.3).

La Dra. María M. Gómez Cabrera (Universidad de Las Palmas de Gran Canaria - Departamento de Biología) ha dirigido esta Tesis en co-dirección con el Dr. Héctor Mendoza (Instituto Tecnológico de Canarias - Jefe del Departamento de Biotecnología) y el Dr. Juan Manuel Ruiz Fernández (Instituto Español de Oceanografía - Centro Oceanográfico de Murcia - Grupo de Ecología de Angiospermas Marinas).

Esta Tesis consta de una parte escrita en castellano y estructurada en una Introducción General, donde se exponen los antecedentes y estado del arte, los objetivos de cada capítulo y principales resultados obtenidos, así como una discusión general, futuras líneas de investigación y conclusiones generales. Esta parte consta de las 50 páginas en castellano requeridas por el Reglamento de Elaboración, Tribunal, Defensa y Evaluación de Tesis Doctorales de la Universidad de Las Palmas de Gran Canaria (BOULPGC. Art.2 Cap.1, 5 de noviembre 2008).

The presentation of the thesis entitled "*Dilution and dispersion of Gran Canaria desalination plant brine discharge: influence on nearby seagrass meadow and potential corrective measures*" (Dilución y dispersión de un vertido de salmuera de una planta desaladora en Gran Canaria: su influencia en las praderas marinas y posibles medidas correctoras) is the result of studies conducted within the INTERREG III C Interregional Cooperation Project "Regional cycle development through coastal cooperation seagrass and algae focus / CosCo – Project" and the experimental development plan of the 2008-2011 Spanish National RDI Plan "Technical feasibility study of venturi diffusers in desalination plant brine discharges to enhance the dilution process and reduce the environmental impact on marine ecosystems" (Estudio de viabilidad técnica de los difusores venturi en vertidos de salmuera procedentes de desaladoras como mejora del proceso de dilución y reducción del impacto ambiental en los ecosistemas marinos) through the Spanish Ministry of the Environment and Rural and Marine Affairs, Environment and Eco-Innovation Sector (File No:004/RN08/0.3).

Doctor María M. Gómez Cabrera, of the University of Las Palmas de Gran Canaria – Department of Biology (Universidad de Las Palmas de Gran Canaria - Departamento de Biología) codirected this thesis with Doctor Héctor Mendoza, of the Canary Islands Institute of Technology – Head of the Biotechnology Department (Instituto Tecnológico de Canarias - Jefe del Departamento de Biotecnología) and Doctor Juan Manuel Ruiz Fernández, of the Spanish Institute of Oceanography – Murcia Oceanography Centre, Marine Angiosperm Ecology Group (Instituto Español de Oceanografía - Centro Oceanográfico de Murcia - Grupo de Ecología de Angiospermas Marinas).

This thesis includes one section in Spanish, structured in a General Introduction that explains the background and the current status, the objectives of each chapter and the principal results obtained, and a General Discussion that indicates future lines of research. This section comprises the 50 pages in Spanish required by the University of Las Palmas Doctoral Thesis Regulations, in Article 2, Chapter 1, in the version of 5 November 2008 (Reglamento de Elaboración, Tribunal, Defensa y Evaluación de Tesis Doctorales de la Universidad de Las Palmas de Gran Canaria - BOULPGC. Art.2 Cap.1, 5 de noviembre 2008).

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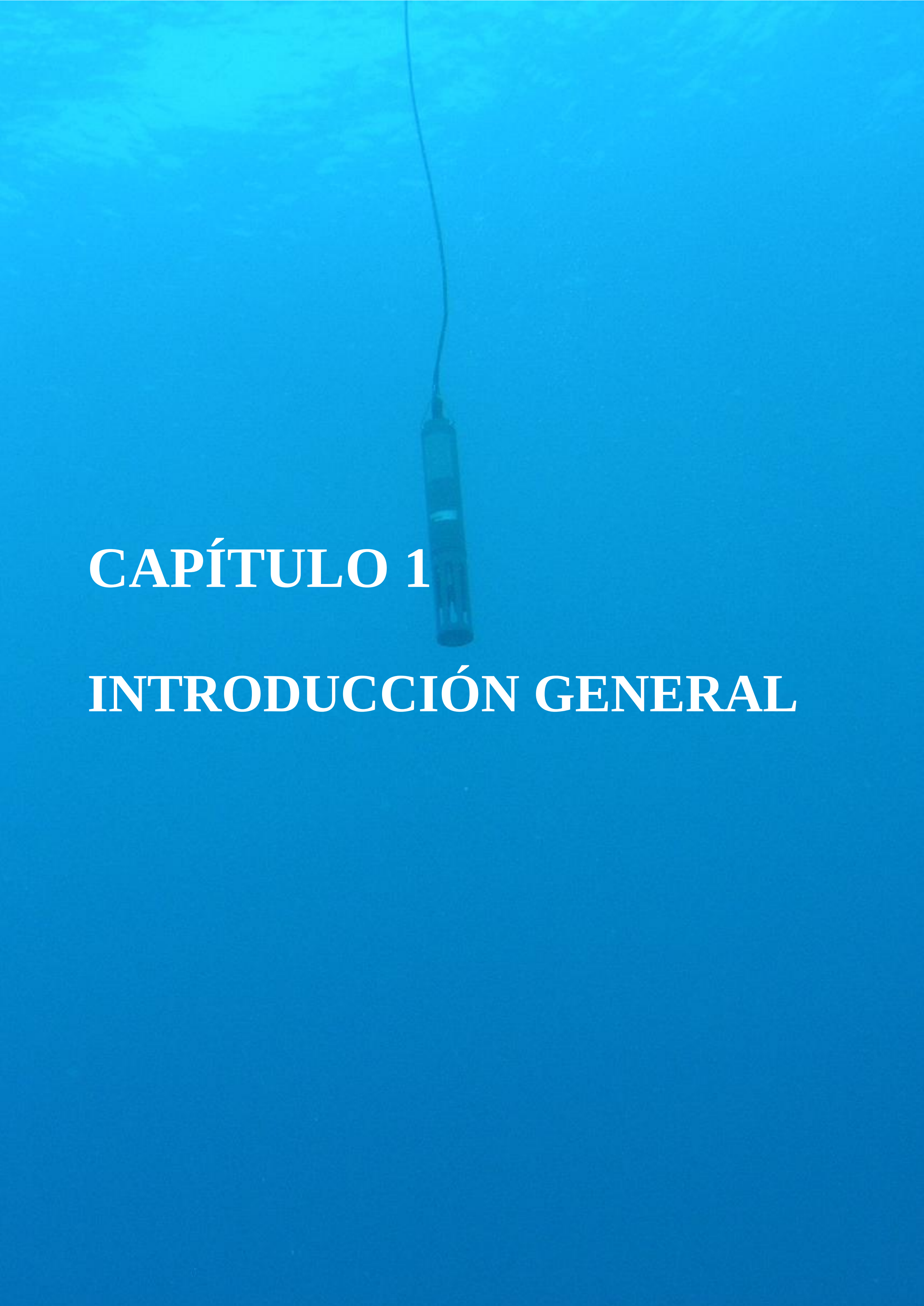
And I know what I have to do now. I gotta keep breathing. Because tomorrow the sun will rise. Who knows what the tide could bring?"

William Broyles Jr., Cast Away (2000): The Shooting Script



CAPÍTULO 1

INTRODUCCIÓN GENERAL

CAPÍTULO 1. INTRODUCCIÓN GENERAL

1. INTRODUCCIÓN GENERAL

1.1. ANTECEDENTES

En la actualidad la desalación de agua de mar representa, en muchas regiones costeras del sur de España, la mejor apuesta tecnológica de aporte de agua potable (Medina, 1999; Martínez, 2006), mientras que en las Islas Canarias constituye, en algunos casos, la única posibilidad de suministro para satisfacer su creciente demanda (Veza, 2001; Sadhwani and Veza, 2008). Las condiciones climáticas (baja tasa de precipitación anual, periodos de sequía, escasez de otros recursos de agua, etc.) y las condiciones socio-demográficas (incremento de la población, desarrollo de la industria turística, etc.) de sus zonas costeras han dispuesto que el presente y futuro del abastecimiento de este bien tan preciado sea cubierto a través de la desalación de agua de mar. En el caso concreto de las Islas Canarias, el crecimiento del sector turístico en algunas islas, como Lanzarote y Fuerteventura, ha conllevado que la desalación sea la única fuente disponible de agua potable (Fundación Centro Canario del Agua, 2007).

Esta necesidad y demanda de agua potable ha generado un aumento espectacular de plantas desaladoras en Canarias y en gran parte del litoral peninsular, con el consiguiente impulso en la investigación y desarrollo de las tecnologías de desalación. En la costa, se vienen explotando dos procesos de desalación: la destilación y la ósmosis inversa, este último el más extendido por su menor coste de inversión, menor consumo energético y menor necesidad de espacio (Morton *et al.*, 1996; Schiffler, 2004).

La ósmosis inversa consiste en hacer pasar el agua a presión por una membrana permeable que permite solamente el paso del agua, por lo que las sales quedan retenidas al otro lado de la membrana conformando un medio hipersalino (Fig. 1). Esta tecnología consigue alcanzar unos rendimientos [(agua producto/agua alimentación)×100] del orden del 50 %, por lo que se puede generar un agua de rechazo con una concentración en sales mayor o igual del doble que el agua de mar, denominado salmuera (Fariñas, 1999).

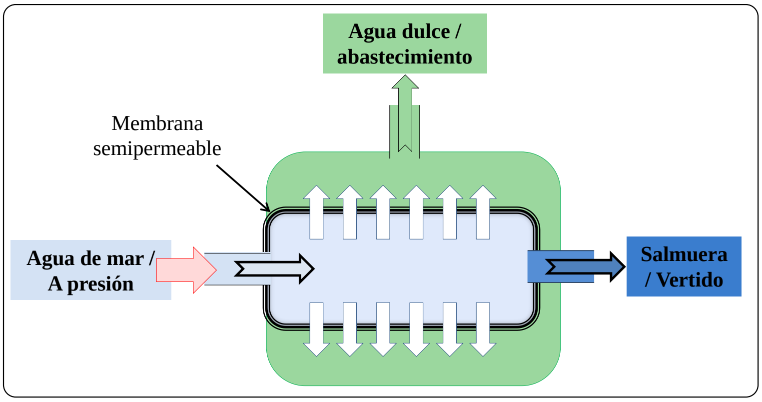


Figura 1. Diagrama del proceso de desalación por ósmosis inversa.

La mayoría de las desaladoras vierten esta salmuera directamente al mar a través de diferentes sistemas de descarga (emisario submarino con o sin sistemas difusores, aliviadero superficial, rebose desde acantilado, vertido en escollera, etc.; Fig. 2).

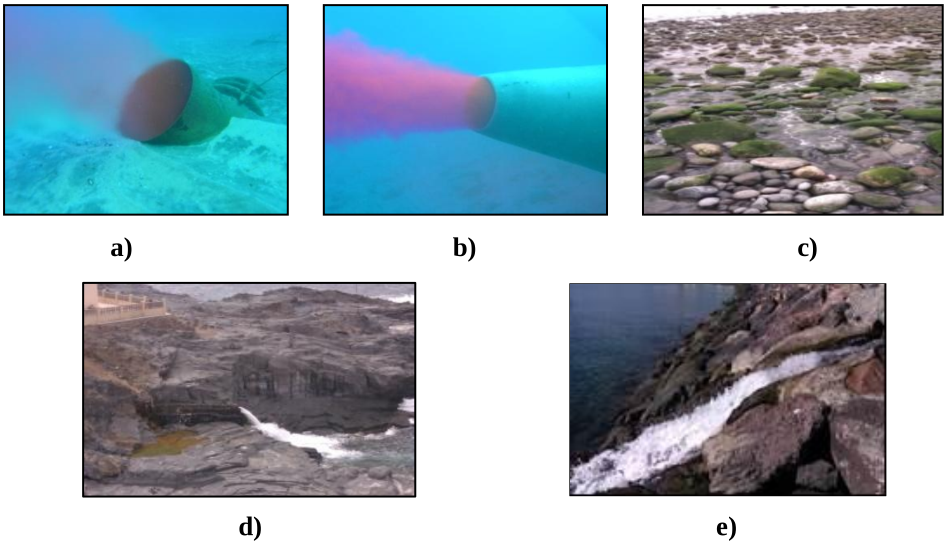


Figura 2. Imágenes de diferentes sistemas de descarga: a) emisario submarino sin sistema difusor, b) emisario submarino con sistema difusor, c) aliviadero superficial, d) rebose desde acantilado, e) vertido en escollera.

En las proximidades del punto de descarga, zona señalada como el campo cercano, es donde se pueden y suelen generar los mayores procesos de dilución y mezcla de dichos vertidos de salmuera debido a las turbulencias asociadas al sistema de descarga o al propio medio receptor. La caída de la salmuera al mar desde acantilado, los choques y obstáculos con la estructura de una escollera o playa de callaos, el impulso con el que se vierte, así como las propias condiciones del medio receptor (zona de rompientes, tipo de oleaje, corrientes, etc.) pueden favorecer los procesos turbulentos y por consiguiente el aumento y eficacia de los procesos de mezcla (Fig. 2).

En el caso de vertidos mediante emisarios submarinos, la energía cinética con que el efluente suele llegar al mar genera las turbulencias que favorecen los procesos de mezcla con el agua del entorno (Ruiz Mateo, 2007; Fig. 3 y 4). Sin embargo, a cierta distancia del punto de descarga, donde se acaba el impulso de avance del efluente y por tanto la turbulencia asociada, la salmuera se hunde por mayor densidad (Fig. 3 y 4). En ese momento, la salmuera se convierte en una pluma hipersalina que se dispersa por el fondo sin apenas dilución (Roberts and Sternau, 1997) y siguiendo las líneas de máxima pendiente (Payo *et al.*, 2010). A esta región se le denomina campo lejano y es en esta zona donde la columna de agua se presenta como un fluido bicapa, donde el agua marina ocupa la capa superior y la salmuera la inferior (Fig. 3 y Fig. 4b).

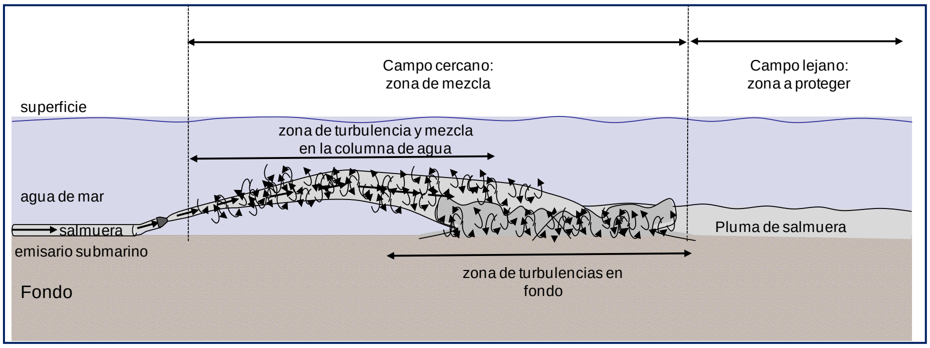
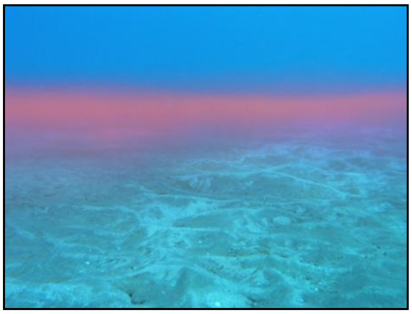


Figura 3. Representación longitudinal de un vertido mediante emisario: campo cercano y lejano (Portillo *et al.*, 2013).

A medida que avanza la salmuera por el lecho marino va aumentando, por un lado, su ancho por esparcimiento lateral, y por otro lado, disminuyendo consecuentemente su espesor (Ruiz Mateo, 2007). Sin embargo, el grado de estratificación es tan grande entre ambas capas que hace que los procesos de intercambio y dilución sean muy lentos aun existiendo cierto grado de hidrodinamismo (Palomar and Losada, 2008).

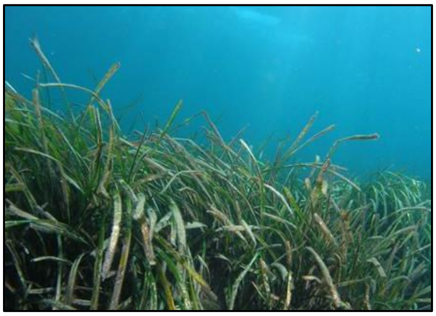


a) b)

Figura 4. Imágenes del: a) Campo cercano, b) Campo lejano

Por esta razón, los vertidos de salmuera, cuyos sistemas de descarga no consiguen desarrollar una alta capacidad de dilución y mezcla inicial, evolucionan en plumas con salinidades muy altas y por consiguiente se propagan sobre amplias extensiones (Fernández-Torquemada *et al.*, 2009) pudiendo afectar a su paso a las comunidades bentónicas presentes (Morton *et al.* 1996; Einav *et al.*, 2002; Ruiz, 2005; Palomar and Losada, 2008). El alcance y la magnitud de dichos impactos depende finalmente de muchos factores relacionados con la vulnerabilidad de las comunidades bentónicas presentes y su estado de conservación, prevaleciendo características y factores ambientales (batimetría, rugosidad del fondo, condiciones meteorológicas y oceanográficas reinantes de la zona, etc.), así como del tipo de sistema de descarga, su caudal, salinidad y de los subproductos derivados de los tratamientos químicos (Höpner and Widember, 1996; Einav *et al.*, 2002). Estudios recientes han demostrado que estos vertidos de salmuera causan efectos adversos en las comunidades de fondo (infauna, epifauna, suprabentos y macrofauna bentónica y demersales) (Castriota *et al.*, 2001; Fielder *et al.*, 2005; Miri and Chouikhi, 2005; Del-Pilar-Ruso *et al.*, 2007, 2008, 2009; Riera *et al.*, 2011) y en praderas marinas (Fernández-Torquemada and Sánchez-Lizaso, 2005; Gacia *et al.*, 2007).

Las praderas marinas son hábitats predominantes en la zona infralitoral de la costa Española Mediterránea y Atlántica hasta 30-40 m, siendo *Posidonia oceanica* (L.) Delile y *Cymodocea nodosa* (Ucria) Ascherson las especies más abundantes y de mayor importancia ecológica de las zonas costeras (Procaccini *et al.*, 2003) por la gran biodiversidad que albergan y por múltiples razones tanto ecológicas como económicas (Costanza *et al.*, 1997; Duarte, 1999).



a)

b)

Figura 5. Fotos de fanerógamas marinas de: a) *Posidonia oecanica (Foto: Juan Manuel Ruiz)* b) *Cymodocea nodosa*

Estas praderas marinas se comportan además como una zona de atracción para las comunidades pelágicas, que aprovechan la estructura de este ecosistema como refugio y sustento de muchos invertebrados y peces, y/o área de reproducción y cría de muchas especies de peces con alto interés comercial. La existencia de estas praderas aporta también múltiples servicios ecológicos al medio marino (Costanza *et al.*, 1997):

- la estabilización del sedimento, que redunda en la calidad de las aguas (aguas oxigenadas y transparentes),
- el reciclaje de nutrientes,
- la incorporación de CO_2 y producción de carbono orgánico y oxígeno,
- la retención de la arena y atenuación del oleaje y corrientes,
- la reducción de los procesos erosivos de la línea de costa a través de las acumulaciones masivas de restos de la pradera marinas en la playa, que se desprenden del fondo cíclicamente por el efecto del oleaje (denominados arribazones).

Sin embargo, estos hábitats bentónicos y las comunidades asociadas son particularmente vulnerables a los efectos directos e indirectos de impactos humanos (Boudouresque *et al.*, 2009), por lo que la presencia de praderas marinas es un buen indicador de la salud de las aguas de la zona. Cualquier cambio en su distribución, como la reducción de su límite máximo batimétrico, o reducción de los arribazones en las playas anexas indicaría serias variaciones en el ecosistema. Por esta razón, se les denomina también como *coastal canaries*, ya que revelan cualquier degradación, perturbación o contaminación en el ecosistema marino (Orth *et al.*, 2006).

Por otra parte, en los últimos cuarenta años se ha producido una dramática regresión de los ecosistemas de praderas marinas en todo el mundo convirtiéndose en uno de los temas más acuciantes de la ecología marina y conservación de la naturaleza (Short and Wyllie-Echeverria, 1996; Duarte, 2002). Entre mediados de los años 80 y 90 del siglo pasado, se ha documentado una pérdida de unos 2.900 km^2 de praderas marinas debido a afecciones antrópicas, directas o indirectas (Spalding *et al.*, 2003), o de 33.000 km^2 en una estimación posterior realizada por Short (2003). Esta regresión supondría una pérdida entre el 7 y 19 % de la cobertura mundial de praderas marinas en el caso que ésta fuese del orden de 117.000 km^2 (mediante una estimación conservadora; Spalding *et al.*, 2003). Estimaciones más recientes, pero en el área Mediterránea como la de Boudouresque *et al.* (2009), sitúan los valores de esta regresión en un rango de 0 y 10 % a partir de principios del siglo XX. La principal causa de su desaparición apunta al desarrollo costero que ha existido en estos últimos años y sobre todo en las zonas donde se ha producido el boom turístico con el consiguiente desarrollo insostenible del sector. En el caso de las costas mediterráneas y de las Islas Canarias, este desarrollo ha conllevado a múltiples construcciones de muelles, obras en el litoral, dragados, contaminación del mar por vertidos, represas, encauzamientos y acondicionamientos de barrancos y ríos limitando y reduciendo el aporte natural y cíclico de áridos, fondeos no responsables de embarcaciones, etc.

Estas posibles afecciones antrópicas sobre las praderas marinas, la detección del estado de regresión en muchas zonas, así como la necesidad de seguir incrementando la industria de la desalación en estas regiones costeras fue lo que motivó a la realización de los primeros proyectos científicos destinados a evaluar y establecer criterios adecuados para evitar, minimizar y controlar estos efectos en las praderas marinas, como el de los vertidos de salmuera en estos ambientes marinos (Sánchez-Lizaso *et al.*, 2008).

Tras los primeros estudios científicos se comenzó a corroborar la afección de los vertidos de la salmuera procedente de las plantas desaladoras sobre estos ecosistemas, por lo que el impacto de este tipo de vertido empezó a requerir de una mayor atención. Estos ensayos experimentales comenzaron en el área Mediterránea, donde se evidenció que la exposición a corto plazo a incrementos de la salinidad del medio sobre la especie endémica dominante *P. oceanica* causaba una serie de efectos tóxicos que llegaban a comprometer su vitalidad

(Fernández-Torquemada and Sánchez-Lizaso, 2003, 2005) y sus funciones fisiológicas (Marín-Guirao *et al.*, 2011, 2013). Por otro lado, mediante otro tipo de aproximaciones in situ Gacia *et al.* (2007) y Ruiz *et al.* (2009) se obtuvieron evidencias experimentales de que tales efectos pueden ser responsables del deterioro de la vitalidad y estructura de las praderas a más largo plazo (meses-años).

En el año 2003, el Departamento de Ciencias Ambientales de la Universidad de Alicante, el Centro Oceanográfico de Murcia del Instituto Español de Oceanografía, el Departamento de Ecología de la Universidad de Barcelona y al Centre d´Estudis Avançats de Blanes del CSIC, todos ellos coordinados por el Centro de Estudios y Experimentación de Obras Públicas del Ministerio de Fomento (CEDEX), estudiaron, tanto en laboratorio como in situ, el efecto de los aumentos de salmuera sobre *P. oceanica*. Entre las conclusiones del estudio se extrajeron una serie de recomendaciones para la protección de las praderas marinas frente a estos vertidos de salmuera procedentes de plantas desaladoras (CEDEX, 2003; Sánchez-Lizaso *et al.*, 2008); destacando que:

- en ningún punto de la pradera podrá superarse la salinidad de 38,5 psu en más del 25% de las observaciones,
- en ningún punto de la pradera la salinidad podrá superar 40 psu en más del 5% de las observaciones.

En el caso de praderas de *C. nodosa* no se dispone de criterios de este tipo, ya que la mayoría de todos estos estudios se centraron en *P. oceanica* y el conocimiento de la tolerancia de *C. nodosa* al incremento de la salinidad fue comparativamente mucho menor, a pesar que en los últimos años ha comenzado a aumentar el número de publicaciones en este aspecto. Desde el punto de vista biológico y ecológico se le atribuye a *C. nodosa* un comportamiento más euribionte, con una mayor capacidad que *P. oceanica* de tolerar cambios en las condiciones del medio (Drew, 1978). Las primeras evidencias experimentales apoyan esta hipótesis para *C. nodosa*, capaz de mantener sus características morfológicas y fisiológicas hasta niveles de salinidad superiores a los niveles críticos definidos para *P. oceanica* (Fernández-Torquemada and Sánchez-Lizaso, 2006; Pagès *et al.*, 2010; Sandoval-Gil *et al.*, 2012a, 2012b). No obstante, se desconocen los efectos a largo plazo del estrés hipersalino en praderas de *C. nodosa*. Por otro lado, a excepción de algún trabajo aislado, la ausencia de estudios en praderas de *C. nodosa* en Canarias (conocidas como sebadales) en este campo es absoluta, a pesar de representar un papel clave en el ecosistema marino costero del archipiélago.

Por otra parte, muy pocos de estos trabajos han considerado otros factores diferentes a la salinidad que pudiesen explicar los efectos perjudiciales de los vertidos de salmuera procedentes de los procesos de la desalación (Fernández-Torquemada and Sánchez-Lizaso, 2003). Uno de estos factores son los componentes que puede contener la salmuera tras los distintos tratamientos químicos que se realizan en estas plantas. Hasta el momento estos productos químicos (agentes antiincrustantes, coagulantes, acidificantes, desinfectantes, etc.) han sido considerados elementos trazas y de poca importancia en estos estudios de vertido, aunque presumiblemente podrían tener un alto potencial para causar efectos tóxicos en los organismos marinos, no tanto por su concentración, sino por su efecto persistente en el medio marino (Sánchez-Lizaso *et al.*, 2008). Además, las frecuentes operaciones de limpieza de membranas de ósmosis inversa que se realizan en las plantas desaladoras suelen generar un vertido de salmuera rico en el detergente utilizado tras dichos procesos. Por tanto, estos vertidos tendrían que someterse a procesos de depuración independiente o verterse escalonadamente y diluido en la salmuera para que no implique, en principio, una contaminación adicional significativa (Palomar and Losada, 2008). En muchas de estas plantas desaladoras esta desinfección de las membranas de ósmosis inversa se realiza mediante tratamientos en continuo o periódicos de choque de metabisulfito sódico ($Na_2S_2O_5$; a partir de ahora SMBS). Durante los tratamientos de choque, el producto se aplica periódicamente por lo que su presencia (y sus sub-productos) en la salmuera aparece durante pequeños pulsos de tiempo (de minutos a horas) con una frecuencia semanal. Tras la adición del SMBS se produce una reacción con el oxígeno disuelto del agua de mar liberándose dióxido de azufre en forma de gas (SO_2) y combinándose con el agua se producen un incremento de sustancias ácidas (HSO^{-3} como H_2SO^4; Singh and Singh, 1984). En relación con otros de los residuos producidos por las reacciones químicas entre el producto y la salmuera (Na_2SO^3, CaSO, $CaSO^4$; Medina, 1999), sus productos de disociación alteran las propiedades físico-químicas del medio que conducen a su acidificación e hipoxia hasta valores de pH < 5,5 o de saturación de oxígeno disuelto < 1 % (DOsat) (Fig. 6). Tales condiciones son absolutamente adversas para el desarrollo y la supervivencia de la vida marina bentónica (Singh and Singh, 1984; Silva, 1988; Macintosh and Phillips, 1992; Figueiredo *et al.*, 2006; Galli *et al.*, 2012) y por lo tanto son susceptibles de alterar significativamente la estructura y distribución de los hábitats y las comunidades bentónicas. Sin embargo, al comienzo de la realización de esta Tesis no se disponía de estudios sobre los efectos de estos productos químicos presentes en los efluentes de salmuera en las comunidades bentónicas marinas.

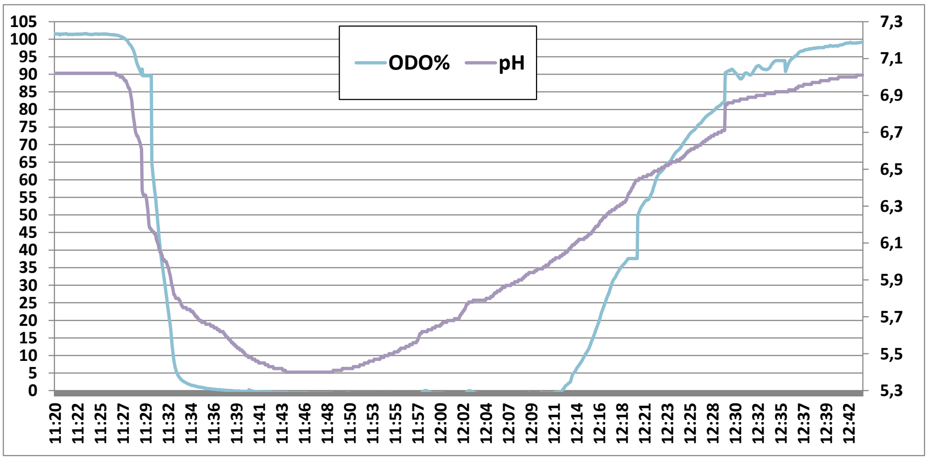


Figura 6. Registro en continuo de pH y DOsat (ODO %) del agua de rechazo a la salida de los trenes de ósmosis inversa en la planta desaladora Maspalomas II tras la adición de SMBS.

Todos estos primeros resultados sobre el impacto de los vertidos de salmuera motivaron nuevos estudios sobre el comportamiento de los procesos de dilución, dispersión y sobre sus efectos, así como sobre los planes de gestión y recomendación de su descarga en el medio marino. En las plantas desaladoras en funcionamiento se comenzó a desarrollar, proceder y testar con diferentes medidas correctoras y de minimización como el incremento de difusores en los emisarios, aumentando la longitud del emisario a zonas más profundas o más hidrodinámicas, la dilución del agua de rechazo antes de su descarga, la mezcla con aguas depuradas, etc. Por esta razón, a la hora de proyectar y ubicar nuevas desaladoras se comenzó a plantear nuevos diseños, estrategias y recomendaciones que tendiesen a evitar daños altamente lesivos en entornos de tanta sensibilidad como las praderas marinas (Einav *et al.*, 2002; Afrasiabi and Shahbazali, 2011). Por tanto, el futuro de la producción de agua potable por medio de la desalación hace imprescindible el desarrollo de mejoras tecnológicas en los procesos de vertido, que sean viables económicamente y efectivos tanto para plantas de nueva creación como para las ya instaladas.

En el sur de la isla de Gran Canaria (Islas Canarias), al abrigo de los frecuentes mares de fondo y de viento procedentes del Atlántico Norte y donde se encuentran gran parte de los fondos arenosos, se asienta el sebadal de *C. nodosa* de mayor extensión e importancia ecológica de la isla, el cual ha sido declarado recientemente como Zona Especial de Conservación (ZEC) bajo el nombre de Sebadales de Playa del Inglés (ES7010056) (BOE, 2009). En estos sebadales se ha determinado que pueden albergar más de 45 especies de peces, de las cuales 18 son de interés pesquero y 14 se reclutan como alevines en estos ecosistemas, por lo que se realizó una primera aproximación del valor que generan estas praderas en la isla de Gran Canaria con una estimación de unos 360.000 €/año (Tuya *et al*, en revisión).

En el marco de un proyecto de cooperación interregional INTERREG III C "Regional cycle development through coastal cooperation seagrass and algae focus / CosCo – Project", el Instituto Tecnológico de Canarias, S.A. (ITC) evaluó el fenómeno de los arribazones procedentes de estos sebadales de la zona sur de la isla de Gran Canaria: las causas, su cuantificación, su composición y su periodicidad y frecuencia (Portillo, 2008). Este fenómeno de los arribazones de plantas marinas, ha sido documentado en varias ocasiones a lo largo de diferentes zonas alrededor del mundo, como en la región oriental Africana (Hemminga and Nieuwenhuize, 1990; Ochieng and Erftemeijer, 1999), Australia (Kirkman and Kendrick, 1997), Europa (Milchakova, 1999; Mateo *et al.*, 2003; Duarte, 2004; Kotwicki *et al.*, 2005; Roig and Martín, 2005; Ballestri *et al.*, 2006; De Falco *et al.*, 2008; Portillo, 2008; Mateo, 2010; Cocozza *et al.*, 2011; Mossbauer *et al.*, 2012; Simeone and De Falco, 2012) y Norte América (Behbehani and Croker, 1982; Roman and Able, 1988), sin embargo se ha publicado muy poco acerca de las causas y su relación con el oleaje (Ochieng and Erftemeijer 1999; Ballestri *et al.*, 2006). Se ha determinado que un elevado grado de hidrodinamismo o de movimientos bruscos del mar pueden hacer desprender las hojas o arrancar las plantas de una pradera marina (Preen *et al.*, 1995; Fourqurean and Rutten, 2004; Ballestri *et al.*, 2006) y causar posteriormente acumulaciones de los restos en la costa de determinadas playas del Mediterráneo (Medina *et al.*, 2001; Duarte, 2004) o de Australia (Department of the Environment and Heritage, 2004).

Los estudios recientes que se han realizado acerca de la interacción entre el oleaje y las praderas marinas sólo han tenido en consideración la altura de la ola (Fonseca and Cahalan, 1992; Granata *et al.*, 2001;

Koch *et al.*, 2006) o el efecto que tienen estas praderas marinas sobre la propagación del oleaje y su atenuación (Bradley, 2009; Stratigaki *et al.*, 2011, Hansen and Reidenbach, 2012; Infantes *et al.*, 2012, Paul *et al.*, 2012). No obstante, no habían referencias escritas sobre el efecto que podían tener diferentes tipos de oleaje (mar de fondo y viento) sobre estas praderas marinas y si éstos podían significar la diferencia entre hacer desprender las hojas de muda o arrancar la planta entera (hojas verde-fresca junto con rizomas y raíz). En dicho proyecto, CosCo, se trató de determinar la relación entre los diferentes tipos de oleaje que afectan a esta zona, mares de fondo procedentes del Atlántico Sur (Portillo *et al.*, 2007) y mares de viento procedentes de profundas borrascas que azotan el archipiélago, con las pérdidas masivas de sebas a través de la evaluación cuantitativa y cualitativa (hojas de muda o plantas enteras) de los arribazones recogidos a posteriori por los servicios de limpieza de playas (Fig. 7).

a) b)

Figura 7. Arribazones de *C. nodosa* en el sur de Gran Canaria: a) hojas de muda tras mares de fondo del sur, b) plantas enteras (hojas verde-fresca junto con rizomas y raíces) tras mares de viento del sur.

A partir de este estudio se pudo entrever, a través de testimonios orales y apuntes de control del personal del servicio de limpieza de playa que venía trabajando en Playa del Inglés y Maspalomas desde 1977 hasta 2007, una disminución lenta, pero bastante importante de la cantidad de material vegetal arrastrado a la orilla, de hasta un 90% (Portillo, 2008). Esta reducción tan drástica se muestra con ejemplos como el de la Playa del Cochino, donde desde hace casi 15 años se requieren apenas 2 camiones para la retirada de los arribazones, cuando en los años 70 y a principios de los 80 se necesitaban todos los veranos en torno a 20 y 30 camiones para esa labor. O como el caso de Playa del Inglés, donde antaño la retirada de arribazones de *sebas* era una ardua tarea que les llevaba varios día de faena y sin embargo, desde principios de los años 90, ese mismo trabajo les lleva una mañana e incluso con menos operativo y personal (Portillo, 2008).

Esta disminución tan significativa de arribazones en la zona podría ser debida a una posible regresión de los sebadales durante estas tres últimas décadas. Este estado regresivo de los sebadales en Canarias quedó patente en los Informes del SEGA encargados por la Consejería de Medio Ambiente y Ordenación Territorial del Gobierno de Canarias (Seguimiento de poblaciones de especies amenazadas; Espino *et al.*, 2003), donde se llevó a cabo el seguimiento y evaluación de las poblaciones de sebadales en las islas orientales. En este Informe se detectó la situación de desaparición y regresión de muchos de los sebadales en todas estas islas. Otros trabajos, como el de Tuya *et al.* (2013), donde se muestrearon 5 praderas de la isla de Gran Canaria (algunas cercanas a los sebadales de Playa del Inglés y Maspalomas), encontraron también una drástica caída en la densidad, estado fisiológico y cobertura de las mismas en los últimos 17 años. En todos estos trabajos se identificó que las actividades humanas asociadas al desarrollo litoral (obras civiles, fondeos y los vertidos de la zona) son la principal amenaza y causa del mal estado de las poblaciones de estos sebadales. El intenso crecimiento del sector turístico de la zona en estos últimos 30 años ha producido un desarrollo insostenible e incontrolado de las distintas instalaciones, equipamientos e infraestructuras necesarias para el sostenimiento y mantenimiento de esta industria (Fig. 8). Además, los tratamientos de aguas residuales, así como sus vertidos, se llevaron a cabo sin la gestión y los procedimientos más adecuados y óptimos.

Figura 8. Afecciones antrópicas en la zona sur de la isla de Gran Canaria donde se encuentra el sebadal más extenso de la isla. Distribución sebadales (Dirección general de Costas, Estudio Ecocartográfico de la isla de Gran Canaria 2006-2008). Infografía de la posible cobertura del sebadal hace 30 años.

Estos sebadales actúan como amortiguadores del oleaje, compactadores y estabilizadores del sedimento (Koch *et al.*, 2006), por lo que se hace indispensable valorar el efecto de su posible reducción. Una regresión tan drástica de estas praderas marinas en los últimos 30 años en la zona de Playa del Inglés y Maspalomas, podría, además, tener una incidencia directa en la aceleración de los procesos de pérdidas de arena que en estos sistemas dunares se están produciendo. Esta reducción de arena se estimó en el trabajo de Medina *et al.* (2007) en unos 40.000 m^3/año, sin embargo sólo se consideraron como posibles causas cualquier efecto en la parte emergida del sistema de playas y dunas. No se tuvo en cuenta, por ejemplo, que una posible disminución drástica de sebadales en la parte sumergida de las zonas circundantes pudiera tener una relación directa o indirecta con este proceso alarmante de pérdida de arena en estas zonas de Playa del Inglés y Maspalomas. Por esta razón, sería conveniente intentar estimar el tamaño y extensión de la población de dichas praderas marinas antes de los distintos y variados efectos antropogénicos a los que se vieron sometidos estos sebadales (Fig. 8), así como apoyar las medidas que garanticen su conservación y recuperación.

A partir de los primeros años de este milenio fue cuando se procedió a corregir y mejorar los tratamientos de aguas residuales, así como sus sistemas de vertidos. Con estos últimos se ha procedido a la ampliación de los emisarios submarinos hasta profundidades fuera del alcance de la distribución batimétrica de asentamiento de los sebadales, además de incorporar nuevos y diferentes sistemas de descarga. Sin embargo, con los vertidos de salmuera no se propuso ni previó ningún tipo de mejora, ya que se consideró un agua de mar con una mayor concentración de sales que se diluía rápidamente con el mar y por tanto no estaba causando ningún efecto tóxico sobre el ecosistema marino.

Este es el caso de la planta desaladora Maspalomas II, localizada al sur de la isla de Gran Canaria (Fig. 9), con un caudal de salmuera bastante relevante, en torno a unos 1.000 m^3/h, con una salinidad final de casi el doble que la del agua de mar del entorno ($\approx$ 69,5 psu) y que vierte dentro de la zona potencial de asentamiento de los sebadales, a 4 m de profundidad en la bajamar máxima viva equinoccial (BMVE). Además, la limpieza de membranas de esta planta se realiza a través de tratamientos semanales de choque de SMBS, por lo que vierte la salmuera junto con los subproductos derivados de dicho proceso químico.

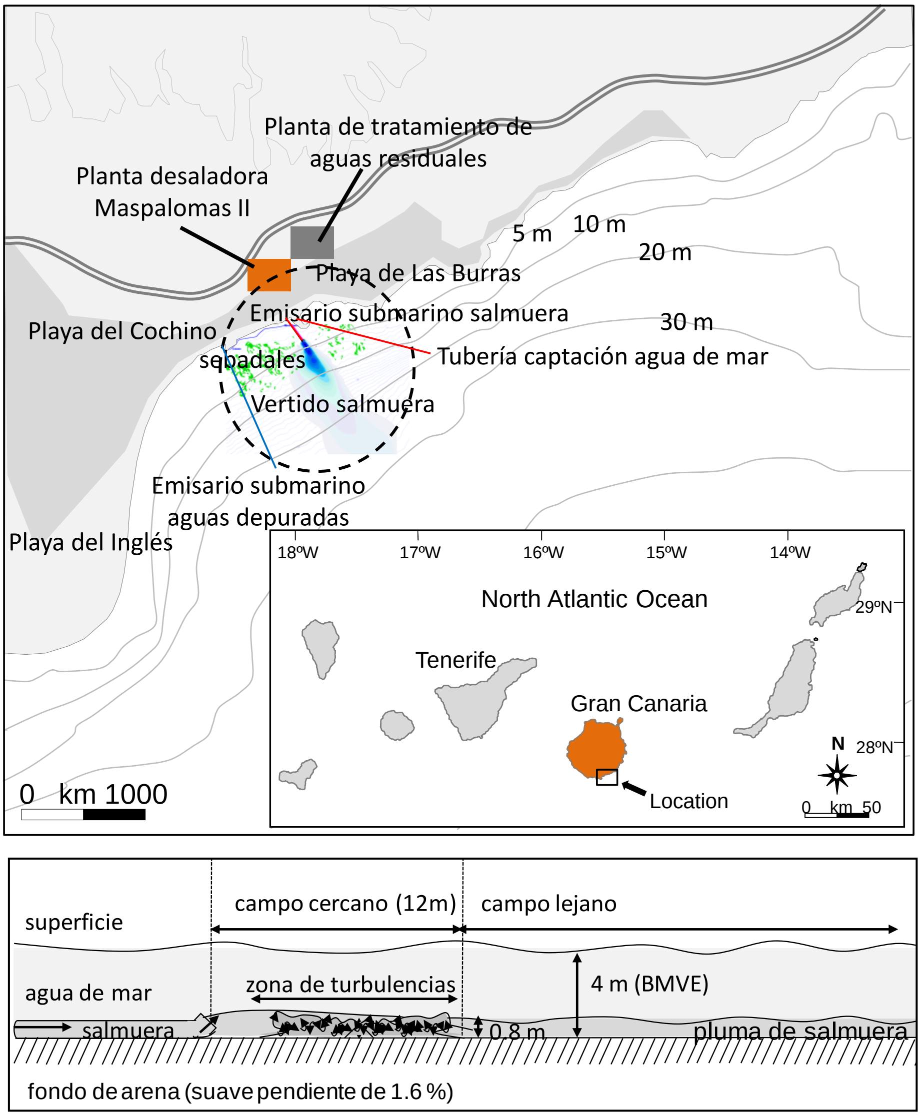


Figura 9. Localización planta desaladora Maspalomas II al sur de la isla de Gran Canaria, emisario de vertido y captación al sur de la isla de Gran Canaria, zona y esquema de vertido.

Una vez que se empezaron a conocer los posibles impactos de estos vertidos sobre las praderas marinas, la medida correctora sugerida por las autoridades competentes consistió en la ampliación del emisario en unos 1.000 m como mínimo, hasta alcanzar una profundidad de 25 m y quedar fuera de la zona potencial de crecimiento de los sebadales. Sin embargo, esta medida suponía una inversión muy alta, de aproximadamente unos 2 MEUR, que representaba un valor considerable comparado con el valor de las instalaciones de la planta desaladora, que era cercano a los 5 MEUR. Además, esta ampliación requería de tiempos de ejecución muy largos, así como de importantes impactos asociados (superficie de afección en el trazado, volúmenes de excavaciones, movimientos de arenas, etc.). Por esta razón, la planta desaladora buscó otro tipo de posible solución tecnológica alternativa y más económica. No obstante, por un lado, las distintas y posibles configuraciones con dispositivos difusores convencionales para su sistema de descarga no posibilitaban el alcance de la capacidad de dilución necesaria para evitar salinidades mayores a las recomendadas para *P. oceanica*. En este caso se requería como mínimo una ampliación del emisario submarino en 500 m (hasta los 10 m) junto con un tramo difusor de 150 m paralelo a la costa con numerosos dispositivos difusores, pero el coste aproximado de 1,5 MEUR suponía también una elevada inversión. Por otro lado, una posible predilución con agua de mar conllevaba un aumento de caudal del bombeo de agua de mar del doble al requerido, lo que hubiese requerido del doble de consumo en electricidad. Esta opción, además, hubiera generado también un elevado coste en diseño, construcción, fabricación y montaje, ya que se tendría que haber modificado tanto la estación de bombeo, como las tuberías submarinas de captación de agua de alimentación (agua de mar). Por último, por su cercanía a una estación depuradora, se valoró la mezcla de la salmuera con el agua depurada, pero también se terminó por descartar. Aunque dichos procesos de mezcla hubiesen conseguido reducir la salinidad hasta los valores recomendados (Portillo *et al.*, 2011), hubieran podido surgir riesgos de afección por los contenido en nutrientes y compuestos orgánicos disueltos residuales que siguiesen residiendo en el agua depurada.

En el año 2008, la Fundación Centro Canario del Agua a través de su página web anunció los eductores venturi de una empresa americana para su posible uso como sistemas difusores en vertidos de salmuera. Esta tecnología del efecto venturi aplicada en procesos de mezcla ya ha sido testada y utilizada en infinidad de procesos de dilución y mezcla tanto en el sector de la industria química, del petróleo como más recientemente en el de la acuariofilia. Se utiliza para mezclar de una manera efectiva líquidos de distinto peso específico, eliminar estratificaciones, homogeneizar pH y temperatura, para la adición de químicos (gases y líquidos), etc. No obstante, no se conocían propuestas de testeo y evaluación sobre la aplicación de esta tecnología para la mezcla y dilución con el medio marino de vertidos realizados mediante emisarios submarinos. La novedad de esta tecnología, destinada a la mezcla de este tipo de vertidos en el mar, radica en el acople de unas estructuras de efecto venturi, con forma de campana/trompeta, delante de boquillas reductoras. Éstas a su vez actúan como dispositivos difusores convencionales pero con secciones de salida mucho menores para el desarrollo de velocidades muy altas, conformando el conjunto el eductor venturi (Fig.10).

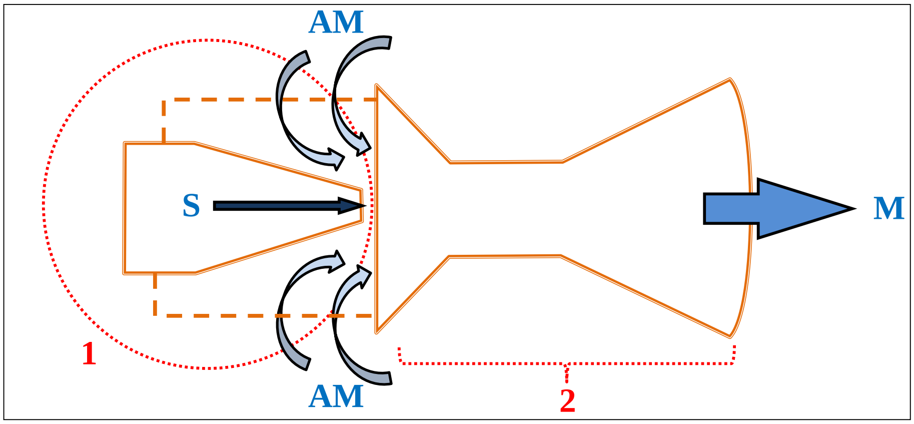


Figura 10. Eductor venturi: Sistema difusor comprendido por una boquilla difusora convencional o boquilla reductora (1), por donde se aumenta la velocidad de salida del vertido de la salmuera (S) y el acople de una estructura en forma de campana/trompeta de efecto venturi (2), por donde se succiona el agua del entorno (AM) saliendo la mezcla por la salida (M).

Estas velocidades de salida, tras la boquilla reductora, mucho mayores que las recomendadas para dispositivos convencionales, son fundamentales para poder generar la caída de presión necesaria a la entrada de la estructura de efecto venturi y de esta manera producir el efecto de succión dentro de la misma. La salmuera, después de pasar por la boquilla reductora, se adentra a gran velocidad en la estructura en forma de campana/trompeta, cuya sección va disminuyendo hasta llegar a un cuello de menor diámetro, donde a partir de ahí vuelve a aumentar. La diferencia de la velocidad del vertido al pasar por la sección más estrecha respecto a la más ancha de dicha estructura, produce la caída de presión y por tanto el efecto de succión del agua del entorno a través de la misma. La zona de succión de estas estructuras comprendería 360º alrededor del cono de succión de esta estructura en forma de campana/trompeta, por lo que esta gran zona de succión puede garantizar, dependiendo de la presión diferencial que se haya generado y alcanzado para su buen funcionamiento, hasta una dilución de 1 a 4 al salir del eductor. De esta manera, justo a la salida de estos dispositivos, se potencia la capacidad de mezcla entre el agua de mar succionada y la salmuera y por tanto la mejora en los procesos de dilución en el campo cercano.

Por otro lado, existen ciertas consideraciones y recomendaciones sobre las velocidades de salida adecuadas y recomendadas en el caso de vertidos en chorro de fluidos hiperdensos. Mientras que velocidades en torno a 4-6 m/s garantizarían una maximización de los procesos de dilución en el campo cercano, velocidades menores a 3,5 m/s reducirían la posible afección sobre las larvas y juveniles de los peces circundantes (Palomar and Losada, 2011). En la *U.S. EPA Technical Support Document For Water Quality-based Toxics Contro*l se sugiere la utilización de velocidades de descarga mínimas de 3 m/s, con el objeto de lograr una corriente de chorro con suficiente energía cinética que favorezca una rápida mezcla y por consiguiente la dilución del efluente, disminuyendo al mismo tiempo la posibilidad de obstrucción de los difusores (US EPA, 1991). En la legislación española (BOE, 1993), se recomienda superar las velocidades mínimas de salida de 0,6 y 0,8 m/s, pero no incluye ningún criterio en cuanto a velocidades máximas, a diferencia de su ley predecesora donde se indicaba que dicha velocidad no debería superar los 5 m/s. La utilización de los eductores venturi requiere de velocidades mayores que las recomendadas por las diferentes fuentes anteriormente citadas para poder generar el efecto de succión propio del dispositivo. No obstante, estas velocidades tan altas (≥ 12 m/s), tras salir de la boquilla reductora, se reducen nada más adentrarse en la estructura en forma de campana/trompeta por el propio efecto de succión hasta valores menores a 3 m/s. En el interior de esta estructura de efecto venturi las velocidades vuelven a aumentar hasta velocidades de 6 m/s conforme va reduciéndose la sección del primer lóbulo de esta estructura para posteriormente volver a disminuir en el segundo lóbulo, donde la sección del mismo se va ensanchando (velocidades de salida ≤ 3 m/s). Por tanto, las velocidades de descarga justo a la salida del eductor, así como las de succión, estarían dentro del rango de las velocidades utilizadas habitualmente con difusores convencionales y no afectarían al medio marino.

La viabilidad técnica de los eductores venturi como dispositivos que mejoran los procesos de dilución respecto a los convencionales no había sido testada y evaluada hasta la fecha, por lo que los estudios destinados a la adquisición de estos conocimientos resultaron de gran interés para la mejora de los procesos de vertido en la industria de la desalación. Su implantación ayudará a reducir los impactos ambientales de los vertidos de salmuera a un bajo coste de equipamiento, infraestructura y mantenimiento.

Por todas estas razones expuestas, a lo largo de este apartado de la Introducción General (Antecedentes), en la planta desaladora de Maspalomas II existía una necesidad de:

- caracterizar los procesos de dilución y dispersión de su vertido de salmuera bajo diferentes condiciones hidrodinámicas y determinar las zonas de afección,
- evaluar la influencia e interacción del vertido en la distribución espacial de los sebadales circundantes y su asentamiento en dicho área,
- determinar el efecto de la salmuera sobre *C. nodosa* y
- valorar otras soluciones tecnológicas alternativas para minimizar el impacto del vertido.

A partir de ese momento, se decidió, por un lado, elegir la tecnológica venturi para su posible testeo y estudio de viabilidad en la planta desaladora Maspalomas II, y por otro lado, llevar a cabo los trabajos experimentales y de demostración, así como los diferentes estudios de evaluación, viabilidad y críticos, para adquirir y verificar nuevos conocimientos y técnicas con vistas a contribuir y solventar estas necesidades. Estos trabajos se pudieron llevar a cabo en el marco de proyecto de desarrollo experimental del Plan Nacional de I+D+i 2008-2011 "*Estudio de viabilidad técnica de los difusores venturi en vertidos de salmuera procedentes de desaladoras como mejora del proceso de dilución y reducción del impacto ambiental en los ecosistemas marinos - VENTURI*" del Ministerio de Medio Ambiente y Medio Rural y Marino del Sector de Medio Ambiente y Ecoinnovación (NºExpdte:004/RN08/0.3), que constituyeron la columna vertebral en la que se estructura esta Tesis.

Por último, reiterar que la idea del proyecto VENTURI, la cual permitió la realización posterior de esta Tesis, surgió dentro del Departamento de Biotecnología tras la participación en el proyecto InterregIIIC-CosCo, donde se detectó a través del estudio de la cuantificación de los arribazones de la zona de Playa del Inglés y Maspalomas, la posible reducción de hasta un 90% de los sebadales que cohabitaban en dicha área. De la búsqueda de las posibles causas, así como del planteamiento de soluciones, surgió dicho proyecto y Tesis, en donde se ha podido desarrollar ambas acciones con unos resultados muy reveladores e innovadores.

1.2. OBJETIVOS

1.2.1. CAPÍTULO 2

Evaluar la relación entre diferentes tipos de eventos de oleaje significativos, tanto de mar de fondo como de viento, que alcanzaron a la zona sur de la isla de Gran Canaria con los fenómenos de arribazones que acontecieron en las playas circundantes los días posteriores, a través de su cuantificación y composición (hoja de muda o planta entera). El estudio de la relación entre los arribazones recolectados por los servicios de limpieza de las playas de la zona con dichos eventos de oleajes que azotaron la zona fue evaluado durante 3 años, de Enero 2004 hasta Enero 2007.

1.2.2. CAPÍTULO 3

Caracterizar el proceso de dispersión del vertido de salmuera de la planta desalaladora Maspalomas II, al sur de la isla de Gran Canaria, bajo diferentes condiciones hidrodinámicas.

Estudiar el efecto de las variaciones del grado de exposición hidrodinámica del medio receptor en el comportamiento habitual del proceso de dispersión de la pluma de salmuera.

1.2.3. CAPÍTULO 4

Evaluar la influencia e interacción del vertido de salmuera de la planta de desalaladora Maspalomas II en la distribución espacial de los sebadales en la zona de influencia y afección.

Analizar la posible relación entre la zona de afección del vertido de salmuera con la ausencia de sebadal en dichos recorridos de la pluma hipersalina.

Relacionar la causa-efecto entre la presencia o ausencia del sebadal en la zona de afección del vertido a través de estudios experimentales.

Establecer diferentes ensayos experimentales de trasplante de *C. nodosa* en el área de influencia de la descarga de salmuera y determinar y evaluar su estado, así como después de la incorporación de la medida correctora (sistema difusor con eductores venturi) con el fin de verificar la eficacia de esta medida de minimización de impacto.

1.2.5. CAPÍTULO 5

Evaluar el impacto sobre el medio marino del proceso de limpieza de membranas de ósmosis inversa de la planta desaladora Maspalomas II, mediante la adición semanal y de choque de SMBS.

Evaluar la hipótesis de que las modificaciones ambientales causadas por incrementos de salinidad y las adiciones de estos compuestos, tras la limpieza de choque semanal de las membranas, asociadas a los vertidos de salmuera, podrían ser las posibles causas de la desaparición de los sebadales en el área de influencia del efluente.

Realizar una caracterización espacial detallada de la variación de las variables físico-químicas (salinidad, pH y oxígeno disuelto) para evaluar la magnitud de las alteraciones ambientales causadas por el vertido de salmuera en la zona tras la adición de SMBS.

Efectuar diferentes bioensayos para evaluar experimentalmente los efectos potenciales de los incrementos de la salinidad y de SMBS inducidos por estas alteraciones físico-químicas en la vitalidad y supervivencia de *C. nodosa* y en otro organismo característico y clave de esta comunidad bentónica, el pez lagarto *S. synodus*.

Tras la incorporación del sistema de difusión con eductores venturi como medida correctora, verificar su capacidad para reducir al mínimo los efectos de estos vertidos durante estos procesos de limpieza de membranas donde se utilizan adiciones de SMBS.

1.2.6. CAPÍTULO 6

Estudiar la viabilidad técnica, económica y medioambiental de la tecnología venturi aplicada a sistemas difusores de vertidos mediante emisarios submarinos.

Evaluar los procesos de dilución del vertido de salmuera procedente de la planta desaladora Maspalomas II sin sistema difusor.

Incorporar en el emisario submarino la boquilla reductora necesaria para generar el efecto de succión y evaluar los procesos de dilución y su variabilidad temporal como presunto dispositivo convencional.

Instalar la estructura de succión y evaluar la mejora de la capacidad de dilución y su variabilidad temporal respecto al funcionamiento de sólo la boquilla reductora y sin sistema difusor.

1.3. PRINCIPALES RESULTADOS OBTENIDOS

1.3.1. CAPÍTULO 2: Relación entre tipos de oleaje y arribazones de plantas marinas (*Cymodocea nodosa*) en el sur de Gran Canaria (Islas Canarias – España).

En la zona sur de la isla de Gran Canaria, concretamente en la Playa del Inglés y Maspalomas, los fenómenos de arribazones durante el periodo de estudio (Enero 2004 – Enero 2007), ocurrieron sí y sólo si eran precedidos por eventos de oleajes considerables. La cantidad del material vegetal recolectado por los servicios de limpieza en estas playas estuvo en función de la fuerza y potencia de los episodios de oleajes que acontecieron los días previos. La cantidad de arribazón recolectado de dichas playas se correlacionó con la potencia del oleaje de los eventos significativos durante todo el periodo de estudio. La relación que mejor se ajustó fue la lineal con un coeficiente de determinación de 0.85, que indicó que un incremento de la potencia del oleaje tiene un aumento lineal y proporcional en la cantidad del material de arribazón recolectado.

La mayoría del material vegetal (> 84 %) recolectado en ambas playas fueron restos de *C. nodosa* (hojas, rizomas, raíces, etc.) que arribaron en cualquier parte tanto de Playa del Inglés como de Maspalomas.

Por un lado, el fenómeno de estas acumulaciones de sebas aconteció en ambas playas cuando a la isla llegó un mar de fondo provenientes del Atlántico Sur (habitualmente en primavera y verano) con una altura de ola de más de 1,4 m y con un periodo de pico mayor a 15 s (potencia del oleaje ≥ 15 kW/m). Los arribazones aparecieron en una o ambas playas unos días más tarde y, bajo estas condiciones, el material vegetal siempre consistió en su gran mayoría (> 97 %) en hojas muertas de *C. nodosa* del proceso de muda de la planta marina. La mayor cantidad de material recolectado fue precedida por el evento más significativo de mar de fondo del sur. Tras el episodio más fuerte de este tipo de oleaje, el día 5 de junio de 2004 (Hs máx.: 1,9 m; 27,8 kW/m), se recolectó una cantidad de material estimada de unos 2.800 kg peso seco, o en el año 2005, después del mayor oleaje de mar de fondo del sur acontecido en ese año (4 mayo; Hs máx.: 1,8 m y 24,3 kW/m), donde se llegaron a recolectar unos 2.400 kg peso seco.

Por otro lado, los arribazones que acaecieron tras el azote de grandes tormentas de sur procedentes de profundas borrascas (en pleno invierno: enero y febrero) se produjeron cuando este tipo de oleaje alcanzó una potencia mayor a 14,6 kW/m y con dirección sur (115º a 225º). En este caso el 99 % del material vegetal recolectado consistió en plantas enteras de *C. nodosa* (hoja verde-fresca junto con rizomas y raíces). Tras las fuertes tormentas del 11 de febrero de 2005 (Hs máx.: 2,2 m; 20.3 kW/m), 8 febrero de 2006 (Hs máx.: 2,5 m; 23,8 kW/m) y 13 de enero de 2007 (Hs max.: 2,2 m; 16 kW/m), los servicios de limpieza de playas recolectaron una cantidad estimada de 400, 200 y 800 kg peso seco de arribazón respectivamente. La mayor cantidad, 2.400 kg peso seco, correspondió al evento de mayor oleaje después de la borrasca más potente que alcanzó el archipiélago en los tres años de estudio, del 27 de enero de 2007 (Hs máx.: 3 m; 32.9 kW/m). Sin embargo, tanto en invierno como verano, tras grandes mares de viento originados por fuertes anticiclones, no aparecieron arribazones en las playas que requiriesen del servicio de limpieza de playas (tractor y camión), a pesar que en algunos casos el potencial del oleaje generado fue mayor a 14,6 kW/m. No obstante, tras estos eventos de oleaje (procedentes de anticiclones), las pequeñas acumulaciones de material vegetal que aparecieron en la playa correspondieron a plantas enteras y no a hojas de muda.

1.3.2. CAPÍTULO 3: Dispersión de un vertido de salmuera bajo diferentes condiciones hidrodinámicas al sur de la isla de Gran Canaria.

Los vertidos de salmuera caracterizados en la planta desaladora Maspalomas II, al sur de Gran Canaria, se constituyeron en plumas hipersalinas de forma alargada que discurrieron por el fondo por su mayor densidad y perpendicular a la costa siguiendo la dirección de máxima pendiente.

En los primeros 125 m de estas plumas hipersalinas, los campos de salinidades se redujeron a un estrecho efluente de apenas 60 m de ancho, donde se concentraron salinidades superiores a 42 psu. Estos campos salinos mayores a 42 psu siguieron discurriendo por el fondo aumentando, por un lado, su ancho hasta 150 m y, por el otro, su largo hasta distancias de 400 m desde el punto de descarga. A estas distancias, las profundidades existentes eran entre 8 y 9 m, que se encuentran dentro de la distribución batimétrica más frecuente de los sebadales en Canarias (Reyes *et al.*, 1995; Espino *et al.*, 2008). Además se observó como el asentamiento del sebadal localizado en los márgenes laterales de las plumas coincidió con dicha distribución batimétrica.

A partir de esta distancia, 400 m, y conforme nos distanciábamos del punto de descarga, los campos de salinidades altas (> 42 psu) comenzaron a desaparecer, pero no así los correspondientes a salinidades mayores a 38 psu. Estos campos salinos se extendieron, a lo largo, hasta profundidades y distancias, desde el punto de descarga, mayores a 20 m y a 1.000 m respectivamente, mientras que, a lo ancho, se fueron agrandando y ampliando paulatinamente, pero con notables diferencias en su ensanchamiento entre las distintas campañas.

Las caracterizaciones donde se obtuvieron mayor esparcimiento lateral correspondieron con los días donde se registraron las condiciones de menor hidrodinamismo, mientras que las de menor extensión se produjeron cuando se registraron las mayores velocidades de corriente de fondo. Además, se observó que estas condiciones hidrodinámicas afectaron sólo en el alcance de las áreas de influencia, pero no así en la dirección del vertido que siguió siempre la dirección de máxima pendiente. Por tanto, las plumas hipersalinas conservaron su misma forma alargada y dirección, pero estrechándose o ensanchándose en función del grado de exposición hidrodinámica del medio receptor.

El 30 de septiembre 2009, durante la campaña de menor grado de hidrodinamismo, el alcance máximo de la zona afectada correspondiente al campo salino superior a 38 psu respecto al punto de descarga fue de 2.100 m de distancia, que correspondió con 35 m de profundidad. A esta distancia tan lejana, la pluma de salmuera todavía conservaba un incremento de salinidad respecto al medio receptor de 1,2 psu.

Esta variación del tamaño de sus zonas de afección correspondiente y relativa a la distribución espacial de los campos de salinidades superiores a 38 psu se relacionó con la media de las velocidades de la corriente de fondo registradas durante la caracterización del vertido. El tipo de tendencia y ecuación que mejor se ajustó a dicha relación fue la forma potencial, que nos indicó que un ligero aumento entre las velocidades bajas de corriente de fondo tiene una mayor repercusión en la disminución porcentual de las áreas de las zonas de afección que entre las velocidades altas.

Área total de la zona de afección (ha) = 61,24*(promedio de la velocidad de la corriente de fondo (cm/s))$^{-0,78}$ (R^2 = 0,92, n=8)

1.3.3. CAPÍTULO 4: Evaluación experimental in situ del efecto del vertido de una desaladora en una pradera marina (*Cymodocea nodosa*).

El recorrido de las diferentes plumas de salmuera caracterizadas bajo diferentes condiciones hidrodinámicas coincidió con un auténtico pasillo de ausencia de cobertura vegetal. Los sebadales próximos o circundantes, que presentaron una distribución espacial en manchas, quedaron delimitados por el área de influencia máxima correspondiente a la distribución espacial de los campos salinos mayores a 39 psu de las 8 campañas caracterizadas bajo distintas condiciones hidrodinámicas (Portillo *et al*., 2014a). Por tanto la pluma hipersalina, a partir de pequeños incrementos de salinidad (≥ 2,2 psu), separó el asentamiento del sebadal en dos poblaciones, un sebadal más próximo a la Playa del Cochino, que correspondería con el sebadal de Playa del Cochino descrito por Espino *et al.* (2003), y otro en frente de la Playa de Las Burras, que denominamos sebadal de Playa de Las Burras.

En las dos zonas seleccionadas para los trasplantes, dentro de la zona de impacto, la media de las salinidades registradas durante una semana de fondeo, así como a través de medidas puntuales durante todo el tiempo de la experimentación, coincidieron prácticamente con las salinidades pretendidas, de 39 y 40 psu. Sin embargo, en ambos emplazamientos, se presentaron variaciones de dichas salinidades respecto a la media de más de 1 psu en reiteradas ocasiones, así como máximos y mínimos mayores a 1,5 psu. Por otro lado, en la zona control, sin interacción e influencia del vertido, el registro de salinidad fue prácticamente constante con una salinidad media en torno a 36,8 psu.

En los experimentos de trasplantes se evidenció en ambas épocas, primavera y verano, la gran diferencia entre las plantas que fueron plantadas en la zona de control, sin afección de la pluma de salmuera y por tanto con una salinidad estable del entorno de 36,8 psu, frente a los trasplantes en el interior de la zona de impacto, a 39 psu y 40 psu. Mientras que en la zona control el número de haces aumentaba o permanecía constante, en los dos emplazamientos dentro de la zona de impacto los haces disminuían drásticamente a partir del segundo mes y en ambas épocas, y por lo tanto, la supervivencia de los mismos.

Estas diferencias también se corroboraron con los datos del porcentaje medio de hoja necrosada, dónde los valores de necrosis en la zona de control se mantuvieron estables o aumentaron ligeramente con valores próximos al 10% tanto en primavera como verano, mientras que en las zonas de impacto superaron el 30 % tras los seis meses de exposición a los incrementos de salinidad.

A través de las fotos de los trasplantes bajo los diferentes tratamientos y tras los seis meses de exposición se pudo evidenciar de una manera muy gráfica este efecto dañino de la salmuera sobre las sebas. En la zona control el trasplante apareció invariable, mientras que en ambas zonas de impacto se apreció como las plantas prácticamente habían desaparecido.

Tras la incorporación de los eductores venturi como medida correctora, la salinidad de las dos zonas de trasplantes dentro de la antigua zona de impacto, de 39 psu y 40 psu, se redujo hasta la salinidad del entorno, de 36.8 psu, por lo que dejó de existir afección del vertido de salmuera en ambos puntos. Los nuevos trasplantes que se realizaron, después de la incorporación de esta medida correctora (sistema difusor con eductores venturi), se mantuvieron en un buen estado de conservación, tanto en la zona control como en los emplazamientos dentro de la antigua zona de impacto. Las sebas trasplantadas se comportaron de manera similar en los tres emplazamientos, donde la supervivencia fue prácticamente del 100 %, el nº de haces se mantuvo constante y el porcentaje de necrosis no superó el 5 %.

1.3.4. CAPÍTULO 5: Evaluación del efecto abiótico y biótico del vertido del metabisulfito sódico (SMBS), procedente de los tratamientos químicos por pulsos de plantas desaladoras, en hábitats de plantas marinas (*Cymodocea nodosa*) en las Islas Canarias.

Los registros en continuo de pH y saturación de oxígeno disuelto (DOsat), en el fondo marino durante el proceso de limpieza de membrana, de la planta desaladora Maspalomas II, a distintas distancias desde el punto de descarga del vertido (0, 250 y 700 m respectivamente), mostraron un decrecimiento bastante acusado de ambos parámetros una vez que los subproductos del SMBS alcanzaban dichos puntos y como dicho efecto se mantenía durante aproximadamente 40 minutos. Las condiciones de hipoxia y acidificación más acusadas se registraron en la boca del emisario, donde todavía no se había podido producir ningún tipo de dilución con el entorno y por tanto con la misma concentración de producto que la adición en la planta, 1500 ppm. Sin embargo, a 250 m, cuando el factor de dilución correspondió a D = 12 (39,2 psu), la salmuera todavía contenía una concentración de subproductos de SMBS bastante significativa, de 123 ppm, por lo que produjo valores de DOsat menores a 5% durante 40 minutos y pH menores a 6 durante casi 20 minutos. A 700 m de distancia del punto de descarga el factor de dilución era elevado (D = 60) y la concentración de los subproductos de SMBS bastante baja, de 23 ppm. A esta concentración los procesos de acidificación y anoxia fueron mucho más leves, con valores mínimos de DOsat y pH de 58 % y 7,6 respectivamente y durante sólo 15 minutos. Con estos registros de los fondeos de los CTD en estas tres posiciones (0, 250 y 700 m respectivamente) se pudo estimar la velocidad de la pluma de salmuera en su dispersión por el fondo, en torno a 9,4 cm/s, que fue de gran utilidad para el diseño y planificación de los trabajos de caracterización de la dispersión de los subproductos del SMBS por el fondo marino.

En ausencia de subproductos de SMBS el vertido de salmuera se conformó en una pluma hipersalina, donde el pH apenas se reducía respecto al agua de mar en 0,2 puntos, mientras que la DOsat se mantuvo inalterable en todos los puntos de muestreo, con valores de 100%.

Sin embargo, tras el tratamiento de limpieza con SMBS (sin sistema difusor), el vertido de salmuera se conformó en los primeros 125 m como un estrecho efluente hipersalino de apenas 60 m de ancho, donde se concentraron valores de salinidades muy altas, superiores a 42 psu, y de pH y ODO% menores a 6 y 5 % respectivamente. Por tanto, en esta zona próxima a la descarga del vertido, se produjo una alta acidificación y prácticamente una total desoxigenación del medio receptor. Estas condiciones anormales siguieron discurriendo por el fondo, aumentando, por un lado, su ancho hasta 100 m y, por el otro, su largo hasta distancias de 300 m desde el punto de descarga, abarcando un área de influencia de 1-2 ha en los que los campos de DOsat y pH eran menores al 10 % y a 6,2 respectivamente. A partir de esta distancia y conforme nos distanciábamos del punto de descarga, estos campos con estas salinidades tan altas, pH muy ácidos y sin prácticamente oxígeno disuelto no prosiguieron extendiéndose, pero no así los correspondientes a salinidades mayores a 38 psu o a pH y ODO% menores a 7,4 y 50 %. Por el contrario, estas distribuciones espaciales horizontales se extendieron, a lo largo, hasta profundidades y distancias desde el punto de descarga mayores a 18 m y a 850 m respectivamente, mientras que, a lo ancho, se fueron agrandando y ampliando paulatinamente, abarcando amplias extensiones de hasta 15 ha, mientras que el área correspondiente a la isolínea de 39 psu fue de 8 ha.

Por el contrario, una vez incorporado los eductores venturi las salinidades fueron similares a las del medio receptor a excepción en la zona más próxima al sistema difusor, donde fueron ligeramente superiores, mayores a 37 psu pero menores a 37,5 psu. Por esta razón, la zona de afección se minimizó considerablemente y la zona de impacto se redujo totalmente (0 ha). Esta alta capacidad de dilución en las cercanías del punto de descarga (D > 39) debido a la gran eficiencia del sistema difusor, consiguió a su vez eliminar, casi en su totalidad, los efectos de acidificación y desoxigenación de la zona del vertido. Las distribuciones espaciales horizontales correspondientes a los campos de pH y ODO% fueron casi despreciables, ya que los valores registrados en la malla de puntos se equipararon prácticamente con los del medio receptor. Solamente en la zona próxima al sistema difusor, en determinados puntos de la malla (números 4 y 5 de los puntos de muestreo) donde se registraron las salinidades próximas a 37,5 psu, se obtuvo cierta ligera reducción de pH y de ODO% del orden de 0,2 y de 5 % respectivamente.

En el estudio de tolerancia del metabisulfito sódico en el pez lagarto (*S. synodus*) se determinó la alta sensibilidad de esta especie a exposiciones con bajas concentraciones de este producto (> 50 ppm) y durante periodos muy cortos (< 12 minutos). A partir de la concentración de 50 ppm, donde el porcentaje en saturación de oxígeno disuelto fue en torno al 10 %, y con una acidificación del pH en 1,3 puntos, la mortandad fue del 100 % en un promedio de tiempo de 10 minutos. Los porcentajes en saturación de oxígeno para las concentraciones mayores, de 75 y 100 ppm, fueron aproximadamente del 5 y 0 % respectivamente y las tasas de mortandad para ambos casos fueron también del 100 %. A estas concentraciones los peces, con promedios de peso aproximados, comenzaron incluso a morir con mayor brevedad que a la concentración de 50 ppm, del orden de 2 minutos antes en ambos casos. Por el contrario, a partir la concentración de 25 ppm, donde la reducción en el porcentaje de saturación de oxígeno disuelto fue de un 50 %, y durante 40 minutos, la tasa de supervivencia fue del 100 %. Por tanto, a partir de concentraciones mayores a 50 ppm el efecto de este producto es letal y rápido, mientras que a partir de concentraciones menores a 25 ppm se garantiza la supervivencia para exposiciones menores a 40 minutos.

En la evaluación de tolerancia del metabisulfito sódico en *C. nodosa*, la supervivencia fue inferior en los tratamientos con adición de metabisulfito sódico (100 ppm) tanto a 36,8 como a 39 psu respecto a los tratamientos sin adición, los cuales presentaron valores de supervivencia similares entre sí. La tasa de elongación fue mayor en el control a 36,8 psu, e iba disminuyendo a medida que le aumentábamos la concentración de sales, a 39 psu, y superior a los tratamientos con adición de metabisulfito sódico, que presentaron una tasa de elongación menor. El análisis SNK confirmó que las tasas de elongación de las plantas sometidas a salmuera (39 psu) más adición semanal de metabisulfito sódico fueron menores que las plantas que no fueron sometidas al choque de este producto. El mismo comportamiento se observó en los valores de superficie foliar, que presentó mayor superficie de hoja en aquellas plántulas sin ningún tipo de tratamiento (control a 36,8 psu), no existiendo diferencias significativas entre las plántulas sometidas a los tratamientos restantes (S, SM y CM). Por último, el porcentaje de hoja necrosada fue aumentando progresivamente desde el control (C), salmuera (S), control más metabisulfito sódico semanal (CM) y salmuera más este producto (SM). Los valores de ancho de hoja y número medio de hojas por plántula no resultaron significativos.

1.3.5. CAPÍTULO 6: Eductores venturi como dispositivos difusores eficaces para los procesos de dilución en vertidos de salmuera procedente de plantas desaladoras.

La velocidad de salida del vertido del emisario submarino de la planta desaladora Maspalomas II en su estado original, sin ningún sistema difusor, fue muy baja, de apenas 1 m/s. Por el contrario, las velocidades que se generaron a través del sistema difusor fueron mucho mayores y casi idénticas, de 12,01 m/s en febrero 2012 con sólo las boquillas reductoras y un poco menor, de 11,9 m/s, en julio 2011 con el eductor venturi (boquilla reductora + estructura en forma de campana/trompeta de efecto de succión). Las distancias desde la zona de descarga hasta la zona de impacto y hasta el inicio del campo lejano variaron significativamente entre el sistema difusor sin y con estructura de succión por efecto venturi, de 18 m se reducía a 16 m y de 30 m se incrementaba a 36 m respectivamente, y por el contrario las distancias hasta la altura máxima del chorro fueron similares, cinco veces mayor que la distancia sin sistema difusor, 10 m frente a 2 m.

Las diluciones correspondientes para cada sistema de descarga y punto de muestreo mostraron la incapacidad de mezcla del sistema de descarga original (sin ningún sistema difusor). La dilución en el inicio del campo lejano fue de 3,3 frente a diluciones casi 9 ó 12 veces superiores con la boquilla reductora o con el eductor venturi respectivamente. La mejora en la capacidad de dilución del sistema tras la incorporación de la estructura de succión respecto a sólo las boquillas reductoras en la zona de impacto como en el inicio del campo lejano fue aproximadamente del 20 y 35 % respectivamente, a pesar que la velocidad de la corriente del medio receptor fue mayor sin la estructura de succión de efecto venturi.

El sistema de descarga sin sistema difusor no se comportó como un vertido en chorro representativo, ya que no consiguió separarse del fondo y en apenas unos metros la salmuera se hundía en su totalidad. Además la pluma resultante conformó un espesor menor a un metro, mientras que con ambos sistemas difusores tenía un grosor prácticamente del doble.

Por otro lado, quedó patente como los sistemas de descarga, con boquilla reductora y junto con la estructura de efecto venturi, debido a las altas velocidades de salida reprodujeron un chorro con movimiento parabólico con un gran alcance en ambos casos, a pesar que dichos chorros correspondieron a sólo la mitad del caudal. El grosor del chorro en el punto de altura máxima fue de unos 2 m aproximadamente, quedando a unos 3-3,5 m por debajo del nivel del mar y por tanto salvaguardando su posible elevación sobre la superficie del mar. Además se evidenció las diferencias entre los eductores venturi respecto las boquillas reductoras convencionales sin la estructura de succión. Estas diferencias fueron fundamentalmente en un ligero mayor grosor del chorro y de la pluma resultante en el inicio del campo lejano, en una mayor extensión de la zona de turbulencias, en un mayor alcance del campo cercano, en una mayor capacidad de reducción de la salinidad de la pluma de salmuera resultante y por consiguiente en una mayor eficiencia en su capacidad de dilución (38 frente a 28, o de 39,2 frente a 27,4 en el registro semanal).

CAPÍTULO 1. INTRODUCCIÓN GENERAL

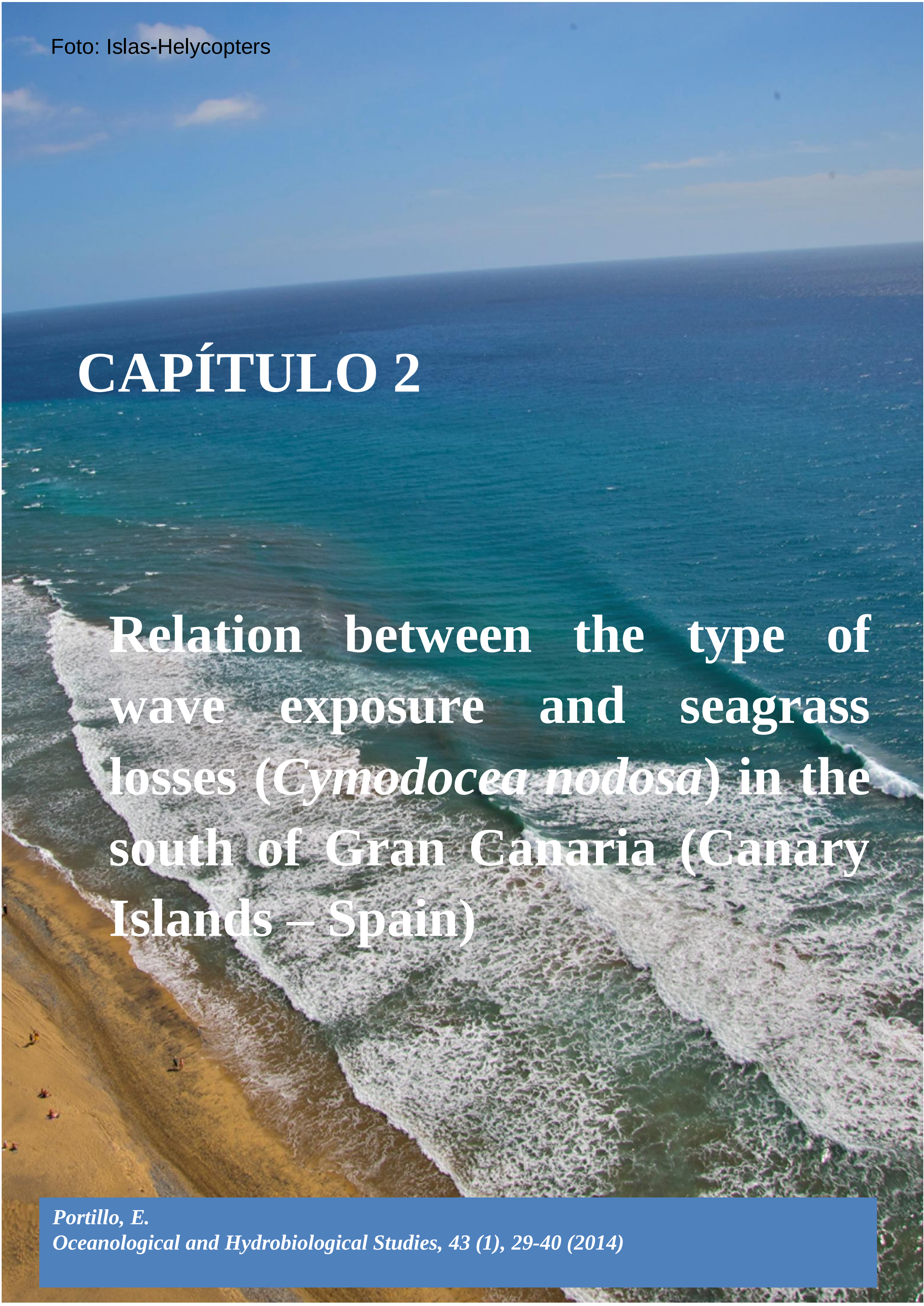


Foto: Islas-Helycopters

CAPÍTULO 2

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Relation between the type of wave exposure and seagrass losses (*Cymodocea nodosa*) in the south of Gran Canaria (Canary Islands – Spain)

Eduardo Portillo*

Instituto Tecnológico de Canarias, S.A
Santa Lucía, 35119 Las Palmas SPAIN

Key words: *Cymodocea nodosa*, seagrass, wave forces, swell, wind waves, storms

Abstract

Effects of different types of wave events on *Cymodocea nodosa* seagrass meadows were observed and investigated by quantitative and qualitative evaluation of material washed ashore a few days after the events. The studied seagrass meadows are located on the south coast of the island of Gran Canaria (Canary Islands – Spain) and they are protected from frequent swells arriving from the North Atlantic. However, sporadic phenomena associated with winter storms occasionally hit this coastline, causing the loss of entire plants (fresh leaves with rhizomes and roots attached). An unusual type of southern swells generated in the South Atlantic also reaches the Islands in spring and summer. A clear relation was observed between the wave events (southern swells and storm waves) and the material cast ashore over the following days, with differences in composition (fresh vs. decaying leaves) depending on the type of event. After southern swells, detached portions of *C. nodosa* consisted mostly of decaying leaves shed after senescence. These old swells cause frictional drag with moderate oscillations over a wider range at greater depths, removing only decaying leaves from the seagrass meadows and favoring the natural clean-up process.

* Corresponding author: *eportillo@itccanarias.org*

INTRODUCTION

Seagrass accumulations have been documented on beaches in several locations around the world, such as East Africa (Hemminga and Nieuwenhuize 1990, Ochieng and Erftemeijer 1999), Australia (Kirkman and Kendrick 1997), Europe (Milchakova 1999, Mateo et al. 2003, Duarte 2004, Roig and Martín 2005, Kotwicki et al. 2005, Ballestri et al. 2006, De Falco et al. 2008, Portillo 2008, Mateo 2010, Cocozza et al. 2011, Mossbauer et al 2012, Simeone and De Falco 2012) and North America (Behbehani and Croker 1981, Roman and Able 1988), but little has been published about their relation to wave exposure (Ochieng and Erftemeijer 1999, Ballestri et al. 2006).

Strong hydrodynamics and sudden disturbances in the sea can snap off leaves and uproot whole plants from seagrass meadows (Preen et al. 1995, Fourqurean and Rutten 2004, Ballestri et al. 2006), which results in massive accumulations of material on beaches in certain parts of the Mediterranean (Duarte 2004, Medina et al. 2001) and Australia (Department of the Environment and Heritage, 2004).

Earlier studies of interaction between waves and seagrasses addressed only wave height (Fonseca and Cahalan 1992, Granata et al. 2001, Koch et al. 2006) and the effect of seagrass meadows on wave propagation and attenuation (Bradley 2009, Stratigaki et al. 2011, Hansen and Reidenbach 2012, Infantes et al. 2012, Paul et al. 2012). Nothing has been mentioned about the effects of different types of waves (swells and wind waves) and whether they could determine high rates of canopy defoliation (shedding leaves) or uprooting of entire plants (fresh leaves with rhizomes and roots attached).

Seagrass meadows are particularly vulnerable to direct and indirect effects of human impact

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2.1. INTRODUCTION

Seagrass accumulations have been documented on beaches in several locations around the world, such as East Africa (Hemminga and Nieuwenhuize, 1990; Ochieng and Erftemeijer 1999), Australia (Kirkman and Kendrick, 1997), Europe (Milchakova, 1999; Duarte, 2004; Kotwicki *et al.*, 2005; Roig and Martín, 2005; Ballestri *et al.*, 2006; De Falco *et al.*, 2008; Portillo, 2008; Mateo, 2010; Cocozza *et al.*, 2011, Mossbauer *et al.*, 2012, Simeone and De Falco, 2012) and North America (Behbehani and Croker, 1982; Roman and Able, 1988), but little has been published about their relation to wave exposure (Ochieng and Erftemeijer, 1999; Ballestri *et al.*, 2006).

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Seagrass meadows are particularly vulnerable to direct and indirect effects of human impact (Boudouresque *et al.*, 2009), making their presence a good indicator of the health of the water in the area. Any change in their distribution, such as a decrease in beach-cast material on neighbouring beaches, would indicate serious changes in the ecosystem. This is why seagrass meadows act as “coastal canaries”, because they indicate any degradation, disturbance or contamination in the marine ecosystem (Orth *et al.*, 2006).

The main aims of this investigation were to answer the following research question: Is there any relation between the quantity and the composition (shed leaves or entire plants) of these depositions of beach-cast seagrass and the type of wave (swell and wind waves) or the type of material present in the meadow at the time of the wave event?

The study was conducted at Playa del Inglés and Maspalomas beaches, in the south of the island of Gran Canaria (Canary Islands – Spain). Through quantitative and qualitative assessment, a study was conducted of the relation between the beach-cast seagrass collected by the local beach cleaning service and the wave type preceding each event, from January 2004 to January 2007.

2.2. MATERIAL AND METHODS

Study site and meteorological and oceanographic conditions

The Canary Islands are an Atlantic Archipelago of seven volcanic islands off the northwest coast of Africa (Fig. 1). The seagrass *Cymodocea nodosa* (Ucria) Ascherson is the most abundant marine phanerogam in the Archipelago and forms extensive sub-tidal meadows (Barberá *et al.*, 2005; Tuya *et al.*, 2006). The largest *C. nodosa* seagrass meadows in Gran Canaria are in the southern coastal region of the island, at Playa del Inglés and Maspalomas beaches (Fig. 1), occupying shallow sandy bottoms at depths from 5 to 21 m, with an average seagrass cover of 50% in a total area of 525 ha and a mean density of 848 shoots per m^2 (Espino *et al.*, 2003). This southern location with a gentle beach slope of 0.016 is protected from frequent swells arriving from the North Atlantic (Haroun *et al.*, 2003; Tuya and Haroun, 2006) and wind waves generated by high pressure systems, which occur in all seasons in the Canary Islands with prevalent NE winds known as trade winds (the most common wind system on these islands). The gentle beach slope and the protected shore of the area explain why it is home to sandy sea bottoms and therefore how the seagrass meadows (known locally as *sebadales*) can settle and grow without disturbance from waves or currents, constituting the island's largest seagrass meadow. For this reason, the entire area has been made a Special Area of Conservation (SAC) under the name of *Sebadales de Playa del Inglés* (ES7010056) (BOE, 2009).

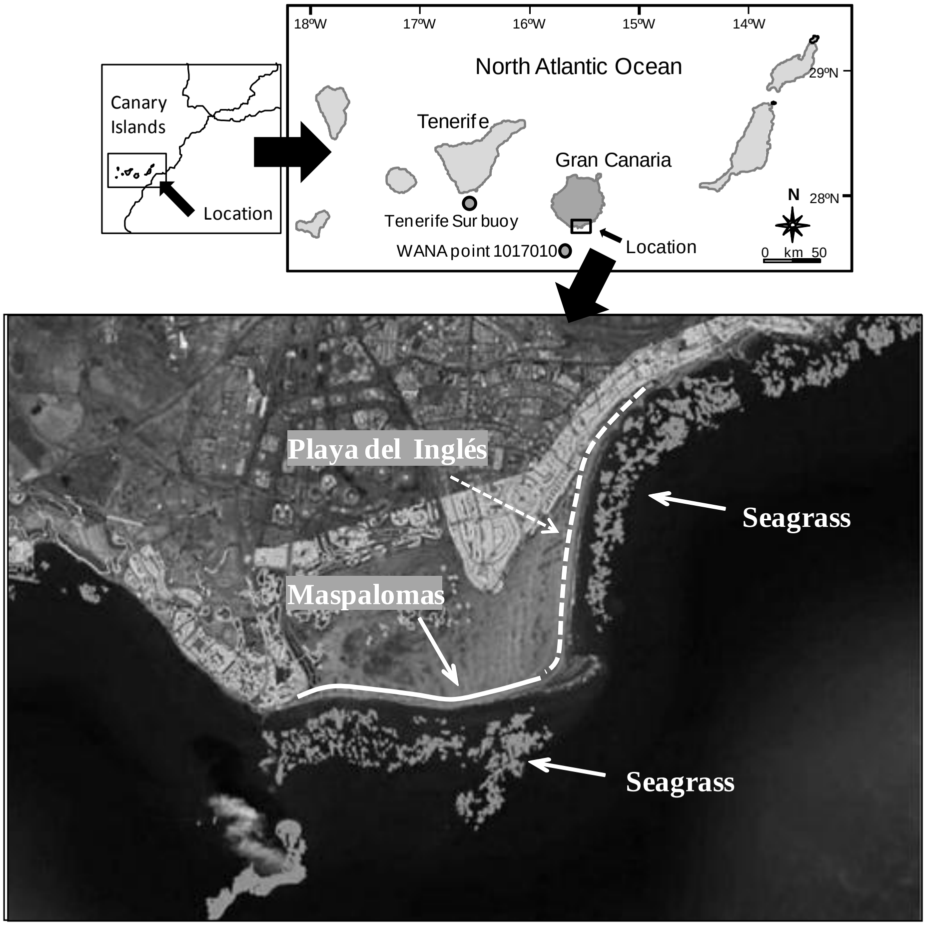


Figure 1. - Map of the Canary Islands showing Tenerife Sur buoy, WANA Point 1017010, the locations of Playa del Inglés and Maspalomas beaches with maps of the seagrass meadows.

Nevertheless, natural and sporadic phenomena associated with significant wave events cause seagrass losses in the area.

On the one hand, severe winter storms near the Canary Islands (Bullón, 2003; Yanes *et al.*, 2006) occasionally reach the south of Gran Canaria, crossing the area and battering it with west-south-west (WSW) to east-south-east winds (ESE) (8-9 Beaufort scale) from the sea (Medina *et al.*, 2007), directly hitting the seagrass meadows. The predominant direction and height of the wind waves generated depend on the strength, path and spread of the storm. Additionally, wind waves generated by powerful high pressure systems, which can occur sporadically in winter and summer usually extend eastward, generating E to ESE wind waves, and could also affect this protected shoreline.

On the other hand, in spring and summer, a southern swell occasionally arrives in the Canary Islands from deep low pressure systems in the South Atlantic (austral autumn and winter). This strong depression, with a tendency to generate travelling fetch, sporadically results in waves up to 9 m high that head for the Canary Islands through the small passage between eastern South America and western North Africa (Portillo *et al.*, 2007). The swells produced travel more than 5000 nmi for 6 to 8 days until they reach the southern shores of the Canary Islands. As a result, they show good internal organization (sets of up to 8 waves and a standard "wait-time" of 10-20 minutes) when they reach the shoreline, with high peak periods of 15-20 seconds and low significant wave heights of 1-1.5 m in deep waters, although up to 3 m in some breakers (Portillo *et al.*, 2007).

Wave forecast and data

Wind waves and southern swells were forecast by the third generation wave model WAVEWATCHIII (WW3), developed at NOAA/NCEP and run on the Fleet Numerical Meteorology and Oceanography Center (FNMOC), and the WAM wave model, developed by the WAMDI Group (WAMDI, 1988) and provided by the Spanish Meteorological Agency. The Spanish Ports System, attached to the Ministry of Public Works, provided the archived directional wave data from the Ports System deep sea Measurement Networks taken from the *Tenerife Sur* buoy, located at 28ºN 16º34.8'W at a depth of 781 m, very close to the beaches of Playa del Inglés and Maspalomas (Fig. 1). As the buoy was inoperative on 28 November 2005 during cyclone Delta, wave data were recorded by the WANA Point located in the closest proximity to these beaches (WANA Point 1017010) from the WANA data set, which comes from the WAM model output.

Wave power was determined in deep water, through extrapolation of the Airy wave theory (1845), where the water depth is greater than half the wavelength (the region of the Tenerife Sur buoy). In this case, wave power can be presented using the following formula $P \approx 0.5\ Hs^2Tp$ (kw/m) (Brooke, 2003).

Sampling and data analysis

Sampling was carried out on beach-cast seagrass collected on the two beaches by the cleaning service URBASER SA, which removes debris every morning. As Playa del Inglés and Maspalomas are very important beaches for tourism, the cleaning service is responsible for clearing any beach-cast accumulation in this area. We were notified only when the collected beach-cast material was more than 1 ton fresh weight, i.e. when tractors and lorries are normally required for removal. However, after significant wave events that did not require collection of beach-cast material, we visited these beaches to determine the type of *C nodosa* material washed ashore (decaying or fresh leaves).

The collected beach-cast material was randomly removed from a lorry until 1 m^3 was obtained and washed in seawater tanks to remove sand. During this process, the collected material was immersed in floating sifters, favoring decantation and separation of the sand downward through the net, then dried in a solar/wind drying area to determine dry weight. Stones and other residue (plastic, wood, remnants of clothing, etc.) were easily removed from the dried material and various components (sand, stones, seagrass, seaweed, other residue, etc.) were weighed separately. The variation in the weight of salt content in the dried seagrass material was considered constant, as the local salinity (oceanic waters) is quite stable. Once the percentages were determined, the total amount of beach-cast seagrass collected was quantified by the number and capacity of the lorries used. The 5 kg samples of washed beach-cast material were sorted by species before drying at 60ºC to constant weight. Percentages of the taxonomic composition of the samples were estimated from dry weights.

C. nodosa leaves were defined as “decaying” when their cover was dark brown and no rhizomes or roots were attached, and “fresh” when their cover had a fresh green color and rhizomes and roots were attached.

2.3. RESULTS

Composition of beach-cast material

All beach-cast material collected from Playa del Inglés and Maspalomas by the cleaning service contained up to 84% of detached portions (leaves, rhizomes, roots, etc.) of *C. nodosa* (Table 1) cast ashore anywhere on the two beaches. The entire submerged area in the vicinity is covered by large seagrass meadows of *C. nodosa* (Fig. 1), so the small amount of the remaining material included a variety of seaweeds that occur in the seagrass meadows (*Caulerpa racemosa*, *Caulerpa prolifera*, *Sporochnus pedunculatus*, etc.) or grow on the rocky substrate of the surrounding areas (*Haliptilon virgatum*, *Halopithys incurva*, *Halopteris filicina*, *Jania rubens*, *Liagora spp*., etc.). The highest percentages reached *H. incurva* among the red algae, *S. pedunculatus* among the brown algae and two green algae, *C. prolifera* and *C. racemosa*. Percentages varied during the study, but no differences in relation to season or beach were observed.

Table 1. Composition of beach-cast material during the period: a) January 2004 - December 2005, b) January 2006 - January 2007. Data shown as a percentage of total dry weight of beach-cast material.

	Maspalomas	Inglés and Maspalomas	Inglés	Inglés	Inglés	Inglés and Maspalomas
	6 June 2004	5 Sept 2004	13 Feb 2005	9 April 2005	6 May 2005	29 Nov 2005
Seaweed material						
Caulerpa prolifera	0.4	3.1	0.8	1.2	3.1	1
Caulerpa racemosa	0.1	1.8	0.2	0.9	2.1	0.4
Dictyota spp.				0.2		
Enteromorpha sp.		0.2		0.2	0.2	
Haliptilon virgatum	2.5		1.5		0.2	
Halopithys incurva	5.1	1	1		1.5	0.2
Halopteris filicina				0.5		
Jania rubens				0.3	0.3	
Liagora spp.					0.1	0.2
Lobophora variegata	0.3	0.1				
Sporochnus pedunculatus	3.3	1	1	0.2	1	0.2
Ulva sp.				0.1		
Seagrass material						
Cymodocea nodosa	88.3	92.8	95.5	96.4	91.5	98
Total	100	100	100	100	100	100

a)

	Inglés and Maspalomas	Inglés and Maspalomas	Maspalomas	Maspalomas	Inglés	Inglés and Maspalomas	Inglés
	10 Feb 2006	8 May 2006	11 June 2006	6 July 2006	12 Sept 2006	13 Jan 2007	28 Jan 2007
Seaweed material							
Caulerpa prolifera	0.4	1.4	0.8	2.1	1.3	0.4	0.8
Caulerpa racemosa	0.8	0.2	0.3	1.8	1.4	0.2	0.2
Dictyota spp.	0.3		0.3		0.6		
Enteromorpha sp.	0.2				0.2		
Haliptilon virgatum		1.1		0.1			
Halopithys incurva	0.8	8	1.1	3.8	1.5	0.1	
Halopteris filicina		0.4			0.2		
Jania rubens		0.1			0.3	0.3	
Liagora spp.			2		0.2		
Lobophora variegata	0.5		0.2		0.1		
Sporochnus pedunculatus	0.7	4	1	0.4			
Ulva sp.	0.3		0.1		0.1		
Seagrass material							
Cymodocea nodosa	96	84.8	94.2	91.8	94.1	99	99
Total	100	100	100	100	100	100	100

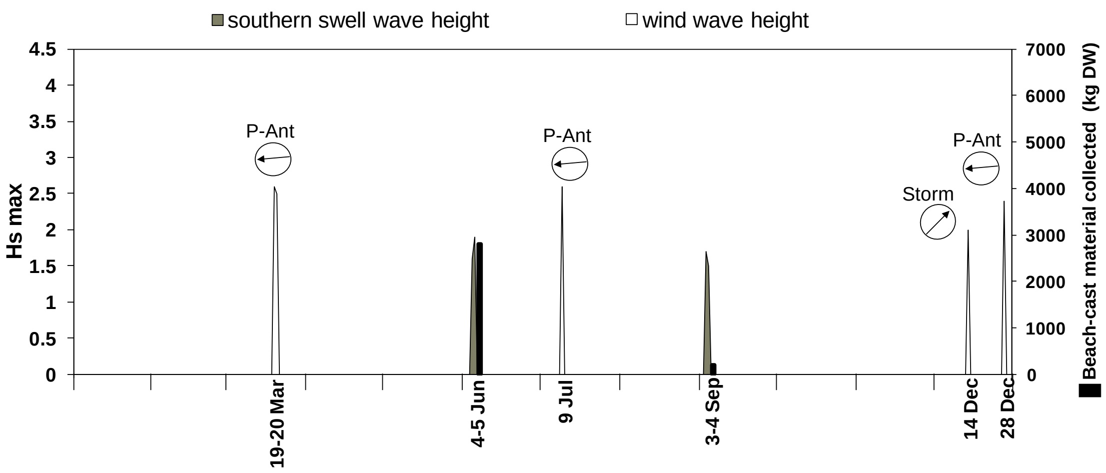
b)

Quantitative and qualitative assessment (fresh or decaying leaves) of beach-cast seagrass collected and wave events

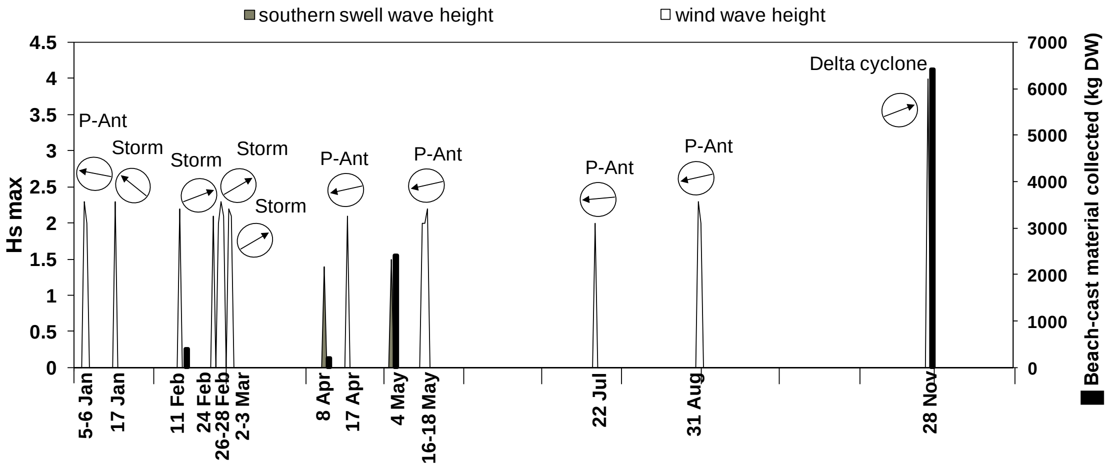
Significant wave events (with high energy), consisting in southern swells and storm wind waves (but not from powerful anticyclones), presented a clear relation to beach-cast seagrass collected some days after these events (Table 2 and Fig. 2).

Table 2. Maximum significant wave height of the day (Hs max), peak period (s), direction (°), type of wave (with origin) and wave power of all the significant wave events occurred from January 2004 to January 2007. Beach-cast material collected some days after these events (kg DW) at Playa del Inglés and Maspalomas.

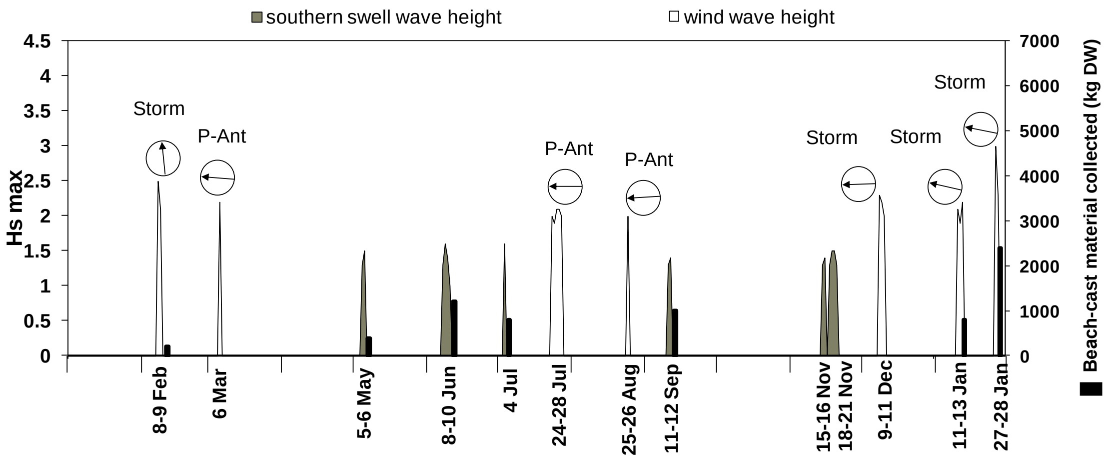
Date	Hs max (m)	Tp (s)	Direction (°)	Type of wave / Origin	Wave Power (kW/m)	Beach-cast material collected (kg DW)
20/03/2004	2.5	10	82	wind waves / anticyclone	31.3	0
05/06/2004	1.9	15.4	214	southern swells	27.8	2800
09/07/2004	2.6	7.6	79	wind waves / anticyclone	25.7	0
03/09/2004	1.7	15	210	southern swells	21.7	200
14/12/2004	2	6.7	237	wind waves / storm	13.4	0
28/12/2004	2.4	6.4	80	wind waves / anticyclone	18.4	0
05/01/2005	2.3	6.5	120	wind waves / anticyclone	17.2	0
17/01/2005	2.3	6.1	153	wind waves / storm	16.1	0
11/02/2005	2.2	8.4	115	wind waves / storm	20.3	400
24/02/2005	2.1	8.4	231	wind waves / storm	18.5	0
27/02/2005	2.3	6.6	225	wind waves / storm	17.5	0
02/03/2005	2.2	7.2	239	wind waves / storm	17.4	0
08/04/2005	1.4	15.4	217	southern swells	15.1	200
17/04/2005	2.1	11.1	76	wind waves / anticyclone	24.5	0
04/05/2005	1.8	15	205	southern swells	24.3	2400
18/05/2005	2.2	5.9	90	wind waves / anticyclone	14.3	0
22/07/2005	2	6.2	75	wind waves / anticyclone	12.4	0
31/08/2005	2.1	6.2	83	wind waves / anticyclone	13.7	0
28/11/2005	4	9	225	wind waves / Delta cyclone	72.0	6400
08/02/2006	2.5	7.6	158	wind waves / storm	23.8	200
06/03/2006	2.2	6.2	101	wind waves / anticyclone	15.0	0
06/05/2006	1.5	15.4	217	southern swells	17.3	400
09/06/2006	1.6	15.4	208	southern swells	19.7	1200
04/07/2006	1.6	15.4	214	southern swells	19.7	800
26/07/2006	2.1	7.2	84	wind waves / anticyclone	15.9	0
25/08/2006	2	5.5	87	wind waves / anticyclone	11.0	0
12/09/2006	1.4	15.4	217	southern swells	15.1	1000
15/11/2006	1.3	15.4	208	southern swells	13.0	0
19/11/2006	1.5	15.4	211	southern swells	17.3	0
09/12/2006	2.3	7.2	87	wind waves / storm	19.0	0
13/01/2007	2.2	6.6	124	wind waves / storm	16.0	800
27/01/2007	2.8	8.4	127	wind waves / storm	32.9	2400


southern swell wave height
wind wave height
Hs max
Beach-cast material collected (kg DW)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
7000
6000
5000
4000
3000
2000
1000
0
P-Ant
P-Ant
Storm
P-Ant
19-20 Mar
4-5 Jun
9 Jul
3-4 Sep
14 Dec
28 Dec

a)


southern swell wave height
wind wave height
Hs max
Beach-cast material collected (kg DW)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
7000
6000
5000
4000
3000
2000
1000
0
P-Ant
Storm
Storm
Storm
Storm
P-Ant
P-Ant
P-Ant
P-Ant
Delta cyclone
5-6 Jan
17 Jan
11 Feb
24 Feb
26-28 Feb
2-3 Mar
8 Apr
17 Apr
4 May
16-18 May
22 Jul
31 Aug
28 Nov

b)


southern swell wave height
wind wave height
Hs max
Beach-cast material collected (kg DW)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
7000
6000
5000
4000
3000
2000
1000
0
Storm
P-Ant
P-Ant
P-Ant
Storm
Storm
Storm
8-9 Feb
6 Mar
5-6 May
8-10 Jun
4 Jul
24-28 Jul
25-26 Aug
11-12 Sep
15-16 Nov
18-21 Nov
9-11 Dec
11-13 Jan
27-28 Jan

c)

Figure 2. - Seasonal variation (X-axis: date) of beach-cast material collected, showing the quantity in kg dry weight (kg DW) at Playa del Inglés and Maspalomas and maximum significant wave height of the day (Hs max) with origin, southern swells or wind waves (from Storm (*Storm*) or Powerful Anticyclones (*P-Ant*)), and direction in a) January 2004 - December 2004, b) January 2005 - December 2005, c) January 2006 - January 2007. Only wind wave heights greater than 2 m from storms (direction: WSW-ESE; *Storm*) and powerful anticyclones (direction: ENE-ESE; *P-Ant*) and only southern swell wave heights greater than 1.3 m with peak periods of more than 15 s are shown (direction: SSW-S; *southern swell*).

Seagrass accumulations occurred only when preceded by significant wave episodes a few days earlier: southern swells in spring-summer and wind waves caused by storms in winter. The collected beach-cast material was associated with the wave power of significant wave events during the whole period of the study, as shown in Figure 3. The trend type and equation that best fitted this relation was the linear form with a determination coefficient higher than 0.85. This type of relation indicated that the increased wave power has a proportional linear effect increase on the amount of beach-cast material collected.

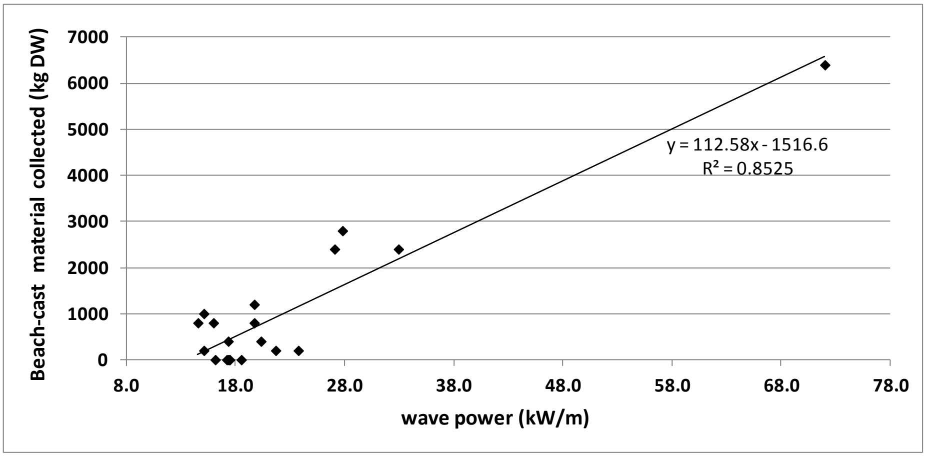
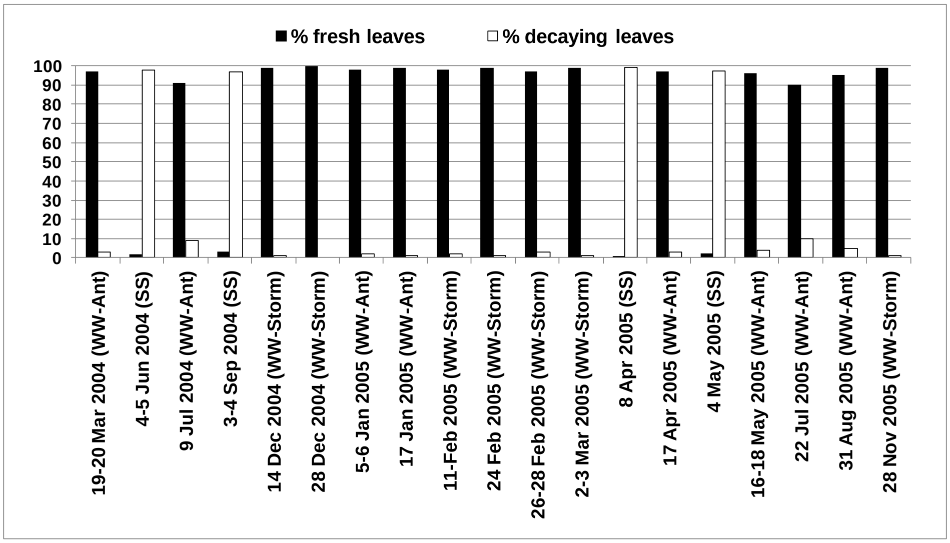


Figure 3. Relation between wave power (kW/m) for significant wave events occurred from January 2004 to January 2007 with southern direction (from 115° to 225°) and beach-cast material collected some days after (kg DW) at Playa del Inglés and Maspalomas.

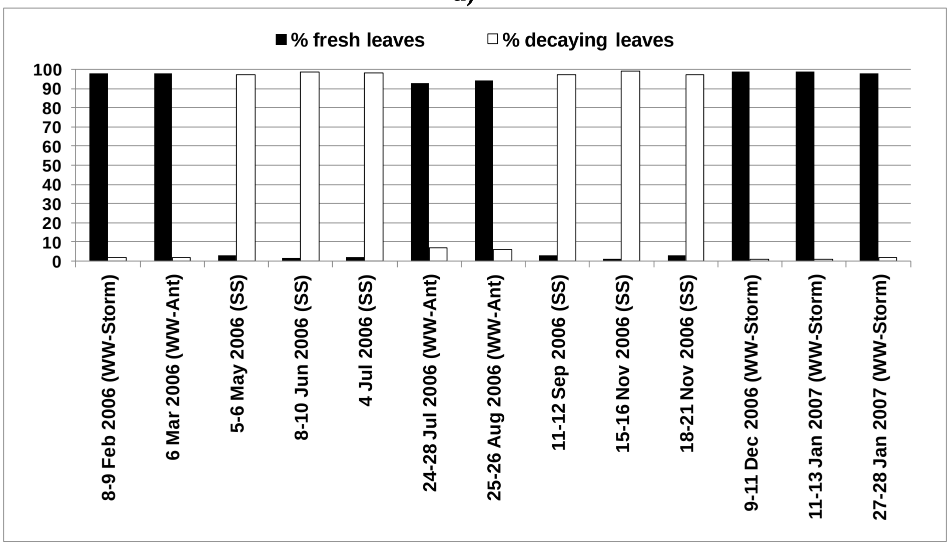
On the one hand, the phenomenon of deposition of beach-cast seagrass preceded by southern swells occurred only when these swells had reached the Canary Islands with a wave height of more than 1.4 m and a peak period of more than 15 s some days earlier (wave power ≥ 15 kW/m) (Fig. 2 and Table 2). Beach-cast material was collected at one or both of the beaches and in all cases the material was mostly decaying *C. nodosa* leaves (>97%) (Fig. 4). The largest amount collected was preceded by the largest southern swell during the study period. An estimated 2800 kg dry weight of collected beach-cast seagrass was preceded by the strongest event − on 5 June 2004 (Hs max: 1.9 m; 27.8 kW/m) and in 2005, after the largest southern swell for the year (4 May; Hs max: 1.8 m and wave power of 24.3 kW/m), when 2400 kg dry weight was collected. Three days after the major swells in 2006, i.e. on 9 June (Hs max: 1.6 m; 19.7 kW/m), the cleaning service collected 1200 kg dry weight, the largest landing of beach-cast seagrass for the year. As an exception, southern swell events on 19 November 2006, with the maximum significant wave heights of 1.5 m (wave power of 17.3 kW/m), hit the area in autumn (austral spring), but no beach-cast material was collected in Playa del Inglés or Maspalomas. However, *C. nodosa* remains found on the shore after both southern swells consisted mainly of decaying leaves.

On the other hand, the phenomenon of material cast ashore after wind waves occurs in winter (January and February), only when southerly (115° to 225°) storm waves reach the islands with wave power greater than 14.6 kW/m. Approximately 99% of the seagrass material collected after these severe storms during the study period was fresh *C. nodosa* leaves (Fig. 4). After the severe storms of 11 February 2005 (Hs max: 2.2 m; 20.3 kW/m), 8 February 2006 (Hs max: 2.5 m; 23.8 kW/m) and 13 January 2007 (Hs max: 2.2 m; 16 kW/m), the cleaning company collected 400, 200 and 800 kg dry weight, respectively. The highest amount (2400 kg dry weight) corresponded to the largest wave event generated in the heaviest squall of 27 January 2007 (Hs max: 3 m; 32.9 kW/m). Other winter storms with similar characteristics, e.g. those on 17 January 2005 (16.1 kW/m) and 27 February 2005 (17.5 kW/m), were not followed by accumulations of beach-cast seagrass, but the detached portions of *C. nodosa* observed on the beaches after all these events were fresh leaves with rhizomes and roots attached (Fig. 4). Conversely, wind waves originating from strong anticyclones (P-Ant), in both winter and summer, were not associated in any way with beach-cast seagrass (when tractors and lorries are normally required for removal), even though in some cases the generated wave power was more than 14.6 kW/m. However, the seagrass material observed on the shore consisted of fresh leaves in approximately 90%.

An exceptional event occurred on 28 November 2005, in mid autumn, with the unusually severe tropical cyclone Delta, which was accompanied by the largest amount of beach-cast material collected in the whole study period (6400 kg dry weight). No wave data were recorded at this time as the *Tenerife Sur* buoy was inoperative, so the specified wave height of 4 m and peak period of 9 s was predicted by the WAM model, incorporating the wind field generated by the HIRLAM model.



a)



b)

Figure 4. Dates of beach-cast seagrass and types of wave events (southern swells (SS), wind waves from storms (WW-Storm) and wind waves from powerful

anticyclones (WW-Ant)) preceding each deposition of beach-cast material during the study period (X-axis), showing the composition as a percentage of decaying and fresh leaves: a) From January 2004 to December 2005, b) From January 2006 to January 2007.

2.4. DISCUSSION

Quantifying the beach-cast material collected on these types of tourist beaches is one approach to estimate and assess the loss of marine plants in this area, as the cleaning service always removes any material washed ashore, and this is one way to estimate the condition of the surrounding seagrass meadows (growth, stability or regression) (Orth *et al.*, 2006). However, mechanical removal of this material is not an environmentally friendly practice, as seagrass remains help to maintain the shoreline by reducing the wave forces and favor sedimentation processes (Hemminga and Nieuwenhuize, 1990). Similarly, a large amount of sand is lost (> 80%) when seagrass is collected mechanically (Portillo, 2008).

The considerable southern swell and wind waves generated by storms normally coincided with a large volume of beach-cast material on the beaches of Playa del Inglés and Maspalomas several days later, but similar sea conditions were not always followed by depositions of beach-cast material. The quantity of beach-cast material depended on the force of incident wave events (Fig. 3), although other factors were also involved: whether stronger or similar events had previously occurred; the plant cover existing at that time of year; and in particular, whether, as a result of the local hydrodynamic conditions (currents, tides, residual waves and wave type, etc.) occurring immediately after these wave events, the material was washed up on nearby beaches or drifted to submerged areas (Portillo, 2008).

In spring-summer, after southern swells with wave power higher than 15 kW/m, all the beach-cast material collected at these beaches consisted of decaying *C. nodosa* leaves. An exception occurred with the swell event in autumn 2006, which did not result in beach-cast accumulations even though its wave power exceeded 15 kW/m. This could be related to the explanation given above, as the southern swell events occurring in spring and summer could have removed all the leaves shed by the seagrass meadow, and leaf production begins to decline in autumn, with less frequent defoliation. Nevertheless, the limited materials found at these beaches after the two swell episodes in autumn 2006 consisted of decaying *C. nodosa* leaves, whereas only fresh leaves were observed in the same season (late November) after tropical storm Delta.

In winter, storms that hit the Canary Islands and generated southern wind waves (from 115° to 225°; Table 2) (Storm; Fig. 2) with high wave power (up to 14.6 kW/m; Table 2) clearly caused erosion of the seagrass bed as all the seagrass material collected after these events consisted of fresh *C. nodosa* leaves (with rhizomes and roots attached). Other storm events with high wave power of up to 14.6 kW/m have occurred without subsequent collection of beach-cast material, although this does not mean that canopy uprooting did not occur as we found remains of fresh leaves washed ashore. Throughout the study, wind waves generated by powerful high pressure systems (P-Ant; Fig. 2) with high wave power of up to 14.6 kW/m (Table 2) were not associated with beach-cast seagrass material. This type of wind wave never resulted in beach casts, even in winter, spring or summer (when southern swells normally wash the decaying *C. nodosa* leaves ashore). These wind waves generated by powerful anticyclones usually arrive on the shore with more easterly directions (wind wave directions from *P-Ant* varied from 75° to 120°, whereas wind wave directions from *Storms*, which caused beach-cast accumulation, varied from 115° to 225°; Fig. 2 and Table 2), and therefore they hit this coastline less directly than storm wind waves. However, the small accumulations of material that appeared on the beaches after these wind waves generated by powerful anticyclone systems were fresh *C. nodosa* leaves in all seasons, with no decaying leaves. For this reason, a clear difference was observed in spring-summer between the different types of wave events (southern swells vs. wind waves) and the amount and composition of beach-cast material (whole plants vs. senescent leaves).

The first consideration is that the differences observed in the type of seagrass cast ashore (whole plants vs. senescent leaves) could be related to seasonal changes in the abundance and growth stage of *C. nodosa*. In spring-summer, when southern swells normally wash the decaying *C. nodosa* leaves ashore, the leaf shedding process occurs which involves the highest frequency of new leaf production per shoot and leaf loss, and senescence of plants due to cooler waters and shorter days in winter (Reyes *et al.*, 1995; Espino *et al.*, 2006; Tuya *et al.* 2006), resulting in considerable replacement of old leaves. Moreover, the winter period, when storms cause the loss of entire plants, coincides with more limited development of rhizomes and roots (Reyes, 1993), which could facilitate the uprooting.

The second consideration is whether the wave type could be related to rates of canopy defoliation (shedding leaves) or uprooting of entire plants (fresh leaves with rhizomes and roots attached). A clear difference was observed in the composition of beach-cast material (whole plants vs. senescent leaves) when different types of wave events (southern swells vs. wind waves) occurred in the same seasons. Wind waves always uproot the whole plants, whereas southern swells detach only decaying leaves from seagrass meadows, regardless of the season. Southern swells are old swells resulting from long distances travelled and therefore start to touch the bottom at a deeper level of the sea floor than wind waves do (Open University Course Team, 1989). As a result, *C. nodosa* meadows feel the drag effect over a wide range of deep depths. These old swells can therefore be related to harmonic movements over a wider range of greater depths compared to wind waves and are referred to as monami (Ackerman and Okubo, 1993), which could produce slight drag forces, strong enough to detach decaying leaves from seagrass meadows. In contrast, high wind waves normally interact with the sea floor at a narrow range of low depths in comparison with southern swells, but inside the seagrass meadow (at depths of more than 5 m). Moreover, as this type of surface wave consists of many short, steep waves of varying heights, the frictional drag in shallow waters may be associated with irregular, strong rips and movements over this shorter range of lower depths. There is a maximum horizontal water particle velocity at breaking under the wave crest (Le Roux, 2008) and for such severe storm waves the increased effect of wave setup and setdown causes pressure differences and undertows that tend to exceed landward particle velocities under the wave crest and are capable of eroding the bottom (Davis and Fitzgerald, 2004) and uprooting the whole plants at these breaking depths. Therefore, wind waves could generate near-bottom turbulence frictional drags at lower depths of the seagrass meadows capable of uprooting the entire plants (fresh leaves with rhizomes and roots attached) and consequently result in high rates of canopy uprooting.

This is one of the first studies attempting to link the wave type to seagrass uprooting or “leaf cleaning”, as the few earlier studies accounted only for wave height. However, a variety of new approaches are needed to corroborate that different types of waves determine high rates of canopy defoliation or uprooting, such as in situ wave measurements with hydrodynamic force instruments (dynamometers) and studies of seasonal seagrass cover (dynamics of biomass and phenology of seagrass populations) before and after significant wave events.

The following can be concluded from this study:

- the occurrence of wave events (wind waves generated by storms and southern swells) is a *sine qua non* condition for the appearance of landings of beach-cast seagrass,

- in spring and summer, when plants are senesced and leaf loss reaches the highest frequency, southern swells detach only the decaying leaves from the seagrass meadows (favoring the natural clean-up process, which results in accumulations of beach-cast seagrasses); however, southern swells never uproot the whole plant, even in other seasons (i.e. autumn),

- in winter, when sporadic winter storms occasionally hit this coastline, the southern wind waves cause uprooting of whole plants (fresh leaves with rhizomes and roots attached) and accumulations of beach-cast seagrasses,

- significant wind waves generated by powerful anticyclones tend to uproot the entire plant regardless of the season, but do not produce accumulations of beach-cast seagrasses,

- the present approach of sampling beach-cast material collected by a cleaning service is innovative and provides a useful context for evaluating the relation between the type of wave exposure and seagrass losses in the south of Gran Canaria.

Acknowledgements

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CAPÍTULO 3

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

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

E. Portillo[a,*], M. Ruiz de la Rosa[b], G. Louzara[b], J. Quesada[c], J.M. Ruiz[d], H. Mendoza[a]

[a]Instituto Tecnológico de Canarias, S.A. (Canary Islands Institute of Technology) Playa de Pozo Izquierdo s/n, Santa Lucía, Las Palmas 35110, Spain
Tel. +34 928 727537; email: eportillo@itcanarias.org
[b]ECOS, Estudios Ambientales y Oceanografía, S.L., C/ Alfred Nobel 31B, Las Palmas de Gran Canaria 35013, Spain
[c]Canaragua, S.A. Avda. Manuel Hermoso Rojas, 4, Santa Cruz de Tenerife 38003, Spain
[d]Instituto Español de Oceanografía. Centro Oceanográfico de Murcia. (Spanish Institute of Oceanography. Oceanographic Center) C/ Varadero, 1, Murcia 30740, Spain

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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

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

*Corresponding author.

CAPÍTULO 3

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

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.

3.1. 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 (Medina, 1999; Martínez, 2006), and in the Canary Islands it has become the most important source of artificial water (Veza, 2001; Sadhwani and Veza, 2008). In these coastal areas, the climate conditions (low annual rainfall, periods of drought, scarcity of other water resources) and the sociodemographic context (population increase, 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 (Fundación Centro Canario del Agua, 2007).

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 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 (Morton and Callister, 1996; Schiffler, 2004). 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 (Fariñas, 1999). 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 (Ruiz Mateo, 2007). 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 (Roberts and Sternau, 1997), following the steepest gradients (Payo *et al.*, 2010). 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 (Ruiz Mateo, 2007), 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 (Palomar and Losada, 2008). Brine discharges through systems with limited initial dilution capacity therefore become plumes with very high salinities that spread out over broad areas (Fernández-Torquemada *et al.*, 2009) and affect the benthic communities encountered along the way (Einav *et al.*, 2002; Ruiz, 2005; Del-Pilar-Ruso *et al.*, 2007, 2009; Riera *et al.*, 2011; Yoon and Park, 2011). Because of this, large capacity desalination plants require appropriate exit velocities of brine jet discharges as well as flatter discharge angles of around 30° to 45° to ensure optimization of near-field dilution processes and minimize the environmental impact (Roberts *et al.*, 1997; Bleninger and Jirka, 2008; Bleninger *et al.*, 2010). 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 (Höpner and Widemberg, 1996; Einav *et al.*, 2002). 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 (Fernández-Torquemada and Sánchez-Lizaso, 2003, 2005) and physiological functions (Marín-Guirao *et al.*, 2011). Using a different type of estimate in situ, Gacia *et al.* (2007) and Ruiz *et al.* (2009) obtained experimental evidence to show that these effects can be responsible for the decline in the vitality and 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 (CEDEX, 2003; Sánchez-Lizaso *et al.*, 2008). 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 (Einav *et al.*, 2002; Fernández-Torquemada *et al.*, 2003; CEDEX, 2007; Afrasiabi and Shahbazali, 2011).

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.

3.2. MATERIAL AND METHODS

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).

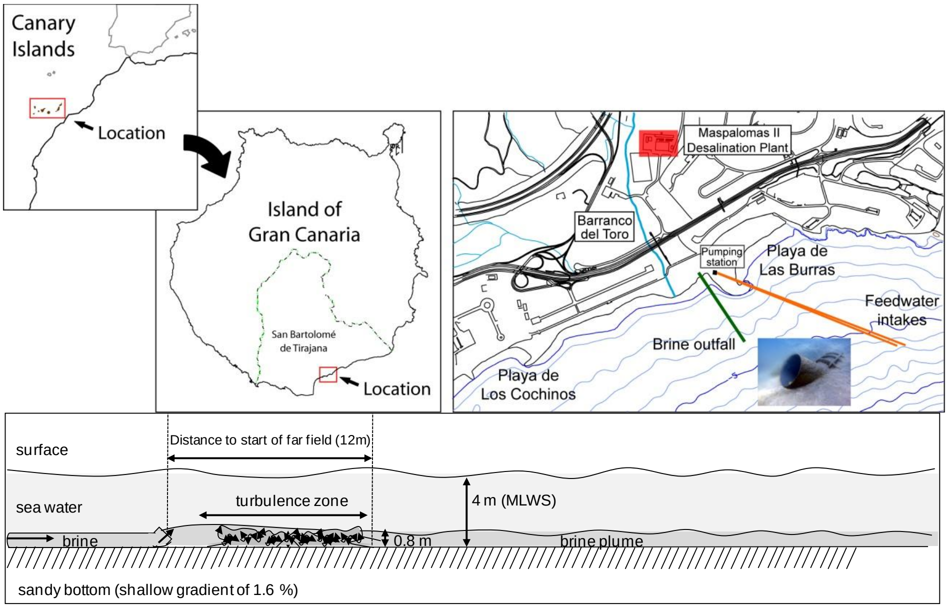


Figure 1. Location of Maspalomas II desalination plant, underwater outfall and brine discharge scheme.

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

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 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 69.5psu (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 most ecologically important seagrass meadow of *C. nodosa* and has been declared both a Site of Community Interest (SCI) under the name of *Sebadales de Playa del Inglés* (Playa del Inglés Seagrass Meadows) - ES7010056 – (OJEC, 2002) and a Special Area of Conservation (SAC) (BOE, 2009). 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 (Espino *et al.*, 2003).

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 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 (Reyes *et al.*, 1995; Espino *et al.*, 2008), particularly that of the neighboring seagrass meadow (Afrasiabi and Shahbazali, 2011). 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 (25x25 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 (150x150 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 8 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 Figure 2, were points of reference used to find the maximum range of the plume.

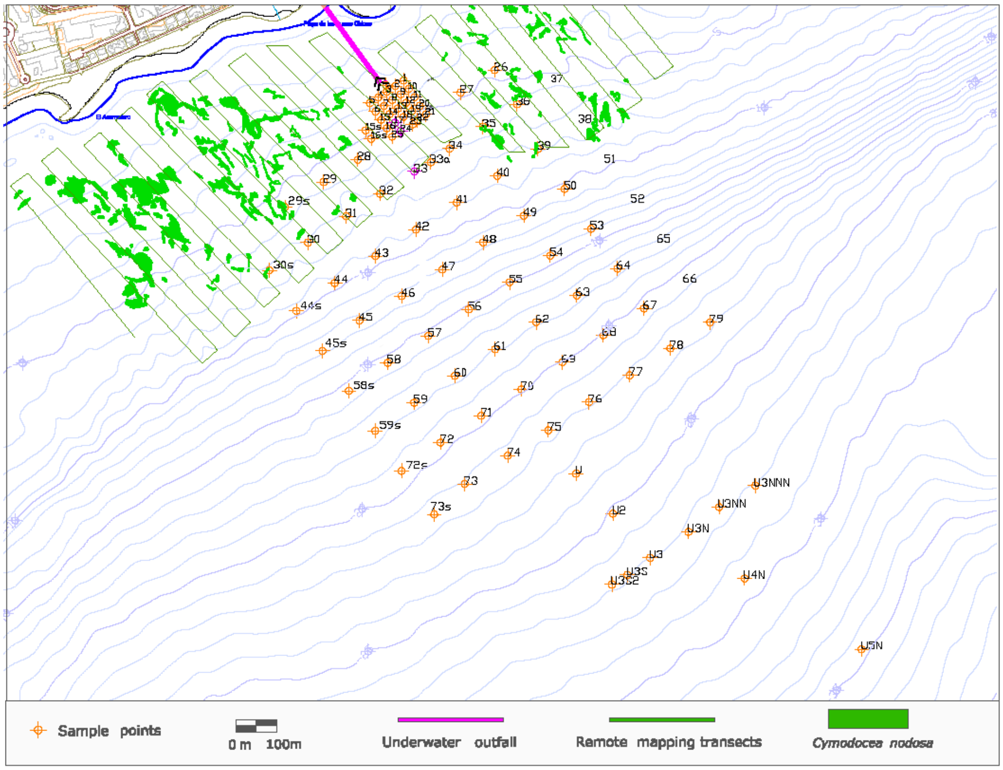


Figure 2. Sampling points and bathymetry map.

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 Waste Water (Clesceri *et al.*, 1989). 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 (Lewis, 1980; Unesco, 1981), 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 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 10cm 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 minutes, 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.

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.

3.3. RESULTS

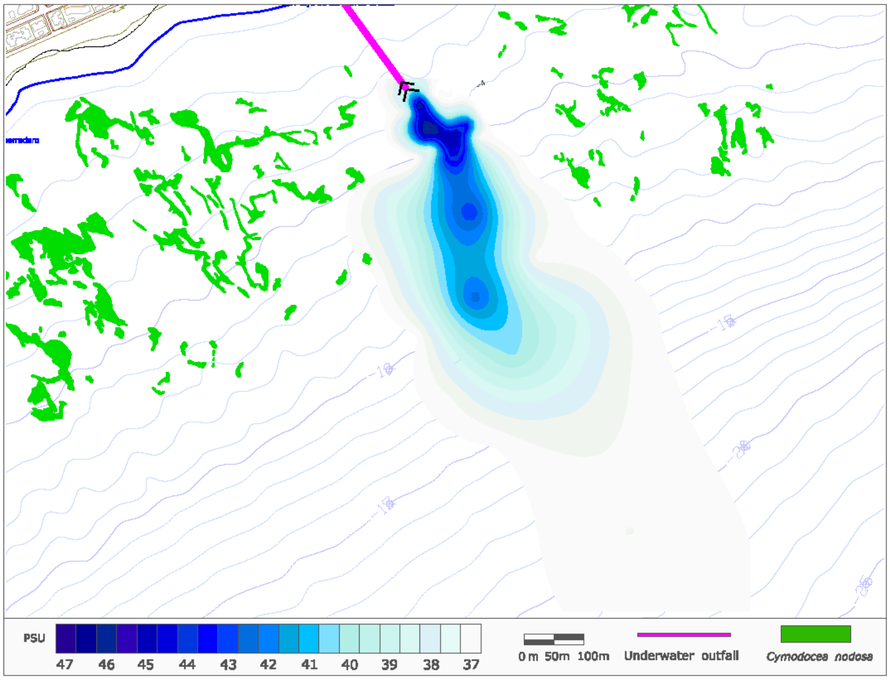
Table 2 shows the salinity of the receiving environment, the salinity and flow of discharge during far-field sampling, mean velocity of the near-bottom current during sampling and total area of the affected zone. The total area of the affected zone was the area corresponding to a salinity field greater 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.

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.

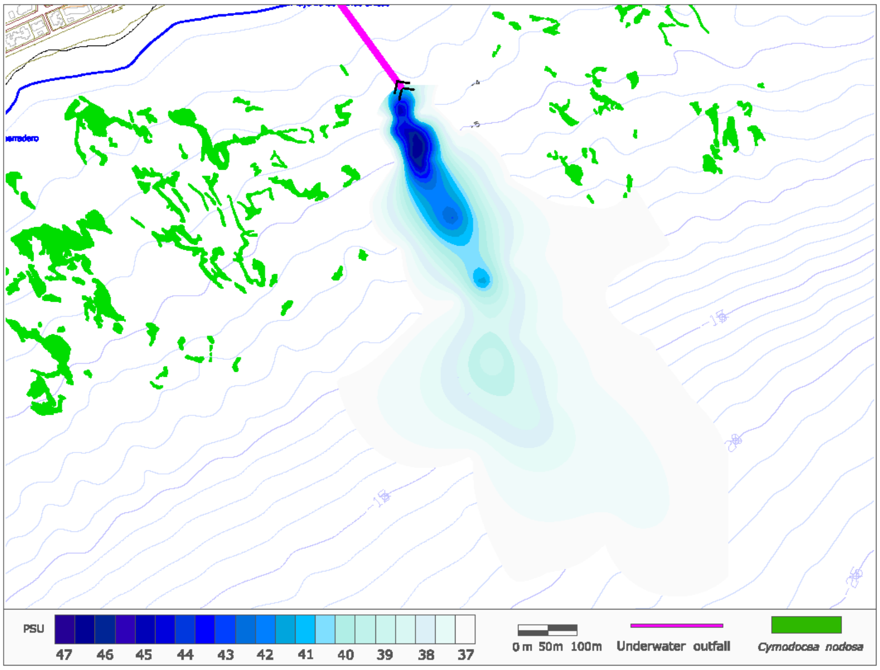
date / parameter	22/07/2009	23/07/2009	29/09/2009	30/09/2009	30/03/2010	10/09/2010a	10/09/2010b	17/01/2011
brine salinity (psu)	73.2	72.2	68.4	73.0	69.3	72.7	71.1	67.0
seawater salinity (psu)	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8
brine flow (m^3/h)	1,025	1,041	1,107	1,014	1,055	996	1,043	1,157
Froude 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

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 (Reyes *et al.*, 1995; Espino *et al.*, 2008). 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.



a)


PSU
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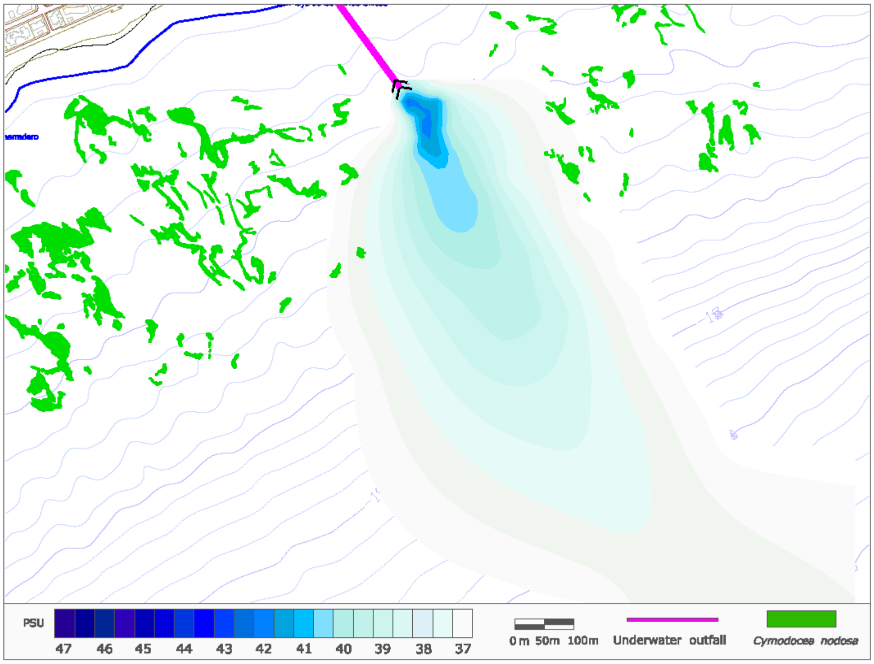
0 m 50m 100m
Underwater outfall
Cymodocea nodosa

b)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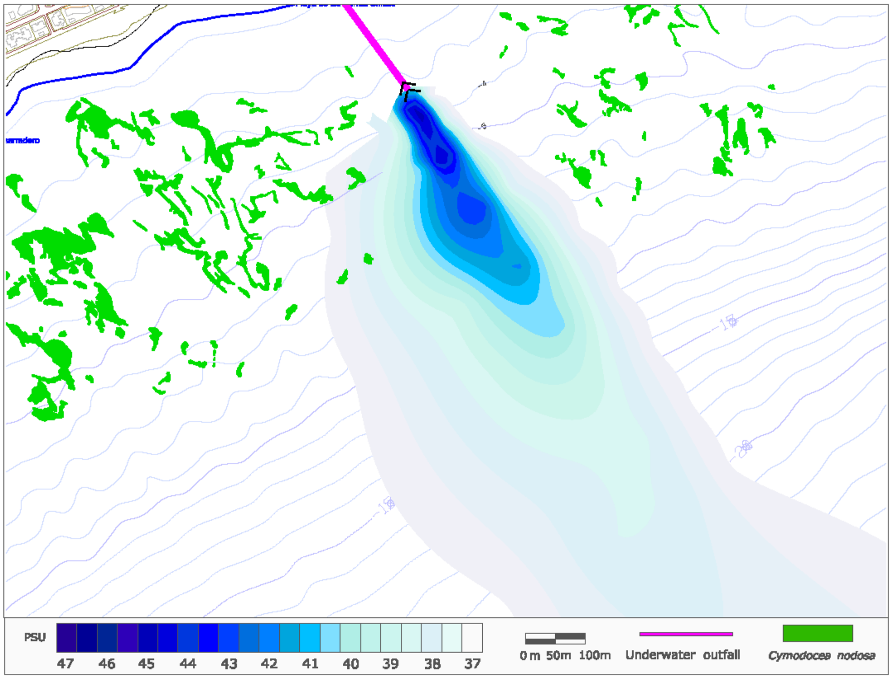
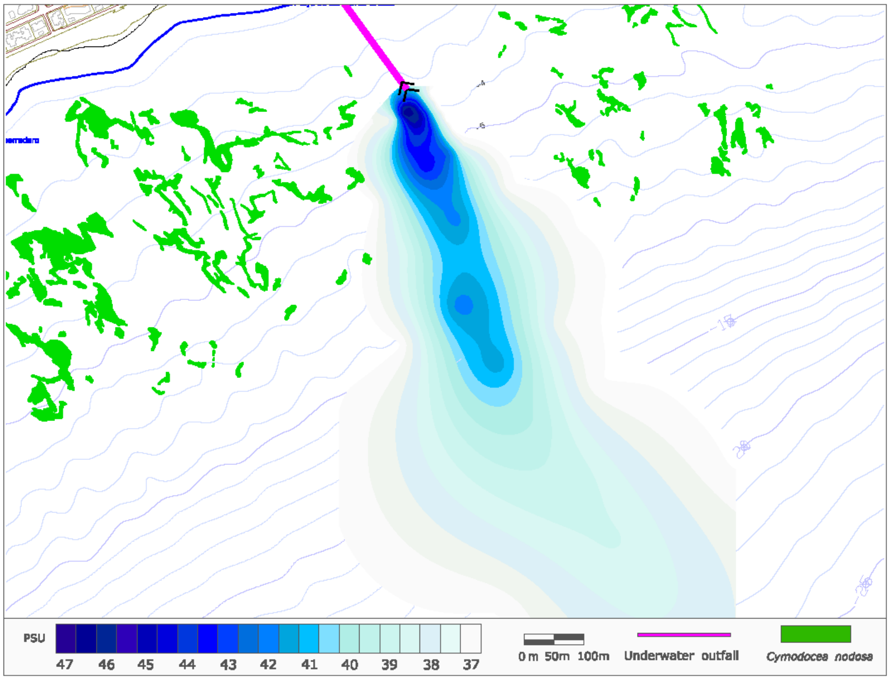
0 m 50m 100m
Underwater outfall
Cymodocea nodosa

c)


PSU
47 46 45 44 43 42 41 40 39 38 37
0 m 50m 100m
Underwater outfall
Cymodocea nodosa

d)


PSU
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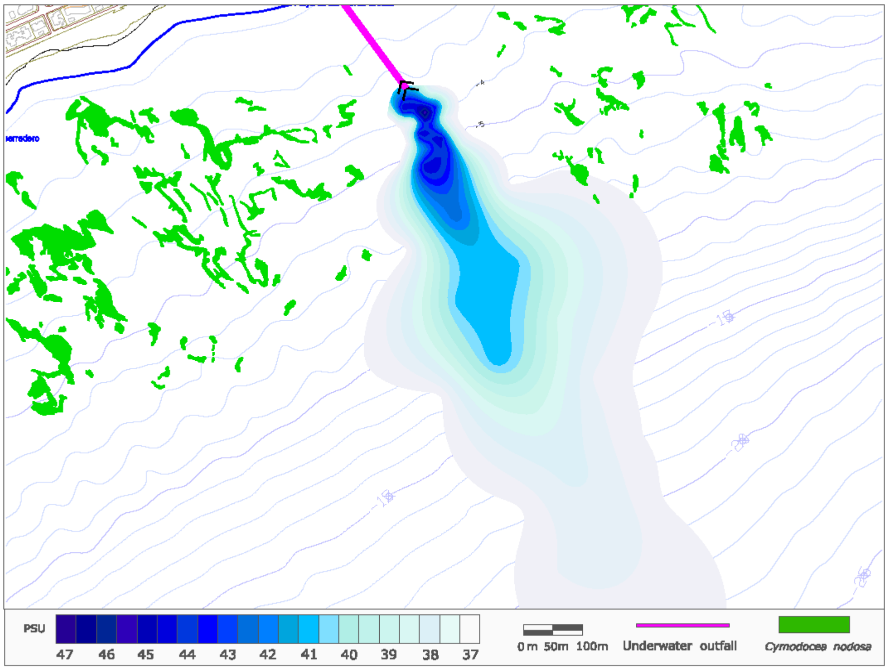
0 m 50m 100m
Underwater outfall
Cymodocea nodosa

e)


PSU
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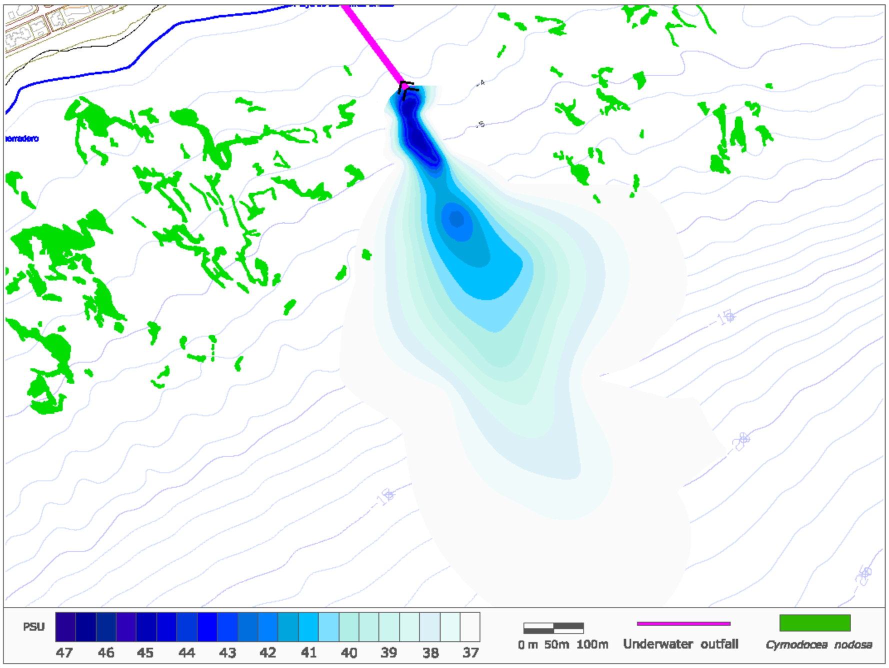
0 m 50m 100m
Underwater outfall
Cymodocea nodosa

f)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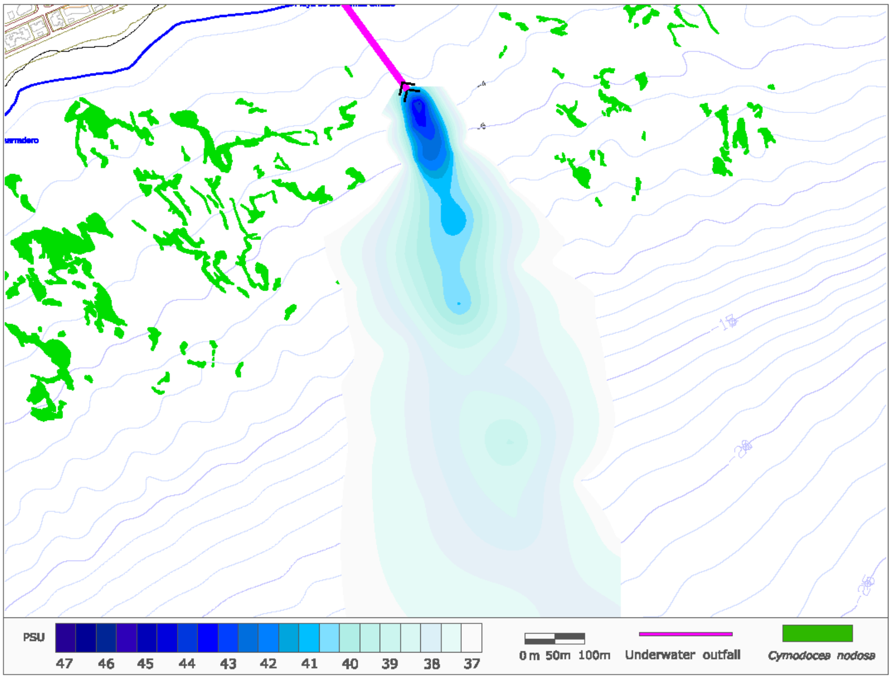
0 m 50m 100m
Underwater outfall
Cymodocea nodosa

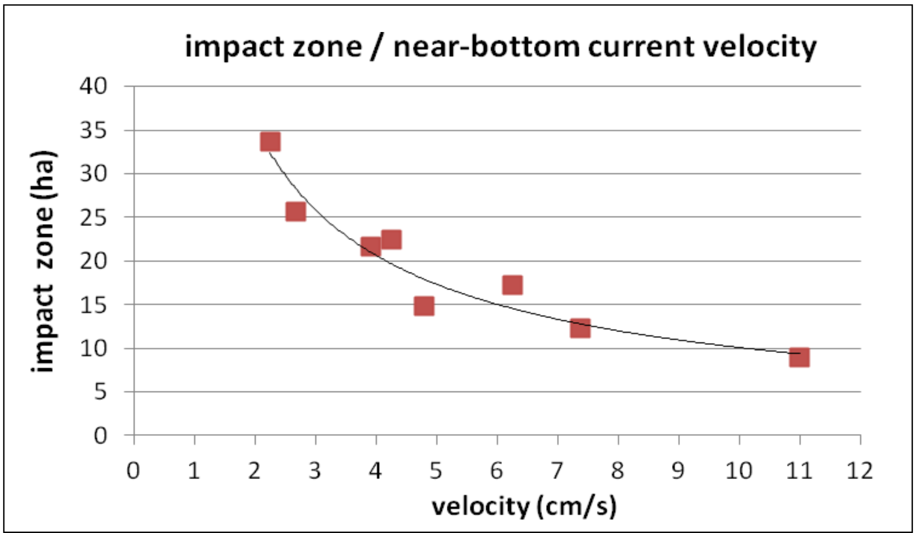
g)



h)

Figure 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).

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 Figure 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 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.



Total area impact zone (ha) = 61.24*(mean near-bottom current velocity (cm/s))$^{-0.78}$
(R^2 = 0.92, n=8)

Figure 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.

3.4. 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 feedwater spills out of the feed tank into the drain and 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).

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 (US EPA, 1991; Roberts *et al.*, 1997; Bleninger and Jirka, 2008; Bleninger *et al.*, 2010; Palomar and Losada, 2011; Portillo *et al.*, 2013). 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 (Portillo *et al.*, 2013). 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.* (2013), 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 (Ruiz Mateo, 2007). 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 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.* (2010), 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.* (2009), 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 (Fernández-Torquemada *et al.*, 2009) 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.).

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.

Acknowledgements

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CAPÍTULO 3

CAPÍTULO 4

In situ experimental assessment of the effect of brine discharge from a desalination plant on seagrass (*Cymodocea nodosa*) habitats.

Portillo, E., Ruiz de la Rosa, M., Louzara, G., Ruiz, J.M., Marín-Guirao, L., González, N., Mendoza, H.
Marine Environmental Research (submitted)

CAPÍTULO 4

In situ experimental assessment of the effect of brine discharge from a desalination plant on seagrass (*Cymodocea nodosa*) habitats.

Abstract:

The Maspalomas II desalination plant, in the south of the island of Gran Canaria (Canary Islands-Spain), discharges brine through an underwater outfall over part of the island's largest seagrass meadow of *Cymodocea nodosa*. The trajectories of the brine plumes coincided with a corridor completely lacking in plant cover. The seagrass meadows occurred beyond the outer edges of the brine discharge impact zones, suggesting the sensitivity of *C. nodosa* to these discharges. The cause-effect relation between the presence or absence of a seagrass meadow and brine were established through an in situ experimental transplanting survey of *C. nodosa* in the impact zones, as well as after the incorporation of venturi eductors as diffusers in order to evaluate the effectiveness of this corrective and mitigating measure. The results of the transplants showed the effect of the brine in the mid-long term, from the second month and after small increases in salinity (≥ 2.2 psu). After incorporation of the diffuser system with venturi eductors, the new transplants remained in a good state of conservation at the same sites within the former impact zone, which means that we managed to minimise the impact and also allowed the seagrasses to grow again in the affected area.

4.1. INTRODUCTION

Brine discharges from desalination plants have a demonstrated capacity to cause significant impact on benthic organisms and habitats. Discharge systems without initial dilution cause hypersaline plumes with very high salinities and a high degree of stratification, making the exchange and dilution processes very slow (Palomar and Losada, 2008). Brine discharges spread out over large areas of the sea floor (Fernández-Torquemada *et al.*, 2009) following the steepest slopes (Payo *et al.*, 2010) and affecting the benthic communities in their path (Einav *et al.*, 2002; Ruiz, 2005; Del-Pilar-Ruso *et al.*, 2007, 2008, 2009; Palomar and Losada, 2008; Riera *et al.*, 2011; Yoon and Park, 2011). These discharges are considered a potential threat to the marine biodiversity of coastal ecosystems, particularly when the ecosystems are based on foundation (habitat-forming) species such as seagrasses and rhodolith beds (maërl) that have limited ability to recover after disturbances (Ruiz, 2005). Special attention has been given to seagrass habitats because a) they are a keystone species, b) they dominate many coastal zones in arid and semi-arid regions where the desalination industry is experiencing significant development (e.g. the Mediterranean, the Canary Islands and Western Australia), and c) increasing experimental evidence indicates that some seagrasses are highly vulnerable to the hypersaline conditions created by brine plumes. The impact of the brine will depend on the type of ecosystem in the discharge area, the bathymetry and bottom roughness, the predominant meteorological and oceanographic conditions in the area, the characteristics of the discharge system and its flow and salinity (Höpner and Widember, 1996; Einav *et al.*, 2002), and the by-products of the chemical treatment used at the desalination plant (e.g. Portillo *et al.*, 2014b). As a consequence, coastal managers in the Mediterranean and the Canary Islands have requested scientific knowledge about the effects of brine on seagrass meadows as a way to define environmental criteria to control brine effluent and minimise its impact on seagrass habitats (e.g. Sánchez-Lizaso *et al.*, 2008).

Causal relations between brine effluent and seagrass vitality and survival can be obtained only through experimental approaches. Most experimental evidence has been obtained under controlled conditions in micro- and mesocosm laboratory systems. These experiments have proven to be very efficient at determining threshold tolerance levels of seagrass species and identifying their tolerance mechanisms to hypersaline stress. The earliest studies in the Mediterranean showed that short term exposure of the predominant endemic species, *Posidonia oceanica* (L.) Delile, to small salinity increases in the environment can cause a series of toxic effects capable of compromising plant vitality (Fernández-Torquemada and Sánchez-Lizaso, 2003, 2005) and physiological functions (Marín-Guirao *et al.*, 2011). Using other approximations in situ, Gacia *et al.* (2007) and Ruiz *et al.* (2009) obtained experimental evidence to show that these effects can cause decline of seagrass meadow vitality and structure in the longer term (months-years).

However, knowledge is still limited and it has not been possible to extrapolate conclusions obtained in the laboratory to much more complex, real situations; i.e., a seagrass meadow affected by brine discharge. Most studies have focused on salinity as the primary factor responsible for the impact of brine on seagrasses. Few have included interaction with other factors such as population origin (i.e., intraspecific variability; Sandoval-Gil *et al.*, 2013) or other potentially toxic brine components (Portillo *et al.*, 2014b). Similarly, experiments have included few seagrass species obtained from a small pool of local populations and therefore further studies are needed.

Experimental approaches in the field are necessary to gather evidence to complement information obtained in laboratory mesocosm systems under controlled conditions. However, experimental manipulation of brine in the field is extremely complex and has been performed in only one study (Ruiz *et al.*, 2009). Real case studies of seagrass meadows affected by brine plumes have been conducted (Gacia *et al.*, 2007; Fernández-Torquemada *et al*., 2005, 2009), although in these cases other factors (e.g. nutrients, pollutants, turbidity, spatial heterogeneity, etc.) have complicated the identification of cause-effect relations between the effect of the brine and seagrass health and abundance. In some countries (e.g. Spain), application of strict environmental criteria to regulations governing the desalination industry has meant that few case studies of this type have been conducted.

A field experimental study (in situ) was used to test the general hypothesis that brine plumes from desalination plants can cause decline and loss of seagrasses in the area of influence created by the hypersaline discharge. We surveyed the vitality (% leaf necrosis) and survival (% initial shoot numbers) of *Cymodocea nodosa* (Ucria) Ascherson transplants in areas with varying levels of influence from brine discharges at the Maspalomas II desalination plant, in the Canary Islands. The brine plume associated with this case study and the temporal variability of its spatial spread have been well documented in earlier studies as a function of hydrodynamic conditions (Portillo *et al.*, 2014a), not only in terms of salinity but also in relation to other key physical and chemical variables which, when altered, could also have toxic effects on benthic organisms (Portillo *et al.*, 2014b). Seagrass maps obtained for these studies showed discontinuity in the distribution of a *C. nodosa* meadow just inside the area of influence defined by the brine plume. In these studies we hypothesised that a *C. nodosa* meadow had existed in this area before the desalination plant was built (1988) and the brine had caused rapid seagrass decline. Experimental evidence obtained through short-term laboratory bioassays (Portillo *et al.*, 2014b) supports this hypothesis, although further experimental evidence is required. The experimental transplants were carried out before and after installation of a dilution system at the discharge outfall. This procedure has been proven to be highly efficient in minimising the influence of the brine plume and returning environmental conditions to the values found in unaffected surrounding areas (Portillo *et al.*, 2013). Through this experimental approach we tested the hypothesis that transplant success depended not only on the influence of the brine but also on other local factors that had limited seagrass growth before construction of the desalination plant.

4.2. MATERIAL AND METHODS

Description of the study area and brine discharge

The Maspalomas II reverse osmosis desalination plant, in the south of the island of Gran Canaria (Canary Islands, Spain), began operating in 1988. After renovations and enlargements, it now produces around 944 m3 /h potable water and discharges a brine flow of 1,062 m3 /h with a mean salinity of 69.5 psu. Its reverse osmosis membranes are disinfected and cleaned by weekly shock treatments with sodium metabisulphite ($Na_2S_2O_5$ - SMBS). Both the brine and the by-products from this chemical process are carried to a pebble beach between Playa de Las Burras and Playa del Cochino, where they meet a 300 m cast iron underwater outfall pipe with a diameter of 600 mm. The original discharge system comprised a simple elbow joint, with the same diameter as the outfall pipe, at a vertical angle of 42.5º to the sea floor (Fig. 1). The discharge point is at a depth of 4 m at mean low water spring tide (MLWS) and the effluent is discharged over a wide sandy bottom with a shallow gradient of 1.6 % that is home to the island's largest and most ecologically important *C. nodosa* seagrass meadow. This area, known as Sebadales de Playa del Inglés (Playa del Inglés Seagrass Meadows), was recently made a Special Area of Conservation (SAC) (BOE – Official Spanish Gazette, 2009). The discharge emerges onto an area with a smaller, patchy seagrass meadow of 15.2 ha at Playa del Cochino. The population size of the meadow is 1.5 ha and plants occur at depths of 4-10 m (Espino *et al.*, 2003). The brine discharge spreads out over large areas of influence with salinity fields greater than 38 psu, ranging in size from approximately 9-34 ha, corresponding to a maximum size difference of almost four times. A higher near-bottom current velocity favours dilution of the outer edges of the plume and therefore helps to reduce the affected zone (Portillo *et al.*, 2014a). Several sampling campaigns were carried out to map the distribution of the seagrass meadow at the brine discharge and in the surrounding area (Fig. 1). The method of in situ observation using a boat-towed video camera described by McKenzie *et al.* (2001) was applied, following transects perpendicular and parallel to the coastline from a slow-moving boat (1-2 kt). A boat-towed video camera georeferenced with the XeoTV viewing system enabled these transects to be georeferenced on an orthophoto in real time. The study was completed with direct in situ observation by divers at sites not covered by the video transects. In terms of the spatial distribution of seagrass meadows in the area of influence of the hypersaline plume (Fig. 1), no plants were found inside the maximum area of influence of the plume corresponding to the spatial distribution of salinity fields greater than 39 psu in the eight campaigns described by Portillo *et al.* (2014a). A corridor completely lacking in plant cover coincided with the trajectory of the maximum area of influence. The seagrass meadows next to or near this maximum area, with patchy spatial distribution, were delimited by this area of influence (corresponding to the maximum spatial distribution of salinity fields greater than 39 psu studied during the eight campaigns). Because of this, the impact zone was defined as the spatial distribution of salinity fields above which no vegetation occurs. However, the maximum area of influence corresponding to the maximum spatial distribution of salinity fields greater than 38 psu (in the eight campaigns) reached some small patches of seagrass. The hypersaline plume therefore divided settlement of the seagrass meadow into two populations, one closer to Playa del Cochino, corresponding to the Playa del Cochino meadow described by Espino (Espino *et al.*, 2003) and the other opposite Playa de Las Burras, which we named the Playa de Las Burras meadow (Fig. 1). After venturi eductors were added at the underwater outfall, the dilutions obtained with the new discharge system achieved an average reduction of brine salinity to values of 37.45 psu and these areas of influence disappeared as a result (Portillo *et al.*, 2013, 2014b). Furthermore, the spatial gradients of pH and DOsat associated with the brine effluent after addition of SMBS during membrane cleaning operations virtually disappeared (Portillo *et al.*, 2014b).

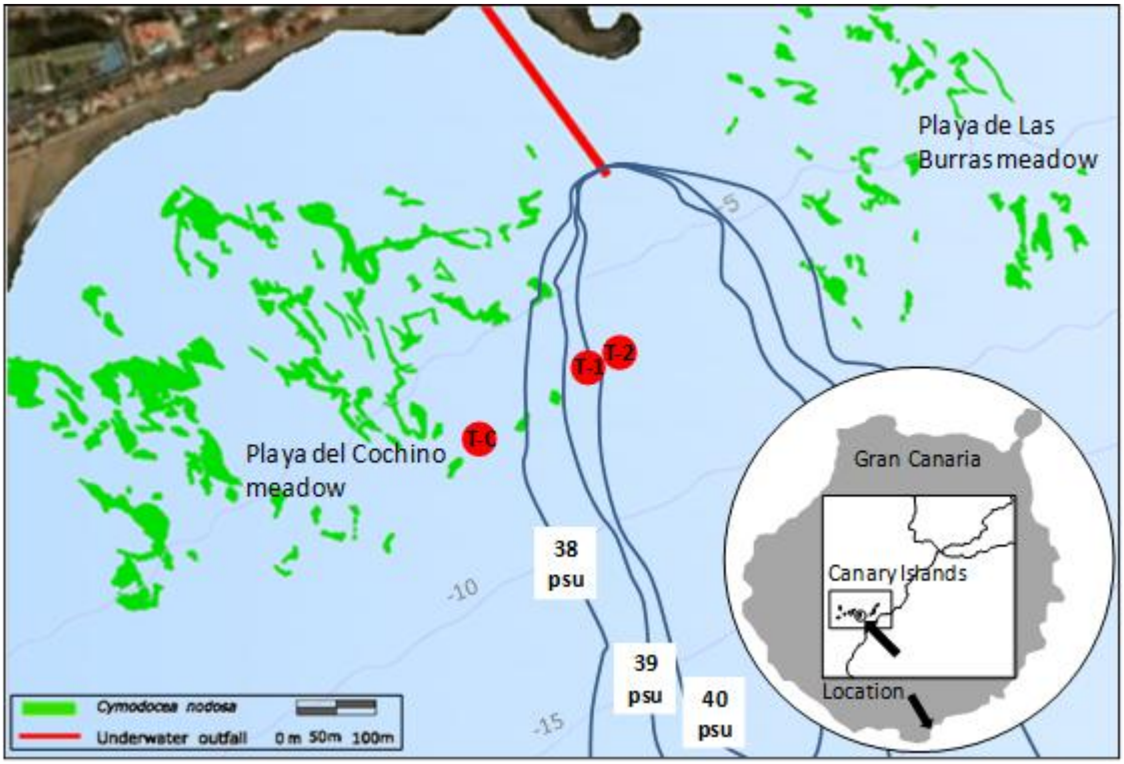


Figure 1. Location of Maspalomas II desalination plant, bathymetry map and underwater outfall. Superimposition of the map of the seagrass meadow onto the maximum area of influence corresponding to the spatial distribution of salinity fields greater than 38 psu (a), 39 psu (b) and 40 psu (c) in the eight campaigns described by Portillo *et al.* (2014a). Transplant experiment sites (red circles): in a control area near a natural seagrass meadow (T-C); inside the impact zone with mean salinity of 39 psu (T-1); and at 40 psu (T-2).

Experimental design

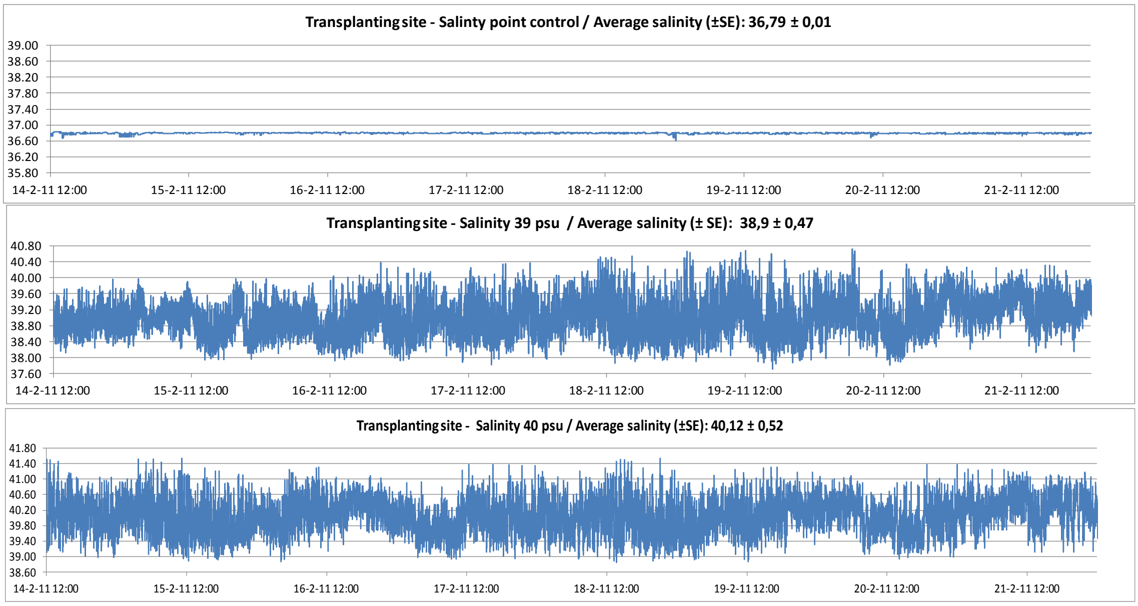
Earlier studies showed that the vitality of *C. nodosa* seedlings in the study area was significantly affected by salinities of 39 psu; i.e., 2.2 points over the mean ambient salinities. These effects became more severe and even lethal when we considered the experimental addition of the toxic chemical compounds regularly added to the brine (Portillo *et al.*, 2014b). No living plants were present inside the maximum area of influence corresponding to the spatial distribution of salinity fields greater than 39 psu (in the eight campaigns). Based on these observations and the known distribution of the salinity fields, an in situ experimental approach using transplants was performed to evaluate the effect of the brine effluent on the seagrass (*C. nodosa*). Two transplant sites with different levels of influence (based on mean salinity) were selected: one with 39 psu and another with a higher influence (40 psu; Fig. 1). A third site was located away from the influence of the brine plume in a neighbouring area where the *C. nodosa* meadow has not been affected by the brine discharge or any other human pressure (Fig. 1). This site was used as a control. Experimental *C. nodosa* transplants at the three sites (control, 39 psu and 40 psu) were conducted in 2011, in early spring (T1; 15 April) and early summer (T2; 25 June) (close to T1 transplants), both with the original brine discharge (before venturi), and again in 2012, in early spring (T3; 17 April), after venturi diffusers had been installed at the brine discharge outlet (after venturi). These seasons are ideal for transplants in the Canary Islands because of the physiological factors of the plants, such as their optimum growth phase. It is also a more stable time of year in terms of storms and plants are therefore able to settle better (Ruiz de la Rosa, 2011). In the three transplant experiments the technique used was environmental recovery with portions of seagrass meadow (Fonseca *et al.*, 1998; Ruiz de la Rosa, 2006, 2011) from a neighbouring meadow that served as a donor. The transplants (T1, T2 and T3) were performed in triplicate using a similar number of plants extracted from seagrass patches in the vicinity (40 ± 10 shoots). Transplants were monitored monthly for six months through scuba diving. The descriptors used for monitoring were shoot survival and percentage of necrosed leaf, measured randomly on 10 leaves at the transplant site. The salinity of the three transplant sites (Control, 39 psu and 40 psu) was checked before transplanting through continuous measurements with a CTD profiler (YSI 6600 V2) (one-week soundings) before and after the venturi diffusers were installed (Fig. 2). Salinity was recorded during the whole study period and at each monthly monitoring of the transplants (T1, T2 and T3) by lowering the profiler for one hour (Fig. 3).

Data Analysis

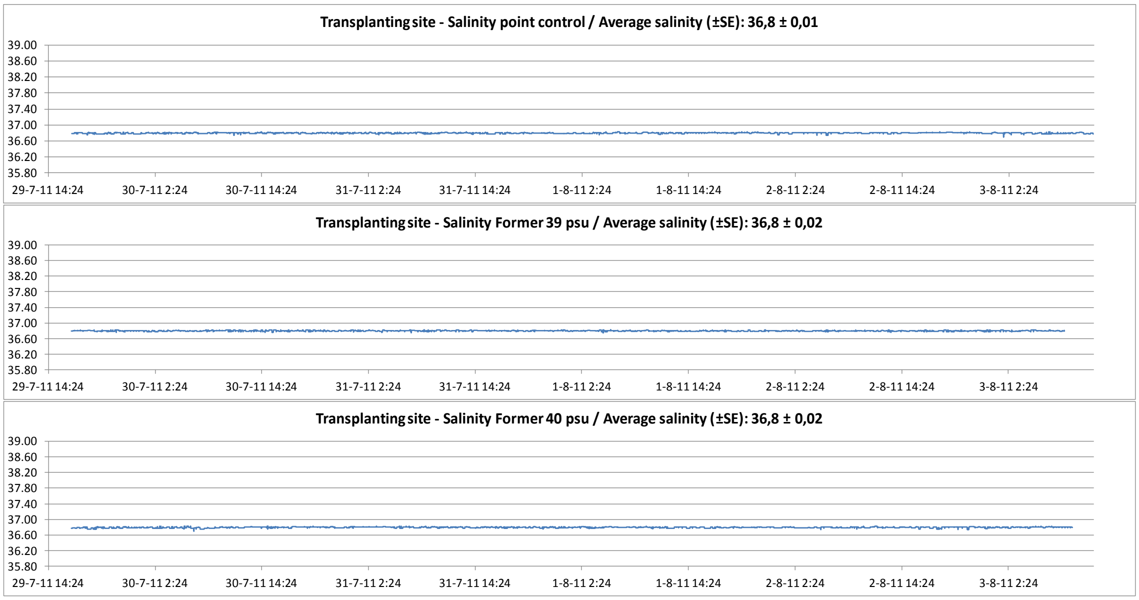
Repeated measures ANOVA was used for data analysis, with the STATISTICA statistical package V6, to assess the differences between shoot density, survival and necrosis between the three treatments. Before this, data homogeneity was tested using Mauchly's sphericity test. In both analyses, the significant comparisons were compared through subsequent analysis with the Student-Newman-Keuls (SNK) test, Zar (1984), to determine which elements caused the significant differences. For all treatments $p<0.05$ was considered statistically significant. When a significant difference was detected, an SNK test for multiple comparisons was applied.

4.3. RESULTS

Figure 2 shows that the mean salinities recorded - during the week when profilers were lowered at the two transplant sites inside the impact zone and the regular measurements made throughout the experiment (Figure 3) - were virtually the same as the target salinities (39 and 40 psu). However, high variability was seen in the salinity measurements both during the week of profiling and throughout the experiment (6 months). At both sites, the one-week profiler recordings showed variations from the mean of more than 1 psu on several occasions, as well as maximums and minimums higher than 1.5 psu. The deviations from the means in the regular recordings throughout the six months of the experiment were slightly lower than the standard deviations when the profiler was in place for a week. The salinity recorded at the control site, which had no interaction with the discharge or influence from it, was virtually constant both for the one-week profiler recording and for the regular measurements, with a mean salinity of around 36.8 psu. The slight variations were characteristic of the profiler readout due to conditions in the field, mainly because of interference with sand in suspension after waves with greater energy.



a)



b)

Figure 2. Continuous salinity recordings and mean (± SE) salinity values at the three experimental transplant sites (Control, 39 psu and 40 psu) before (a) and after (b) installation of venturi diffusers.

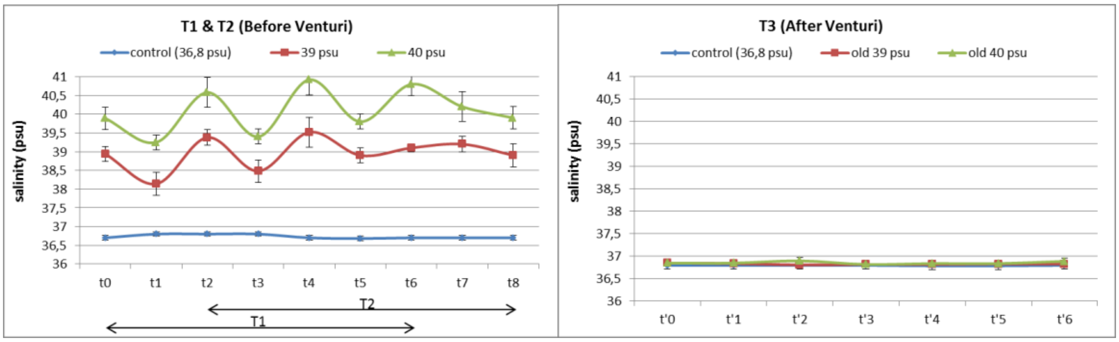


Figure 3. Monthly salinity recordings (mean ± SE) at the three experimental transplant sites (Control, 39 psu and 40 psu) before and after installation of venturi diffusers.

A major difference was observed in both seasons (spring, T1 and summer, T2) between plants in the transplant experiments inside the impact zone, at 39 psu and 40 psu, and plants in the control site. This area was not affected by the brine plume and therefore had stable salinity of around 36.8 psu. Whereas survival increased or remained constant in the control site, shoots declined drastically in the two sites inside the impact zone after the second month in both seasons and therefore their survival rate also decreased (Fig. 4).

These differences concur with the data of the mean percentage of necrosed leaf. Necrosis values in the control site remained stable or increased slightly, with values close to 10 % in both spring and summer, whereas values in the impact zones were more than 30 % after six months of exposure to salinity increases. In spring, leaf necrosis in plants transplanted in the sites affected by the brine increased considerably after the second month and after six months of study percentages were around 35 % at 39 psu and 45 % at 40 psu. In summer, the increase in leaf necrosis in plants transplanted at 40 psu followed the same pattern as in spring, although at 39 psu the increase was more gradual and after six months of exposure a slightly lower percentage (30 %) was recorded in the spring experiment.

In the second replicate (T2), transplants in the sites not affected by the brine discharge were once again in an optimum state and well conserved, whereas the transplants in the impact zone succumbed after the second month. Figure 5 shows this situation very clearly in the photos of the transplants under the three treatments after three and six months of exposure. In the control site, transplants appeared to be invariable, whereas in both impact zones and in the two seasonal experiments, T1 and T2, the plants virtually disappeared.

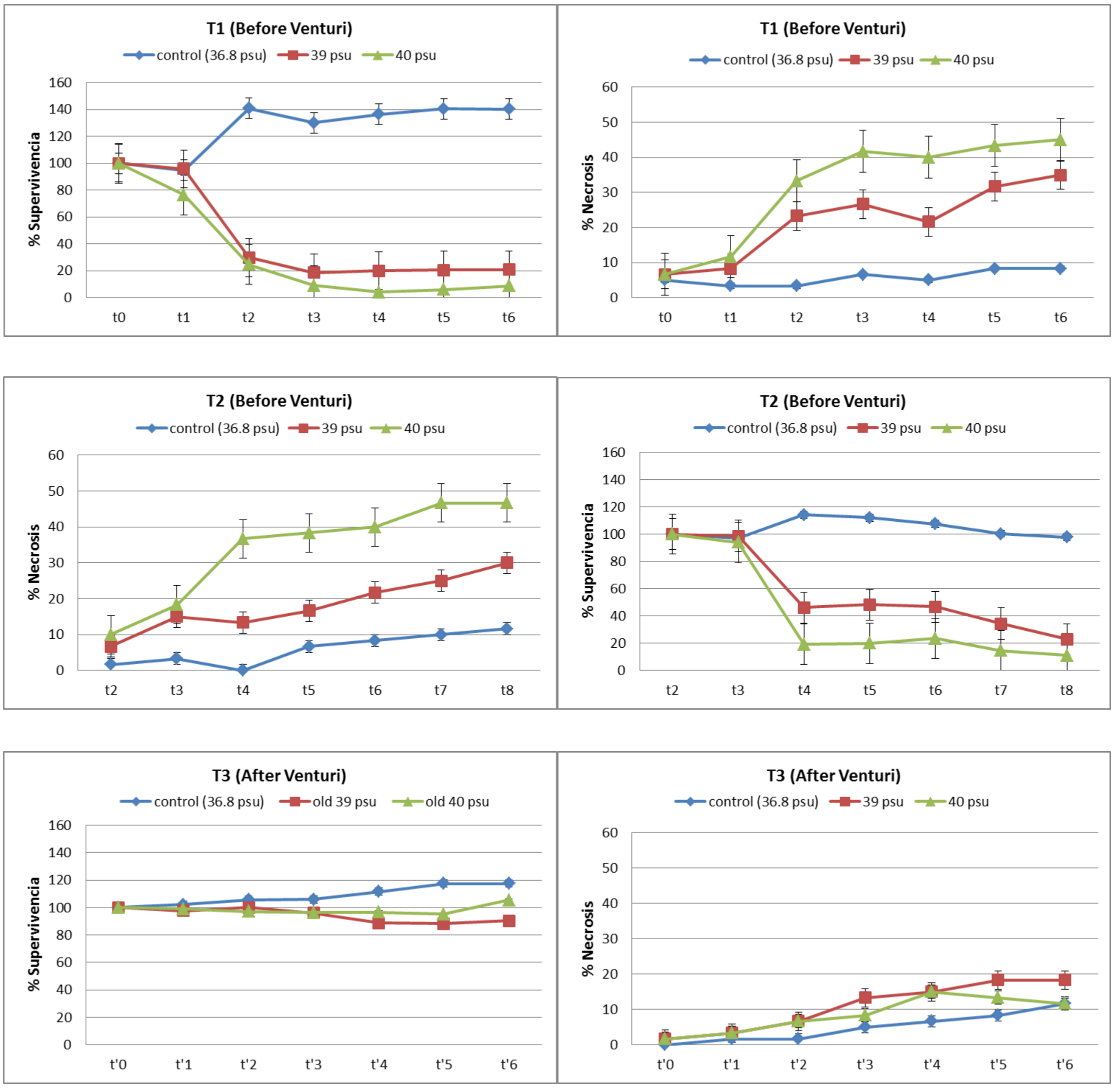


Figure 4. Percentages of survival and shoot necrosis of transplants T1 and T2 (Before venturi) and T3 (After venturi).

When we applied repeated measures variance analysis and compared the descriptors used throughout the monitoring of the experiment, we saw that for the three treatments (Control, 39 psu and 40 psu) and the two seasons assessed (spring and summer; T1 and T2), the treatment factor was significant for the three variables analysed

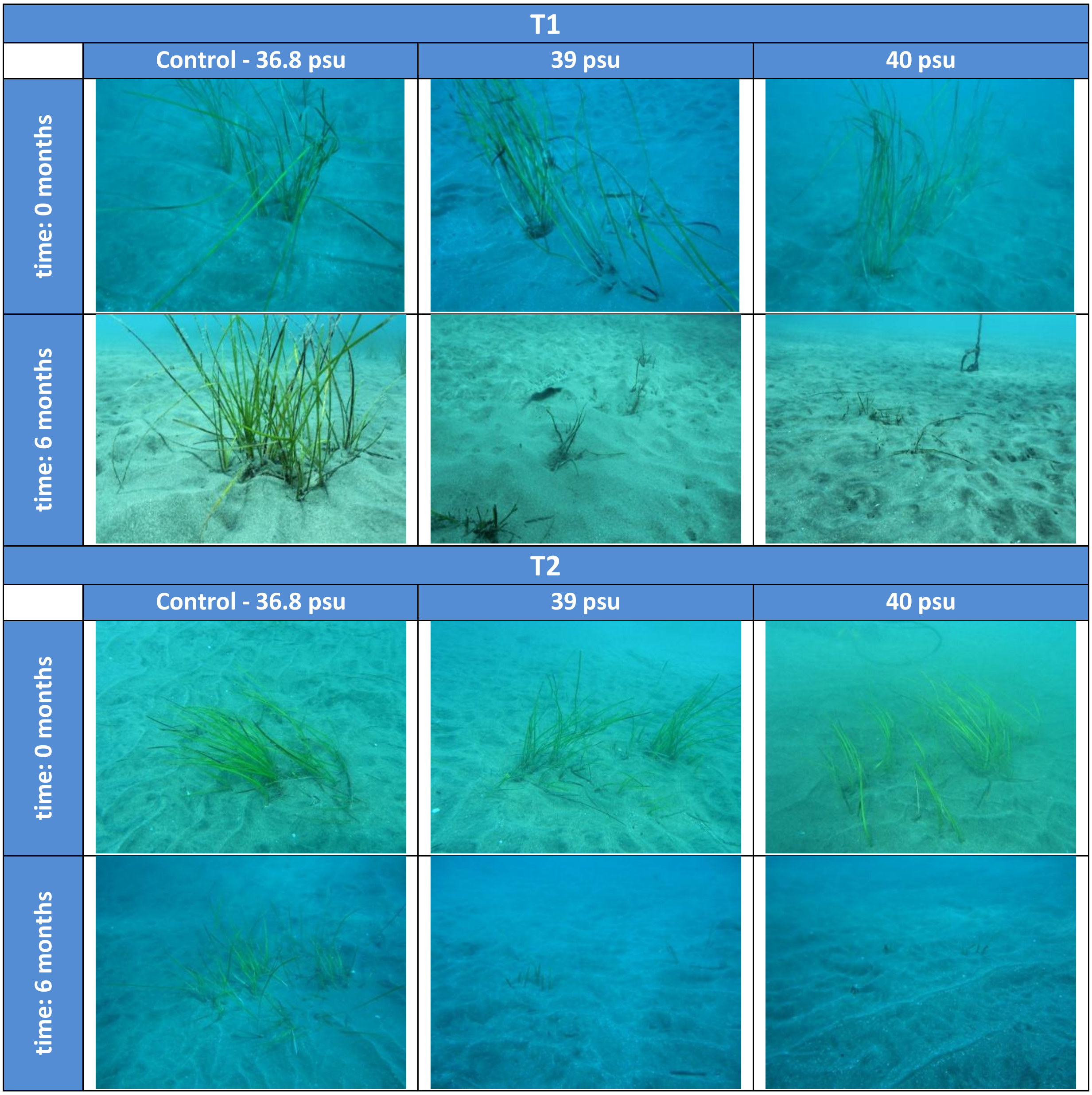
(Table 1) and there were no significant differences between the season factor. However, some significant differences were detected between each monitoring time (t), in the interactions between monitoring and treatment (txTreatment), and between the monitoring time and the season sampled (txSeason) for the three variables analysed. Subsequent analysis (SNK Test) showed significant differences between the three treatments for shoot density and percentage of necrosis, as each treatment was different, whereas shoot survival was different between the control (36.8 psu) and the two treatments (39 psu and 40 psu). No differences were observed between these two treatments. For the interaction between the treatments at each time, t0 showed no significant differences between the three times for any of the variables. Differences began after t1 in shoot density and percentage of necrosis, between the control and the 39 psu and 40 psu sites. After t2 differences were observed between all three sites. Differences in shoot density and survival were observed between the control site and the two treatments, and for necrosis the difference was between all three sites (Control, 39 psu and 40 psu) (See Table 1, SNK Test).

Table 1. Summary of the repeated measures ANOVA analysis to assess the effect of the brine on treatments T1, T2 and T3 at the three transplant sites (36.8, 39 and 40 psu) for survival and percentage of necrosis.

		Shoot density		Survival		Necrosis	
Between subjects	df	MS	*F*	MS	*F*	MS	*F*
Season (S)	1	1704.40	7,95*	27103.30	23.64	2726.32	73.88
Treatment (T)	2	7044.43	32,85***	67114.20	58,53***	5841.40	158,28***
S*T	2	724.66	3,38*	12500.60	10.90	1023.15	27.72
Within subjects							
Time (ti)	6	1130.79	61,42***	2834.60	44,60***	1519.58	83,35***
ti*T	12	614.27	33,36***	2336.00	36,75***	192.33	10,55***

SNK TEST		Shoot density	Survival	Necrosis
*p<0,05, **p<0,001, ***p<0,0001, n.s. no significativo	**t0**	36,8>39=40	36,8=39=41	37=39=41
	t1	39>36,8=41	36,8=39=41	37?39?41
	t2	36,8>39>41	36,8>39=41	37<39<41
	t3	36,8>39>41	36,8>39=41	37<39<41
	t4	36,8>39>41	36,8>39=41	37<39<41
	t5	36,8>39?41	36,8>39=41	37<39<41
	t6	36,8>39?41	36,8>39=41	37<39<41

After the venturi eductors had been added as a corrective measure, salinity at the two transplant sites inside the former impact zone (39 psu and 40 psu) decreased to the level of ambient salinity (36.8 psu) (Fig. 2b and 3b) and therefore these areas were no longer affected by the brine plume. Figure 4 shows that the plants remained in a good state of conservation after incorporation of the venturi eductors, both at the control site and at the sites inside the former impact zone. The transplants followed a similar pattern at the three sites, where survival was virtually 100 % and the percentage of necrosis was no higher than 10 %. The photos in Figure 5 show the good state of conservation of the new transplants at the three sites and their condition after six months of exposure.



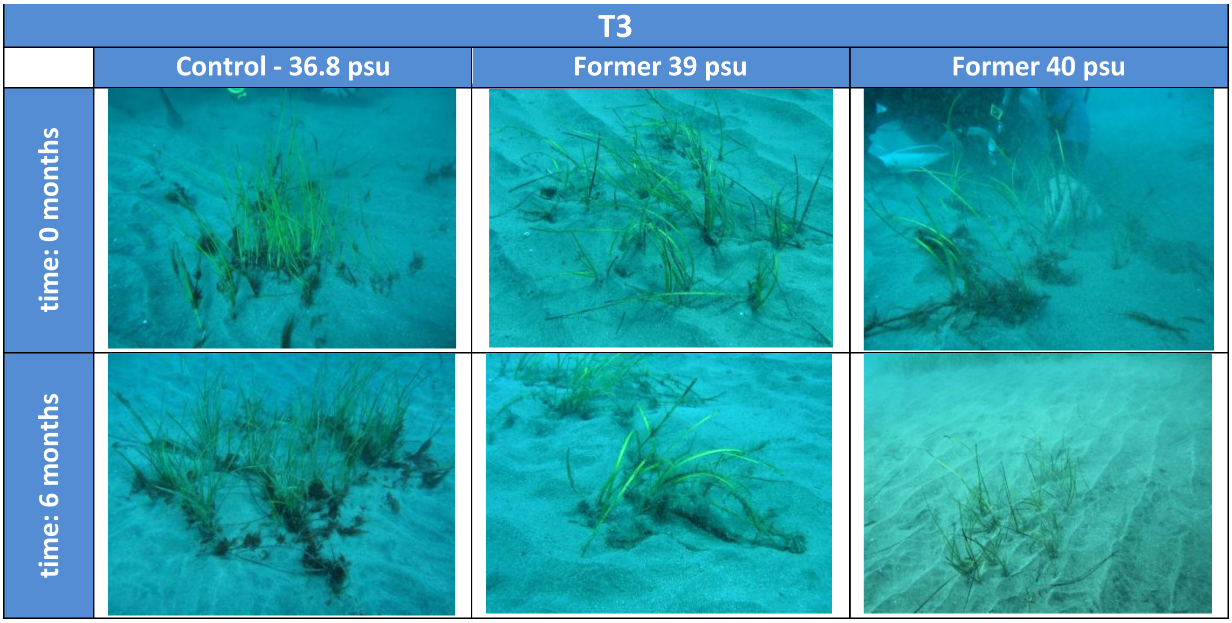


Figure 5. Plants at the time of transplant (t0) and after six months of exposure (t6) at the T1 and T2 sites (Before venturi) and the T3 site (After venturi).

4.4. DISCUSSION

The trajectories of the brine plumes coincided with a corridor completely lacking in plant cover, where the seagrass meadows occurred from the outer edges of the areas affected by the brine discharge, suggesting the sensitivity of *C. nodosa* to the discharge. All the spatial distributions of the salinity fields greater than 39 psu delimited the presence of seagrass meadows, although only a few areas of influence corresponding to salinity fields greater than 38 psu reached certain seagrass patches. These situations coincided when unusual meteorological and oceanographic conditions that occurred with very low hydrodynamic exposure. These conditions of such low hydrodynamism are quite regular and occur for short periods a few times a month. These patches would therefore often be reached by salinities of 38 psu, but for short periods of time and not by higher salinities. Because of this, seagrass growth in the area appears to be inhibited by a slight salinity increase in the brine dispersion process over the sea floor when dispersion is constant over time. The spatial distribution of the habitat obtained from the mapping for this study clearly showed how distribution stopped right at the impact area of the brine discharge. The distribution map of the *C. nodosa* patches suggested that the impact of the hypersaline plume caused the loss of an area roughly equivalent to this habitat in this area.

No mapping was carried out before the desalination plant was built (1988). Testimony from the diver who worked on the installation of the underwater discharge and from local divers and fishermen confirmed the existence of the seagrass meadow before the discharge began. Dead rhizomes found buried under the sand at various points of the impact zone bear witness to former colonisation of these zones by *C. nodosa*. The remains of this dead seagrass meadow provided no information about when it might have disappeared and its extinction may have been due to natural causes, although it would be too much of a coincidence for a natural disturbance to have acted in the same place and on the same spatial scale as the brine plume. We therefore consider it highly likely that the impact of the brine discharge caused the total loss of the *C. nodosa* meadow in an area equivalent to the area of the impact zone. Factors capable of causing acute and chronic toxic and/or deleterious effects on marine angiosperms and explaining their disappearance in the impact zone of the brine include increased salinity, the isolated or synergic effect of certain compounds from both periodic and ongoing chemical treatments at the desalination plant, and physical and chemical variations in the sediments and the water column caused by the discharge. This was particularly evident in the central parts of the plume, where salinity is very high (42 psu) in comparison with the normal salinity seagrasses are adapted to in this area, which maintains a very constant mean value of 36.8 psu. The absence of *C. nodosa* was observed even in areas of the salinity field where the salinity increase is smaller, at just 1.2 psu. This result is unexpected, considering that *C. nodosa* was thought to be more tolerant to chronic increases of this type than more vulnerable species such as *P. oceanica* (Fernández-Torquemada and Sánchez-Lizaso, 2006; Pagès *et al.*, 2010; Sandoval-Gil *et al.*, 2012a, b). With some speculation, this could be explained in various ways: a) *C. nodosa* has a greater capacity to tolerate small to moderate increases in salinity in the short to medium term (days or up to a month), but would be incapable of resisting the accumulated effects of continuous or intermittent exposure for many years (as in this case: 24 years); or b) factors other than salinity acting in isolation or in combination could be the cause of the toxicity and death of plants in this area; or c) a combination of these scenarios.

In the final instance, the cause-effect relation between the presence or absence of a seagrass meadow and brine can be established only through experimental studies. In line with this, the experimental approach (in situ) of this study was used to determine whether or not the changes in the spatial distribution of the seagrass meadow of *C. nodosa* are due to the acute, chronic influence of the brine impact zone.

The results obtained in the in situ transplant experiments inside the impact zone concur with the trend found in earlier studies conducted in mesocosms for *P. oceanica* (Fernández-Torquemada *et al.*, 2005; Marín-Guirao *et al.*, 2011, 2013) and *C. nodosa* (Pagès *et al.*, 2010, Fernández-Torquemada *et al.*, 2011) showing the sensitivity of marine phanerogams to conditions of hypersalinity. The transplants in the area of influence of the brine discharge (mean salinities 39 psu and 40 psu) showed an obvious decline in the number of shoots and shoot survival and an increase in the percentage of leaf necrosis, mainly because of the negative effect of the brine. The transplanted plants may have experienced an added period of stress and adaptation and would therefore have been more sensitive to abrupt or negative changes in the environment. An attempt was made to mitigate these circumstances by selecting a suitable time of year and a good location for transplanting and ensuring the plants were handled correctly (Ruiz de la Rosa, 2011). However, whereas the plants affected by the brine showed a decline in the number of shoots in both spring and summer, with a decrease in the 39 psu site of almost 80% and nearly 90% in the 40 psu site, survival of plants transplanted in the control site was constant in both seasons and shoot density increased in relation to t0. This allowed us to assume that the presence of brine with concentrations of 39 psu and 40 psu directly affected plant behaviour. The symptoms observed, such as decreased shoot density and survival and increased necrosed area in the leaves, were similar to those described by various authors when marine phanerogams were subjected to hypersaline stress (Fernández-Torquemada *et al.*, 2005; Pagès *et al.*, 2010; Fernández-Torquemada *et al.*, 2011; Marín Guirao *et al.*, 2011). These studies identified the same symptoms in controlled laboratory conditions, both for *P. oceanica* and *C. nodosa*, and in short periods of time (10-17 days). Symptoms were generally detected in *C. nodosa* above 43 psu. In the marine environment, experiments with *P. oceanica* in naturally occurring seagrass meadows (Gacia *et al.*, 2007; Ruiz *et al.*, 2009) detected phenological and physiological changes above concentrations of 39 psu. Various studies have explained these phenological changes produced by hypersaline stress as the result of alterations in plant biochemical and physiological processes (McMillan and Moseley, 1967; Walker and McComb, 1990; Vermaat *et al.*, 2000; Fernández-Torquemada *et al.*, 2005) such as photosynthetic capacity (Biebl and McRoy, 1971; Ralph *et al.*, 1998; Fernández-Torquemada *et al.*, 2005, 2006, 2009; Marín-Guirao *et al.*, 2011, 2013), which could have directly affected growth capacity.

After incorporation of the venturi eductors a fourth transplant site was chosen closer to the discharge point where salinities had been higher than 45 psu (before venturi). The salinities recorded in this experiment were practically the same as the ambient salinities, with salinity increases of less than 0.5 psu. The transplants remained in a good state of conservation for a similar period (more than five months; unpublished data).

The transplant experiment determined that the levels of sensitivity of *C. nodosa* plants to the hypersaline plume increased under chronic effects, i.e., in the long term. The negative response observed in the transplants to salinities of 39 psu after six months of exposure was similar to the negative effects recorded in mesocosms for the same species above 43 psu in a period of just a few days (Pagès *et al.*, 2010; Fernández-Torquemada *et al.*, 2011). Moreover, the good state of conservation of transplants at the sites inside the impact zone after installation of the venturi eductors demonstrated even further the cause-effect relation between the discharge and the disappearance of the seagrass meadow in this zone.

Thus the effects of brine discharges from desalination plants can be due to:

- the toxic effect of the highly hypersaline conditions of the brine or the chronic effect due to small salinity increases;
- the persistent effect, either isolated or synergic with increased salinity, of certain compounds from the chemical treatments at the desalination plant, whether these are ongoing or periodic;
- and the continuous physical and chemical variations produced during the dispersion process of the discharge over the sea floor.

This means that the effect of

- small salinity increases,
- any compound resulting from treatments at the desalination plant,

- continuous variations in the brine in a receiving marine environment with high physical and chemical stability,
- or a combination of these factors with no negative effects on the marine ecosystem in weeks or months, could have accumulated toxic effects in the longer term.

This opens up new lines of research that include the ability to minimise the impact of a discharge or recover a degraded area of seagrass meadows after incorporation of efficient corrective measures such as adding venturi technology to diffuser systems. A further line of research would be to assess the long-term effect of brine in mesocosms. This would provide a more reliable simulation of the behaviour of the brine plume in the natural environment and allow us to differentiate between hypersaline seawater and brine, as the other compounds included in brine can directly affect plants.

4.5. CONCLUSIONS

The trajectories of the plumes coincided with an area completely lacking in plant cover. Seagrass meadows became established and settled beyond the outer edges of the plumes, suggesting the sensitivity of *C. nodosa* to brine discharges. The experimental study (in situ) on the response of *C. nodosa* to discharge from a desalination plant helped to clarify the real impact of brine discharges on these ecosystems. The results of the transplants showed the effect of the brine in the mid-long term, from the second month and after small increases in salinity ($\geq$ 2.2 psu). After incorporation of the diffuser system with venturi eductors, the new transplants remained in a good state of conservation at the same sites within the former impact zone, which means that we managed to minimise the impact and also allowed the seagrasses to grow again in the affected area. This is why it is advisable to develop enhanced technologies and appropriate management and action plans for discharge processes to minimise their impact zones and associated effects.

Acknowledgements

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CAPÍTULO 5

Assessment of the abiotic and biotic effects of sodium metabisulphite pulses discharged from desalination plant chemical treatments on seagrass (*Cymodocea nodosa*) habitats in the Canary Islands.

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E. Portillo [a,*], M. Ruiz de la Rosa [b], G. Louzara [b], J.M. Ruiz [c], L. Marín-Guirao [c], J. Quesada [d], J.C. González [e], F. Roque [e], N. González [f], H. Mendoza [a]

[a] *Instituto Tecnológico de Canarias, S.A. (Canary Islands Technological Institute) Playa de Pozo Izquierdo s/n, 35110 Santa Lucía, Las Palmas, Spain*
[b] *ECOS, Estudios Ambientales y Oceanografía, S.L., C/Alfred Nobel 31B, 35013 Las Palmas de Gran Canaria, Spain*
[c] *Instituto Español de Oceanografía, Centro Oceanográfico de Murcia, C/Varadero, 1, 30740 Murcia, Spain*
[d] *Canaragua, S.A. Avda. Manuel Hermoso Rojas, 4, 38003 Santa Cruz de Tenerife, Spain*
[e] *Elmasa Tecnología del Agua, S.A., Av. de Tirajana no 39, Edificio Mercurio Torre 2, Sexta Planta, 35100 San Bartolomé de Tirajana, Las Palmas, Spain*
[f] *Instituto Canario de Ciencias Marinas, Ctra. de Taliarte, s/n, 35200 Telde, Las Palmas, Spain*

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ABSTRACT

Reverse osmosis membranes at many desalination plants are disinfected by periodic shock treatments with sodium metabisulphite, which have potentially toxic effects to the environment for marine life, although no empirical and experimental evidence for this is yet available. The aim of this study was to characterise for the first time, the physico-chemical modification of the marine environment and its biological effects, caused by hypersaline plumes during these membrane cleaning treatments. The case study was the Maspalomas II desalination plant, located in the south of Gran Canaria (Canary Islands, Spain). Toxicity bioassays were performed on marine species characteristic for the infralittoral soft bottoms influenced by the brine plume (*Synodus synodus* and *Cymodocea nodosa*), and revealed a high sensitivity to short-term exposure to low sodium metabisulphite concentrations. The corrective measure of incorporating a diffusion system with Venturi Eductors reduced nearly all the areas of influence, virtually eliminating the impact of the disinfectant.

1. Introduction

Brine discharges from desalination plants where the discharge system lacks a high initial dilution capacity become hypersaline plumes with very high salinities and a high degree of stratification, making the exchange and dilution processes very slow (Palomar and Losada, 2008). As a result, brine discharges spread out over large areas of the sea floor (Fernández-Torquemada et al., 2009), following the steepest gradients (Payo et al., 2010), and with a high potential to alter the structure and distribution of benthic communities (Morton et al., 1996; Einav et al., 2002; Ruiz, 2005; Palomar and Losada, 2008). Brine effluents have been shown to cause adverse effects on benthic infaunal communities and fishes (Fielder et al., 2005; Miri and Chouikhi, 2005; Del-Pilar-Ruso et al., 2007, 2008, 2009; Castriota et al., 2001; Riera et al., 2011) and seagrass habitats (Fernández-Torquemada and Sánchez, 2005; Gacia et al., 2007). The extent and magnitude of such impacts ultimately depend on many factors related to the vulnerability of the benthic assemblages and their conservation status, prevailing environmental characteristics (bathymetry, climate and oceanography) and characteristics of the brine discharge, its chemical composition and the discharge system (Höpner and Windelberg, 1996; Einav et al., 2002; Fernández-Torquemada et al., 2009; Ruiz, 2005).

Seagrass meadows are dominant habitats of infralitoral environments of the Spanish Mediterranean and Atlantic coasts up to 30–40 m in depth, with *Posidonia oceanica* (L.) Delile and *Cymodocea nodosa* (Ucria) Ascherson being the most abundant and ecologically relevant species (Procaccini et al., 2003). These benthic habitats and the communities they contain are particularly vulnerable to the effects of human impact (Boudouresque et al., 2009), which motivated the first scientific projects that aimed to establish the adequate criteria to avoid, minimise and monitor the effects of brine effluents on marine environments (Sánchez-Lizaso et al., 2008). In the Mediterranean Sea, most of this initial research was dedicated to the endemic, dominant species, *P. oceanica*. This is a typical stenohaline species with a high sensitivity to chronic salinity increase, as demonstrated by diverse studies based on

* Corresponding author. Tel.: +34 928 72 75 37.
E-mail addresses: eportillo@itccanarias.org (E. Portillo), mruiz@ecoscanarias.com (M. Ruiz de la Rosa), juanm.ruiz@mu.ieo.es (J.M. Ruiz), jquesada@aqualogy.net (J. Quesada), jcgonzalez@elmasa.es (J.C. González), froque@elmasa.es (F. Roque), ngonzalez@iccm.rcanaria.es (N. González), hmendoza@itccanarias.org (H. Mendoza).

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CAPÍTULO 5

Assessment of the abiotic and biotic effects of sodium metabisulphite pulses discharged from desalination plant chemical treatments on seagrass (*Cymodocea nodosa*) habitats in the Canary Islands.

Abstract:

Reverse osmosis membranes at many desalination plants are disinfected by periodic shock treatments with sodium metabisulphite, which have potentially toxic effects to the environment for marine life, although no empirical and experimental evidence for this is yet available. The aim of this study was to characterise for the first time, the physico-chemical modification of the marine environment and its biological effects, caused by hypersaline plumes during these membrane cleaning treatments. The case study was the Maspalomas II desalination plant, located in the south of Gran Canaria (Canary Islands, Spain). Toxicity bioassays were performed on marine species characteristic for the infralittoral soft bottoms influenced by the brine plume (*Synodus synodus* and *Cymodocea nodosa*), and revealed a high sensitivity to short-term exposure to low sodium metabisulphite concentrations. The corrective measure of incorporating a diffusion system with venturi eductors reduced nearly all the areas of influence, virtually eliminating the impact of the disinfectant.

5.1. INTRODUCTION

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Seagrass meadows are dominant habitats of infralitoral environments of the Spanish Mediterranean and Atlantic coasts up to 30–40 m in depth, with *Posidonia oceanica* (L.) Delile and *Cymodocea nodosa* (Ucria) Ascherson being the most abundant and ecologically relevant species (Procaccini *et al.*, 2003). These benthic habitats and the communities they contain are particularly vulnerable to the effects of human impact (Boudouresque *et al.*, 2009), which motivated the first scientific projects that aimed to establish the adequate criteria to avoid, minimise and monitor the effects of brine effluents on marine environments (Sánchez-Lizaso *et al.*, 2008). In the Medierranean Sea, most of this initial research was dedicated to the endemic, dominant species, *P. oceanica*. This is a typical stenohaline species with a high sensitivity to chronic salinity increase, as demonstrated by diverse studies based on different field and laboratory experimental approaches (Fernández-Torquemada and Sánchez-Lizaso, 2005; Gacia *et al.*, 2007; Ruiz *et al.*, 2009). More recently, the stress-response mechanisms induced in this seagrass species by hypersaline conditions have been studied (Marín-Guirao *et al.*, 2011; Sandoval-Gil *et al.*, 2012a). Similar studies have been also performed with *C. nodosa*, a more euryhaline seagrass species with a broader ecological and geographical distribution than *P. oceanica* (Drew, 1978; Procaccini *et al.*, 2003). Accordingly, the available evidence indicates a higher capacity of this seagrass species to tolerate chronic salinity increases (Pagès *et al,.* 2010; Fernández-Torquemada and Sánchez-Lizaso, 2011), due to specific physiological adaptations to cope with hypersaline stress (Sandoval-Gil *et al.*, 2012a, b; Marín-Guirao *et al.*, 2013).

However, very few studies have considered other factors than salinity that might explain the deleterious effects of brine effluents on seagrass communities (Fernández-Torquemada and Sánchez-Lizaso, 2003). One of these factors is the addition of diverse chemical products (anti-fouling agents, coagulants, acidifiers, disinfectants, etc.), the presence of which is usually considered sporadic and of little importance, although presumably with a high potential to cause persistent toxic effects on marine organisms (Sánchez-Lizaso *et al.*, 2008). Sodium metabisulphite ($Na_2S_2O_5$; herafter, SMBS) is among the most common chemical additives used in shock or continuous cleaning treatments of reverse osmosis membranes. During the shock treatments, the product is applied periodically, so that its presence (and its sub-products) in the brine appears as a short-term pulse (minutes to hours) at a weekly frequency. The SMBS reacts with the oxygen dissolved in the water, releasing the gas sulphur dioxide (SO_2), which combines readily with water and results in an increase in the level of acidic substances (HSO_3^- as H_2SO_4; Singh and Singh, 1984). As well as the residues produced by the chemical reactions between the product and the brine (Na_2SO_3, CaSO, $CaSO_4$; Medina, 1999), its dissociation products alter the physico-chemical properties of the medium, leading to acidification (pH < 5) and hypoxia (dissolved oxygen saturation < 5% DOsat). Such conditions are extremely adverse for the development and survival of benthic marine life (Silva 1988; Singh and Singh, 1984; Macintosh and Phillips, 1992; Figueiredo *et al.*, 2006; Galli *et al.*, 2012) and therefore are highly likely to significantly alter the structure and distribution of benthic habitats and communities. Nonetheless, to date, no studies are available concerning the effects of these chemical products present in brine effluents on any marine benthic community.

The aim of this study was to characterise for the first time, the physico-chemical modification of the marine environment, and the biological effects caused by hypersaline plumes during the operation of membrane cleaning treatments using SMBS. To this end, a location on the island of Gran Canaria (Canary Islands, Spain) was selected, where the spread of a brine discharge delivered by a desalination plant has been well characterised in previous studies in relation to different hydrodynamic conditions (Portillo *et al.*, 2014a). Furthermore, this locality is an area of special conservation interest due to the presence of the most extensive and ecologically relevant *C. nodosa* seagrass meadow on the island. However, results from these previous studies showed that *C. nodosa* was absent in most of the area affected by the hypersaline plume, associated with the brine effluent. In this study, we evaluated the hypothesis that environmental modifications caused by salinity increases and SMBS additions associated with the brine effluent might be potential causes for the disappearance of the seagrass and its associated community in the area of influence of the effluent. To evaluate this hypothesis, a detailed spatial characterisation of physico-chemical variables (salinity, pH and DOsat) was initially performed, to assess the extent of environmental alterations caused by the brine discharge in the area. Secondly, various bioassays were performed to experimentally assess the potential effects of increases in salinity and SMBS-induced physico-chemical alterations on the vitality and survival of *C. nodosa* and on other key component characteristics of this benthic community, such as the predator Lizard fish, *Synodus synodus*. Thirdly, after the incorporation of a diffusion system with venturi eductors as a corrective measure, their ability to minimise the effects of such discharge during cleaning membrane operations using SMBS additions was evaluated.

5.2. MATERIAL AND METHODS

Study area and brine discharge

The studied brine discharge was delivered from the reverse osmosis desalination plant Maspalomas II, located in the South of Gran Canaria Island (Canary Islands, Spain; Fig. 1). The discharge was initiated in 1988 and, at the time of this study, it had a brine flow of 1,062 m^3/h with a salinity of 69.5 psu. Shock treatment to clean the reverse osmosis membranes is applied weekly to feedwater in the storage tank after it has been pumped from the marine environment and filtered. SMBS (1,225 kg) is added to this tank every 45 min and enters the membrane system with a concentration of ca. 800 ppm. After the osmosis process, the product is delivered into the sea with the brine through a pipeline (300 m length and a 600 mm diameter) at a concentration of ca. 1, 600 ppm. The discharge point is at a depth of 4 m at mean low water spring tide (MLWS) and discharges over sedimentary bottoms with a slope of 1.6% and dominated by a large, patchy *C. nodosa* seagrass meadow of recognised ecological importance for the island (Special Conservation Zones of the UE Nature 200 network; BOE, 2009). The distribution of the *C. nodosa* meadows in the study area is shown area is shown in Figure 1, together with the mean spatial spread of the hypersaline plume under low hydrodynamic exposure obtained in previous studies in this area (Portillo *et al.*, 2014a). A discontinuity in the seagrass distribution at the level of the discharge point and the adjacent areas influenced by the hypersaline plume was appreciated.

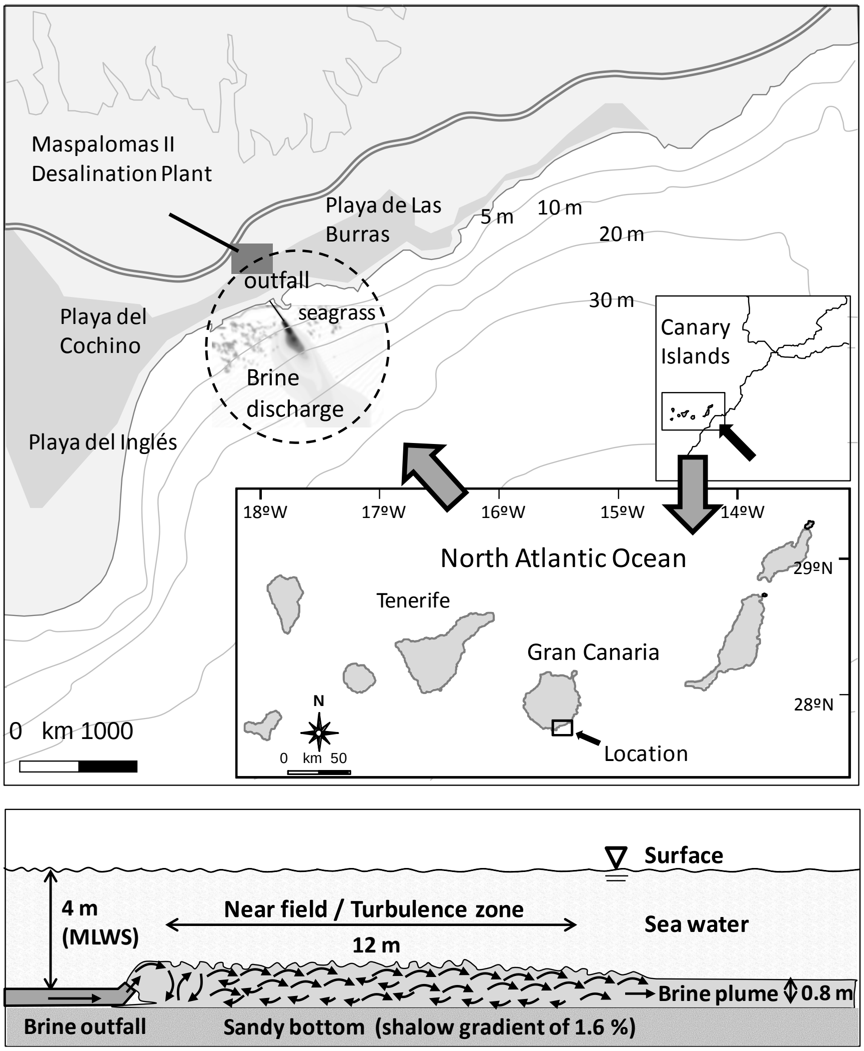


Figure 1. Location of the study area, indicating the path of the underwater outfall and discharge and its brine discharge scheme.

In 2012, a new discharge system with venturi diffusers was installed in the final end of the pipeline to allow a higher and more efficient dilution of the brine and to minimise its effect on the marine environment (Portillo *et al.*, 2013). After the installation of the venturi eductors, it was observed that the salinities of the discharge zone almost equalled normal ambient salinity values for this coastal area, although modifications of other seawater physico-chemical characteristics are unknown, particularly during cleaning membrane operations using SMBS additions.

Field sampling for spatial characterization of physico-chemical variables

Before the realisation of the extensive sampling campaigns, three YSI-6600-V2 sondes were deployed on the seabed for 6 h to obtain continuous recordings of pH and near-bottom dissolved oxygen (DOsat, %) values at fixed positions located 0, 250 and 700 m from the discharge point (Fig. 2). The objective of this was to precisely characterise the temporal evolution of the above-mentioned variables in these locations, following the addition of SMBS, to obtain some basic information necessary for the design of sampling campaigns and bioassays. We specifically needed to determine a) the duration of the exposure to deoxygenation and acidification conditions once the brine arrived at a particular point and b) the velocity of the displacement of SMBS subproducts as the brine spread over the seabed.

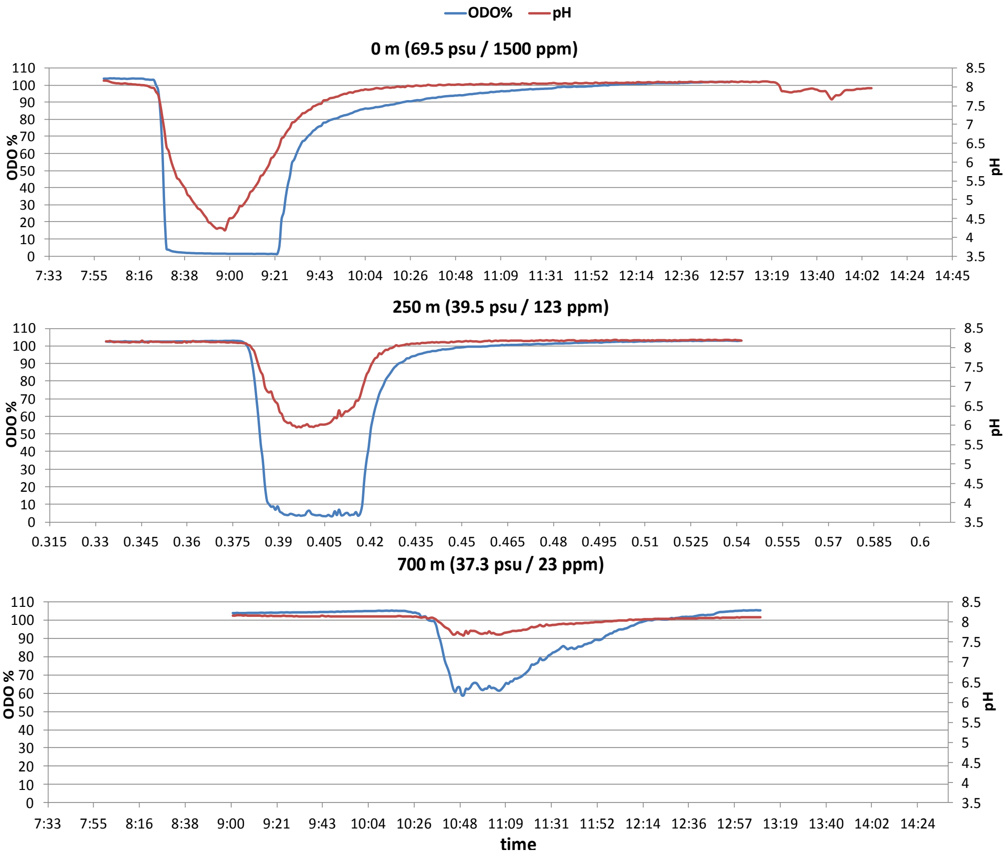


Figure 2. Continuous recording of DOsat (ODO%) and pH on the sea bottom, obtained by CTD sondes at 0, 250 and 700 m from the discharge point. The salinity and the estimated concentration of SMBS at each point are indicated in parentheses.

Two sampling campaigns were performed for the spatial characterisation of physico-chemical characteristics of the brine discharge on the same days and at the same time that SMBS was added for the cleaning treatment of the membranes. The first campaign was performed on 17 January 2011 for the measurement of near-bottom salinity, pH and DOsat using the multiparametric sonde, following the protocol described by Portillo *et al.* (2014a). This first sampling was performed before the installation of the venturi diffusers (i.e. without brine dilution) and under low hydrodynamic conditions; not enough to favour the dilution of the brine (i.e. near-bottom current velocities lower than 5 cm/s; Portillo *et al.*, 2014a). Measurements were performed at a network of 75 regularly distributed points, but with a higher density in the area closer to the discharge point (Fig. 3).

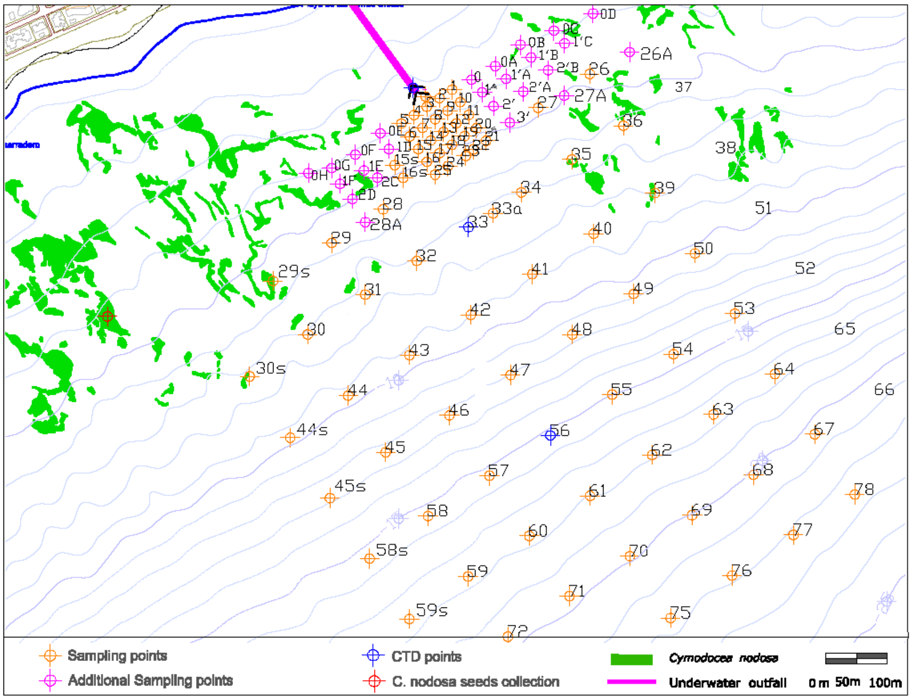


Figure 3. Sampling points, bathymetry map, locations of CTD sondes and *C. nodosa* seeds collection.

This sampling network was the same as that already established and used in previous studies for the characterisation of the brine effluent (Portillo *et al.*, 2014a), so that comparisons among the different studies were possible. The sampled area had a total surface of 145 ha, covering distances up to 1,150 m from the discharge point and a range depth of

4–22 m. The second sampling campaign was performed on 29 June 2011, when the discharge system with venturi diffusers was added as a corrective measure i.e. with the brine that was previously diluted. In this case, extra sampling points at both lateral margins of the discharge system were required.

Previous measurements explained at the begining of this section allowed the determination of the duration of the exposure to SMBS subproducts at each sampling point and the velocity at which they moved forward from one point to the neighbouring points, and these were the key parameters used for the synchronisation of sampling operations across the grid of sampling points during each campaign. Both campaigns were conducted when the desalination plant was operating under normal conditions, with all osmosis racks and most concentrators functioning optimally, and with medium-low hydrodynamic conditions and near-bottom current velocities lower than 5 cm/s (Portillo *et al.*, 2014a). A SONTEK ADCP Argonaut XR current profiler was used to control hydrodynamic conditions during the sampling operations, in particular near-bottom current velocities, which were used as a reference parameter for the degree of hydrodynamic exposure of the recipient environment. Results of the selected physico-chemical variables obtained in these two campaigns were compared with those obtained in previous studies from the same case-study and under comparable conditions (near-bottom current velocities <5 cm/s), but obtained on days without the addition of SMBS (Portillo *et al.*, 2014a).

Salinity was determined from the relationship between the temperature and conductivity readings in accordance with the algorithms in Standard Methods for the Examination of Water and Waste Water (Clesceri *et al.*, 1989). Use of 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 KCl at 15ºC in 1 kg (Lewis, 1980; Unesco, 1981), although following convention, these were shown as practical salinity units (psu).

The dilution achieved by the discharge system at a given point was calculated as follows:

D = [(brine discharge salinity – seawater salinity)/(salinity at the sampling point – seawater salinity)], with D being an adimensional value. The minimum dilution achieved beyond the mixing zone was estimated using the maximum salinity value recorded in the zone closest to the discharge point in the sampling grid (Fig. 3).

The initial concentration of sodium metabisulphite at the brine discharge point was calculated as follows:

M (ppm) = [(amount of sodium metabisulphite (kg) × 1,000)/(brine discharge flow (m^3/h) × addition time (h))]

The concentration of the sodium metabisulphite by-products at a given point of the sampling network was estimated as follows:

m (ppm) = [initial concentration of sodium metabisulphite/dilution achieved by the system at a given point].

Values of the physico-chemical variables of salinity, pH and DOsat (ODO%), and the concentration of SMBS obtained at each point of the sampling grid were interpolated to the whole area for the spatial representation of these variables over the seafloor. The Surfer Programme (V.8) was used to map the mentioned variables by the kriging interpolation method. The obtained maps were superimposed onto the maps of the seagrass meadow and the bathymetry in the area using Autocad mapping software.

Bioassays

Different bioassays were designed to experimentally assess the effect of seawater anoxia and acidification induced by SMBS additions on the vitality and survival of the seagrass *C. nodosa* and the demersal predator fish *S. synodus* or Lizard fish. As already explained, *C. nodosa* is the dominant seagrass species that forms extense meadows, known locally as ‘Sebadales’, which are vulnerable to environmental alterations caused by the impact of human activity (Tuya *et al.*, 2002, 2013). Preliminary samplings showed that *S. synodus* was the most abundant macrofaunal species in visual censuses performed along two 550 m transects following standard census methods (Harmelin, 1987); during these samplings, we repeatedly observed dead individuals of *S. synodus* spread over the influence area of the brine immediately following the addition of SMBS on days upon which membrane cleaning operations occurred in the desalination plant, and this observation motivated the selection of this fish species for the bioassays.

Fish were caught by traditional fishing methods and were transported in water barrels with artificial aeration to the closest dock (Pasito Blanco, which is 4.5 nmi southwest of the study area), where the experimental system was installed. Experimental treatments consisted of 40 min exposures to SMBS concentrations of 25, 50, 75 or 100 ppm, which encompassed the range of concentrations estimated across the salinity fields created by the brine dilution process. The duration of the treatment exposure was based on the results obtained with multiparametric sondes deployed at the seabed, immediately prior to the extensive campaigns, to obtain basic information on the temporal evolution of physico-chemical variables since the SMBS addition in the desalination plant (see section 2.2 and Results section). Six, 30-L tanks filled with seawater were prepared for each treatment level of product concentration and another six tanks without product addition, which were used as the control treatment. Once the SMBS was added to the tank, the seawater was continuously stirred, until the total dissolution of the product and was maintained for 10 min to allow the stabilisation of pH and DOsat (ODO%) values before the introduction of fish individuals. For each tank, one adult fish of similar size and weight was introduced for 40 min, the time to mortality was noted and the pH and DOsat were recorded using the YSI-6600-V2 sonde.

For the seagrass bioassay, *C. nodosa* seeds were collected by divers in neighbouring meadow areas (Fig. 3). The experiment was performed with 45-day-old seedlings obtained from the germination and development of the collected seeds under sterile conditions following the technique described by Zarranz *et al.* (2011). The experimental system was placed in the laboratories at the Canary Islands Technological Institute, in the southeast of the island of Gran Canaria, and basically consisted of 24, 5-L aquaria filled with filtered seawater and with a sand layer (4 cm thick) at the bottom, carefully cleaned to eliminate living animals and organic matter. The system was installed in an acclimated room with stable temperature (22ºC) and each aquarium received aeration and an irradiance of 200 µmol m^{-2} s^{-1}, which is the mean value obtained from measurements performed using a LI-COR (LI1400) radiometer in *C. nodosa* seagrass meadows at a depth of -15 m in Canary Island waters. A photoperiod of 14 h:10 h (light:dark) was applied, to mimic summer daylight hours in the Canary Islands. To avoid variations in light, the aquaria were moved at random every three days. To avoid the possible influence of environmental heterogeneity between aquaria on treatment responses, their position was randomly changed each three days. Seawater salinity was maintained at 36.8 psu, which corresponded to the mean value observed throughout the year in the study area. In each aquarium, salinity was controlled daily and kept constant by adding water to compensate for losses by evaporation. Furthermore, all aquaria were covered with transparent film to minimise evaporation and maintain the salinity and temperature conditions of the experiment stable. Fifteen seedlings were placed in each aquarium rooted in the sediment layer and were maintained under the described conditions for one week for acclimation before the onset of the experimental treatments.

A two-way factorial design (Quinn and Keough, 2002) was used to evaluate the hypothesis that the absence *C. nodosa* in the influence area of the brine plume might be caused by the toxic effects of an increase in salinity, or by the physico-chemical alterations associated with SMBS additions, or their interaction, on seagrass vitality. Factors were: 1) chronic salinity increase (with two levels: normal seawater i.e. 36.8 psu and hypersaline i.e. 39 psu) and SMBS addition (with two levels: 0 or 100 ppm). According to this basic design, six randomly selected aquaria (i.e. n = 6 replicates) were assigned to each of the following experimental treatments: a) normal seawater at 36.8 psu (control, C); b) chronic salinity increase (hypersaline, 39); c) SMBS addition (M); d) chronic salinity increase + SMBS addition (39+M).

The level of salinity increase (39 psu) was selected based on observations from previous studies, which indicated that many seagrass species are sensitive to increases in salinity beyond the upper limits of the normal salinity range to which natural populations are adapted (CEDEX, 2003; Sánchez-Lizaso *et al.*, 2008). Furthermore, previous studies that dealt with the spatio-temporal characterisation of the brine plume in the studied area (Portillo *et al.*, 2014a) showed that the area in which *C. nodosa* meadow is absent, coincided with salinity fields defined by salinities higher than 39 psu and hence salinity increases above this salinity level might be responsible for the absence of this seagrass species in this area. The addition of 100 ppm SMBS corresponded to the estimated concentration after the dilution achieved by the dispersion process at 39 psu.

Exposure to the experimental treatments lasted for 25 days. An increase in salinity was achieved by the addition of high-quality artificial marine salt (Seachem Reef Salt^{TM}) to normal seawater. This was first performed in an auxiliary tank and was then applied to the aquaria, to progressively replace the normal seawater by hypersaline solution. Treatments of ‘pulsed SMBS additions’ consisted of the addition of 100 ppm SMBS to aquaria once a week for 40 min, which simulated the effects of SMBS subproducts on the seabed during the membrane cleaning operations performed each week in the desalination plant (see section 2.2 and Results section). This dose of product caused a reduction in pH and DOsat up to values of 6.3 and 1.1%, respectively. After 40 min exposure, seedlings were carefully removed from the sediment, washed in clean seawater to remove all SMBS subproducts and transferred to new aquaria without SMBS. This operation was performed each week not only for treatments with SMBS addition, but also with those without product addition, to prevent possible artifact effects associated with seedling manipulation. At the end of the experiment, the number of surviving seedlings was recorded, to estimate plant survival in each treatment, and shoots of the surviving plants were processed to determine morphological descriptors and growth rates as described by Ruiz *et al.* (2009) and Marín-Guirao *et al.* (2011). Morphological descriptors were the leaf surface (cm^2 $shoot^{-1}$) and the proportion of necrotic photosynthetic tissue per shoot. The growth rate was determined as the leaf elongation rate by marking all leaves on a shoot with a hypodermic needle at the beginning of the experimental period; at the end of the period, the length of leaf segments between the mark (hole) and the leaf base was measured and divided by the number of days, to obtain the leaf elongation rate expressed in cm^2 $shoot^{-1}$ day^{-1}.

The significance of the effects of SMBS on the Lizard fish was evaluated using one-way ANOVA. A two-way ANOVA was applied, to test the effects of salinity and SMBS on the analysed variables of the *C. nodosa* bioassay. Before carrying out the ANOVA test, the data were checked for assumptions of normality and homoscedasticity, and were transformed when necessary. *Post-hoc* mean comparisons (Student-Kneuman-Keuls, SNK) were performed to identify specific treatment level(s) that caused significant effects. Treatment effects were considered statistically significant at $p < 0.05$.

5.3. RESULTS

Figure 2 shows a representative example of the continuous recording of near-bottom values of pH and DOsat obtained by the YSI-6600-V2 sondes in a day in which membrane cleaning operations took place (see methods). A sudden and acute decrease in pH and DOsat (%ODO) was observed when the SMBS sub-products arrived at the point where the sonde was placed and this effect lasted for about 40 min, which is a similar length of time as the duration of the cleaning operations in the desalination plant. The most severe hypoxia and acidification were observed at the discharge point before any dilution of the brine with the surrounding seawater occurred. At 250 m from the discharge point, the dilution factor of the brine was D = 12 (39.2 psu), but the estimated concentration of SMBS sub-products were still relevant (123 ppm); in such conditions, DOsat values were below 5% for more than 40 min and the pH was below 6 for almost 20 min. At 700 m from the discharge point, the dilution factor was very high (D = 60) and the estimated concentration of SMBS was very low (23 ppm). This concentration caused less severe seawater anoxia and acidification, with minimum values of DOsat and pH of 58% and 7.6, respectively, for about 15 min. From these values, the velocity at which the front with SMBS sub-products moved from one point to other could be determined. At 250 m from the discharge point, the pass of SMBS sub-products was detected 45 min after their detection at the discharge point and after 124 min at 700 m from the discharge point (Fig. 2). This leads to a flow velocity of the brine plume of 9.4 cm/s. This information was used for the design of field samplings and bioassays (see methods).

Table 1 shows that brine characteristics (flow, salinity and estimated concentration of SMBS) and also environmental conditions (bottom current velocity and seawater salinity) were in general similar between both sampling campaigns, although small differences were observed in some parameters such as the brine flow (10% higher in the January campaign). Mean near-bottom current velocities during the campaigns on 17 January (4.8 cm/s) and 29 July (4.0 cm/s) 2011 showed medium-to-low levels of hydrodynamic exposure and therefore, hydrodynamic conditions that would have aided the dilution processes of the brine on its trajectory over the sea floor did not occur.

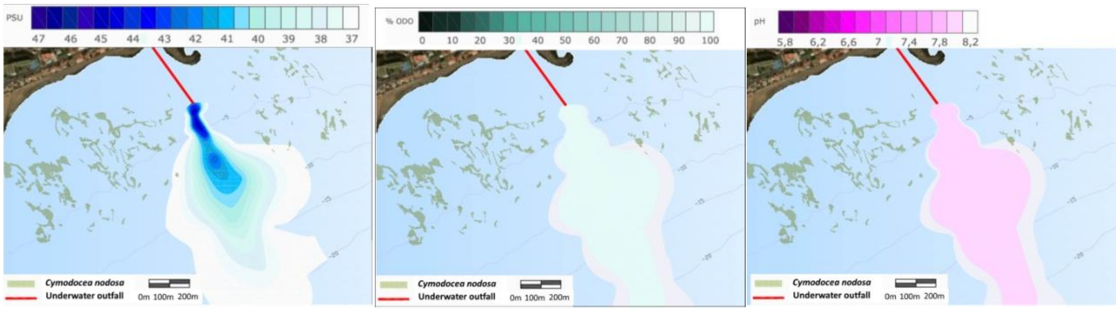
Table 1. Mean values (± standard errors) of brine characteristics and environmental conditions of the receiving environment during the two sampling campaigns with the addition of SMBS. The Table also shows the minimum dilution achieved beyond the mixing zone and the total area of the impact zone (ha) corresponding to salinity fields greater than 38 and 39 psu, the dissolved oxygen percentage saturation (DOsat, ODO%) field less than 10% and pH field less than 6.2. *Campaign from previous studies of the same case-study, with no diffuser, and under comparable conditions, but without the addition of SMBS (Portillo *et al.*, 2014a).

parameter / date	brine salinity (psu)	sea water salinity (psu)	brine flow (m^3/h)	bottom current (cm/s)	Sodium metabisulfite SMBS (ppm)	minimum dilution beyond the mixing zone	38 psu (ha)	39 psu (ha)	ODO% 10 % (ha)	pH 6,2 (ha)
17/01/2011 (no diffuser; with SMBS)	67.0 ± 0.5	36.8 ± 0	1157	4.8 ± 1.2	1411	3.6	14.8	8.0	2,0	1,0
29/07/2011 (venturi eductor; with SMBS)	69.5 ± 0.8	36.7 ± 0	1050	4.0 ± 0.8	1556	39.0	0	0	0	0
10/09/2010b* (no diffuser; without SMBS)	71.1 ± 0.9	36.8 ± 0	1043	3.9 ± 1.1	0	3.8	21.6	13.2	0	0

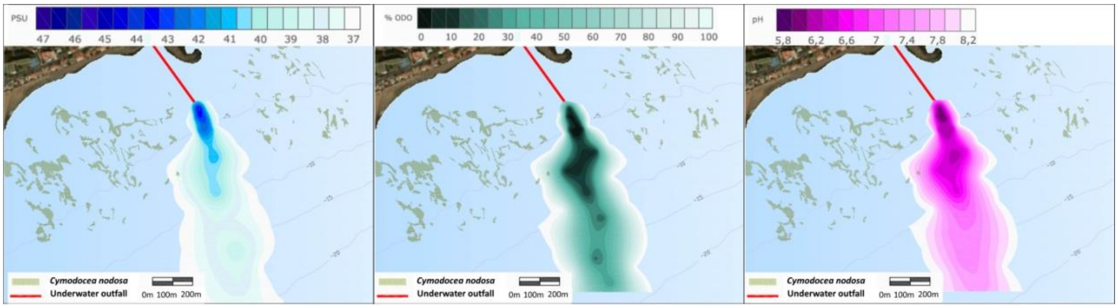
In the absence of SMBS by-products in the brine effluent (i.e. the 10 September 2010 campaign; Fig. 4a) and under comparable brine characteristics and hydrodynamic conditions (Table 1), the pH in the hypersaline plume was reduced only by 0.2 with respect the pH of the adjacent normal seawater (i.e. 8.2 ± 0.2) and DOsat was unaltered at any point within the sampling area (100%).

In the January campaign (Fig. 4b), salinities beyond the mixing zone in the areas nearest the discharge point reached values close to 45 psu, corresponding to dilution factors lower than four. The horizontal spatial distribution of both the salinity and the pH and ODO% (DOsat) consisted of elongated plumes that spread out over the sea floor due to their greater density than ambient sea water, perpendicular to the coast and following the steepest gradient. The plume initially formed a narrow (60 m wide) hypersaline discharge in the first 125 m, which had salinity values greater than 42 psu and extreme acidification and anoxia (i.e. pH < 6 and DOsat < 5 %). These conditions continued to travel over the sea floor, increasing in width to 100 m and reaching 300 m from the discharge point, covering an influence area of 1–2 ha (based on DOsat and pH fields less than 10% and 6.2). Beyond these distances from the discharge point, fields corresponding to salinities greater than 38 psu (with pH and DOsat less than 7.4 and 50%, respectively) extended in length to depths of more than 18 m and reached more than 850 m from the discharge point, covering an influence area of up to 15 ha; the area delimited by the 39 psu isoline had a surface of 8 ha (Table 1).

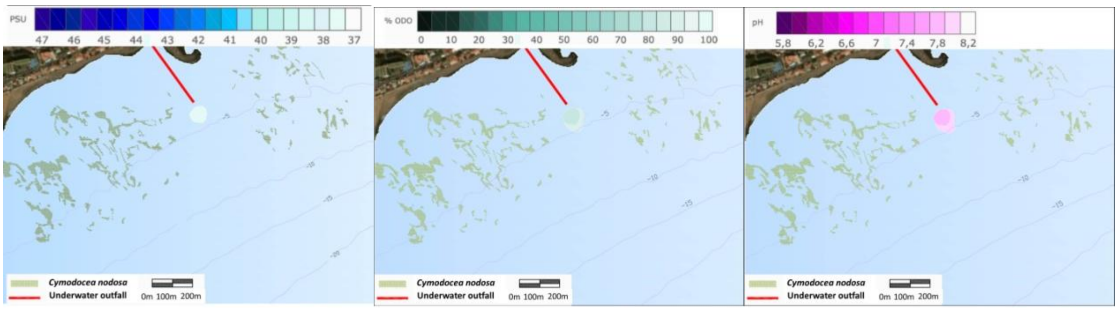
In the July campaign (Fig. 4c), after the incorporation of the venturi eductors into the discharge system, the influence areas reported in the January campaign disappeared (0 ha). In the area nearest to the discharge point, no salinities greater than 37.5 psu were detected, corresponding to a relatively high minimum dilution factor of 39. As a consequence of this high dilution capacity, the effects of acidification and anoxia also disappeared in the discharge area. Only significant reductions in pH and DOsat of about 0.4 and 30%, respectively, were obtained only in the area nearest to the discharge point (sampling point 4 and 5).



a)



b)



c)

Figure 4. Maps of the horizontal distribution of maximum values of salinity, pH and DOsat recorded on the sea bottom during the absence of SMBS in the brine (a), and during membrane cleaning treatments with SMBS without dilution (i.e. no diffuser system) on 17 January 2011 (b) and with dilution (i.e. after the installation of venturi diffusers) on 29 July 2011 (c).

Results of the bioassay performed to assess the tolerance of diamond Lizard fish (*S. synodus*) to the effects of SMBS additions showed an extremely high sensitivity of this species to exposure to low concentrations of the product over very short periods (Table 2). Dissolved oxygen saturation in treatments with the highest product concentrations (75 and 100 ppm) were between 5 and 0% and mean pH values were 6.2–6.3. Under these extreme conditions, mortality rates were 100%, 7–8 minutes after the product was added. The addition of SMBS at concentrations of 50 ppm caused a less drastic reduction in the mean DOsat (10.8%) and pH (6.6) with respect to control values, but fish mortality was also 100% and very rapid (10 min). However, no mortality took place in relation to the 40 min exposition to anoxia (DOsat = 51%) and acidification (pH = 7.2) levels produced by a 25 ppm SMBS concentration. Therefore, for an exposure time of 40 min, the threshold of fish tolerance to the effects associated with the addition of SMBS must be a concentration between 50–25 ppm. All pH and DOsat readings remained virtually constant during the exposure time for each treatment and control, which allowed us to rule out the possibility that mortality was related to deoxygenation in the container caused by fish respiration.

Table 2. Mean pH and DOsat measurements during testing, percentage of mortality and time to mortality of the fish *Synodus synodus*, and the mean of their respective weights for the control and the concentrations of 25, 50, 75 and 100 ppm sodium metabisulphite.

Concent. metabisulph. (ppm)	100	75	50	25	0 (control)
mean pH	6.2 ± 0.0	6.3 ± 0.0	6.6 ± 0.2	7.2 ± 0.0	7.9 ± 0.0
mean DOSat (%)	0.3 ± 0.0	4.7 ± 0.2	10.8 ± 2.1	51.1 ± 2.4	101 ± 0.0
mean time to mortality (min)	7.8 ± 1.4	8.3 ± 2.0	10.1 ± 1.7	∞	∞
percentage of mortality	100	100	100	0	0
mean weight adult fish (g)	127 ± 23	144 ± 23	139 ± 23	133 ± 23	150 ± 23

An increase in salinity did not cause significant effects on seedling survival, since initial numbers remained intact at both experimental salinities (99–100%); In contrast, seedling survival was significantly and consistently affected by SMBS addition at both salinities, with a reduction in initial numbers of 9–13% (Table 3 and Fig. 5).

Table 3. Summary of the two-way ANOVA test to assess the effect of salinity increase (S) and sodium metabisulphite (M) on the selected response variables of *C. nodosa*. Df = degrees of freedom, MS = Mean Squares, %var. = percentage of explained variance, *F* = Fisher statistic. *P* = *p*-value, ns = not significant, *$p <$ 0.05, **$p <$ 0.01 and $p <$ 0.001.

variable	effect	df	MS	% var.	F	P
Shoot survival (%)	S	1	3.7	0.5	0.20	ns
	M	1	683.0	94.2	37.13	***
	SxM	1	20.1	2.8	1.09	ns
	residual	20	18.4	2.5		
Leaf elongation rate[1] (cm $shoot^{-1}$ day^{-1})	S	1	0.0045	32.5	8.56	**
	M	1	0.0089	63.6	16.73	***
	SxM	1	0.0000	0.0	0.01	ns
	residual	20	0.0005	3.8		
necrotic leaf surface (%)	S	1	38.1	28.9	9.43	**
	M	1	88.1	66.9	21.81	***
	SxM	1	1.5	1.2	0.38	ns
	residual	20	4.0	3.1		
total leaf surface (cm^2 leaf $shoot^{-1}$)	S	1	0.37	4.6	1.2	ns
	M	1	4.63	58.6	14.8	*
	SxM	1	2.60	32.8	8.3	**
	residual	20	0.31	4.0		
leaf number per shoot	S	1	0.01	1.9	0.09	ns
	M	1	0.02	4.5	0.22	ns
	SxM	1	0.25	72.8	3.50	ns
	residual	20	0.07	20.8		

For this variable, SMBS addition explained about 94% of the total variance. For leaf elongation rate and the proportion of necrotic leaf surface, salinity also had a significant effect on these response variables and accounted for 28–33% of the total variance, although SMBS addition caused a major effect (63–67% of the total variance). The leaf elongation rate significantly decreased by 7.3% and necrotic leaf surface increased by 38.9% in seedlings in response to an increase in salinity; plants in treatments with SMBS addition showed consistently lower (11–15%) or higher (30–56%) mean values of these variables, respectively, relative to the mean values observed in treatments without product addition at their respective salinities. The mean total leaf surface area of shoots maintained at normal salinity (36.8 psu) was

13.6% lower than that obtained at a higher salinity (39 psu); SMBS caused a significant reduction in this variable (22.7%) at 36.8 psu, but no further effect was caused by SMBS at 39 psu (significant interaction term S × M in ANOVA, Table 3). No significant treatment effect was detected on the number of leaves per shoot.

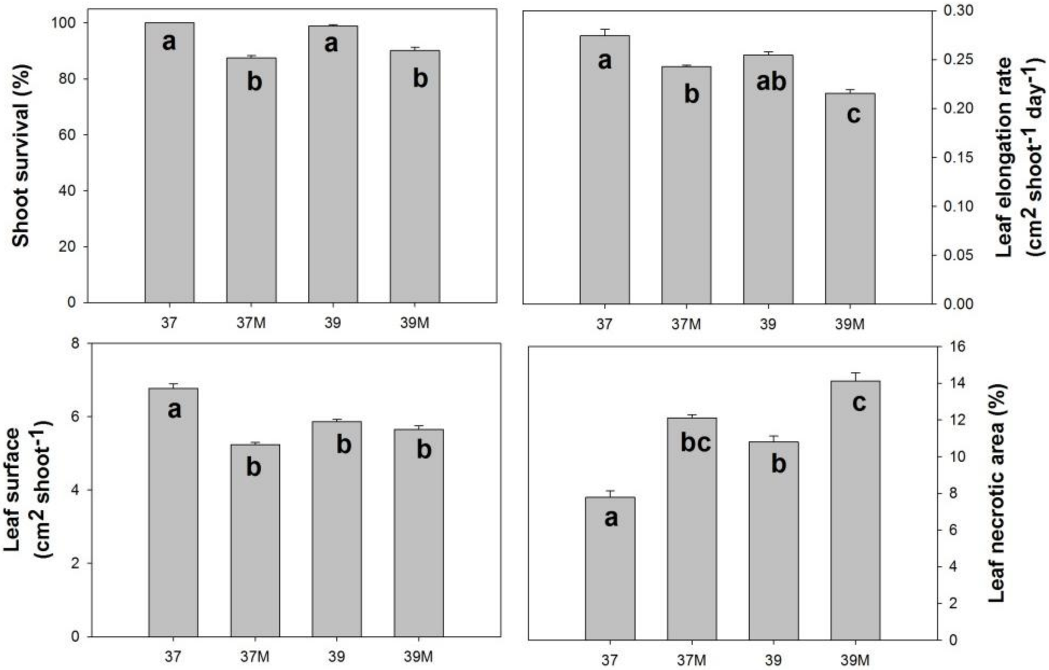


Figure 5. Mean values (± standard error) of the selected *C. nodosa* variables measured in the $Na_2S_2O_5$ toxicity experiment: 37 = ambient salinity of 36.8 psu, 39 = high salinity of 39 psu, M = sodium metabisulphite addition. The different letters indicate the groups of homogeneous means shown by the *post-hoc* Student-Kneuman-Keuls test.

5.4. DISCUSSION

The lower dilution capacity observed in the January campaign is attributable to the absence of some type of diffuser system in the discharge point of the desalination plant, which might allow a spill-out with a kinetic energy high enough to favour the rapid mixing of the brine and hence a higher dilution of the effluent (Portillo *et al.*, 2013). Therefore, in the absence of this diffuser system, the discharge produced a hypersaline plume of high salinity and a high degree of stratification, similar to the behaviour of brine discharges already described in other studied cases (Fernández-Torquemada *et al.*, 2005). Under such circumstances, the surface of the sea bottom with salinity fields greater than 38 psu (and an estimated SMBS concentration of 50 ppm) had an area close to 15 ha. Based on the close negative relationship between the SMBS concentration and the studied physico-chemical variables (pH and DOsat), a similar area was expected to be delimited by values of pH and ODO of about 6.6 and 10%, respectively (see Table 2). However, the area of the sea bottom delimited by these values was considerably lower (2 ha; Fig. 4b). A similar discrepancy was observed between the surface delimited by the salinity field greater than 39 psu (ca 8 ha) and that delimited by pH and DOsat values of 1% and 6.2 (ca 1 ha), respectively, which should correspond to the SMBS concentration estimated at points with that salinity (i.e. 100 ppm). This uncoupling between the estimated SMBS concentration and its effect on physico-chemical variables might be explained by the temporal dynamic of the deoxygenation and acidification processes that occurred as the SMBS sub-products passed through a point on the bottom (Fig. 2) and to a possible concentration-dependent effect. Thus, close to the discharge point, the higher SMBS concentrations (>150 ppm) reacted almost instantaneously, so that lowered pH and DOsat values were immediately reached; however, at sampling points further away from the brine discharge point, SMBS concentrations were lower and the dynamic of deoxygenation and acidification processes is a more gradual and slow process, so that a delay was observed between the moment at which SMBS sub-products passed through a point and the moment at which pH and DOsat reached its minimum values. Therefore, it is possible that the measurement of such variables in these sampling points was not performed in the phase in which they reached minimum values, but in a previous phase. This might explain the weak correspondence between the estimated SMBS values and their effects on the physico-chemical variables described above and suggests that the surface of the influence area delimited by given pH and ODO values might have been underestimated by our spatial analysis.

Results obtained in the *S. synodus* (Lizard fish) bioassay showed that total mortality occurred at SMBS concentrations equal to or higher than 50 ppm (i.e., pH and DOsat values equal to or lower than 6.6 and 10%, respectively; Table 2). It is widely known that hypoxia and acidification beyond certain critical levels becomes detrimental to aquatic organisms or even lethal. Thus, for instance, most fish-lethal levels of DOsat are set at 20 to 40% (Davis, 1975; Fisher *et al.*, 1992), which is consistent with lethal effects observed in the bioassay here, as well as the presence of dead fishes in the influence area of the salinity fields generated by the brine effluent immediately following SMBS treatment in the desalination plant. Similar toxic effects associated with environmental alterations caused by the presence of this chemical product have been already described for other species of fishes and aquatic invertebrates (Aragão *et al.*, 2008), together with other mutagenic and genotoxic effects (Pagano and Zeiger, 1987; Rencuzogullari *et al.*, 2001; Carvalho *et al.*, 2011; Galli *et al.*, 2012). Furthermore, these lethal effects occurred very rapidly (i.e. within the first 10 min of exposure, which is a shorter time period than that of the duration of the SMBS treatment in the desalination plant (40 min) and also shorter than the duration of the effects of SMBS sub-products on physico-chemical variables at a given point within the brine-plume influence area (e.g., at 250 m from the discharge point in Fig. 2). The observation of dead individuals of Lizard fish and other soft-bottom characteristic species spread over the bottom (*Bothus podas, Microchirus azevia* and *Trachinus Draco*) occurred not only in the 2 ha surface area delimited by critical DOsat values (10%), but in a broader area, supporting the previous hypothesis formulated to explain the reported discrepancies between the estimated SMBS concentration and its expected effects on physico-chemical variables. The large and rapid toxicity effect demonstrated by SMBS limits the possibility that dead fishes found in these more remote areas were individuals escaping from areas closest to the discharge point with more severe environmental alterations.

From the previous study of Portillo *et al.* (2014a) performed in the study area, seagrass patches of *C. nodosa* were completely absent within the influence of the salinity field associated with the brine discharge, which corresponded to the area delimited by the 39 psu isoline. This salinity is also higher than the upper limit of the natural salinity range to which *C. nodosa* meadows are adapted in natural areas surrounding this influence area (36.6–36.8 psu, see Table 1; Mouree *et al.*, 2008). These observations, together with the bulk of experimental evidence that indicates the high sensitivity of many seagrass species to increases in salinity (Fernández-Torquemada and Sánchez-Lizaso, 2005, 2006, 2011; Pagès *et al.*, 2010), suggest the tentative hypothesis that the salinity increases caused by the brine plume might be a key factor to explain the absence of *C. nodosa* within the influence area of the brine discharge. Results obtained from the *C. nodosa* bioassay partly support this hypothesis, since the exposure of seedlings to a moderate salinity increase (i.e. 2.2 psu over the normal seawater salinity) for one month, caused significant (but mild, sublethal) adverse effects on their vitality and physiological status, relative to those cultured under normal conditions (i.e. controls, 36.8 psu). This result also suggests that this salinity level employed in hypersaline treatments must be close to the threshold of the tolerance limit of this seagrass species, but this contrasts with conclusions obtained from similar experimental approaches with Mediterranean populations of this seagrass species (Pagès *et al.*, 2010; Fernández-Torquemada and Sánchez-Lizaso *et al.*, 2011; Sandoval-Gil *et al.*, 2012a, 2012b). These studies established that Mediterranean *C. nodosa* populations adapted to an ambient mean salinity of 37 psu are able to tolerate chronic salinity increases for one month (or more) of 41 psu (i.e. 4 psu over the mean ambient salinity) without apparent and significant effects on their physiology, growth and survival. Several factors might explain this discrepancy. First, there is evidence that populations from the Canary Islands are genetically distinct from Mediterranean ones (Alberto *et al.*, 2008; Masucci *et al.*, 2012), which suggest a differential capacity to tolerate hypersaline stress in geographically separated populations (Touchette, 2007). Second, our experiment performed with Canarian populations used *C. nodosa* seedlings, whereas all Mediterranean experiments were performed with adult plants i.e. developed shoots integrated into the clonal structure characteristic of seagrass populations. Some studies have demonstrated that the existence of differential sensitivity to hypersalinity increases between seedlings and adult stages of seagrass species (Tyerman, 1989; Fernández-Torquemada and Sánchez-Lizaso, 2013). In some species, younger plant stages (seeds and seedlings) showed a higher sensitivity to stressful conditions than adult stages and hence the possible influence of ontogenic factors cannot be discarded to explain the reported differences in salinity tolerance between this and other studies. Therefore, further experimental research is necessary to clarify the role of this and other factors in the tolerance of this seagrass species to salinity increases and to understand its intra-specific variation.

The *C. nodosa* bioassay also showed that the weekly, short-term exposure (40 min) of the seedlings to concentrations of 100 ppm of SMBS was sufficient to cause a significant reduction in plant vitality and survival. As demonstrated with the Lizard fish, the toxic effect of this product is due to a critical reduction in pH and DOsat, both of which are key environmental factors that can affect fundamental physiological functions of seagrasses, such as photosynthesis (Larkum *et al.*, 2006). The severe acidification of the medium can directly affect the photosynthetic capacity by affecting the availability of dissolved inorganic carbon (Beer *et al.*, 1977; Beer and Waisel, 1979; Invers *et al.*, 1997; Invers, 2001; Fernández-Torquemada and Sánchez-Lizaso, 2003) or by altering electrochemical gradients and proton fluxes through thylakoid membranes (Touchette and Burkholder, 2000; Beer *et al.*, 2001). Oxygen desaturation of the medium can modify the carboxylation function of the enzyme Rubisco (Larkum *et al.*, 2006) and cause further alterations in photosynthetic metabolism. The toxic effect of SMBS concentrations similar to those employed in our experiments has been demonstrated on green algae and cyanophytes (Singh and Singh, 1984) and are attributed not only to the aforementioned effects on pH, but also to the direct damage caused by its dissociation products HSO_3^- and H_2SO_4.

In addition, as well as the above-described individual effects of pH and DOsat on seagrass vitality and survival, the intensity of such toxic effects appears to be enhanced when SMBS is added under hypersaline conditions, as suggested by the more pronounced effects of the product on leaf vitality (growth rate and proportion of necrotised tissues) at a salinity of 39 psu, with respect to the effects observed at normal salinity. Therefore, the hypothesis that both individual and synergistic effects of salinity increase and SMBS sub-products are responsible for the absence of *C. nodosa* patches in the influence area of the brine effluent is reasonable, at least within the area delimited by the 39 psu isoline This in turn, corresponds to SMBS concentrations equal to or higher than 100 ppm when membrane cleaning treatments are applied in the desalination plant. Under the conditions evaluated in this study, this influence area was 8 ha, but it can be greater under conditions of low hydrodynamism and fit better with the extent of the bottom area without benthic vegetation within the influence area of the effluent (Portillo *et al.*, 2014a). After the installation of venturi diffusers (Portillo *et al.*, 2013), the dilution capacity of the system was able to maintain the salinity field created by the effluent below 37.3 psu. Only at points closest to the discharge point did salinity increase by 0.7 psu relative to the mean ambient salinity (36.8 psu), which is very low considering that the increment was 8 psu before the installation of the venturi diffuser. Furthermore, spatial gradients of pH and DOsat associated with the brine effluent after SMBS additions during membrane cleaning operations almost disappeared, indicating the effectiveness of this dilution system to mitigate the critical effects of SMBS in the medium.

Results obtained in this study suggest the need to implement effective dilution systems to minimise the environmental impact of brine effluents from desalination plants and their adverse effects on vulnerable marine habitats. In our case-study, and based on the high plasticity of this seagrass species (Olesen *et al.*, 2002), the recovery of environmental conditions might allow the re-colonisation of the brine's influence area by *C. nodosa*, by means of sexual (i.e. seeds) and vegetative (runners) propagation of the neighbouring meadows. Additional experience of the authors concerning the same case-study (unpublished data) demonstrated that *C. nodosa* transplants died when placed within the brine's influence area before the installation of the venturi diffuser system (i.e. without brine dilution), but the transplanted populations survived and even grew following the installation of the dilution system; this experimental evidence supports the hypothesis above, that the effects of the brine effluent on the marine environment (in terms of salinity, pH and DOsat) might be a potential cause of the absence of *C. nodosa*, and that the recovery of this habitat, and the associated community might be possible after the minimisation of such impacts, however, additional experimental study is required, to generalise the findings to other study cases, environmental situations and geographical regions.

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CAPÍTULO 5

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

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

E. Portillo[a,*], G. Louzara[b], M. Ruiz de la Rosa[b], J. Quesada[c], J.C. Gonzalez[d], F. Roque[d], M. Antequera[e], H. Mendoza[a]

[a]Instituto Tecnológico de Canarias, S.A. (Canary Islands Institute of Technology), Playa de Pozo Izquierdo s/n, 35110 Santa Lucía, Las Palmas, Spain; Tel. +34 928 72 75 37; email: eportillo@itccanarias.org
[b]ECOS, Estudios Ambientales y Oceanografía, S.L., C/ Alfred Nobel 31B, 35013 Las Palmas de Gran Canaria, Spain
[c]Canaragua, S.A., Avda. Manuel Hermoso Rojas, 4, 38003 Santa Cruz de Tenerife, Spain
[d]Elmasa Tecnología del Agua, S.A. (Elmasa Water Technology Ltd.), Av. de Tirajana no 39, Edificio Mercurio Torre 2 Sexta Planta 35100, San Bartolomé de Tirajana, Las Palmas, Spain
[e]CEDEX (Public Works Study and Experimentation Centre), Centro de Estudios de Puertos y Costas (Ports and Coasts Study Centre), C/ Antonio López no 81, 28026 Madrid, Spain

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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 ($\geq$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

*Corresponding author.

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CAPÍTULO 6

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

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 ($\geq$ 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.

6.1. 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 (Payo *et al.*, 2010). 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 the receiving environment (Ruiz Mateo, 2007). However, a certain distance from the discharge point, where the movement of the effluent and the associated turbulence collapses, the brine sinks due to its greater density, forming a hypersaline plume that spreads out over the sea floor virtually undiluted (Roberts and Sternau, 1997; Palomar and Losada, 2008). This means that the hypersaline plumes from these discharges spread over large areas (Fernández-Torquemada *et al.*, 2009) and can affect the benthic communities encountered along the way (Einav *et al.*, 2002; Ruiz, 2005; Del-Pilar-Ruso *et al.*, 2007, 2008, 2009; Palomar and Losada, 2008; Riera *et al.*, 2011; Yoon and Park, 2011). 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. The few studies to date have revealed the high sensitivity of marine phanerogam *Posidonia oceanica* (L.) Delile to small increases in salinity (Fernández-Torquemada and Sánchez-Lizaso, 2003, 2005; Sánchez-Lizaso *et al.*, 2008; Ruiz *et al.*, 2009) and the long-term effect on plant vitality (Fernández-Torquemada *et al.*, 2005). Studies undertaken both on site and in the laboratory into the effect of increased brine on *P. oceanica* recommended that salinity should be no higher than 38.5 psu or 40 psu in more than 25 % or 5 % of observations, respectively, in any part of the seagrass meadow (CEDEX, 2003; Sánchez-Lizaso *et al*., 2008).

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 (Einav *et al.*, 2002; Fernández-Torquemada *et al.*, 2003; CEDEX, 2007; Afrasiabi and Shahbazali, 2011).

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 a 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 to 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.

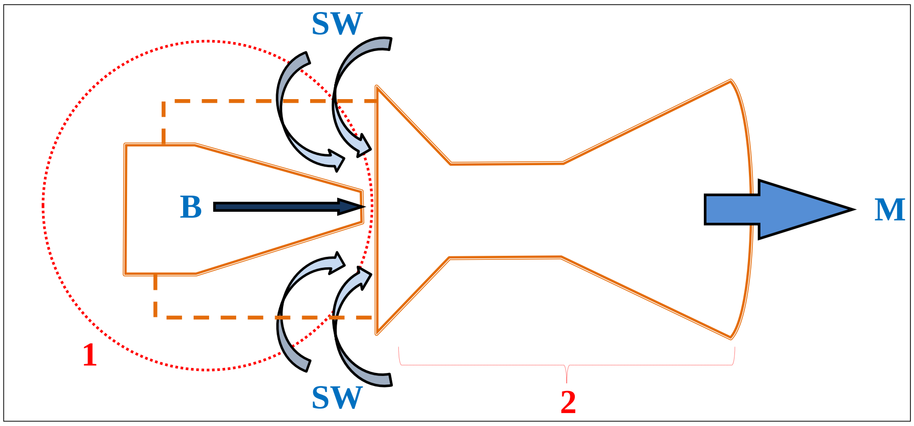


Fig. 1. Venturi eductor: Diffuser system comprising a conventional diffuser nozzle, or reducer nozzle (1), where the exit velocity of the brine discharge increases (B) after attachment of a venturi effect trumpet-shaped structure (2) through which ambient water is suctioned (SW); the mixture emerges 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 (Palomar and Losada, 2011). The US EPA Technical Support Document For Water Quality-based Toxics Control (1991) 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 US EPA (1991) 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 (BOE, 1993) 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 ($\geq$ 69 psu),
- with no diffuser system of any kind,
- over part of the island’s largest and most ecologically important seagrass meadow.

6.2. MATERIAL AND METHODS

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).

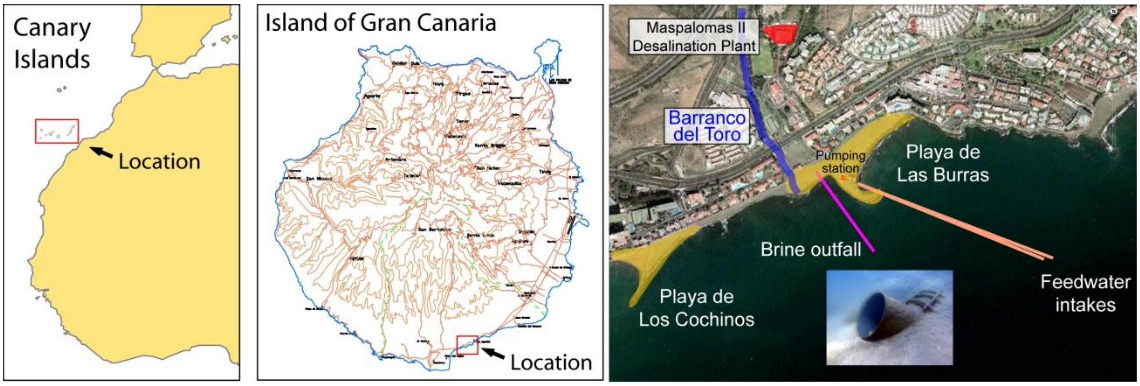


Figure 2. Location of Maspalomas II desalination plant and underwater outfall.

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, 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 feed water) 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, 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 (SCI) under the name of *Sebadales de Playa del Inglés* (Playa del Inglés Seagrass Meadows) - ES7010056 – (OJEC, 2002) and a Special Area of Conservation (SAC) (BOE, 2009). 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 (Espino *et al.*, 2003).

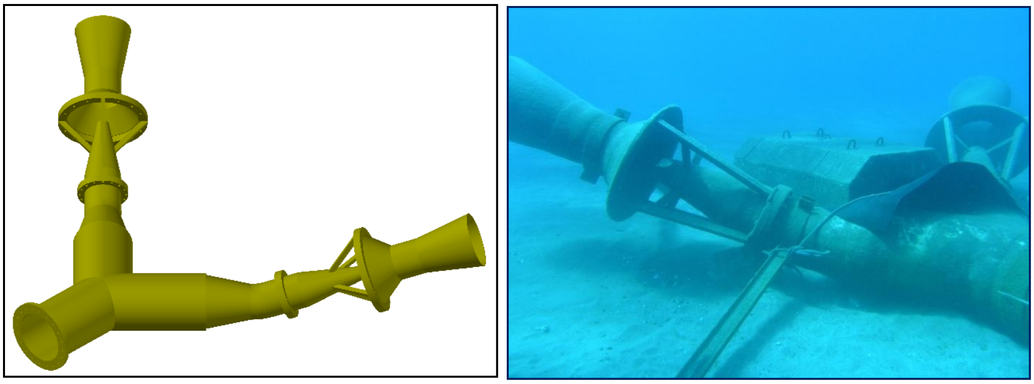
Design and construction of the venturi diffuser system

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 (Jirka, 2008), on the US EPA supported

Cormix Modeling System (Doneker and Jirka, 2007) for near-field mixing predictions, and physical model experiments conducted by CEDEX (2010) 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 mm/400 mm diameter reductions lead off, where the reducer nozzles were inserted (conventional diffusers) (Fig. 3a). 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. 3a and 3b). 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 FRP (fiberglass reinforced polyester) and secured to the sea floor with clamps and mooring blocks (Fig. 3b).



a) b)

Figure 3. Diffuser system with Y bifurcation and 90° aperture from where the two branches decreasing from 600 mm/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.

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.

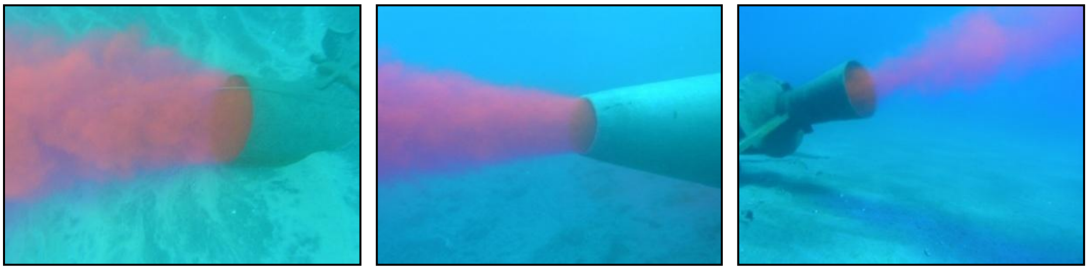
Sampling consisted of characterizing the process of discharge, dispersion and dilution of the discharge system in the near field through three profiles taken at three very significant points representative of this behavior. These were:

- 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 (Photos 1a, 1b, 1c);
  - 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 (Photos 2a, 2b).

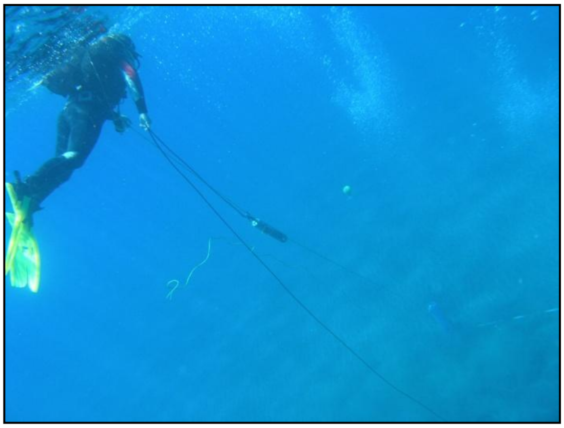


a) b) c)

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

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* (Clesceri *et al.*, 1989). 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 (Lewis, 1980; Unesco, 1981), although they are conventionally presented as practical salinity units (psu). The measuring interval for salinity was 0 to 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 3a). The interval between 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 minutes.

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 (Photos 2a and 2b) 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 2b). 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.



a) b)

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.

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 feed water into the drain from some height. Salinity in the receiving environment was determined by taking discharge samples every 2 minutes 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 the 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 5m 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.

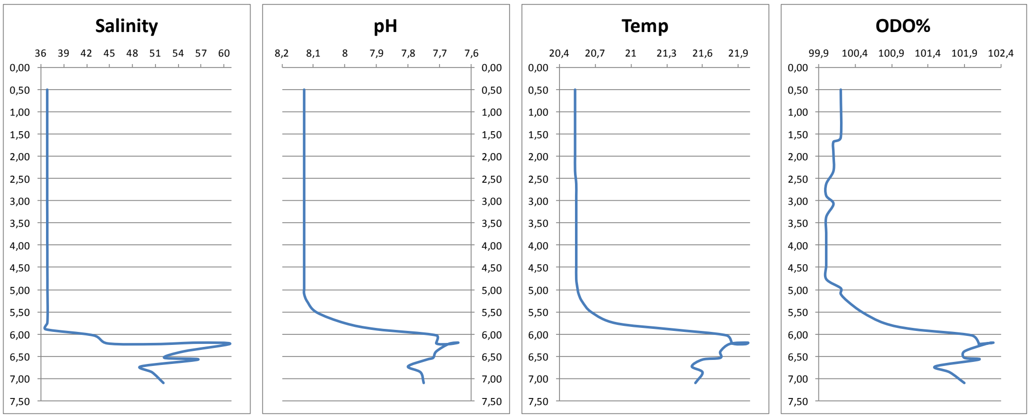
6.3. RESULTS

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 with the venturi eductors 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 eductors. 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 eductors 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 m to 16 m and increasing from 30 m 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 eductors, respectively. The enhanced dilution capacity of the system after 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.

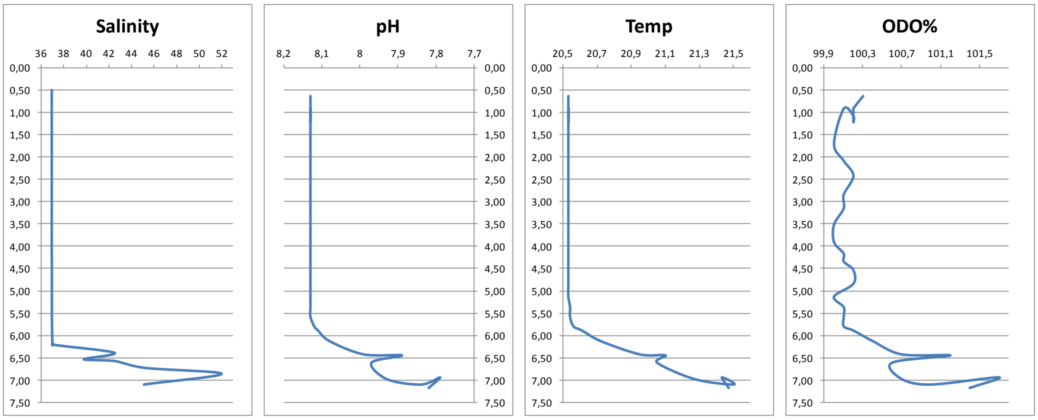
Table 1. Salinity of the brine and its receiving environment; flow and discharge velocity of the brine in the discharge systems studied and dates of sampling; measurements of the distances from the discharge area to the sampling points; respective minimum dilutions and current velocity for profiling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

parameter / discharge system	brine salinity (psu)	sea water salinity (psu)	brine flow (m3/h)	discharge velocity (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

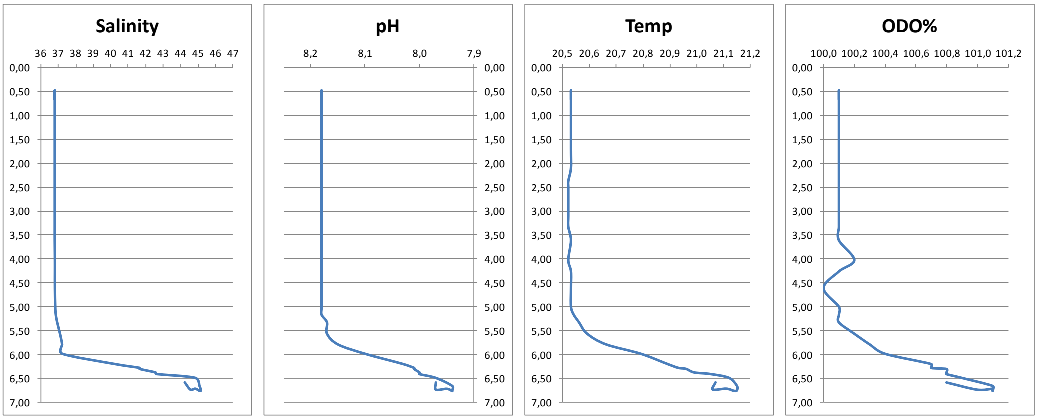
The profiles obtained by the sounder in the water column and at the three sampling points for each discharge system are shown in Fig. 4, where the differences in variation in the profiles on coming into contact with the brine discharge can be seen. For the discharge system with no diffuser system the 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. 4a), 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. 4b and 4c) 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 eductors and a little less for the system with reducer nozzle only. The maximum salinity readings for the eductor 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°C, 0.5, and 2.4%, respectively, these parameters varied less with reducer nozzles only (0.15°C, 0.04°C and 0.6 %), showing almost no variation with the venturi eductors. 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 eductors were 52, 38.16 and 38 psu, respectively.



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

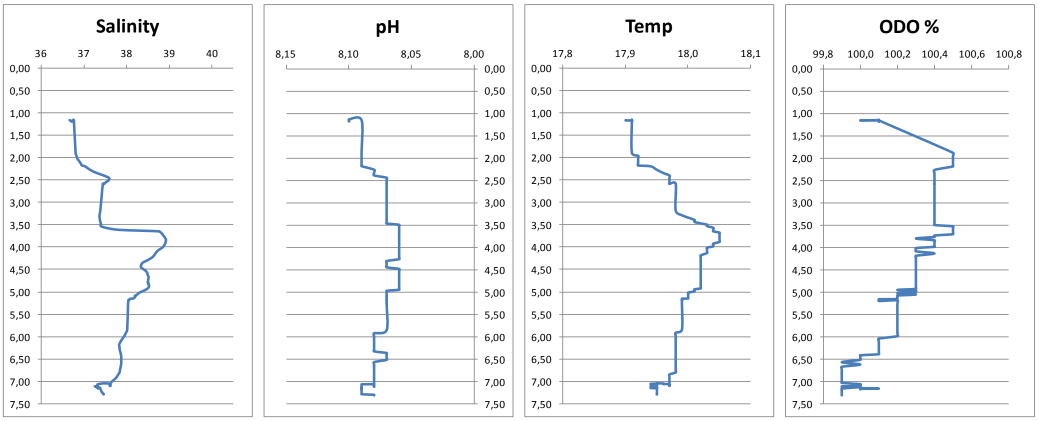


Profile point of impingement 4.5 m from discharge point (no diffuser)

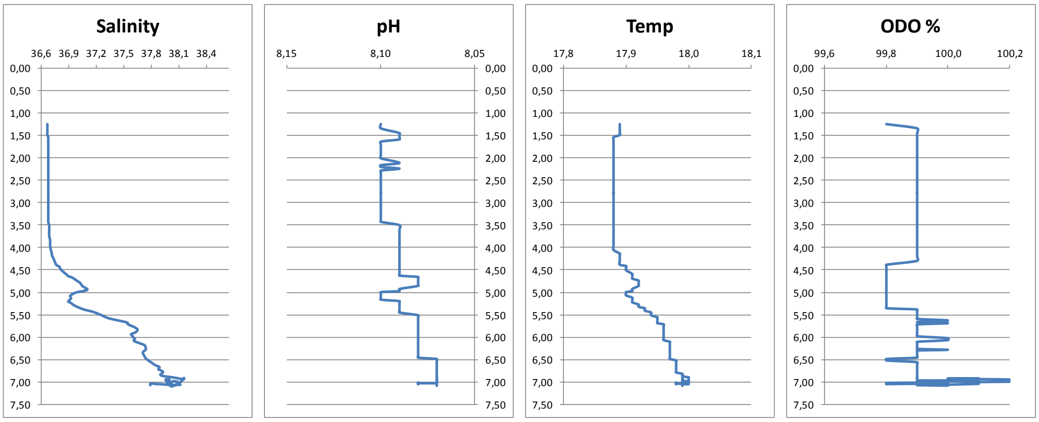


Profile start of the far field 10 m from discharge point (no diffuser)

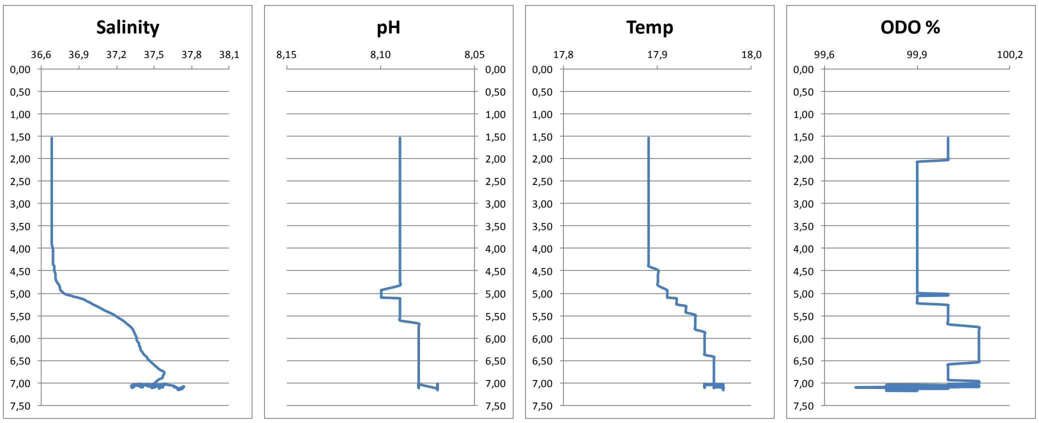
a)



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

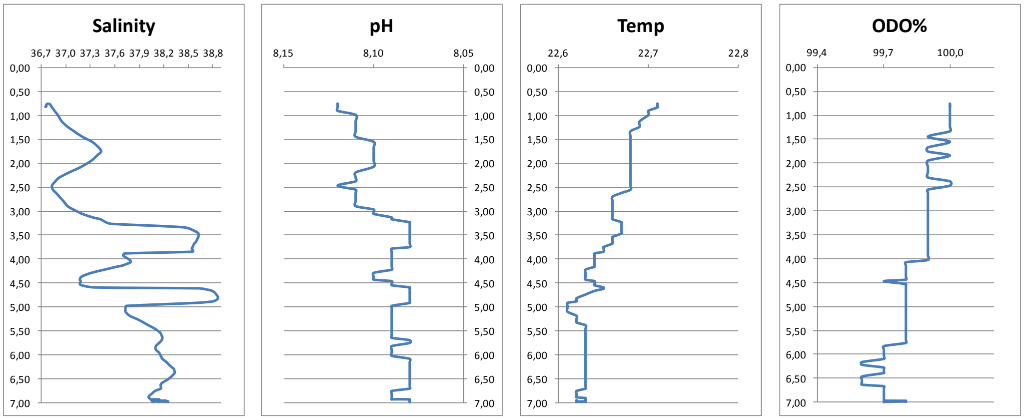


Profile point of impingement 18 m from discharge point (with reducer nozzle)

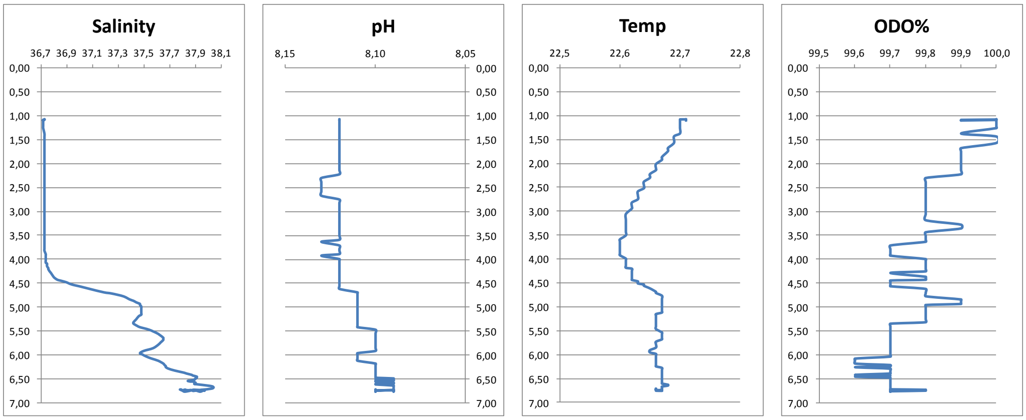


Profile start of the far field 30 m from discharge point (with reducer nozzle)

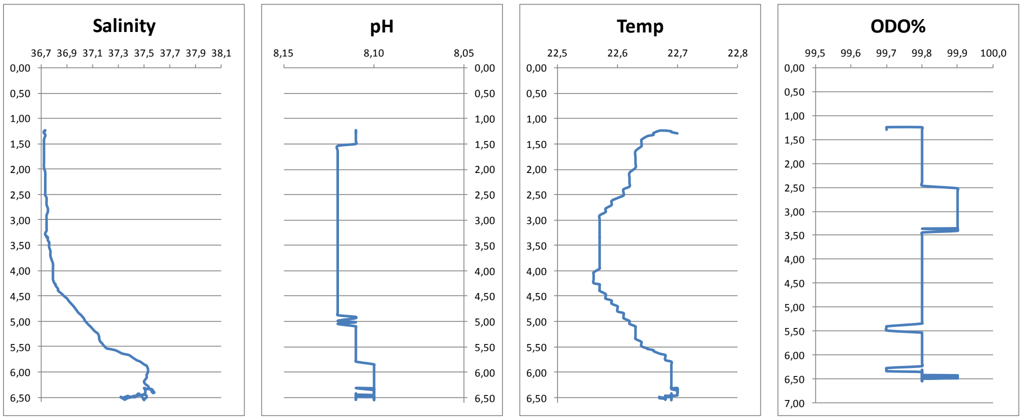
b)



Profile maximum height of rise 10 m from discharge point (venturi eductor)



Profile point of impingement 16 m from discharge point (venturi eductor)



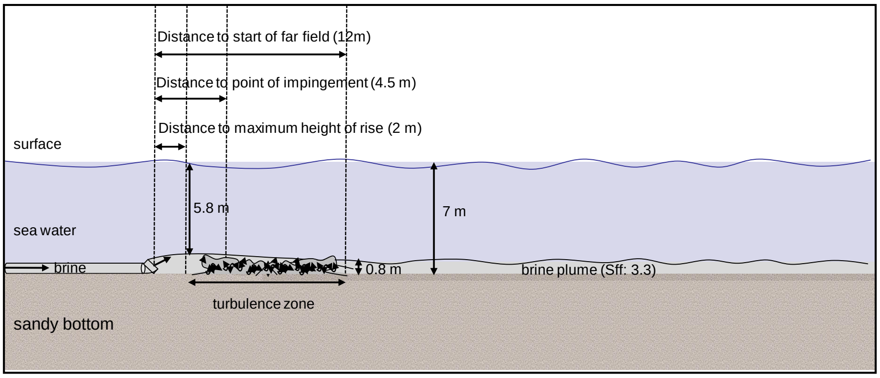
Profile start of the far field 36 m from discharge point (venturi eductor)

c)

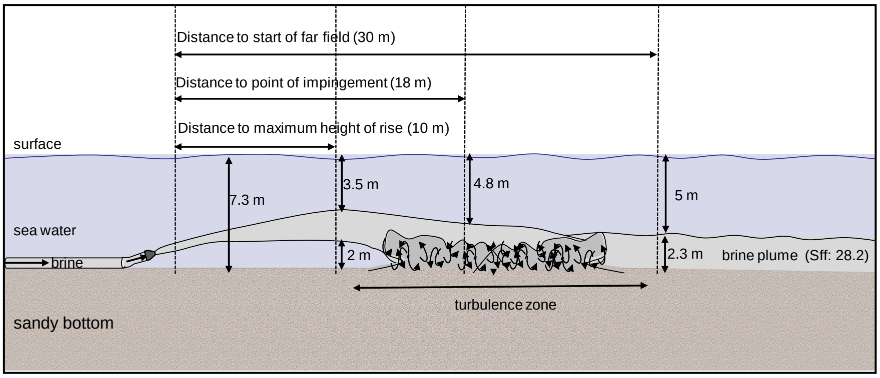
Figure 4. Profiles in the water column of salinity, pH, temperature and percentage of dissolved oxygen saturation obtained with the YSI-6600-V2 sensor at the three sampling points (maximum height of rise, point of impingement and start of the far field) for each discharge system: a) with no diffuser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

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 favourable hydrodynamic conditions; i.e., with much smaller current velocities during sampling.

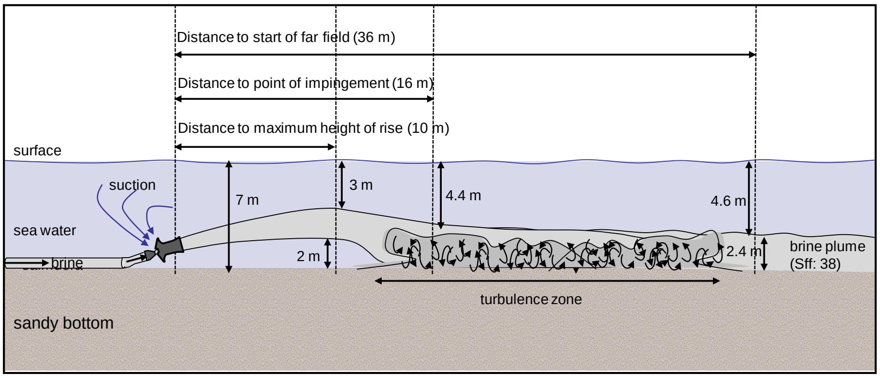
Figure 5 is a scale representation of the longitudinal distribution of the discharge systems based on the site measurements of the distances to the sampling points and on the profiles at these points. The graphical representation shows the difference between their behavior in the discharge, dispersion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



a)



b)



c)

Figure 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.

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 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 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 maximum height of rise 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.

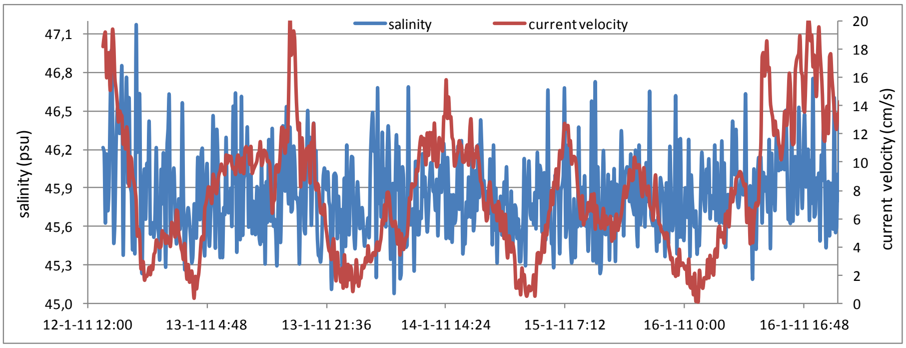
The continuous salinity readings at the start of the far field over several days, including their statistical treatment, are shown in Fig. 6 and Table 2. These dilutions, averaged on the basis of the readings over time, were for the original discharge system, at 3.6 in comparison with dilutions around 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:

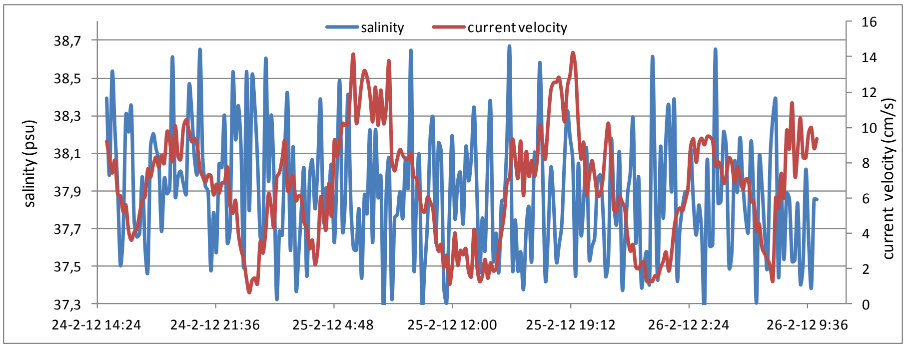
- the high variability of the hydrodynamic exposure the discharge was subjected to in the area near the outflow point; and
- minor fluctuations in exit velocity and salinity.

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.

dyscharge 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



a)



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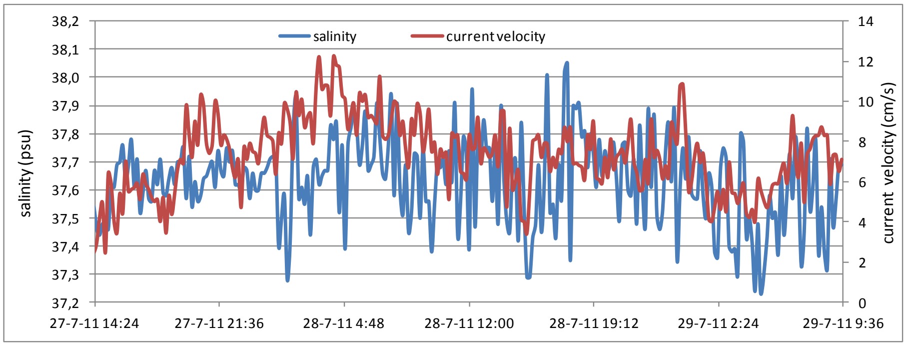

c)

Figure 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.

6.4. 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 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 (US EPA, 1991; Palomar and Losada, 2011). 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 (Palomar and Losada, 2011). 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 eductors. 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 eductors 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 eductors 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 (Portillo *et al.*, 2011), it was formerly colonized by seagrass meadows, as all the adjacent areas are now (Espino *et al.*, 2003; Portillo *et al.*, 2011). 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 eductors 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 minutes. 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 eductors 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 eductors 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 (Jirka, 2008) and in the CORMIX Modeling System (Doneker and Jirka, 2007) 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 minutes. 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 eductors 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;
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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CAPÍTULO 7

DISCUSIÓN GENERAL

7. DISCUSIÓN GENERAL

El registro de la cuantificación de los arribazones de praderas marinas recolectados en determinadas zonas turísticas puede representar una manera muy eficaz de estimar y evaluar la pérdida de plantas marinas de las áreas circundantes, así como el estado de las mismas (en regresión, estable o expansión) (Orth *et al.*, 2006). En muchas de estas regiones costeras se tiende a recoger los arribazones de plantas marinas cuando llegan de una manera masiva para salvaguardar las condiciones higiénico-sanitarias de las playas turísticas, por lo que facilita la posible realización de un registro, control y muestreo de los mismos. Sin embargo, estas recolecciones de los arribazones en las playas constituyen un hábito muy poco respetuoso con el medio ambiente, debido a la gran cantidad de arena que se pierde en dichos trabajos (realizados generalmente con maquinaria pesada) y porque estas acumulaciones naturales favorecen el mantenimiento de la línea de costa reduciendo y amortiguando el oleaje, así como los procesos de sedimentación asociados (Hemminga and Nieuwenhuize, 1990).

Durante el periodo de estudio de la cuantificación y composición de los arribazones en la zona sur de la isla de Gran Canaria (Playa del Inglés y Maspalomas; Enero 2004 - Enero 2007) se determinó que la mayoría del material vegetal presente en los mismos consistió en restos de *C. nodosa*, ya que toda la zona sumergida anexa está conformada por bancos de arena donde se asientan los sebadales más importantes de la isla (Fig. 8).

Los eventos de oleajes considerables que acontecieron en dicho periodo de estudio, mar de fondo del sur (primavera-verano) y mar de viento (invierno; enero-febrero) procedentes de tormentas, coincidieron normalmente con arribazones masivos de sebas los días posteriores. La cantidad de material vegetal acumulado en las playas estuvo relacionado con la energía del evento del oleaje, aunque otros factores pudieron estar envueltos: si otro evento de oleaje similar o mayor aconteció previamente, la cobertura del sebadal en ese momento del año, o si las condiciones hidrodinámicas (corrientes, mareas, tipo de oleaje residual, etc.) durante el proceso o inmediatamente después favorecieron su arribada hacia las playas cercanas o por el contrario hacia las zonas sumergidas (Portillo, 2008). Por esta razón, condiciones de oleajes similares no siempre fueron seguidas por estas acumulaciones de *C. nodosa* en dichas playas (Playa del Inglés y Maspalomas).

La primera consideración que se tuvo en cuenta fue que la diferencia entre el tipo de arribazón (planta entera vs. hoja de muda) podía ser debida a los cambios estacionales en la abundancia y estado de crecimiento de los sebadales. Por un lado, en primavera-verano, cuando los mares de fondo del sur desprenden y arrastran hacia la costa las hojas de muda de los sebadales, en dichas praderas marinas también se está desarrollando el mayor proceso de muda, tras los procesos de enfriamiento del agua y acortamiento de los días durante el invierno, y además comenzando el proceso de producción de hojas nuevas (Reyes *et al.*, 1995; Espino *et al.*, 2006; Tuya *et al.*, 2006). Por otro lado, en invierno, cuando las tormentas ocasionan la pérdida de plantas enteras (hoja verde-fresca junto con rizomas y raíces), los sebadales suelen tener un desarrollo de sus rizomas y raíces más limitado, que podría facilitar el arranque de las sebas (Reyes *et al.*, 1995).

La segunda consideración que estimamos fue la relación existente entre el tipo de oleaje (mar de viento vs. mar de fondo) con su capacidad de arrancar las plantas enteras de raíz de la pradera o de hacer desprender solamente las hoja de muda. La composición del arribazón (planta entera vs. hoja de muda) presentó una clara diferencia según el oleaje incidente (mar de viento vs. mar de fondo) y además fue independiente de la estación del año en que ocurrieron. Los arribazones de plantas enteras aparecieron solamente tras mares de viento, mientras que los arribazones de hojas de muda acontecieron tras los mares de fondo del sur. Los mares de fondo del sur, de muy largo recorrido y con periodos de pico muy altos, alcanzan a sentir fondo sobre profundidades mucho mayores que cualquier tipo de mar de viento (Open University Course Team, 1989) y por consiguiente los sebadales sienten dichos efectos de arrastre sobre un mayor rango de profundidades. Sin embargo, los arrastres en el fondo que produce este tipo de oleaje están más relacionados con movimientos harmónicos y suaves, además de sobre una amplia gama de profundidades altas, denominados monami (Ackerman and Okubo, 1993). Estos movimientos ondulantes producen pequeñas fuerzas de arrastres en el fondo lo suficientemente enérgicas como para conseguir desprender solamente las hojas de muda de la pradera e ir enredándolas en especies de ovillos. Por el contrario, los mares de viento consistieron en un tipo de oleaje más irregular y con periodos más bajos que normalmente interacciona con el fondo en un rango de profundidad mucho menor que el mar de fondo (Airy, 1845). Además, esta zona con un fondo arenoso de tan baja pendiente favorece la velocidad horizontal de fondo bajo la cresta de la ola (Le Roux, 2008). Por otra parte, el paso de este tipo de oleaje procedente de estas tormentas severas, con un marcado efecto entre los ascensos y descensos del nivel del mar (cresta y valle), puede producir grandes diferencias de presión que incrementen las velocidades orbitales de fondo hacia tierra justo bajo la cresta de la ola, y por consiguiente generar procesos erosivos de fondo (Davis and Fitzgerald, 2004) capaces de arrancar las plantas de raíz en estas profundidades más bajas. Por esta razón, los mares de viento tendieron a generar fuerzas de arrastre de fondo turbulentas en profundidades más someras del sebadal, pero capaces de arrancar las plantas enteras de raíz y por tanto producir procesos erosivos en la cobertura del sebadal.

Durante el estudio de las arribadas de este material vegetal a esta zona sur de la isla de Gran Canaria se obtuvo acceso a la información/documentación obtenida del personal del servicio de limpieza de playa que trabajaba en Playa del Inglés y Maspalomas desde 1977 hasta 2007. A través de la misma se detectó una disminución del 90 % de los arribazones de sebas recolectados en estas playas en los últimos 30 años (Portillo, 2008). Esta reducción tan grande pudo haber sido debido a un importante estado de regresión de los sebadales de la zona por el desarrollo insostenible e incontrolado en esta costa durante estos últimos decenios: con vertidos sin la gestión y los procedimientos más adecuados y óptimos, construcciones de muelles, dragados, represa y encauzamiento de los barrancos, etc.

Para determinar el efecto del vertido de salmuera de la planta desaladora Maspalomas II sobre los sebadales de esta zona, se procedió a caracterizar el proceso de dilución y dispersión de su vertido bajo diferentes condiciones hidrodinámicas, así como su influencia e interacción en la distribución de los sebadales de la zona.

Las campañas se realizaron bajo situaciones meteorológicas y oceanográficas habituales, pero con ligeras variaciones de oleaje, viento y mareas. Estas leves diferencias en las condiciones hidrodinámicas determinaron la variabilidad en la intensidad de la corriente de fondo registrada en las diferentes campañas y esta corriente de fondo, a su vez, influyó en el proceso de dispersión de la pluma sobre el lecho marino. Por esta razón, la velocidad de la corriente de fondo sirvió como parámetro de referencia del grado de exposición hidrodinámica del medio receptor para la evaluación de su efecto sobre la dispersión de la pluma de salmuera sobre el lecho marino.

El sistema de vertido de salmuera al mar empleado por esta planta desaladora produjo diluciones muy bajas, con registros de salinidades superiores a 44 psu en todo la zona próxima al vertido. El sistema de vertido de esta planta se comportaba como un simple aliviadero al no contemplar ningún sistema de difusión adecuado, que producía diluciones muy bajas y por consiguiente una pluma hipersalina resultante con un alto grado de estratificación. Los procesos de intercambio y dilución que se producen una vez la pluma hipersalina discurre por el fondo son muy escasos y lentos, por lo que este vertido de salmuera se extendió sobre amplias extensiones afectando a las comunidades bentónicas presentes.

Los estudios de caracterización del recorrido de la pluma hipersalina por el fondo determinaron que las condiciones hidrodinámicas influyeron en las variaciones del alcance de las grandes áreas de afección que se conformaron. Los vertidos de salmuera caracterizados durante las campañas donde las velocidades de corriente de fondo fueron bajas presentaron campos salinos muchos más extensos que las plumas hipersalinas de las campañas donde se registraron velocidades de corriente mayores. El alcance de los campos de salinidades superiores a 38 psu estuvo en consonancia con el devenir de estas velocidades de la corriente de fondo manteniendo una razonable regresión potencial (coeficiente de determinación > 0,9) que podría explicar su relación causa-efecto. Según esta tendencia, la disminución de la zona de afección era en torno al 60 % cuando la velocidad de corriente de fondo aumentaba de 1 a 3 cm/s, mientras que al incrementar de 9 a 11 cm/s existía una reducción porcentual mucho menor, de sólo el 7 %. Este tipo de tendencia potencial nos indicó que un ligero aumento en las velocidades bajas de corriente de fondo tenía una mayor repercusión en la disminución porcentual de las zonas de afección del vertido que entre las velocidades altas. Esta tendencia podría explicarse a través del propio proceso de dispersión de la pluma por el fondo. La pluma hipersalina a medida que avanza se va ensanchando, por lo que disminuye su espesor y el campo de salinidades (Ruiz Mateo, 2007). Por esta razón, los bordes laterales de la pluma hipersalina presentan, por un lado, grosores más pequeños, y por otro, un menor grado de estratificación al presentar salinidades menores. En las situaciones de bajo hidrodinamismo, que correspondieron con velocidades de corriente de fondo pequeñas, no se favoreció la dilución de los márgenes laterales de la pluma por lo que las zonas de afección, correspondientes a la distribución espacial horizontal del campo de salinidades superior a 38 psu, alcanzaron extensiones muy superiores. Sin embargo, un ligero grado de exposición hidrodinámico mayor, que corresponde con velocidades de corriente de fondo un poco más altas, ayudó a mejorar el proceso de mezcla y dilución en los bordes del penacho donde existió un menor grado de estratificación. Por esta razón, un mayor grado de exposición hidrodinámica contribuyó a una mejora del proceso de dilución de los márgenes laterales de la pluma y por consiguiente a reducir la zona de afección (correspondientes a los campos salinos mayores a 38 psu). En la parte central de la pluma o en las zonas correspondientes a campos salinos superiores, ≥ 42 psu, el espesor y el grado de estratificación entre ambas capas fue mucho mayor, por lo que en estas zonas se consiguieron procesos de intercambio y dilución mucho menores aun existiendo altos grados de exposición hidrodinámica.

Los escasos estudios que se han realizado hasta la fecha sobre caracterización de vertidos de salmuera procedentes de plantas desaladoras no han estimado el efecto de las condiciones hidrodinámicas sobre los procesos de dispersión, a excepción del trabajo de Payo *et al.* (2010). En este trabajo se estimó el efecto del oleaje sobre la dilución del vertido de salmuera, pero en un punto fijo de observación y registro de la salinidad de fondo. Este punto estaba localizado dentro de la zona de afección del vertido de las plantas desaladoras Alicante I y II en la costa sureste de la península ibérica (España) y se observó como la acción del oleaje incrementaba, por un lado, las velocidades de corriente de fondo, y por otro lado, los procesos de dilución en dicho punto. Este efecto, del incremento de los procesos de dilución cuando aumentaba la velocidad de la corriente de fondo tras episodios de oleajes significantes, aunque en un sólo punto, coincidió con las observaciones del presente trabajo. En nuestro caso, el incremento de las velocidades de las corrientes de fondo favoreció los procesos de dilución de los márgenes laterales de las zonas de afección y por consiguiente la reducción del alcance de los recorridos de las plumas hipersalinas. En el estudio de Fernández-Torquemada *et al.* (2009) sobre las áreas de influencias que originan los vertidos de distintas plantas desaladoras del sureste de España, Jávea, Alicante I-II y San Pedro del Pinatar, se apreció una variación significativa dependiendo de los diferentes niveles de producción de dicha plantas desaladoras, de las diluciones previas alcanzadas, así como del sistema de vertido (a través de emisario o canal, longitud del emisario y profundidad de vertido, con o sin difusores, etc.). Las caracterizaciones de estas plumas hipersalinas no pudieron ser comparadas con las determinadas en este trabajo por tratarse de vertidos con caudales y salinidades, así como con sistemas de evacuación, diferentes. Sin embargo, el comportamiento de estos vertidos de salmuera fue similar en cuanto a su dispersión por el fondo siguiendo la dirección donde la batimetría incrementaba y respecto a las grandes extensiones que alcanzaron si no se disponía de un plan de gestión y actuación apropiado en el sistema de evacuación (sistema difusor, dilución previa, etc.).

En el trabajo de Talavera y Quesada (2001), donde se estudió anteriormente el alcance de este vertido (planta desaladora Maspalomas II), las condiciones oceanográficas de absoluta calma descritas en su campaña de caracterización de la pluma de salmuera podrían corresponder con un estado de la mar como el acontecido durante el 30 septiembre 2009 del presente trabajo (Capítulo 3). A pesar de estas supuestas condiciones de hidrodinamismo semejantes, las plumas hipersalinas caracterizadas en sendas campañas difirieron completamente. En la distribución espacial horizontal de la salinidad en el fondo de la campaña realizada por Talavera y Quesada (2001) la pluma se distribuyó de este a oeste conformando una mínima zona de afección de apenas una hectárea donde la salinidad superaba en sólo 0,2 psu la salinidad del medio receptor. Por tanto sus conclusiones determinaron que la dilución del vertido era suficiente para no afectar negativamente a las poblaciones de sebadales adyacentes y que en la zona próxima al punto de descarga no se encontraron sebadales, ya que la poca profundidad y las dinámicas marinas impedían su asentamiento. Sin embargo, bajo estas supuestas condiciones oceanográficas semejantes, la pluma hipersalina que se monitorizó en nuestro estudio el 30 septiembre 2009 abarcó una zona de afección para el campo de salinidades superiores a 38 psu de casi 34 ha. Respecto a los sebadales se observó cómo éstos se asentaron a partir de la profundidad del punto de descarga pero a partir de los márgenes que delimitan justamente las zonas de impacto, por lo que ni la profundidad ni las condiciones hidrodinámicas limitaron su asentamiento, sino la pluma hipersalina. En el estudio de Talavera y Quesada (2001) las posiciones de los puntos de muestreo seleccionados quedaron fuera de las zonas de afección del discurrir de la pluma hipersalina. La red de puntos de muestreo de esa campaña consistió en sólo tres transectos, donde se alineaban dichos puntos, que partieron desde la boca del emisario hacia mar adentro y separados entre sí en unos 45°. Los diferentes vertidos caracterizados en nuestro trabajo (Portillo *et al.*, 2014a), que se constituyeron en todos los casos en una pluma de forma alargada, quedaban justamente entre dos de estos transectos, el central y sur. Por esta razón, la red de puntos establecida a través de tres transectos en el trabajo de Talavera y Quesada (2001) excluyó cualquier posibilidad de demarcar, localizar, registrar y caracterizar dichas plumas hipersalinas generadas por el vertido de salmuera. Además, la toma de muestras de dicho estudio se realizó a través de la recogida manual y posterior análisis, por lo que se pudieron producir además medidas de salinidad erróneas, ya que al entrar en contacto la botella de muestreo con la pluma pudo generar perturbaciones y mezcla de ambas capas. Este error se agudiza sobre todo en los márgenes laterales de la pluma, donde el grosor de la pluma es más pequeño, menor a 10 cm, y por el posicionamiento de los transectos de dicho estudio fueron las zonas donde previsiblemente se tomaron las pocas muestras dentro de la pluma hipersalina.

Respecto a la influencia del vertido de salmuera de la planta desaladora Maspalomas II sobre los sebadales del entorno, se determinó que el área de influencia máxima correspondiente a la distribución espacial de los campos salinos mayores a 39 psu de las 8 diferentes campañas realizadas delimitaba la presencia de estas praderas marinas en todas las campañas. Sin embargo, el área de influencia máxima correspondiente a la distribución espacial de los campos salinos mayores a 38 psu de las 8 diferentes campañas realizadas alcanzaba a determinadas manchas de sebadales. Las condiciones hidrodinámicas para uno de estos días de campaña fueron de oleaje y viento insignificante, así como durante mareas cortas, por lo que la velocidad de corriente de fondo resultante fue mucho más baja que para la mayoría del resto de las campañas de caracterización del recorrido de la pluma hipersalina por el fondo, donde existieron condiciones de mayor hidrodinamismo. Esta situación de tan baja exposición hidrodinámica no favoreció los procesos de intercambio y mezcla entre la pluma de salmuera y el medio receptor, por lo que el vertido de salmuera que se caracterizó este día reprodujo el comportamiento de la pluma hipersalina en el caso más desfavorable. Estas condiciones de tan bajo hidrodinamismo, aunque se reproducen con cierta asiduidad, se mantienen en cortos periodos de tiempo y pocas veces al mes, ya que tiene que coincidir con una situación de pantano barométrico, sin ningún tipo de oleaje residual de mar de fondo, durante mareas cortas y en los momentos no coincidentes con los instantes de bajamar o pleamar. Por tanto, dichas manchas de sebadal serían alcanzados con cierta frecuencia, pero en cortos periodos de tiempo, por salinidades de 38 psu, pero no así por salinidades mayores.

Por esta razón el mapa de la distribución de las manchas de *C. nodosa* sugirió que la influencia de la pluma hipersalina pudo ser la causa de la pérdida de una superficie más o menos equivalente de este hábitat en esta zona. La distribución espacial del hábitat obtenida a partir de la cartografía realizada en este trabajo mostró claramente cómo dicha distribución se interrumpió coincidiendo justo en el área de influencia del vertido de salmuera. Por un lado, se dispuso del testimonio de buzos (que instalaron y construyeron el emisario), así como de pescadores locales, que confirmaron la existencia del sebadal antes de la presencia del vertido de salmuera, hace unos 23 años. Por otro lado, a través de pequeños dragados en varios puntos del área de influencia (en ausencia de cobertura vegetal) se constató la presencia de rizomas muertos enterrados bajo la arena, lo que atestiguó que *C. nodosa* colonizaba estas zonas. La presencia de estos restos de sebadal muerto no aportó información alguna sobre el momento de su desaparición y podrían explicarse por causas naturales, pero sería demasiada casualidad que una perturbación natural hubiera actuado en el mismo sitio y en la misma escala espacial que la pluma de salmuera. Así pues, en ese momento se pensó que con muy alta probabilidad la influencia del vertido de salmuera fue la causa de la pérdida total de pradera de *C. nodosa* en un área equivalente a dicha área de influencia. El incremento de la salinidad, el efecto aislado o sinérgico de determinados compuestos procedentes de los tratamientos químicos tanto periódicos como continuos de la planta desaladora, así como variaciones físico-químicas causadas por el vertido en la columna de agua y los sedimentos, son factores que pueden potencialmente causar efectos tóxicos agudos y crónicos, y/o deletéreos, sobre las angiospermas marinas y explicar su desaparición en el área de influencia de la salmuera. Esto fue especialmente obvio en las zonas centrales de la pluma donde la salinidad es muy elevada (≥ 42 psu) con respecto a la salinidad normal a la que están adaptadas estas plantas en este área, que mantiene un valor medio muy constante de 36,8 psu. Sin embargo, la ausencia de *C. nodosa* se observó incluso en zonas del campo salino donde el incremento de salinidad no era tan grande, de tan solo 2,2 psu, lo cual fue un resultado inesperado si tenemos en cuenta que se esperaba que esta especie fuese más tolerante a incrementos crónicos de este tipo respecto a otras especies más vulnerables como *P. oceanica* (Fernández-Torquemada and Sánchez-Lizaso, 2006; Pagès *et al.*, 2010; Sandoval-Gil *et al.*, 2012). Este hecho podría ser explicado, aunque de forma bastante especulativa, de varias maneras como: a) *C. nodosa* tiene mayor capacidad de tolerar a incrementos bajos –moderados de salinidad a corto-medio plazo (días-mes), pero no sería capaz de resistir a los efectos acumulados de exposiciones continuadas o intermitentes durante decenas de años (como en este caso; 23 años), o b) otros factores diferentes de la salinidad que actúen de forma aislada o combinada podrían ser la causa de la toxicidad y muerte de la planta en esta zona, o c) una combinación de lo anterior. En última instancia, la relación causa-efecto entre la presencia o ausencia de sebadal y la salmuera solo pudo establecerse mediante estudios experimentales. Por esta razón se desarrollaron una serie de trabajos mediante diferentes aproximaciones experimentales diseñados para discernir si los cambios en la distribución espacial de la pradera de *C. nodosa* fueron debidos o no a la influencia aguda y crónica del campo de influencia de la salmuera: de laboratorio (algunos resultados pertenecen al Capítulo 5), mesocosmos e in situ (trasplantes; Capítulo 4).

Los ensayos experimentales in situ, que se realizaron con trasplantes en dos zonas impactadas, con salinidades medias de 39 y 40 psu, así como una de control ayudaron a corroborar la hipótesis de que el vertido de salmuera fue la causa de la pérdida total de pradera de *C. nodosa* en un zona equivalente a dicha área de influencia.

Por un lado, los registros de salinidad confirmaron que las zonas seleccionadas para los trasplantes dentro de la zona de impacto coincidieron prácticamente con las salinidades pretendidas, 39 y 40 psu. Tanto los registros continuos durante una semana como las medidas puntuales a lo largo de los seis meses de tratamiento verificaron estas salinidades como promedios. Por otro lado, los resultados obtenidos en estos experimentos de trasplantes (in situ) dentro de esta zona de impacto presentaron una clara disminución del número de haces y de su supervivencia, así como un aumento del porcentaje de necrosis foliar, debida principalmente al efecto negativo producido por la salmuera. Las plantas trasplantadas pudieron tener un periodo de estrés y adaptación añadido y por ende ser más sensibles a cambios bruscos y negativos en su entorno, por lo que se intentó minimizar dichas condiciones seleccionando una correcta época para llevar a cabo el trasplante, una buena ubicación, así como una correcta manipulación de las plantas (Ruiz de la Rosa, 2011). No obstante, mientras que las plantas sometidas a la afección de la salmuera mostraron, tanto en primavera como en verano, una reducción del número de haces total, llegando a reducirse en la zona de 39 psu en casi un 80% y en la de 40 psu en cerca del 90%, las trasplantadas en la zona de control mantuvieron en ambas épocas la supervivencia y aumentaron incluso la densidad de haces con respecto al inicio. Por este motivo, pudimos asumir que la presencia de salmuera con salinidades de 39 psu y 40 psu afectó directamente al comportamiento de la planta. Estos síntomas observados, como la disminución de densidad de haces y de la supervivencia o el aumento de la superficie necrótica en hojas, fueron similares a los descritos por diversos autores cuando las fanerógamas marinas se sometieron a un estrés hipersalino (Fernández-Torquemada *et al.*, 2005, 2011; Marín Guirao *et al*, 2011, 2013; Pagès *et al.*, 2011). Dichos trabajos determinaron estos síntomas en condiciones controladas de laboratorio, tanto para *P. oceanica* como para *C. nodosa*, así como en periodos cortos de tiempo, que fueron de 10 a 17 días, siendo por lo general detectados en *C. nodosa* a partir de 43 psu. En el medio marino, experimentos llevados a cabo con *P. oceanica* en praderas naturales (Gacia *et al.*, 2007; Ruiz *et al.*, 2009), detectaron cambios fenológicos y fisiológicos a partir de concentraciones de 39 psu. Por otro lado, diversos estudios justifican estos cambios fenológicos producidos por el estrés hipersalino a alteraciones en los procesos bioquímicos y fisiológicos de la planta (McMillan and Moseley, 1967; Walker and McComb, 1990; Vermaat *et al.*, 2000; Fernández-Torquemada *et al.*, 2005), como puede ser la capacidad fotosintética (Biebl and McRoy, 1971; Ralph, 1998; Fernández-Torquemada *et al.*, 2005, 2006, 2009; Marín-Guirao *et al.*, 2011), lo que influye directamente en la capacidad de crecimiento.

Este experimento de trasplantes vino a determinar que los niveles de sensibilidad de la planta *C. nodosa* a la pluma hipersalina aumentan en efectos crónicos, es decir a largo plazo. La respuesta negativa que se observó en los trasplantes a salinidades de 39 psu tras seis meses de exposición fue similar a los efectos negativos que se registraron en mesocosmos para la misma especie a partir de 43 psu en un periodo de pocos días (Pagès *et al.*, 2010, Fernández- Torquemada *et al.*, 2011). Además, el buen estado de conservación de los trasplantes en los mismos emplazamientos de la zona de impacto, pero tras la instalación de los eductores venturi, evidenciaron aún más la relación causa-efecto entre el vertido de salmuera y la desaparición de la pradera marina en dicha zona de impacto.

Un estudio reciente sobre el impacto de este mismo vertido, de la planta desaladora Maspalomas II, pero sobre la meiofauna fue también concluyente sobre las consecuencias negativas de la salmuera (Riera *et al.*, 2011). En este estudio se observó alteraciones en los patrones de la abundancia y en las estructuras de las poblaciones de la meiofauna del submareal y fondos arenosos. A 0 m, 5m y 15 m de distancia del punto de descarga existió una menor abundancia en los más destacados grupos de la meiofauna, especialmente nematodos.

En relación al efecto del proceso de limpieza de membranas (de ósmosis inversa) de la planta desaladora Maspalomas II sobre el medio marino, mediante la adición semanal y de choque de SMBS, se determinó que el vertido, en ausencia de sistema difusor, producía un alto grado de acidificación y desoxigenación durante el discurrir de los subproductos de SMBS junto con la salmuera por el fondo marino. Bajo tales circunstancias, el campo salino mayor a 38 psu (con una concentración estimada de SMBS de 50 ppm) abarcó una extensión de 15 ha. Sobre la base de la estrecha relación entre la concentración de SMBS y las variables físico-químicas estudiadas (pH y DOsat) se contaba con un área similar para los campos de pH y ODO de aproximadamente 6,6 y 10% respectivamente. Sin embargo, el área delimitado por estos valores que se registró en el fondo marino era considerablemente inferior (2 ha). Se observó una discrepancia similar entre la distribución del campo de salinidades mayores a 39 psu (alrededor de 8 ha) y los campos de pH y DOsat menores a 6,2 y 1 % (alrededor de 1 ha), respectivamente, correspondientes a la concentración de SMBS mayor a 100 ppm (estimada). Este desacoplamiento entre la concentración de SMBS estimada y su efecto en las variables físico-químicas podría ser explicado por la propia dinámica temporal de los procesos de desoxigenación y acidificación que se produjeron cuando los subproductos de SMBS pasaron por cualquier punto del fondo y del posible efecto dependiente de la concentración. Por lo tanto, cerca del punto de descarga, las altas concentraciones de SMBS ($\geq$ 150 ppm), reaccionaron con el medio casi instantáneamente, por lo que los valores bajos de pH y de DOsat se alcanzaron de inmediato. Sin embargo, en los puntos de muestreo más alejados de la zona de descarga del vertido, donde las concentraciones de SBMS fueron menores, los procesos de desoxigenación y acidificación se producen de una manera más lenta y gradual, de modo que se produjo un retraso entre el momento en que el subproducto de SMBS comenzó a pasar través de un punto y el momento en que el pH y DOsat alcanzaron sus valores mínimos. Por esta razón, es posible que la medición de dichas variables en estos puntos de muestreo no se realizara en muchos de ellos en la fase donde se alcanzan los valores mínimos, sino en un momento previo. Esto podría explicar la escasa correspondencia entre los valores estimados de SMBS y sus efectos sobre las variables físico-químicas descritas anteriormente y sugiere, por consiguiente, que la superficie que abarcaron campos de pH y DOsat pudo haber sido subestimada por nuestro análisis espacial realizado durante la campaña.

Los resultados obtenidos en el bioensayo del pez lagarto (*S. synodus*) mostraron que la mortalidad de todos los individuos se produjo a partir de concentraciones de SMBS iguales o superiores a 50 ppm (es decir, valores de pH y DOsat iguales o inferiores a 6,6 y 10 %, respectivamente). Es ampliamente conocido que la hipoxia y la acidificación más allá de ciertos niveles críticos se vuelven perjudiciales para los organismos acuáticos o incluso letales. Así, por ejemplo, la mayoría de los niveles letales de DOsat para peces se fijan entre un 20 y 40 % (Davis, 1975; Fisher *et al.*, 1992), lo cual es congruente con los efectos letales observados en este bioensayo, así como la presencia de peces muertos en el área de influencia de los campos de salinidad generados por el efluente de salmuera inmediatamente después del tratamiento de SMBS en la planta desaladora. Efectos tóxicos similares asociados a alteraciones ambientales causados por la presencia de este producto químico se han descrito también para otras especies de peces e invertebrados acuáticos (Aragão *et al.*, 2008), junto con otros efectos mutagénicos y genotóxicos (Pagano and Zeiger, 1987; Rencuzogullari *et al.*, 2001; Carvalho *et al.*, 2011; Galli *et al.*, 2012). Además, estos efectos letales ocurrieron muy rápidamente, es decir, dentro de los primeros 10 minutos de exposición, que es un período de tiempo más corto que el de la duración del tratamiento de SMBS en la planta desaladora (40 min) e incluso más breve que la duración de los efectos de subproductos SMBS sobre las variables físico- químicas en un punto dado dentro del área de influencia del penacho de salmuera (por ejemplo, a 250 m del punto de descarga). La observación de individuos muertos de peces lagarto y otras especies características de fondos blandos que se distribuyen por el fondo (*Bothus podas*, *Microchirus azevia* y *Trachinus draco*) se produjeron no sólo en el área de superficie de 2 ha delimitado por los valores DOsat críticos (10 %), sino en un área mucho más amplia, sustentando la hipótesis anterior formulada para explicar las discrepancias encontradas entre la concentración de SMBS estimado y sus efectos esperados en las variables físico-químicas. El efecto de toxicidad del SMBS era tan importante y rápido que limita la posibilidad de que estos peces muertos encontrados fuesen individuos que se escaparon de las áreas más cercanas al punto de descarga donde existían alteraciones medioambientales más severas.

Del estudio previo de dispersión y asentamiento del sebadal se determinó que los sebadales de *C. nodosa* estaban completamente ausentes dentro del área de influencia máxima correspondiente a la distribución espacial de los campos salinos mayores a 39 psu de las 8 diferentes campañas realizadas. Estas salinidades fueron mayores que el límite superior del rango de salinidad natural al que las praderas de *C. nodosa* se adaptan en los espacios naturales que rodean este área de influencia (36,6 a 36,8 psu, Mouree *et al.*, 2008). Estas observaciones, junto con la mayor parte de la evidencia experimental que indica la alta sensibilidad a los aumentos de salinidad de muchas especies de fanerógamas marinas (Fernández- Torquemada and Sánchez-Lizaso, 2005, 2006, 2011; Pagès *et al.*, 2011), sugirieron la hipótesis provisional de que los aumentos de salinidad provocados por la pluma de salmuera pudieron ser un factor clave para explicar la ausencia de *C. nodosa* en el área de influencia de la descarga de salmuera. Resultados obtenidos en el Capítulo 4, así como a partir del bioensayo de *C. nodosa* del Capítulo 5 apoyaron en parte esta hipótesis, ya que en este último caso, la exposición de las sebas (germinadas mediante semillas) a un aumento de la salinidad moderada (es decir, 2,2 psu sobre la salinidad normal de agua de mar) durante un mes, causaba efectos adversos significativos (pero suaves, subletales) en su vitalidad y estado fisiológico, respecto a aquellos cultivados en condiciones normales (es decir, los controles, 36,8 psu). Este resultado también sugiere que este nivel de salinidad empleado en tratamientos hipersalinos debe estar cerca del umbral del límite de tolerancia de esta especie de fanerógama marina, sin embargo esto contrasta con las conclusiones obtenidas a partir de enfoques experimentales similares con la misma especie pero con las poblaciones del Mediterráneo (Pagès *et al.*, 2010; Fernández-Torquemada and Sánchez-Lizaso *et al.*, 2011; Sandoval-Gil *et al.*, 2012a, 2012b). Estos estudios establecieron que las poblaciones de *C. nodosa* del Mediterráneo adaptadas a una salinidad media ambiental de 37 psu son capaces de tolerar aumentos crónicos de salinidad durante un mes (o más) de 41 psu (es decir, 4 psu sobre la salinidad media ambiental) y sin efectos aparentes y significativos en su fisiología, crecimiento y supervivencia. Varios factores pueden explicar esta discrepancia. En primer lugar, existen evidencias de que las poblaciones de las Islas Canarias son genéticamente distintas de las del Mediterráneo (Alberto *et al.*, 2008; Masucci *et al.*, 2012), lo que sugiere una capacidad diferencial para tolerar el estrés hipersalino en poblaciones geográficamente separadas (Touchette, 2007). En segundo lugar, nuestro experimento realizado con poblaciones canarias utilizó plántulas de *C. nodosa* germinadas de semillas, mientras que todos los experimentos del Mediterráneo se realizaron con plantas adultas, es decir, a partir de haces desarrollados en la característica estructura clonal de la pradera marina en su medio natural. Algunos estudios han demostrado la existencia de la diferente sensibilidad a incrementos hipersalinos entre plántulas germinadas desde semillas y estadios adultos de especies de praderas marinas (Tyerman, 1989; Fernández-Torquemada and Sánchez-Lizaso, 2013). En algunas especies, las etapas de plantas jóvenes (semillas y germinadas) mostraron una mayor sensibilidad a las condiciones de estrés que las etapas adultas y por lo tanto la posible influencia de factores ontogénicas no pueden ser descartados para explicar las diferencias observadas en la tolerancia a la salinidad entre éste y otros estudios. Por esta razón, se requiere un mayor esfuerzo en investigación experimental para aclarar el papel de éste y otros factores sobre la tolerancia de esta especie de fanerógama marina a aumentos de la salinidad y para entender su variación intraespecífica.

El bioensayo de *C. nodosa* también mostró que la exposición semanal y a corto plazo (40 min) de las plántulas (germinadas de semillas) a concentraciones de 100 ppm de SMBS era suficiente para causar una reducción significativa en la supervivencia y la vitalidad de la planta. Como se demostró con el pez lagarto, el efecto tóxico de este producto se debe a la reducción crítica tanto del pH como de DOsat, ambos factores ambientales son claves, ya que sus variaciones pueden afectar las funciones fisiológicas fundamentales de las fanerógamas marinas, como la fotosíntesis (Larkum *et al.*, 2006). La severa acidificación del medio puede afectar directamente a la capacidad fotosintética al disminuir la disponibilidad de carbono inorgánico disuelto (Beer *et al.*, 1977; Beer and Waisel, 1979; Invers *et al.*, 1997; Invers, 2001; Fernández-Torquemada and Sánchez-Lizaso, 2003) o al alterar los gradientes electroquímicos y los flujos de protones a través de las membranas tilacoides (Touchette and Burkholder, 2000; Beer *et al.*, 2001). Por el contrario, la ausencia de oxígeno del medio puede modificar la función de carboxilación de la enzima Rubisco (Larkum *et al.*, 2006) y causar más alteraciones en el metabolismo fotosintético. El efecto tóxico de concentraciones similares de SMBS a las empleadas en estos experimentos se ha demostrado también en algas verdes y cianophytas (Singh and Singh, 1984) y se le atribuye no sólo a los efectos mencionados de su capacidad de disminuir el pH, sino también a los daños directos causados por su disociación en productos como HSO_3^- y H_2SO_4.

Además, así como los efectos individuales descritos anteriormente del pH y DOsat sobre la vitalidad de las fanerógamas marinas y su supervivencia, la intensidad de tales efectos tóxicos parece aumentar cuando la adición de SMBS viene acompañada de condiciones hipersalinas, como se sugiere por los efectos más pronunciados en la vitalidad de la hoja (tasa de crecimiento y la proporción de tejidos necróticos) con el producto (SMBS) pero a una salinidad de 39 psu respecto a los efectos observados con una salinidad normal (+ SMBS). Por lo tanto, la hipótesis de que ambos efectos individuales y sinérgicos de aumento de la salinidad y de los subproductos de SMBS son los responsables de la ausencia de sebadales en la el área de influencia del efluente de salmuera es razonable, al menos dentro de la zona delimitada por la isolínea de 39 psu, que a su vez corresponde con concentraciones de SMBS iguales o superiores a 100 ppm tras los tratamientos de limpieza de membranas semanales. Bajo las condiciones evaluadas en este estudio, esta área de influencia era de 8 ha, pero pudo ser mayor en condiciones de bajo hidrodinamismo y coincidir mejor con la extensión de la zona sin cobertura vegetal dentro del área de influencia del efluente.

Después de la instalación del sistema difusor con eductores venturi, la capacidad de dilución del sistema consiguió mantener el campo de salinidades creado por el efluente por debajo de 37,3 psu. Sólo en los puntos más cercanos a la zona de descarga aumentó la salinidad en un 0,7 psu respecto a la salinidad del medio receptor, un incremento muy bajo considerando que anteriormente era de 8 psu. Además, los gradientes espaciales de pH y DOsat asociados con el efluente de salmuera después de las adiciones semanales de SMBS durante las operaciones de limpieza de la membrana casi desaparecieron, lo que indica la eficiencia de este sistema de dilución para mitigar los efectos críticos del SMBS en el medio.

Los trabajos realizados en este estudio sugieren la necesidad de implementar sistemas de dilución eficaces para reducir al mínimo el impacto ambiental de los vertidos de salmuera de las plantas desaladoras y sus efectos adversos en hábitats marinos vulnerables. En este caso, del vertido de la planta desaladora Masplaomas II, y en base a la alta plasticidad de esta especie de fanerógama marina (Olesen *et al.*, 2002), la recuperación de las condiciones ambientales podría permitir la recolonización natural de *C. nodosa* en las antiguas zonas afectadas por la influencia de dicho vertido a través de la propagación vegetativa (runners) de los sebadales anexos o por medio de germinación de semillas. Los resultados de los ensayos experimentales con trasplantes en las zonas de afección, donde los trasplantes morían, mientras que tras la instalación del sistema difusor con eductores venturi sobrevivían, corroboraron aún más la hipótesis anterior: los efectos de los vertidos de salmuera en el medio marino (en términos de salinidad, pH y DOsat) pueden ser una causa potencial de la ausencia *C. nodosa*. Por el contrario, la recuperación de este tipo de hábitats y las comunidades asociadas podría ser posible después de minimizar dichos impactos, sin embargo, se requerirá de estudios experimentales adicionales para generalizar y extrapolar estos resultados y conclusiones.

El sistema de vertido al mar empleado por la planta, previo a la incorporación del sistema difusor, producía, por tanto, diluciones muy bajas en el inicio del campo lejano, menores a 3. Esta baja capacidad de dilución del sistema de descarga de la planta desaladora se debió a no tener ningún tipo de sistema difusor. Los emisarios submarinos suelen requerir de dispositivos difusores para desarrollar velocidades de salida a partir de las cuales se pueda generar una corriente de chorro con suficiente energía cinética que produzca un movimiento parabólico capaz de favorecer los procesos de mezcla asociados a las turbulencias creadas en su recorrido y por consiguiente conseguir la dilución del efluente (US EPA, 1991; Palomar and Losada, 2011). El emisario submarino de la planta desaladora Maspalomas II disponía de un codo dispuesto a 42,5º justo en la boca de salida, pero del mismo diámetro que el emisario (600 mm de Ø) y sin ningún tipo de reducción o dispositivo difusor acoplado. El caudal medio de vertido de la planta desaladora era de aproximadamente unos 1.062 m3/d, por lo que se producían a la salida del codo velocidades muy bajas, en torno a 1 m/s. Esta velocidad tan baja no conseguía conformar casi movimiento parabólico alguno y por consiguiente el vertido de salmuera tras salir del emisario prácticamente no ascendía ($\leq$ 1,2 m) y en menos de 5 m se posaba sobre el fondo. Por esta razón este vertido distaba mucho de un vertido en chorro representativo, al que sí se le puede atribuir como un método eficaz para maximizar la dilución en el campo cercano.

Sin embargo, y a pesar de la bifurcación del caudal en dos vías, las velocidades de salida generadas tras la incorporación de ambos sistemas difusores fueron muy superiores a las velocidades recomendadas (para evitar posibles efectos adversos sobre la vida pelágica de la zona) (Palomar *et al.*, 2011). Los eductores venturi requirieron de estas velocidades de salida, mayores a 11 m/s (nº Froude > 65), para poder alcanzar la diferencia de presión necesaria (Δp > 10 psi) que generase el efecto de succión propio del dispositivo. Por esta razón, para su aplicación técnica conllevó generar estas velocidades muy superiores a las utilizadas habitualmente en cualquier sistema de vertido convencional. No obstante, al añadir la estructura de efecto venturi a la boquilla reductora, la corriente de chorro resultante difirió totalmente. En este caso la salmuera, después de pasar por la boquilla reductora a estas altas velocidades y aproximarse a la estructura en forma de campana/trompeta, se reduce significativamente por el efecto de succión (≤ 3 m/s) y las velocidades de entrada de agua de mar al interior del eductor también mantienen dicho valor. En el interior del eductor las velocidades de la mezcla vuelven a aumentar en la parte más estrecha (entre los dos lóbulos de la estructura de efecto venturi) hasta valores en torno a 6 m/s para volver a disminuir hasta velocidades menores a 3 m/s justo a la salida del mismo (cuando se ensancha de nuevo en el segundo lóbulo). Por consiguiente las velocidades altas que se generan tras la boquilla reductora no impactan directamente sobre el medio marino cuando se incorpora la estructura de succión y las de salida como de entrada se mantienen dentro del rango de las velocidades utilizadas habitualmente con difusores convencionales.

Los procesos de dilución en el campo cercano estuvieron en relación con dichas velocidades de salida altas. En la zona de mezcla, dichos procesos están relacionados con las turbulencias que se generan, tanto con la corriente ascendente y descendente, como tras el impacto del chorro con el fondo. Por tanto, este incremento en la velocidad de salida, que generó un mayor alcance del movimiento parabólico, favoreció los procesos de dilución. En definitiva, el sistema de descarga sin sistema difusor no tuvo suficiente velocidad de salida para comportarse como un vertido en chorro representativo, mientras que con ambos sistemas difusores se produjeron corrientes de chorro de gran alcance y capacidad de dilución reduciendo a casi su totalidad las zonas de afección del vertido. Dichos procesos de mezcla hubieran sido incluso mucho mayores con ángulos de inclinación de los difusores respecto al fondo superiores y más recomendables, entre 45-60°, pero no se pudo incrementar, ya que había que mantener una distancia de seguridad con la superficie por la baja profundidad de la zona de descarga. Las diferencias de la corriente de chorro entre ambos sistemas difusores en cuanto al grosor y alcance del mismo vinieron determinadas por la capacidad de succión y de mezcla del eductor. El eductor tenía una capacidad máxima de succión por efecto venturi de 4 unidades de volumen de agua de mar del entorno por uno de salida de salmuera, por lo que el caudal final a la salida del eductor se pudo hasta quintuplicar. De esta manera se obtuvo un caudal de salida hasta 5 veces mayor, pero con una velocidad y salinidad menor y por consiguiente una corriente de chorro más ancha y con un mayor alcance de la zona de mezcla que para el sistema sin estructura de succión.

Las diluciones alcanzadas con sólo las boquillas reductoras consiguieron una reducción de la salinidad de la salmuera hasta valores máximos de 37,88 psu, mientras que con el eductor venturi se redujeron hasta 37,45 psu. Esta mejora en torno a un 43 % de la eficiencia en la capacidad de dilución de los eductores venturi respecto a los difusores convencionales también es relativa, ya que podría ser mucho mayor. Con los difusores convencionales se debe evitar sobrepasar las velocidades utilizadas habitualmente, menores a 6 m/s, sin embargo con la tecnología venturi se requieren velocidades de salida mayores a 12 m/s, pero se convierten en valores menores a 3 m/s tras salir justo del eductor. Por tanto en una comparativa real con velocidades de salida final tras el difusor convencional dentro del rango de las utilizadas habitualmente (menores a 6 m/s), la capacidad en la mejora de la dilución de los eductores venturi respecto a éstos en este caso sería en torno a un 130 % (y no del 43 %), o sea diluciones mínimas de 2,3 veces superiores a las obtenidas con los difusores convencionales.

Esta mayor dilución fue de gran utilidad y necesaria, ya que el vertido de salmuera de la planta desaladora Maspalomas II, como se ha comprobado a lo largo de los diferentes estudios y trabajos desarrollados en esta Tesis, había hecho desaparecer una parte del sebadal de *C. nodosa* de mayor extensión e importancia ecológica de la isla, en una extensión aproximada de unas 20 ha. Además, dicha zona de afección del vertido, en forma de pasillo alargado, actualmente desprovista de cobertura vegetal, consiguió separar el sebadal completamente en dos, el Sebadal de Playa de Las Burras del Sebadal de Playa del Cochino.

CAPÍTULO 7

CAPÍTULO 8

FUTURAS LÍNEAS DE INVESTIGACIÓN

8. FUTURAS LÍNEAS DE INVESTIGACIÓN

La presente Tesis ha conseguido varios hitos muy importantes (reveladores e innovadores):

- Detectar los efectos crónicos de bajos incrementos de salinidad (≤ 39 psu; ≥ 2,2 psu) en *C. nodosa* a muy largo plazo. Se ha descubierto que aunque esta planta tiene una alta capacidad de tolerar incrementos moderados de salinidad a corto-medio plazo (días-mes), no puede resistir los efectos acumulados de exposiciones continuadas o intermitentes durante decenas de años. Por tanto, estamos ante una conclusión muy importante y diferente a lo esperado, los efectos crónicos a muy largo plazo (de años).

- Identificar los importantes efectos sobre la vida marina bentónica de los subproductos procedentes de los tratamientos químicos de la planta desaladora, en concreto de la limpieza-desinfección de choque y semanal de las membranas de ósmosis. Hasta la fecha no se había evaluado el efecto e impacto de estos compuestos, y siendo tan determinantes en el decaimiento de la vida marina, abre grandes expectativas de nuevos estudios y revisiones en los procesos de regulación y recomendaciones en los procesos de vertido.

- Proponer el uso de los eductores venturi como una alternativa futura que podría reemplazar a los sistemas difusores convencionales de vertidos (tanto de salmuera como de aguas residuales), ya que:

  - ✓ se convertirán en las estructuras idóneas para soportar velocidades muy altas de salida con los consiguientes y correspondientes aumentos de las capacidades de dilución y reducción de los impactos (impensables con los dispositivos convencionales y habituales),
  - ✓ supondrán una mejora de los impactos ambientales en la construcción de emisarios, al simplificar de forma significativa su longitud, reduciendo por tanto la superficie de afección, volúmenes de excavaciones, movimientos de tierra, pero sobre todo los tiempos de ejecución,
  - ✓ representarán una reducción considerable en las inversiones y gastos (hasta del 95 %), tanto por su bajo coste de diseño/fabricación, instalación y mantenimiento.

Sin embargo, lo innovador y revolucionario de estos sistemas difusores con tecnología venturi radicará en su posible aplicación/instalación antes de la zona potencial de los asentamientos de los sebadales, por lo que se requerirá de futuras investigaciones y trabajos experimentales y de demostración para poder generalizar y extrapolar los resultados y conclusiones de esta Tesis, así como de mejoras tecnológicas que garanticen el control del funcionamiento óptimo del sistema difusor.

Por esta razón se hace imprescindible:

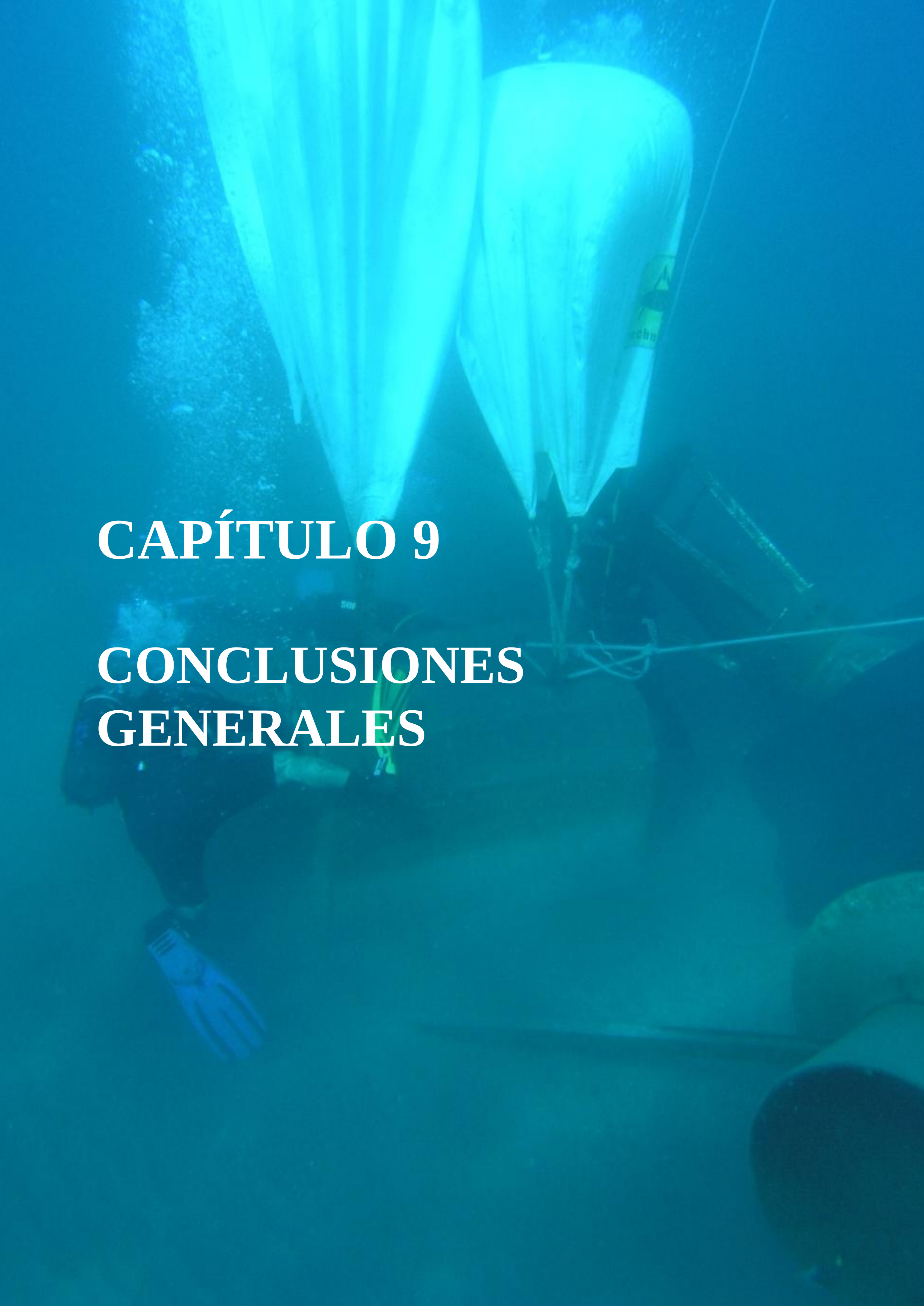
1. Un seguimiento a largo plazo (años) de la recuperación del sebadal afectado por el vertido de la planta desaladora Maspalomas II, tras la instalación de la medida correctora con eductores venturi, para tener una valoración final de la misma.

2. Profundizar en el estudio, con diferentes aproximaciones experimentales (en laboratorio, de mesocosmos, in situ, de campo, …):
   - de los efectos de la salmuera sobre *C. nodosa* (con pequeños incrementos de salinidad pero a medio-largo plazo; los efectos crónicos),
   - del efecto sinérgico y aislado de los diferentes subproductos procedentes de los tratamientos químicos en las plantas desaladoras,
   - de la variación intraespecífica con otras poblaciones (Atlántica vs. Mediterránea).

3. El desarrollo de nuevos estudios experimentales y demostrativos sobre la capacidad de minimización del impacto de esta medida correctora en otras zonas con condiciones similares y distintas tanto del vertido como del ecosistema marino para poder replicar y contrastar los resultados y conclusiones.

4. La puesta en marcha de nuevos desarrollos tecnológicos para la mejora del sistema difusor con eductores venturi. Sería conveniente que este sistema difusor llevase incorporado un sistema en continúo de monitorización de presión que alertase de cualquier desajuste en su funcionamiento, así como de un bypass (offshore, pero con intercomunicación e interaccionado con y desde la planta) que ayudase a liberar la presión en el caso de una avería.

CAPÍTULO 8



CAPÍTULO 9

CONCLUSIONES GENERALES

9. CONCLUSIONES GENERALES

CAPÍTULO 2

1. La llegada de eventos considerables de oleajes a la costa sur de la isla de Gran Canaria fue una condición sine qua non para la aparición de arribazones de sebas en las playas.

2. En primavera y verano, tras el envejecimiento de las hojas y cuando la frecuencia de pérdida de hojas es mayor, los mares de fondo del sur consiguieron hacer desprender las hojas de muda del sebadal; no obstante, estos mares de fondo del sur nunca arrancaron la planta entera de raíz, incluso en otras épocas (es decir, otoño).

3. En invierno, cuando determinadas tormentas esporádicas alcanzaron ocasionalmente la costa sur de la isla de Gran Canaria, el mar de viento de componente sur generado causó el arranque de la planta entera (hoja verde-fresca junto con rizomas y raíces) y acumulaciones de arribazones de la planta entera.

4. Mares de viento procedentes de potentes anticiclones tendieron a arrancar también la planta entera independientemente de la estación del año, sin embargo no llegó a producir acumulaciones de arribazones en la costa.

5. Se estimó que las fuerzas de arrastre de fondo generadas por el mar de fondo del sur, debido a sus características físicas con movimientos ondulantes y harmónicos, tiende a hacer desprender sólo las hojas de muda de la pradera, mientras que el mar de viento procedente de tormentas severas produce movimientos más turbulentos que conllevan a procesos erosivos en el fondo que consiguen arrancar la planta de raíz.

6. El enfoque establecido en el presente trabajo del muestreo de los arribazones recolectados por los servicios de limpieza fue innovador y proveyó una manera muy útil para evaluar la relación entre la exposición de diferentes tipos de oleaje con la pérdida de sebas en el sur de Gran Canaria.

CAPÍTULO 3

1. Los vertidos de salmueras, procedente de una planta desaladora, se conformaron en plumas hipersalinas, que discurrieron por el fondo siguiendo las líneas de máxima pendiente abarcando amplias áreas de influencia bastante variables en su extensión y alcance según las condiciones hidrodinámicas existentes.

2. Se determinaron zonas de afección con campos de salinidades superiores a 38 psu desde 9 a 34 ha aproximadamente, que corresponde a una diferencia máxima de hasta casi el cuádruple.

3. Una mayor velocidad de la corriente de fondo favoreció la dilución de los márgenes laterales de la pluma y por consiguiente la reducción del área de influencia

CAPÍTULO 4

1. El área de influencia máxima correspondiente a la distribución espacial de los campos salinos mayores a 39 psu de las 8 campañas caracterizadas bajo distintas condiciones hidrodinámicas delimitaba la presencia de estas praderas marinas, ya que coincidió con una zona de total ausencia de cobertura vegetal, estableciéndose y asentándose los sebadales a partir de los márgenes externos de esta distribución espacial, por lo que se mostraron indicios de la sensibilidad de *C. nodosa* a estos vertidos.

2. Los resultados de los trasplantes evidenciaron la afección de la salmuera a medio- largo plazo, a partir del segundo mes, y a partir de pequeños incrementos salinos ($\geq$ 2,2 psu).

3. Se detectaron efectos crónicos con bajos incrementos de salinidad ($\leq$ 39 psu) en *C. nodosa* pero a muy largo plazo. Se puso de manifiesto que aunque esta planta tiene una alta capacidad de tolerar incrementos moderados de salinidad a corto-medio plazo (días-mes), no puede resistir los efectos acumulados de exposiciones continuadas o intermitentes durante decenas de años.

4. Tras la incorporación del sistema difusor con eductores venturi los nuevos trasplantes se mantuvieron en un buen estado de conservación en los mismos emplazamientos dentro de la antigua zona de impacto, por lo que se consiguió minimizar el impacto y

además posibilitar de nuevo el crecimiento de sebadales en dicha zona anteriormente impactada.

5. Se recomienda, además de nuevos estudios específicos del impacto asociado a este tipo de vertido y sobre ecosistemas tan sensibles como las fanerógamas marinas, el desarrollo de mejoras tecnológicas de los procesos de descarga, así como apropiados planes de gestión y actuación de los mismos que minimicen las áreas de influencia, así como los impactos asociados.

CAPÍTULO 5

1. El vertido de salmuera, tras el tratamiento de choque de limpieza (desinfección) de membranas con metabisulfito sódico en una planta desaladora, se conformó en una pluma hipersalina con un alto grado de acidificación y desoxigenación, que discurría por el fondo siguiendo las líneas de máxima pendiente abarcando un área de influencia bastante amplio.

2. Se determinó como zonas de afección, tanto de la fauna como flora marina bentónica tras estos tratamientos químicos, la distribución de los campos salinos mayores a 38 psu y 39 psu respectivamente. Estas zonas de afección abarcaron extensiones bastantes amplias, de casi 15 y 8 ha respectivamente, incluso bajo condiciones moderadas de exposición hidrodinámica.

3. Se determinó un efecto tóxico con 100 y 50 ppm respectivamente. Sin embargo, se ha considerado no superar la concentración de 50 ppm como medida de protección y de seguridad, ya que a partir de esta concentración también podría haber efectos tóxicos crónicos sobre *C. nodosa*.

4. La afección de estos vertidos procedentes de la desalación puede ser debida:

   - al efecto tóxico de altas condiciones hipersalinas de la salmuera o crónico por pequeños incrementos salinos,
   - al efecto persistente, aislado o sinérgico con el incremento de salinidad, de determinados compuestos procedentes de los tratamientos químicos tanto continuos como periódicos de la planta desaladora,

- así como a las continúas variaciones físico-químicas que se producen en el proceso de dispersión del vertido por el fondo.

5. Por consiguiente, el efecto

   - de pequeños incrementos salinos,
   - de cualquier compuesto derivado de los tratamientos en la planta desaladora,
   - de las continuas variaciones de la salmuera en un medio marino receptor de una gran estabilidad físico-química,
   - una combinación de las anteriores,

   que no produce efectos negativos en periodos de semanas o meses en el ecosistema marino podría causar efectos tóxicos acumulativos a mayor largo plazo.

6. La medida correctora aplicada consiguió las diluciones necesarias para no superar en ningún punto dicha concentración y reducir por completo las zonas de afección, por lo que se ha garantizado la eliminación del impacto sobre la flora y fauna bentónica de la zona.

7. Este sistema difusor con eductores venturi, al conseguir capacidades de dilución mucho más altas que cualquier sistema difusor convencional, podría suponer en muchas zonas la diferencia entre superar o no el umbral de tolerancia a la exposición de metabisulfito sódico (50 ppm) que afecta tanto a las praderas marinas como a la fauna bentónica.

8. Se identificó el importante efecto sobre la vida marina bentónica de los subproductos procedentes de los tratamientos químicos de la planta desaladora, en concreto de la limpieza-desinfección de choque y semanal de las membranas de ósmosis.

9. Se recomienda la implantación de este tipo de tecnologías en los procesos de descarga, así como apropiados planes de gestión y actuación de los mismos que minimicen las áreas de influencia, así como los impactos asociados.

CAPÍTULO 6

1. El vertido sin ningún tipo de sistema difusor generó diluciones muy bajas por su insuficiente velocidad de salida para poder conformar corrientes de chorro con movimiento parabólico que pudiesen favorecer los correspondientes procesos de dilución.

2. Para velocidades muy superiores a las utilizadas habitualmente en cualquier sistema de vertido convencional, pero necesarias para garantizar la succión propia del dispositivo por efecto venturi:

    - los eductores venturi fueron más eficaces que los difusores convencionales, ya que aumentaban su capacidad promedio de dilución en torno a un 43 % tras la zona de mezcla,
    - en el eductor venturi las altas velocidades de la corriente de chorro a la salida de la boquilla se reducen nada más adentrarse en el interior del eductor, mientras que con el difusor convencional impactan directamente sobre el medio receptor,
    - los eductores venturi, aunque con un mayor caudal final, vierten definitivamente con una menor velocidad y salinidad de salida que los difusores convencionales y dentro del rango de las velocidades utilizadas habitualmente,
    - la mayor capacidad de dilución de los eductores venturi respecto a los convencionales podría suponer en muchas zonas la diferencia entre superar el umbral de tolerancia de la salinidad que afecta a las praderas marinas o no, y por tanto posibilitar o no su asentamiento,

3. Se propone el uso de sistemas difusores con velocidades de descarga muy altas, del orden del doble y triple de las velocidades de salida recomendadas. Esta condición se hace posible, ya que la estructura de succión que conforma el eductor consigue disminuir esta alta velocidad en su interior hasta valores de salida habituales y recomendados para cualquier dispositivo difusor.

4. Los eductores venturi suponen un bajo coste en equipamiento adicional, así como en mantenimiento respecto a las boquillas reductoras convencionales y por tanto, no se entendería un vertido mediante emisario submarino con el uso de velocidades tan altas sin la incorporación de la tecnología de efecto venturi en su sistema difusor.

5. La tecnología de efecto venturi para vertidos mediante emisarios submarinos es viable económicamente y más efectiva que los difusores convencionales, por lo que su implantación podría ayudar a reducir los impactos ambientales de los vertidos de salmuera a un bajo coste de equipamiento, infraestructura y mantenimiento y por tanto ayudar en la mejora de los procesos de vertido en la industria de la desalación.

6. Por lo innovador y revolucionario de estos sistemas difusores con tecnología venturi se requerirá de nuevas investigaciones y trabajos experimentales y de demostración para poder generalizar y extrapolar los resultados y conclusiones de este trabajo, así como de mejoras tecnológicas que garanticen el control del funcionamiento óptimo del sistema difusor.

CAPÍTULO 9

CAPÍTULO 10

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