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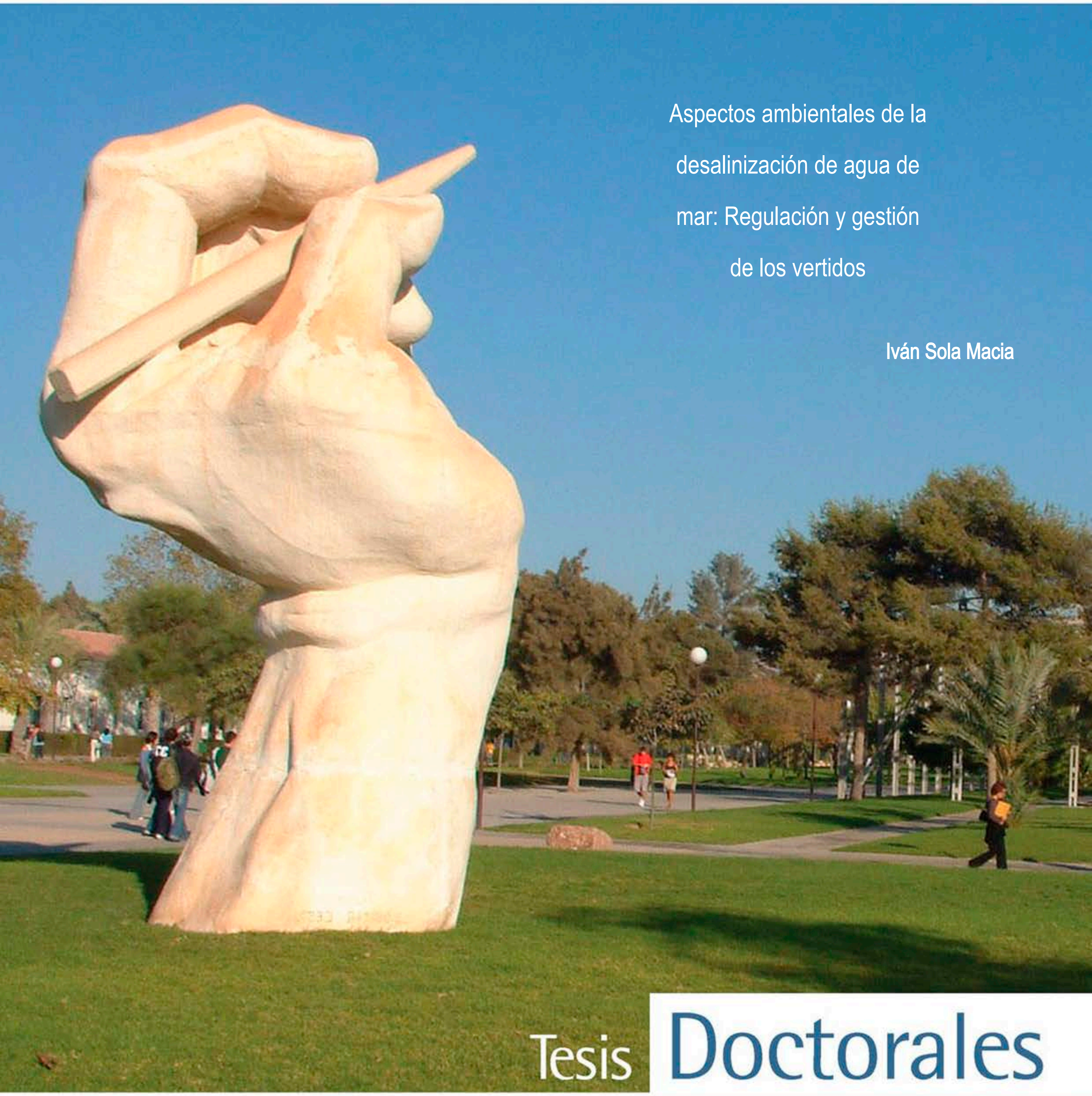

Aspectos ambientales de la desalinización de agua de mar: Regulación y gestión de los vertidos

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Tesis Doctorales
UNIVERSIDAD de ALICANTE

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TESIS EN COTUTELA INTERNACIONAL Y EN COLABORACIÓN CON EMPRESA

Aspectos ambientales de la desalinización de agua de mar: Regulación y gestión de los vertidos

Iván Sola Macia

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AGRADECIMIENTOS

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AEDyR	Asociación Española de Desalación y Reutilización	Spanish Desalination and Reuse Association
CT	Instrumento de conductividad y temperatura	Conductivity and Temperature device
CTD	Instrumento de conductividad, temperatura y profundidad	Conductivity, Temperature and Depth device
EIA/DIA	Declaración de Impacto Ambiental	Environmental Impact Assessment
EIS	Estudio de Impacto Ambiental	Environmental Impact Study
EMP	Programa de Vigilancia Ambiental	Environmental Monitoring Plan
EU	Unión Europea	European Union
GAM	Modelos Aditivos Generalizados	Generalized Additive Model
IDA	Asociación Internacional de Desalación	International Desalination Association
MED	Destilación térmica Multiefecto	Multi-effect distillation
MSF	Destilación térmica Multietapa	Multi-stage flash distillation
RO	Ósmosis Inversa	Reverse Osmosis
SEIA	Sistema de Evaluación de Impacto Ambiental	Environmental Impact Assessment System
SWRO	Ósmosis Inversa de Agua de Mar	Seawater Reverse Osmosis
UAE	Emiratos Árabes Unidos	United Arab Emirates
USA	Estados Unidos	United States of America

RESUMEN

Los vertidos de salmuera generados por las plantas desalinizadoras pueden generar impactos en los ecosistemas marinos cuando no se adopta un correcto proceso de evaluación de impacto ambiental, y/o las medidas preventivas y correctivas implementadas son insuficientes para minimizar dichos impactos negativos. La preocupación por estos aspectos ambientales puede suponer un obstáculo para el desarrollo de proyectos de desalación en ciertos países. El objetivo de la presente Tesis es abordar los aspectos ambientales relacionados con la gestión y regulación de los vertidos de salmuera, para minimizar adecuadamente los efectos producidos por los vertidos de salmuera en los ecosistemas marinos y avanzar hacia el desarrollo de una desalación sostenible. Los resultados obtenidos abordan un estudio de las medidas adoptadas en España (país pionero en el campo de la desalación), que han permitido un desarrollo de la industria de la desalación sin producir impactos significativos en el medio marino, o cuando se han identificado dichos impactos, como se han revertido. Se han evaluado los requerimientos implementados en los programas de vigilancia ambiental que deben garantizar el correcto monitoreo y operación de las plantas desalinizadoras a largo plazo, tomando como referencia España y Chile. Se evaluó un programa de vigilancia ambiental de una planta desalinizadora localizada en una zona de alto valor ecológico, estudiando diferentes indicadores biológicos y físico-químicos a largo plazo, con el fin de estudiar la eficacia de las medidas implementadas en un riguroso proceso de evaluación ambiental en cooperación entre el sector de la industria y científico. Finalmente, se llevó a cabo un análisis global del número de requerimientos implementados en las normativas ambientales, y

que factores, ambientales y socio-económicos, son más limitantes en el desarrollo de proyectos de plantas desalinizadoras. La experiencia obtenida en la presente tesis debería ser considerada en el contexto internacional para reducir correctamente los efectos negativos de los vertidos de salmuera bajo un enfoque integral y científico.

ABSTRACT

Brine discharges from desalination plants can induce several impacts on marine ecosystems when the environmental assessment process is not properly established, and/or the preventive and corrective measures adopted to minimize these negative impacts are insufficient. These environmental concerns may be a barrier for desalination project development in certain countries. The aim of this thesis is to address the environmental aspects regarding the management and regulation of brine discharges, in order to minimize the negative effects from brine discharge on marine ecosystems and to effectively achieve a sustainable desalination development. The results obtained provide a review of the measures adopted in Spain (a desalination pioneer country), which allowed the desalination industry development with no significant impacts on marine environments, or, when these impacts have been observed, how they have been mitigated. The requirements established in the environmental monitoring plans of Spain and Chile for ensuring a proper monitoring and long-term operation of desalination plants were evaluated. A long-term environmental monitoring plan for a desalination plant located in a high ecological value area was assessed, with the aim to analyze the effectiveness of measures established in a rigorous environmental assessment process developed in cooperation with scientific sector. Finally, the number of requirements implemented in environmental regulations and most limiting factors for the successful development of desalination projects in several countries were analyzed. The experience acquired in this thesis should be considered within an international context for managing properly the environmental impacts from brine discharges under a comprehensive and scientific approach.

RESUMEN DE LOS RESULTADOS OBTENIDOS

1. RESUMEN DE LOS RESULTADOS OBTENIDOS

1.1. Antecedentes y justificación

La desalación es una actividad en continua expansión a nivel global, que se presenta como una de las mejores alternativas para proporcionar agua dulce ante la creciente demanda de agua potable en numerosas regiones del mundo. El proceso de desalación consiste en la separación de sales y minerales de un agua con concentración salina para producir agua de calidad para diferentes usos, como el consumo humano, agricultura, actividades industriales, entre otros. La fuente de agua empleada para el proceso de desalación es principalmente agua de mar o agua salobre.

El proceso de desalinización podría ocasionar impactos ambientales en los ecosistemas marinos, ya que la producción de agua dulce implica generar a su vez un vertido de agua concentrado en sales, llamado vertido de salmuera. El vertido de salmuera es principalmente desechado en costa o a través de un emisario submarino en el medio marino, generando impactos en los ecosistemas marinos cuando no se adoptan medidas correctivas y preventivas adecuadas para la mitigación de estos impactos.

El marco regulatorio para la gestión de los impactos ambientales de la desalación desempeña un papel relevante, y cada vez es más exigente en ciertos países. Sin embargo, las exigencias ambientales en los procesos de evaluación ambiental, han sido poco estudiados, y pueden no estar correctamente definidos por las autoridades ambientales, diferir entre proyectos de desalación de características similares y/o ser diferentes entre países. Además, existe un desconocimiento a nivel global de los verdaderos impactos provocados por el proceso de desalación sobre los ecosistemas marinos, especialmente en los países donde la desalación está emergiendo y no se ha implementado una normativa ambiental específica. En algunos casos, este desconocimiento por los impactos ambientales puede suponer un obstáculo al desarrollo de la desalación por la implementación de normativas ambientales muy estrictas.

Por ello, se acentúa la necesidad de evaluar estos aspectos en el contexto internacional, con el fin de garantizar un desarrollo sostenible de la desalación bajo criterio científico-técnico. El desarrollo de esta Tesis tiene como objetivo aportar conocimiento sobre estos aspectos, para evaluar cómo se están llevando a cabo los requerimientos ambientales para la gestión de los vertidos de salmuera, y evaluar qué medidas preventivas y correctivas son adecuadas para avanzar hacia el desarrollo sostenible de la desalación a nivel global.

Esta Tesis doctoral se ha presentado a través del formato por compendio de publicaciones. De acuerdo a las directrices establecidas por la Universidad de Alicante para la elaboración de Tesis doctorales por compendio de artículos, esta Tesis está organizada en cuatro secciones. La sección I contiene el Resumen de los principales resultados obtenidos en la Tesis, incluye la Introducción General y Objetivos, la sección II presenta los artículos publicados, la sección III presenta los artículos no publicados, y la sección IV incluye la Discusión General y Conclusiones.

1.2. Principales resultados obtenidos de los capítulos presentados:

A continuación, se presentan los principales capítulos presentados en esta Tesis doctoral:

1.2.1. Capítulo 1. Revisión de la gestión de los vertidos de salmuera en España

Sola, I., Zarzo, D., Carratalá, A., Fernández-Torquemada, Y., de-la-Ossa-Carretero, J.A., Del-Pilar-Ruso, Y., Sánchez-Lizaso, J.L., 2020. Review of the management of brine discharges in Spain. Ocean Coast. Manag. 196.https://doi.org/10.1016/j.ocecoaman.2020.105301

La desalinización de agua de mar se encuentra en continuo desarrollo para suministrar agua dulce a las regiones costeras con déficit hídrico. El desarrollo de esta industria conlleva un incremento del número de efluentes de salmuera que afectan a los ecosistemas marinos locales, y pone de manifiesto la importante necesidad global de minimizar el impacto asociado en el medio marino. En el

presente estudio se llevó a cabo una revisión de las medidas adoptadas para gestionar los impactos de los vertidos de salmuera en España, a través del análisis de la literatura publicada, documentos no indexados y datos empíricos de campo, obtenidos del seguimiento ambiental de varias plantas desalinizadoras. Se han identificado diferentes estudios mostrando los efectos negativos producidos en las comunidades marinas y cómo se han mitigado. La aplicación de este conocimiento ha facilitado el desarrollo del sector de la desalación en España sin impactar significativamente en el medio marino o, cuando se ha identificado, diseñar estrategias para revertirlos. La cooperación entre la industria y los científicos ha sido un factor crucial para conocer y minimizar los impactos de la desalación. La aplicación de programas de seguimiento ambiental ha proporcionado además importantes herramientas para identificar y corregir los posibles impactos de los efluentes. Por lo mismo, el caso de estudio España puede servir de referencia para el desarrollo sostenible de la desalación en otras zonas del planeta donde el seguimiento ambiental es aún limitado.

1.2.2. Capítulo 2. Evaluación de los requerimientos ambientales para la gestión de los vertidos de salmuera en España

Sola, I., Zarzo, D., Sánchez-Lizaso, J.L., 2019. Evaluating environmental requirements for the management of brine discharges in Spain. Desalination 471, 114132. https://doi.org/10.1016/j.desal.2019.114132

La actividad de desalación puede tener un impacto perjudicial en el medio marino, causado principalmente por los vertidos de salmuera. El objetivo de este trabajo es evaluar la calidad de los Programas de Vigilancia Ambiental (EMP) de las plantas desaladoras en España, y los aspectos que podrían mejorarse para gestionar correctamente los vertidos de salmuera. Se han revisado un total de 30 proyectos de desalación sometidos a Declaración de Impacto Ambiental (EIA) entre 1998 y 2009. Los resultados mostraron un aumento de los requerimientos y sus diseños de muestreo en el tiempo para la monitorización de los vertidos de salmuera para garantizar una mayor protección del medio marino. Sin embargo, esta tendencia es similar para la inclusión de descriptores no asociados con los efectos producidos de un vertido de salmuera. La presencia de especies protegidas en el área de los vertidos de salmuera mostró un aumento significativo del número de requerimientos exigidos en el EMP. Sin embargo, no se observó un aumento de los requerimientos en relación con el aumento de la capacidad de producción de los vertidos de salmuera. En conclusión, sería aconsejable una revisión de las EIA para unificar los requerimientos a nivel nacional, que incluya una mejora de los diseños de muestreo, los descriptores esenciales cuando están ausentes, y eliminar aquellos innecesarios cuando están presentes, ya que generan costes económicos añadidos sin justificación de una mayor protección ambiental. Esta homogeneización debería prestar mayor atención a las plantas desalinizadoras con mayor producción, ya que pueden tener una mayor influencia en ecosistemas costeros.

1.2.3. Capítulo 3. Evaluación de los requerimientos establecidos en los programas de vigilancia ambiental usados para evaluar los impactos ambientales de las plantas de desalación en Chile

Sola, I., Sánchez-Lizaso, J.L., Muñoz, P.T., García-Bartolomei, E., Sáez, C.A., Zarzo, D., 2019. Assessment of the requirements within the environmental monitoring plans used to evaluate the environmental impacts of desalination plants in Chile. Water (Switzerland) 11, 1–17. https://doi.org/10.3390/w11102085

La desalinización de agua de mar representa una solución alternativa para afrontar el reto de la escasez de agua en Chile. Sin embargo, la incertidumbre respecto a los potenciales impactos ambientales de las plantas desalinizadoras representa una barrera para lograr disponibilidad de agua y el desarrollo socioeconómico en Chile. Este estudio tiene como objetivo evaluar la calidad de los EMPs y determinar los aspectos a mejorar dentro de los mismos, con el fin de mejorar la gestión de las plantas desaladoras durante la fase de operación y garantizar un desarrollo sostenible de esta industria. Se revisaron las EIAs y los Estudios de Impacto Ambiental (EIS) de proyectos de desalación de agua de mar publicados en el Sistema de Evaluación de Impacto Ambiental (SEIA) en Chile entre 1997 y 2018. Los resultados mostraron un aumento significativo de la producción de salmuera de las plantas desalinizadoras en la última década (alrededor de 1,6 Mm^3 anuales estimados según los proyectos aprobados o en ejecución). Los EMPs mostraron una heterogeneidad entre proyectos de similares características, y se observó un aumento de los requerimientos a lo largo del tiempo, lo que puede atribuirse al esfuerzo gubernamental por mejorar la protección del medio ambiente. Además, se observó un elevado número de descriptores innecesarios en los EMP. En conclusión, se recomendaría estandarizar los requerimientos ambientales incluidos en los EMPs de Chile de acuerdo al mejor conocimiento científico existente.

1.2.4. Capítulo 4. Desalación sostenible: monitoreo a largo plazo de un vertido de salmuera en el medio marino

Sola, I., Fernández-Torquemada, Y., Forcada, A., Valle, C., Del-Pilar-Ruso, Y., González-Correa, J.M., Sánchez-Lizaso, J.L., 2020. Sustainable desalination: long-term monitoring of brine discharge in the marine environment. Marine Pollution Bulletin 161. https://doi.org/10.1016/j.marpolbul.2020.111813

El desarrollo de un proyecto de desalación puede ocasionar un impacto ambiental en los ecosistemas costeros. La preocupación por el impacto ambiental representa en algunos países un obstáculo para el desarrollo sostenible de la industria. En el presente estudio se muestran los resultados de un EMP a largo plazo, para monitorizar el vertido de salmuera de una planta desalinizadora situada en una zona de alto valor ambiental en España. Se llevaron a cabo Modelos Aditivos Generalizados (GAM) para analizar los parámetros biológicos de las comunidades biológicas. Los resultados de 17 años de seguimiento ambiental del vertido de salmuera, muestran cómo se puede minimizar su impacto ambiental a través de una toma de decisiones correctamente planificada entre científicos y la industria. La dilución del vertido de salmuera previamente a su vertido a un canal artificial de bajo valor ecológico, redujo significativamente el área de influencia de la salmuera en el ecosistema marino. La producción de haces de *P. oceanica* y la abundancia de equinodermos fueron relativamente estables a lo largo de las series históricas, y se observaron valores similares entre las áreas control y el área de impacto. Sin embargo, se demostró que una adecuada gestión del vertido de salmuera, adoptando medidas de prevención y mitigación, resultó en una mayor abundancia y riqueza de especies de peces en la zona de vertido respecto las áreas control. Los resultados obtenidos en el presente estudio deberían considerarse en proyectos de similares condiciones para garantizar el desarrollo sostenible de la desalación a largo plazo.

1.2.5. Capítulo 5. Evaluación de los requerimientos ambientales y socio-económicos para mejorar el desarrollo de la desalación

Sola, I., Sáez, C., Sánchez-Lizaso, J.L., 2021. Evaluating Environmental and Socio-Economic Requirements for Improving Desalination Development. Under Review.

El continuo incremento global de la demanda de agua dulce pone de manifiesto que la tecnología de desalinización es una de las alternativas más factibles para hacer frente a la escasez hídrica en numerosas regiones del mundo. El desarrollo de plantas desalinizadoras ha sido más alto en algunos países respecto a otros, y esto podría indicar que ciertos aspectos socio-económicos y/o ambientales pueden desempeñar un papel relevante en el desarrollo de proyectos de desalación. En el presente estudio, se llevó a cabo una encuesta internacional a expertos en el campo de la desalinización, con el fin de evaluar los principales requerimientos y los factores limitantes que afectan al desarrollo de proyectos en diferentes países a partir de un análisis semicuantitativo. Los resultados obtenidos mostraron una alta heterogeneidad en los requerimientos ambientales y socio-económicos entre los distintos países evaluados. Los principales obstáculos identificados para el desarrollo de proyectos de desalinización fueron el coste de la producción de agua potable, el escaso apoyo financiero y los estrictos requerimientos medioambientales. Se observó que la aceptación social de los proyectos de desalinización es normalmente alta y no representa un factor limitante para su desarrollo. Se identificaron bajos requerimientos medioambientales y/o de participación pública en algunos países. Los conocimientos obtenidos en esta investigación pueden servir de base para el asesoramiento científico en los países que requieran una mejora en los aspectos ambientales o económicos, y para avanzar hacia un desarrollo sostenible de la industria de la desalación.

INTRODUCCIÓN GENERAL Y OBJETIVOS

2. INTRODUCCIÓN GENERAL

2.1. Desalación: Contexto y desarrollo global

La desalación es una actividad en continua expansión global, ya que es una de las alternativas más viables para solventar el continuo incremento de la demanda de agua dulce en numerosas regiones del mundo (Aguilera et al., 2019; Eke et al., 2020; Hernández-Sánchez et al., 2017; Jones et al., 2019). El proceso de desalación (Fig. 2.1.), consiste en la separación de sales y minerales a partir de la captación de fuente de agua de mar o agua salobre para obtener un agua dulce de calidad (Mezher et al., 2011). Actualmente, la principal fuente de agua empleada a nivel global por las plantas desalinizadoras es el agua de mar, representando el 57% de la capacidad de producción instalada (Eke et al., 2020).

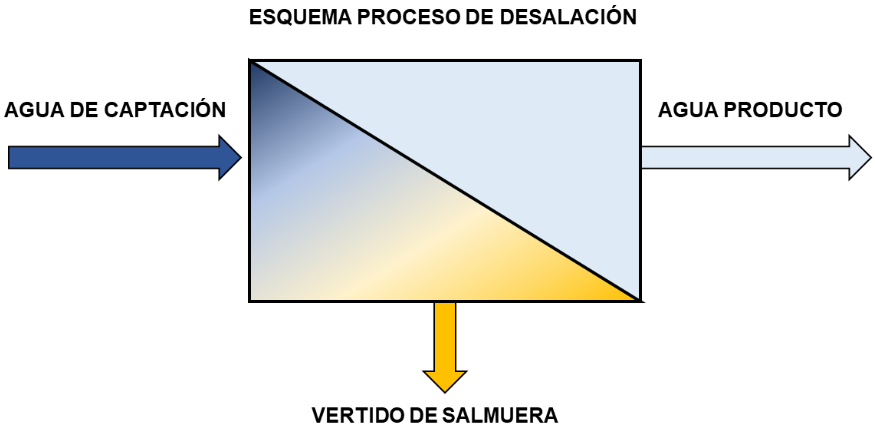

Figura 2.1. Esquema resumen del proceso de desalación (realizado por autor).

El incremento de la demanda de agua global depende de diferentes factores, pero principalmente se debe al crecimiento de la población y al desarrollo económico de los países. Sin embargo, se espera que otros factores, como el cambio climático, afecten significativamente a los recursos hídricos en ciertas regiones del mundo (Bonelli et al., 2014; Hoekstra, 2014; Jones et al., 2019; Sun et al., 2019). En la última década, los proyectos de desalación han aumentado notablemente en todas las regiones del mundo, aunque la mayor capacidad de producción se encuentra principalmente en el Golfo Pérsico, Mar Rojo y costa mediterránea (Jones et al., 2019). Actualmente se han instalado más de 17.000 plantas de desalinización en todo el mundo, representando una capacidad de producción de más de 99 millones de m^3/día. Sin embargo, la capacidad de producción difiere entre los distintos países y regiones, representando la región de Oriente Medio un 39% del total de la capacidad de producción instalada (Eke et al., 2020; Jones et al., 2019).

La desalación proporciona suministro de agua dulce para diferentes usos, destacando la producción de agua para el consumo humano, industria (ej. centrales eléctricas, mineras, refinerías), turismo, agricultura, entre otras (Eke et al., 2020). Ante este contexto de demanda global de agua dulce, la industria de la desalación representa una de las alternativas más plausibles para la mitigación de la escasez hídrica en regiones altamente afectadas (Eke et al., 2020; Gude, 2016; Jones et al., 2019; Shahzad et al., 2017).

Los plantas de desalación pueden dividirse de acuerdo a la tecnología comercial de desalación empleada, estas se pueden dividir en dos grandes grupos: desalación por membranas y desalación térmica (Eke et al., 2020; Mezher et al., 2011; Zarzo and Prats, 2018). La desalación térmica utilizando la destilación multietapa (MSF) y destilación multiefecto (MED) suministra actualmente alrededor el 25% del total de la capacidad de producción, aunque fue la tecnología que dominaba entre los años 1950 - 1970. La desalación por membranas mediante Ósmosis Inversa (RO) representa actualmente un ~ 69% de la capacidad global instalada, siendo la tecnología más empleada globalmente debido a su mayor eficiencia energética y, por tanto, menor coste en la producción; esto ha favorecido la expansión global de la RO comparado con la desalación térmica (Elsaid et al., 2020a; Jones et al., 2019; Mezher et al., 2011; Miller et al., 2014; Qasim et al., 2019; Zarzo and Prats, 2018). Por otra parte, se encuentran las tecnologías de desalación emergentes, que principalmente se llevan a cabo en plantas de investigación y desarrollo representando aproximadamente el 2% del total de la capacidad de producción instalada (Eke et al., 2020; Elsaid et al., 2020a). Ante la creciente demanda de agua global y por su mayor eficiencia energética, se espera un aumento sustancial de la producción de agua desalada dominado principalmente por la tecnología de Ósmosis Inversa de Agua de Mar (SWRO) (Eke et al., 2020; Jones et al., 2019; Shahzad et al., 2017).

2.2. Características de los vertidos de salmuera

El proceso de desalación consiste en la separación de sales de una disolución acuosa para obtener agua dulce a partir de una fuente de agua de mar o salobre; y a su vez, se genera un vertido de rechazo llamado **vertido de salmuera** (Lattemann et al., 2009; Mezher et al., 2011). Los vertidos de salmuera pueden desecharse a través de diferentes métodos de rechazo como: vertido en la red de aguas residuales, vertido en costa, técnicas de evaporación del vertido, inyección en pozos profundos, entre otros (Giwa et al., 2017; Missimer and Maliva, 2018; Panagopoulos et al., 2019). Aunque, el método más común empleado es desechar los vertidos de salmuera al mar en costa (Fig. 2.2) o mediante un emisario submarino debido a su cercanía a costa, ya que supone el menor coste energético-económico respecto a los otros métodos (Fernández-Torquemada et al., 2019; Mezher et al., 2011; Missimer and Maliva, 2018; Panagopoulos et al., 2019).

Figura 2.2. Vertido en costa de las SWRO de Alicante I y II en la costa de Alicante (foto tomada por autor)

Las características de los vertidos de salmuera dependen de diferentes factores, como la tecnología de desalación empleada, salinidad y calidad del agua captada, productos y procesos llevados a cabo durante las fases de pretratamiento, limpieza de filtros y membranas, entre otros (Fernández-Torquemada et al., 2019; Lattemann and Höpner, 2008; Panagopoulos and Haralambous, 2020). Los vertidos de salmuera de las plantas SWRO, se caracterizan principalmente por una alta concentración de salinidad que puede duplicar la salinidad del agua de mar captada tras el proceso (Abessi, 2018; Mezher et al., 2011). Este incremento de la salinidad respecto al agua captada confiere a los vertidos de salmuera una mayor densidad respecto a la densidad de agua de mar, y cuando estos son rechazados al mar forman una pluma salina muy densa que avanza siguiendo la línea batimétrica del fondo hasta que se diluye por completo (Fernández-Torquemada et al., 2009; Loya-Fernández et al., 2018; Palomar et al., 2012). La distribución de la pluma salina puede depender de diferentes características, como la capacidad de producción de la planta, la tasa de conversión del proceso de la tecnología empleada, el método de vertido, las condiciones oceanográficas del punto de vertido, entre otros (Abessi, 2018; Fernández-Torquemada et al., 2019; Fernández-Torquemada et al., 2009; Portillo et al., 2014a).

Los vertidos de salmuera de las plantas térmicas se caracterizan principalmente por ser efluentes salinos, pero con una concentración mucho menor a la obtenida en el proceso de las plantas SWRO. Además, representan un incremento de la temperatura ambiente que puede oscilar entre 5 – 25 ºC (Lattemann and Höpner, 2008; Panagopoulos et al., 2019). En la Tabla 2.1 se resumen las principales características de los vertidos de salmuera en función de la tecnología de desalación empleada.

Tabla 2.1. Resumen de las principales características de los vertidos de salmuera en función de la tecnología empleada para la captación de agua de mar (Elsaid et al., 2020a; Jones et al., 2019; Lattemann and Höpner, 2008; Mezher et al., 2011; Panagopoulos and Haralambous, 2020).

	Ósmosis Inversa	**Térmica**
Tasa de conversión promedio (%)	42 - 45	22
Salinidad (psu)	60 - 85	Incremento del 20 – 50 %, dependiendo de la tecnología de evaporación empleada
Cloro	Neutralizado antes de entrar en contacto con las membranas	~ 10-25%, si el agua captada no está neutralizada
Temperatura (ºC)	0 – 2.5	5 - 25
Oxígeno disuelto	Igual o ligeramente más bajo	Puede ser muy bajo respecto al agua de mar
Métales pesados	Podría contener niveles bajos de Cr, Fe, Mo y Ni si se emplea equipamientos con acero inoxidable de mala calidad	Puede contener concentraciones de Cu y Ni si se emplea equipamiento inadecuado en los intercambiadores de calor. Podría contener Fe, Mo y Cr si se emplea equipamientos con acero inoxidable de mala calidad
Elementos químicos	Pretratamiento, limpieza de filtros y membranas	Pretratamiento

Además, los vertidos de salmuera pueden contener residuos químicos que provienen de los productos empleados durante la fase de pretratamiento, productos empleados durante la limpieza de filtros y membranas durante el proceso de RO, productos químicos empleados como inhibidores para reducir la corrosión de equipos metálicos en plantas térmicas, entre otros. Estos incluyen el uso de: i) antiincrustantes para incrementar la solubilidad de sales poco solubles; ii) antifouling, coagulantes y floculantes para eliminar las partículas en suspensión; iii) ácido y base para regular el pH; iv) agentes oxidantes o cloro para prevenir el crecimiento de comunidades bacterianas en el proceso de desalación; v) agentes reductores para eliminar el impacto de los agentes oxidantes en las membranas; vi) el uso de agentes de limpieza como antiespumantes y biocidas; que son desechados junto al vertido de salmuera y podrían añadir toxicidad al vertido (Agus and Sedlak, 2010; Chang, 2015; Fernández-Torquemada et al., 2019; Lattemann and Höpner, 2008; Liu et al., 2013; Mezher et al., 2011; Panagopoulos and Haralambous, 2020; Portillo et al., 2014b). La Tabla 2.2 presenta los principales elementos o productos químicos empleados durante el proceso de desalación en función de la tecnología de desalación empleada, y si estos podrían estar presentes en el rechazo junto al vertido de salmuera.

Tabla 2.2. Resumen de los principales elementos químicos empleados durante el proceso de desalación y su presencia en los vertidos de salmuera en función de la tecnología empleada para la captación de agua de mar (Missimer and Maliva, 2018; Panagopoulos et al., 2019; Voutchkov, 2017).

Sustancias químicas	Ósmosis Inversa	Térmica
Antiincrustantes	Podrían estar presentes sustancias poliméricas (polifosfatos, fosfonatos y ácidos policarbónicos). Se pueden emplear productos químicos adicionales para tratar otros elementos.	No están presentes
Coagulantes	Podría estar presente cloruro férrico ($FeCl^3$), sulfato de hierro ($Fe^3(SO^4)^3$) y polielectrolitos.	No están presentes
Floculantes	Polímeros catiónicos	No están presentes
Ácido/Base	Se emplea ácido sulfúrico y ácido clorhídrico. No están presentes, reacciona con el agua de mar para dar lugar a compuestos inofensivos y el ácido es consumido de manera natural.	Se emplea ácido sulfúrico y ácido clorhídrico. No están presentes, reacciona con el agua de mar y forma compuestos inofensivos. El ácido es consumido de manera natural.
Agentes oxidantes (Cloro)	No está presente. Neutralizado antes de entrar a las membranas.	~ 10-25%, si el agua captada no está neutralizada.
Agentes reductores	Bisulfito (HSO_3^-). No están presentes.	No están presentes
Agentes de limpieza	El uso de detergentes, biocidas e hidrocarburos halogenados. Podrían estar presentes.	El uso de inhibidores de la corrosión como los detergentes. Podrían estar presentes.

Además, algunos autores describen que los vertidos de salmuera podrían contener trazas de metales pesados que provienen de la corrosión de ciertos elementos metálicos durante el proceso de desalinización, los que se desecharían junto al vertido de salmuera (Alshahri, 2017; Lattemann and Höpner, 2008). Sin embargo, el control de estos elementos es más importante en plantas térmicas donde predominan materiales con aleaciones de cobre y níquel, ya que se necesitan materiales que resistan las altas temperaturas de funcionamiento durante el proceso de desalación (Tabla 2.1). Específicamente, las trazas de metales pesados como el cobre y níquel en las plantas térmicas podrían estar presentes cuando las aleaciones de estos metales en los intercambiadores de calor y bombas se desgastan (Lattemann and Höpner, 2008; Panagopoulos and Haralambous, 2020). Los componentes empleados durante el proceso en las plantas con tecnología de RO son dominados por componentes no metálicos y aceros inoxidables, ya que temperaturas de funcionamiento más bajas permiten la construcción de plantas de desalación con revestimientos más resistentes a la corrosión (Elsaid et al., 2020a; Lattemann et al., 2009; Lin et al., 2013; Panagopoulos et al., 2019; Zhou et al., 2013). Por lo tanto, los valores de concentración de metales pesados en los efluentes de plantas de RO son muy inferiores a los niveles de toxicidad aguda para generar impactos ambientales en los ecosistemas marinos (Gheorghe et al., 2017; Panagopoulos and Haralambous, 2020; Zhou et al., 2013).

2.2. Impactos ambientales asociados a los vertidos de salmuera y captación de agua de mar

Los efectos potenciales de los vertidos de salmuera representan el impacto ambiental más importante asociado al desarrollo de plantas de desalación (Heck et al., 2018, 2016). Las características de los efluentes de salmuera (Tabla 2.1 y 2.2) inducen diversas alteraciones en los ecosistemas marinos cuando no se adoptan medidas adecuadas, afectando principalmente a la abundancia y diversidad de las comunidades bentónicas presentes en el área de afección del vertido de salmuera (De-la-Ossa-Carretero et al., 2016c; Del-Pilar-Ruso et al., 2009; Petersen et al., 2018a; Roberts et al., 2010; Sharifinia et al., 2019).

Entre los efectos estudiados hasta la fecha en los ecosistemas marinos, los vertidos de salmuera de las plantas SWRO pueden tener un potencial efecto en **ecosistemas claves** o prioritarios como las praderas marinas de *Posidonia oceánica* o *Cymodocea nodosa* en el mar Mediterráneo o *Posidonia australis* en Australia, afectando negativamente a sus tasas de crecimiento, tasa fotosintética, supervivencia, potencial osmótico, densidad y cobertura, entre otros factores (Cambridge et al., 2017; Fernández-Torquemada and Sánchez-Lizaso, 2011; Gacia et al., 2007; Garrote-Moreno et al., 2014; Marín-Guirao et al., 2013; Ruíz et al., 2009; Sánchez-Lizaso et al., 2008; Sandoval-Gil et al., 2012). Se ha identificado una reducción de la abundancia de organismos bentónicos sensibles a incrementos de salinidad como los equinodermos (ej, *Echinaster sepositus* o *Holothuria* spp) o alteraciones en la diversidad y abundancia de las comunidades de fondos blandos (ej. Polychaeta o Amphipoda) presentes en el área de vertido (De-la-Ossa-Carretero et al., 2016b, 2016c; Del-Pilar-Ruso et al., 2015, 2009, 2008; Fernández-Torquemada et al., 2013; Ferrero-Vicente et al., 2011). Se han evidenciado efectos tóxicos sobre peces de fondo causados por cambios en las características físico-químicas (ej. pH y oxígeno disuelto) en el área de vertido de salmuera durante los períodos de limpieza de membranas (Portillo et al., 2014b, 2013).

Recientes estudios destacan que los efluentes pueden tener un efecto negativo sobre la diversidad, crecimiento y abundancia de las comunidades de bacterias de los fondos bentónicos (Belkin et al., 2017; Frank et al., 2019, 2017). Además, estos podrían tener un efecto negativo en la fisiología de arrecifes de coral (*Stylophora pistillata*, *Acropora tenuis* o *Pocillopora verrucosa*) aumentando el blanqueamiento del coral y afectando a la abundancia de bacterias y algas simbióticas asociadas (Lykkebo et al., 2018; Röthig et al., 2016). Otros estudios recientes destacan una deterioración de la tasa fotosintética y un aumento del estrés oxidativo en algas pardas (*Ectocarpus* sp.) que fueron trasplantadas a un área de vertido de una SWRO (Rodríguez-Rojas et al., 2020). Finalmente, otros autores sugieren que los vertidos hipersalinos podrían tener un posible impacto sobre las comunidades de zooplancton y larvas de peces, ya que podrían alterar al crecimiento y supervivencia de ciertas especies, aunque es necesario evaluarlo con más estudios de campo o laboratorio (Petersen et al., 2018a; Sharifinia et al., 2019).

La captación de agua de mar puede representar otro impacto en los ecosistemas marinos asociados a las plantas de desalación. El proceso de captación de agua de mar a través de tomas abiertas o emisarios sumergidos en la costa puede afectar succionando a los pequeños organismos marinos como el plancton, huevos de peces y larvas debido a su pequeño tamaño y limitada capacidad de movimiento, induciendo a la mortalidad al llegar al proceso de prefiltración (Missimer and Maliva, 2018; Petersen et al., 2018a). Además, estos métodos de captación de agua de mar aportan valores más altos de partículas en suspensión como materia orgánica, nutrientes y microorganismos que implican el uso de pretratamientos más agresivos y una mayor frecuencia de limpieza de membranas, que son desechados junto al vertido de salmuera, implicando una mayor toxicidad del vertido (Fernández-Torquemada et al., 2019; Panagopoulos and Haralambous, 2020; Sharifinia et al., 2019).

2.3. Procedimientos de regulación ambiental

Los efectos negativos de los vertidos de salmuera sobre los ecosistemas marinos se han observado principalmente cuando no se ha llevado a cabo un riguroso proceso de **evaluación ambiental**, y/o las medidas de mitigación al proyecto de desalinización son insuficientes o incorrectamente aplicadas (Belatoui et al., 2017; Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2013). Para gestionar los impactos ambientales asociados a la implementación de un nuevo proyecto de desalación, estos deben someterse previamente a un proceso de evaluación de impacto ambiental (Fuentes-Bargues, 2014; Kress, 2019a; Lattemann and Höpner, 2008; Sadhwani Alonso and Melián-Martel, 2018). Sin embargo, este proceso de evaluación ambiental no se lleva a cabo en todos los países donde se desarrolla la desalación y/o los requerimientos exigidos durante el proceso de evaluación ambiental pueden ser diferentes entre países (Capítulo 5).

El proceso de **EIA** se establece como la herramienta legal de gestión más importante dentro de la regulación ambiental, para prevenir y/o adoptar medidas de mitigación adecuadas para minimizar el impacto medioambiental del desarrollo de un proyecto o infraestructura, entre los que se incluyen los proyectos de desalación (Elsaid et al., 2020b; Heck et al., 2018; Lattemann and Höpner, 2008). Este incluye una serie de herramientas administrativas y estudios de evaluación ambiental para identificar los posibles impactos ambientales asociados a las plantas de desalación, con el fin de adoptar medidas preventivas, correctivas y de seguimiento ambiental en el medio marino (Fuentes-Bargues, 2014; Liu et al., 2013; Sadhwani Alonso and Melián-Martel, 2018).

El proceso de EIA está regulado legalmente de acuerdo a la legislación de cada país. En el caso de España, el proceso de EIA fue regulado por la normativa europea de acuerdo a la Directiva 85/337/EEC (European Union, 1985). Esta ley fue traspuesta por diferentes leyes, y actualmente está regulada por la Directiva 2014/52/EU (European Union, 2014). Además, el proceso de EIA está regulado por la normativa nacional que traspone la normativa europea de la Directiva 85/337/EEC (European Union, 1985) por el Real Decreto 1302/86 y desarrollado por el Real Decreto 1131/88 (Spanish Government, 1988, 1986). Actualmente, este último decreto se ha traspuesto en única regulación desarrollado por la Ley 21/2013 (Spanish Government, 2013). Los proyectos en España que están sujetos a someterse al proceso de EIA son los que su actividad se encuentra en la lista del Anexo I del reglamento vigente o si está en la lista del Anexo II, y la autoridad ambiental requiere de un proceso de evaluación ambiental. Los proyectos de desalación con capacidades de producción (o ampliación de las existentes) a 3000 m^3/día están sujetos a someterse al proceso de EIA como se específica en el Anexo II, dado que pertenecen al Grupo 8, Sección E: Proyectos de Ingeniería y Gestión del Agua. Finalmente, las Comunidades autónomas están también capacitadas para desarrollar sus propios procedimientos para el desarrollo de un proceso de evaluación ambiental, y pueden proporcionar a los proyectos de desalación una autorización de vertido para poder desechar el vertido de salmuera al mar bajo una serie de requerimientos exigidos al proyecto específico (Fuentes-Bargues, 2014; Sadhwani Alonso and Melián-Martel, 2018; Sadhwani et al., 2005). En Fuentes-Bargues (2014) se puede encontrar una descripción más detallada y normativas traspuestas del proceso de evaluación ambiental en España para el desarrollo de un proyecto de desalación.

En el ámbito internacional, en el caso de Australia, el proceso de EIA está regulado bajo la Sección 46 de la Ley de Desarrollo del 1993. De acuerdo a cada proyecto de desalación existen tres niveles de evaluación, la EIA, el Informe Público de Medio Ambiente y el Informe de Desarrollo. Para el desarrollo de una nueva propuesta, el Ministro de Planificación declara la propuesta de desarrollo para iniciar el proceso habitual de evaluación ambiental, el cual corre a cargo de los promotores. La propuesta presentada por los promotores estará sometida a observaciones y comentarios públicos, y una vez abordadas se presenta la EIA final al Ministro de Planificación. La evaluación se realizará a través del organismo gubernamental que desarrolla el proceso de evaluación ambiental, el cual presentará un informe de evaluación para su autorización. Finalmente, el Gobernador del Gabinete del Estado adoptará una decisión final de acuerdo al informe final obtenido. Además, en el caso de las plantas de desalación, una vez aceptada la fase de EIA deberán someterse a una licencia de explotación negociada entre los promotores y la Autoridad de Protección Ambiental del Estado (Kämpf and Clarke, 2013).

En Chile, el proceso de EIA para la evaluación ambiental de los proyectos de desalación comenzó en el año 1997, regulado por el SEIA que forma parte del Ministerio de Medio Ambiente (Lacy et al., 2017). De acuerdo a las características de los proyectos de desalinización, estos pueden ser evaluados de acuerdo a dos niveles: el proceso de EIA, que afecta a los proyectos que tienen una menor complejidad y/o posible menor impacto medioambiental negativo; y los sometidos a EIS, que corresponde a proyectos de mayor envergadura y/o mayor impacto negativo en el medio ambiente (de la Maza, 2001; Lacy et al., 2017).

Por otro lado, dentro del proceso de EIA se implementan los **EMPs,** con el fin de evaluar la eficacia de las medidas preventivas y correctivas establecidas durante el proceso de EIA y garantizar la operación de las plantas desalinizadoras sin producir impactos ambientales significativos. La identificación temprana de impactos en el medio marino permite adoptar medidas de mitigación para minimizar estos efectos negativos cuando son necesarias (Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2013; Sadhwani Alonso and Melián-Martel, 2018). El coste y responsabilidad de la ejecución de los EMPs corre normalmente a cargo de los operadores de las plantas de desalación, que deben presentar a las autoridades competentes el informe de vigilancia ambiental cumpliendo con todos los requerimientos exigidos en el EMP. Los EMPs establecen una serie de requerimientos de obligado cumplimiento que están principalmente relacionados con la monitorización de los vertidos de salmuera, para identificar si ocurren efectos negativos, de manifiesto en variables biológicas y físico-químicas (De-la-Ossa-Carretero et al., 2016b; Sadhwani Alonso and Melián-Martel, 2018). Además, los EMPs también podrían incluir una serie de requerimientos relacionados con la vigilancia de los efectos de la captación de agua de mar y/o requerimientos relacionados con impactos ambientales en el medio terrestre (Capítulo 1 y 2).

2.4. Objetivos

El objetivo principal de esta Tesis consiste en abordar e integrar los aspectos ambientales relacionados con la **gestión y regulación** de los vertidos de salmuera, con el fin de minimizar correctamente los efectos negativos producidos por los vertidos de salmuera en los ecosistemas marinos y avanzar hacia el desarrollo de una **desalación sostenible**.

A continuación, se presentan los objetivos específicos evaluados en esta investigación:

1. Revisión de las medidas adoptadas y conocimientos adquiridos para gestionar los impactos ambientales de los vertidos de salmuera, usando como modelo a España, país pionero en el desarrollo de la desalación (Capítulo 3).

2. Revisión y evaluación de los requerimientos ambientales implementados en los EMPs para la gestión de los vertidos de salmuera en el medio marino de España y Chile (emergente en desalación), para prevenir que no se produzcan impactos ambientales significativos durante la fase de operación de las SWRO (Capítulos 4 y 5).

3. Evaluación de un EMP a largo plazo de un vertido de salmuera desechado en un área de alto valor ecológico. Estudio del caso de la SWRO de Jávea (España)

4. Evaluación de los principales requerimientos (económicos, ambientales, seguridad jurídica y aspectos sociales) y factores limitantes que influyen en el desarrollo de proyectos de desalación a nivel global, para identificar sus aspectos de mejora y avanzar hacia el desarrollo sostenible ante un incremento en la demanda global (Capítulo 7).

ARTÍCULOS PUBLICADOS

CHAPTER 3: Review of the management of brine discharges in Spain

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Review of the management of brine discharges in Spain

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ABSTRACT

Seawater desalination is an expanding procedure to supply coastal regions with freshwater. Such developments introduce a significant amount of brine effluent into marine environments and highlight an important global need to minimize associated impact on marine environment. We review the measures adopted to manage the impacts of brine discharge in Spain by analyzing published and gray literature and empirical field data of several desalination plants. Several studies have identified the potential impacts of desalination plant effluent on marine communities and their mitigation. Applications of this knowledge have facilitated development of the Spanish desalination sector without significantly impacting the marine environment or, when identified, how such impacts have been reverted. Cooperation between industry and environmental scientists has been a crucial factor for understanding and minimizing the impacts of desalination. The application of environmental monitoring plans has further provided important tools to identify and correct the potential impacts of effluents. The example in Spain provides a comprehensive approach for minimizing the potential environmental impacts of brine discharge that can be applied in regions where desalination practices are under development.

1. Introduction

Seawater desalination is actively expanding in several areas throughout the world, including the Mediterranean coasts (Hernández-Sánchez et al., 2017; Jones et al., 2019). Although a range of desalination methods exist, reverse osmosis (RO) is the most widely used method because of its energy efficiency and low cost of obtaining freshwater (Zarzo and Prats, 2018). Most desalinations plants in Spain were developed using RO technology (Jones et al., 2019; Sadhwani Alonso and Melián-Martel, 2018; Sola et al., 2019b).

Brine discharge from plants using RO is typically characterized using salt concentrations in the range of 40–90 psu (Fernández-Torquemada et al., 2019). These brines are denser than seawater and form a plume that concentrates on the seafloor following the bathymetry (Fernández-Torquemada et al., 2009). Brine discharge may also contain chemical residues from anti-scalants, antifoaming agents, and coagulants commonly used during membrane-cleaning treatment, which may toxify the hypersaline effluent (Agus and Sedlak, 2010; Chang, 2015; Mezher et al., 2011; Portillo et al., 2014b). Such characteristics can affect marine ecosystems, especially benthic fauna in the brine discharge area (Fernández-Torquemada et al., 2019; Petersen et al., 2018; Roberts et al., 2010; Sharifinia et al., 2019).

Large desalination projects in Spain are subject to the environmental impact assessment (EIA), which includes a set of studies and administrative procedures to determine the best location for desalination plants, as well as preventive, corrective, and monitoring measures for managing the environmental impacts on marine and coastal systems (Fuentes-Bargues, 2014; Sadhwani Alonso and Melián-Martel, 2018; Sola et al., 2019b). In Spain, the EIA process is operated through European regulations developed by Directive 85/337/EEC (European Union, 1985). Following subsequent European laws, this regulation was modified and currently adheres to the 2014/52/EU directive (European Union, 2014). European regulations were further transposed into Spanish laws by Royal Decree 1302/86 (Spanish Government, 1986) and developed by Royal Decree 1131/88 (Spanish Government, 1988). Moreover, autonomous Spanish communities are authorized to develop their own procedures for EIAs or discharge protocol, including the establishment of activities subject to the EIA process and associated requirements (Fuentes-Bargues, 2014; Sadhwani Alonso and Melián-Martel, 2018).

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3. REVIEW OF THE MANAGEMENT OF BRINE DISCHARGES IN SPAIN

Abstract

Seawater desalination is an expanding procedure to supply coastal regions with freshwater. Such developments introduce a significant amount of brine effluent into marine environments and highlight an important global need to minimize associated impact on marine environment. We review the measures adopted to manage the impacts of brine discharge in Spain by analyzing published and gray literature and empirical field data of several desalination plants. Several studies have identified the potential impacts of desalination plant effluent on marine communities and their mitigation. Applications of this knowledge have facilitated development of the Spanish desalination sector without significantly impacting the marine environment or, when identified, how such impacts have been reverted. Cooperation between industry and environmental scientists has been a crucial factor for understanding and minimizing the impacts of desalination. The application of environmental monitoring plans has further provided important tools to identify and correct the potential impacts of effluents. The example in Spain provides a comprehensive approach for minimizing the potential environmental impacts of brine discharge that can be applied in regions where desalination practices are under development.

Keywords

Desalination impact; Brine discharge; Environmental management plan; Mitigation; Reverse Osmosis

3.1. Introduction

Seawater desalination is actively expanding in several areas throughout the world, including the Mediterranean coasts (Hernández-Sánchez et al., 2017; Jones et al., 2019). Although a range of desalination methods exist, reverse osmosis (RO) is the most widely used method because of its energy efficiency and low cost of obtaining freshwater (Zarzo and Prats, 2018). Most desalinations plants in Spain were developed using RO technology (Jones et al., 2019; Sadhwani Alonso and Melián-Martel, 2018; Sola et al., 2019b).

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Large desalination projects in Spain are subject to the environmental impact assessment (EIA), which includes a set of studies and administrative procedures to determine the best location for desalination plants, as well as preventive, corrective, and monitoring measures for managing the environmental impacts on marine and coastal systems (Fuentes-Bargues, 2014; Sadhwani Alonso and Melián-Martel, 2018; Sola et al., 2019b). In Spain, the EIA process is operated through European regulations developed by Directive 85/337/EEC (European Union, 1985). Following subsequent European laws, this regulation was modified and currently adheres to the 2014/52/EU directive (European Union, 2014). European regulations were further transposed into Spanish laws by Royal Decree 1302/86 (Spanish Government, 1986) and developed by Royal Decree 1131/88 (Spanish Government, 1988). Moreover, autonomous Spanish communities are authorized to develop their own procedures for EIAs or discharge protocol, including the establishment of activities subject to the EIA process and associated requirements (Fuentes-Bargues, 2014; Sadhwani Alonso and Melián-Martel, 2018).

Projects subject to the EIA process include those with activities in the Annex I or Annex II list with established requirements. In the case of desalination projects (Annex II: Group 8, Section E: Water Engineering and Management Projects), the EIA process is required when new or extended freshwater production capacities exceed 3000 m^3/day. Further detailed information regarding the different stages of the EIA process is provided in Fuentes-Bargues (2014) and Sadhwani Alonso (2018).

Environmental monitoring plans (EMPs) are established within Spanish EIA regulations to ensure the effectiveness of preventive and corrective measures to protect marine communities from the impacts of brine discharge and adopt mitigation measures if environmental impacts are identified (Sola et al., 2019a, 2019b). They provide further information regarding the potential impacts of effluents so that measures can be applied to avoid the environmental impacts of other desalination projects.

Some reviews have been carried out to study the impact of desalination on marine ecosystems (Areiqat and Mohamed, 2005; Baalousha, 2006; Gude, 2016; Lattemann and Höpner, 2008; Miller et al., 2014; Petersen et al., 2018a; Roberts et al., 2010; Sadhwani et al., 2005; Shemer and Semiat, 2017); however, few have focused on mitigation measures to reduce such impacts (Fernández-Torquemada et al., 2019; Missimer and Maliva, 2018; Sadhwani Alonso and Melián-Martel, 2018; Sharifinia et al., 2019). Important developments in the Spanish desalination sector occurred between 1999 and 2009 along the Mediterranean peninsular coast and Balearic and Canary Islands (Sola et al., 2019b) to address water scarcity due largely to tourism, increasing populations, and agricultural demand (Hernández-Sánchez et al., 2017; Sadhwani Alonso and Melián-Martel, 2018). The main desalination plants in Spain are shown in Figure 3.1. Compared with other countries, Spain has substantially conducted more research on the environmental impacts of desalination and how associated problems can be avoided or mitigated.

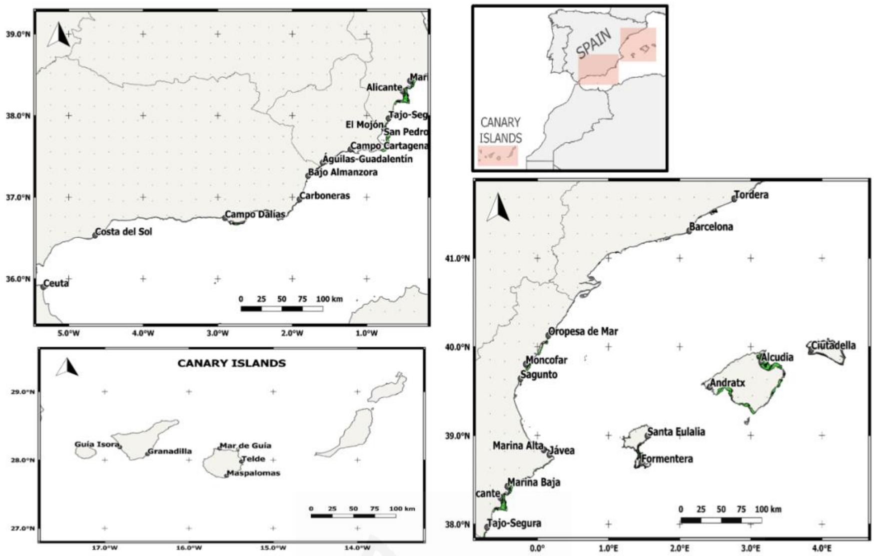

Figure 3.1. Main desalination plants in Spain. Green areas represent meadows of *P. oceanica* meadows, which is the main species selected with salinity thresholds for brine discharge management (modified from Ruíz et al. 2015).

We review the actions and insights acquired in managing the impact of brine discharge on the Spanish Mediterranean coast and Canary Islands. This paper combines: i) a review of published literature related to the environmental impacts of brine discharge in Spain, ii) a review of gray literature, including reports and conference papers that remain unpublished in scientific journals, and iii) empirical field information obtained from EMPs from different seawater reverse osmosis (SWRO) plants in Spain (Jávea, Alicante, San Pedro del Pinatar, and Alcudia desalination plants, Fig. 3.1).

This article is structured in three sections: i) research carried out to establish critical salinity thresholds for key species; ii) scientific advice followed during the development of desalination projects, mainly from environmental impact studies conducted prior to the development of EIAs; and iii) brine discharge monitoring through EMPs and adoption of mitigations measures when the EMPs identified particular impacts that required reduction.

3.2. Establishment of critical salinity thresholds for key species

Vulnerable ecosystems, such as seagrass, should be avoided to reduce the environmental impact of SWRO plants. However, in cases where exposure is inevitable, secure thresholds must be established to ensure that the discharge does not significantly impact vulnerable ecosystems. Seagrasses are habitat-forming species that provide relevant goods and services (Costanza et al., 1997; Duarte et al., 2013; Unsworth et al., 2019) but are also particularly sensitive to changes in water quality (de los Santos et al., 2019; Hemminga and Duarte, 2000; Short and Wyllie-Echeverria, 1996). The dominant seagrass in the Mediterranean Sea is *Posidonia oceanica* (L.) Delile, 1813: an endemic species that can form extensive meadows down to 40 m. These meadows constitute one of the most productive and valuable ecosystems in the Mediterranean (Vassallo et al., 2013). In Spain, the endemic seagrass *Posidonia oceanica* was selected for its ecological importance (Boudouresque and Meinesz, 1982), low tolerance to stressors (González-Correa et al., 2008; Guillén et al., 2013), and because it is protected by habitat Directive 92/43/CEE (European Union, 1992) and national regulations. Moreover, *P. oceanica* is widely distributed along Spanish coasts that are affected by water shortage where most SWRO plants have been constructed (Alicante, Murcia, Almeria, and the Balearic Islands, see Fig. 3.1).

A coordinated project between the University of Alicante, University of Barcelona, Spanish Institute of Oceanography, and Spanish Research Council was conducted to study the tolerance and sensitivity of *P. oceanica* to the impact of hypersaline discharge. The aim was to establish secure thresholds for key species to manage the potential impact of significant developments expected from SWRO plants on the Mediterranean coast (Buceta et al., 2003). This project combined mesocosm experiments, manipulative field experiments, and monitoring of brine discharge near a *P. oceanica* meadow that targeted both the seagrass (Fernández-Torquemada et al., 2005; Gacia et al., 2007; Ruíz et al., 2009) and associated fauna (Barbera et al., 2001; Lloret-Oltra and Sánchez-Lizaso, 2001). The results of these different approaches indicated that *P. oceanica* is highly sensitive to increases in salinity and recommendations therefore advised against discharge in areas where these ecosystems occur. However, when this option is not possible, a critical salinity threshold (38.5 psu) was recommended to protect the ecosystem (Sánchez-Lizaso et al., 2008). This value is low compared to the natural salinity of the western Mediterranean (37.7 psu on average) and has been adopted as a regulatory measure in the EIAs and discharge authorizations by the Spanish environmental authorities (Fuentes-Bargues, 2014; Sola et al., 2019b). This means that brine must be strongly diluted before reaching the meadow and protect most of the species that live therein (Sánchez-Lizaso et al., 2008).

After this initial project, additional studies were conducted using seeds and seedlings of *P. oceanica* (Fernández-Torquemada and Sánchez-Lizaso, 2013) and other Mediterranean seagrasses, *Cymodocea nodosa* (Ucria) *Ascherson*, 1869 and *Zostera noltii* (Hornemann), 1832, which are more tolerant than *P. oceanica* to increasing salinity (Fernández-Torquemada and Sánchez-Lizaso, 2011, 2006; Garrote-Moreno et al., 2014). Several studies were also performed to better understand the physiological mechanisms of Mediterranean seagrasses in response to increased salinity. In particular, osmoregulation mechanisms were addressed to explain different species' tolerance to salinity changes (Garrote-Moreno et al., 2015; Marín-Guirao et al., 2013a, 2013b; Sandoval-Gil et al., 2014, 2012a, 2012b). Table 3.1 summarizes the studies that address the tolerance of seagrasses to increased salinity in the western Mediterranean.

Table 3.1. Studies carried out in the western Mediterranean on the tolerance of seagrasses to increased salinity.

Reference	Research	Species	Salinity tested (psu)	Results
Fernández-Torquemada and Sánchez-Lizaso, 2005	Mesocosm experiments	*P. oceanica*	25–57	Mortality at salinities above 42 psu and below 29 psu. 100% mortality at 50 psu. More tolerant to salinity reductions than increases.
Fernández-Torquemada and Sánchez-Lizaso, 2006	Mesocosm experiments	*C. nodosa* and *Z. noltii*	2–72	Growth and survival of both species affected by salinity above 41 psu. *Z. noltii* tolerate conditions of hyposalinity better than *C. nodosa*.
Gacia et al., 2007	Discharge monitoring	*P. oceanica*	37.6–41.8	High epiphyte load, necrosis marks, and low structural activity. Results suggest a critical threshold value of 39.3. Salinity has an impact above 39.1 psu.
Sánchez-Lizaso et al., 2008	Mesocosm and field experiments	*P. oceanica*	23–57	Effects on structure and vitality in salinities between 39.1 and 39.4 psu. Results recommend not exceeding 38.5 and 40 psu in more than 25% and 5% of annual observations in the meadow, respectively.
Ruíz et al., 2009	Field experiments	*P. oceanica*	37.6–40.1	Decrease in density, structure, and vitality of affected seagrasses. Tolerance of *P. oceanica* is very close to the natural salinity range (38 psu).
Tomasello et al., 2009	Field survey	*P. oceanica*	48	*P. oceanica* is able to survive in a hyperhaline lagoon.
Fernández-Torquemada and Sánchez-Lizaso, 2011	Mesocosm experiments	*C. nodosa* and *Z. noltii*	2–72	Growth and survival of both species were significantly affected by salinity. Both species decreased in leaf growth at salinity levels higher than 41 psu and died above 56 psu. *Z. noltii* tolerate conditions of hyposalinity better than *C. nodosa.*
Sandoval-Gil et al., 2012a	Mesocosm experiments	*P. oceanica* and *C. nodosa*	37–43	Both species decreased their leaf water potential. *P. oceanica* leaves showed reduced osmotic potential and high vulnerability compared to *C. nodosa*, which maintained more efficient osmotic stability.

Sandoval-Gil et al., 2012b	Mesocosm experiments	*C. nodosa*	37–43	Decrease in photosynthetic rate at 39–41 psu. Severe hypersaline conditions (43 psu) reduced net photosynthesis. *C. nodosa* has higher tolerance to hypersaline stress than *P. oceanica.*
Marín-Guirao et al., 2013b	Mesocosm experiments	*P. oceanica*	43	Seagrass showed sub-lethal effects, loss of ionic balance, and decreased leaf growth. Dysfunction recovered after removing the stress of one month of exposure, but did not recover in long-term saline-stressed plants.
Marín-Guirao et al., 2013a	Mesocosm experiments	*P. oceanica* and *C. nodosa*	37, 43	Hypersaline stress did not alter the functioning of the xanthophyll-cycle-photoprotection of both species. Although in combination with high light, the photoinhibition of *P. oceanica* was observed.
Garrote-Moreno et al., 2014	Field experiments	*C. nodosa*	38.6–39.9	Decreased growth and increased mortality. Fluctuations in salinity and slightly higher temperatures may cause additional physiological stress.
Sandoval-Gil et al., 2014	Mesocosm experiments	*P. oceanica* and *C. nodosa*	37, 43	Further reduction of carbon balance in deep *P. oceanica* meadows and shallow *C. nodosa* meadows. Vitality of *P. oceanica* affected. Intraspecific and inter-specific divergences play a key role in their salinity tolerance ranges.
Garrote et al., 2015	Mesocosm experiments	*P. oceanica* and *C. nodosa*	37–59.5	Osmotic potential and ion uptake were significantly reduced in both species above 46 psu. *P. oceanica* showed a greater reduction in the osmotic gradient relative to *C. nodosa* as salinity increased. *C. nodosa* was more tolerant to salinity stress than *P. oceanica*.
Marín-Guirao et al., 2017	Field survey	*P. oceanica*	42	*P. oceanica* was able to survive under the fluctuating influence of hypersaline waters coming from an adjacent coastal lagoon.

3.3. Scientific advice during the development of desalination projects

Cooperation between engineers and environmental scientists can improve desalination projects and minimize environmental impacts. An example of this cooperation is the Jávea SWRO plant. This cooperation started before a regulatory framework and led to changes in the Jávea SWRO project that avoided environmental impacts. This plant is located in a tourist area with sensitive ecosystems (Fig. 3.1) and the priority of its construction was to reduce associated environmental impacts. Seawater intake was performed through 10 beach wells, each at 201-m depth. Seawater intake through beach wells reduces the use of pre-treatment chemicals (Mezher et al., 2011). Scientific recommendations included avoiding vulnerable ecosystems (*P. oceanica* meadows) and placing the discharge in an anoxic artificial channel (Fontana channel). Because the discharge is in a confined area, the effluent was diluted with seawater prior to discharge to reduce its salinity (Fig. 3.2). The discharge passed through 16 diffusers to facilitate dilution (Fariñas et al., 2005; Malfeito et al., 2005; Ramos-Esplá et al., 2001).

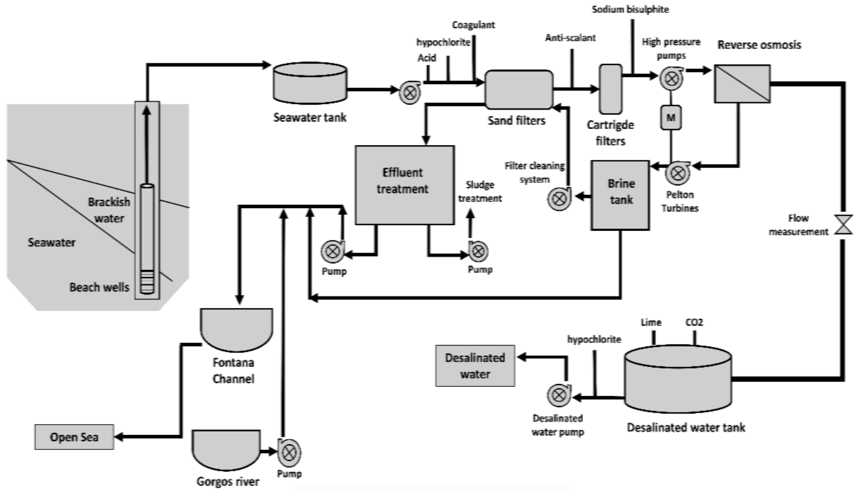

Figure 3.2. Diagram of the Jávea SWRO plant design showing the dilution of brine discharge with seawater (adapted from Malfeito et al. 2005).

The Jávea facility has been continuously monitored since operations began in 2002, and has demonstrated the effectiveness of recommendations established during EIA development and absence of significant environmental impacts (Sánchez-Lizaso et al., 2019, 2004). The salinity in the Fontana channel reached salinity levels below 44 psu, which shows proper dilution of the effluent after dilution processing (Fernández-Torquemada et al., 2009). The area affected by the brine discharge plume is also mainly limited around the channel outfall without reaching the *P. oceanica* meadows (Fig. 3.3).

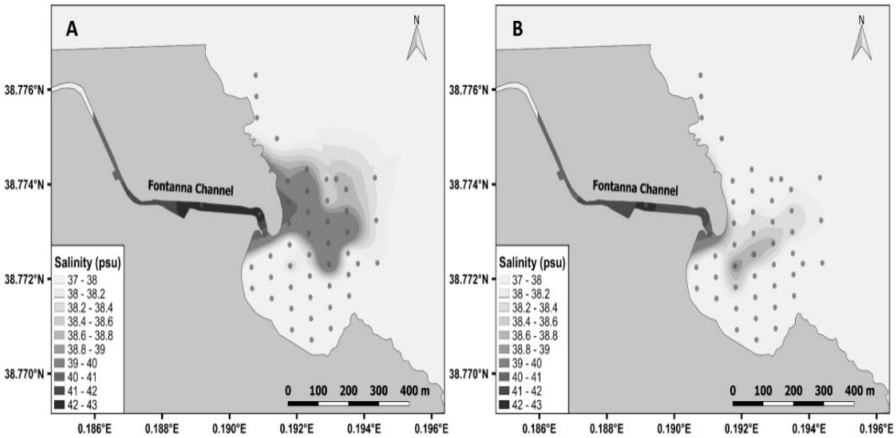

Figure 3.3. Saline plume from discharge of the Jávea SWRO plant in 2015. The salinity distribution is shown on the sea-bottom during (A) summer and (B) winter. Data were obtained from the EMP results of the Jávea SWRO plant.

The abundance of echinoderms in *P. oceanica* meadows was used as an early warning of desalination impacts and was similar at two control stations in areas closer to the discharge between 2002 and 2019 (Fig. 3.4), which can be used as indicator of the zero-impact of effluent from this plant. A recovery of benthic fauna in the previously anoxic Fontana channel was also observed, in addition to a higher abundance of fishes in the channel (Fernández-Torquemada et al., 2004; Sánchez-Lizaso, 2012; Sánchez-Lizaso et al., 2019; 2004).

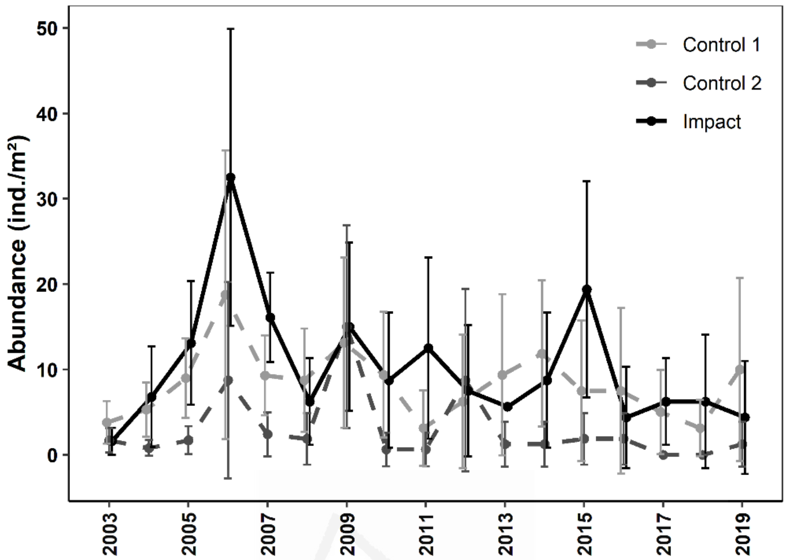

Figure 3.4. Temporal evolution of echinoderm abundance in *P. oceanica* meadows in the area influenced by brine discharge from the Jávea SWRO plant compared with two control stations.

To protect *Posidonia* seagrass meadows from discharge of the San Pedro del Pinatar SWRO plant (Fig. 3.1), environmental authorities proposed the construction of a 5-km long brine outfall across the meadow. However, the plant was finished prior to completion of the outfall. Following the example of the Jávea SWRO plant, effluent of 2-m depth pre-diluted with seawater along the shore was used during pipeline construction (May 2005 to January 2006). A protocol to increase dilution or reduce the lines in operation was established if salinity exceeded the threshold value at the meadows. Six conductivity and temperature devices (CTs) were installed in the seagrass closest to shore to monitor salinity values. This provisional discharge allowed the plant to operate at reduced capacity until the pipeline was completed without detection of environmental impacts on the meadows or other benthic communities due to the application of threshold salinity values based on studies listed in section 2 (Fernández-Torquemada et al., 2007).

Although it is always preferable to avoid locating a desalination plant near areas of high ecological value, this is not possible in some cases, especially on islands. In the Balearic Islands, for instance, it was necessary to adapt the Alcudia SWRO plant project (Fig. 3.1) due to the presence of *P. oceanica* meadows (Ruíz et al., 2015). According to available information, the best option was to place the effluent in a commercial harbor with a discharge system similar to that previously successfully tested in Jávea (Zarzo et al., 2009). Brine discharge was diluted using the pre-dilution system with seawater at a 1:4 ratio to reduce the salinity from 70 to 44 psu. The effluent was also disposed by 10 diffusers at 5.5-m depth to obtain suitable dilution (unpublished data from authors).

3.4. Brine discharge monitoring and modifications to mitigate environmental impacts

The monitoring of desalination plant effluents allows demonstration of the absence of significant impacts on the marine environment or, when identified, that the adoption of supplementary measures to mitigate these impacts is possible (Sánchez-Lizaso, 2012). Such programs should be designed following scientific guidelines to distinguish the effects of brine discharge from normal background environmental variability and other impacts that may occur in the same area (Fernández Torquemada and Sánchez Lizaso, 2007). The EMPs include a set of parameters for monitoring the effects of effluents on the marine environment, although these differ between different countries or desalination projects (Sola et al., 2019a, 2019b). In Spain, the EMPs environmental requirements have significantly increased over time (Sola et al., 2019b).

The monitoring programs for SWRO plants in Spain usually include: a characterization of brine discharge; monitoring of the area influenced by the saline plume; monitoring of ecological engineering works and protected species with high environmental value when present in the discharge area; use of salinity-sensitive species as bioindicators; monitoring of sediment and associated soft-bottom benthic communities; inclusion of protocols to adopt mitigation measures when impacts are identified; and a revision of submerged outfall when possible limitations are detected in the discharge method (De-la-Ossa-Carretero et al., 2016a, 2016c; Del-Pilar-Ruso et al., 2007; Fernández-Torquemada and Sánchez-Lizaso, 2007; Lattemann and Höpner, 2008; Sánchez-Lizaso et al., 2004; Sola et al., 2019a, 2019b).

The EMP of the Jávea SWRO plant was established prior to its requirement by environmental authorities and serves as a model for other EMPs in Spain (Sánchez Lizaso et al., 2004). The Jávea EMP includes the control of effluent before and after dilution and monthly analysis of suspended solids, pH, salinity, temperature, dissolved oxygen, total organic carbon, total nitrogen, and total phosphorus. A CT was also installed for the continuous control of salinity and temperature after effluent dilution, including the flow rate and total weekly effluent production. Marine environment control in the artificial channel (point of discharge, middle, and mouth of the channel) and two control stations include bi-annual (summer and winter) analysis of the salinity, temperature, dissolved oxygen, total nitrogen, and total phosphorus at 1-m depth, as well as weather data (e.g., wind, rainfall, waves). Seasonal (four times per year) saline plume control is performed using a conductivity, temperature, and depth device (CTD) at a minimum of 30 points between the discharge point and 10-m isobath. Annual control of fish communities is performed by visual census along 50-m transects in the effluent area and one control station (both sampled in rocky and *P. oceanica* bottoms). The *P. oceanica* meadows were monitored at least twice per year in three fixed sampling locations, two controls, and one impact location near the discharge area. Within each location, three stations were established at 3-, 7-, and 15-m depth to estimate coverage (four replicates) and over four permanent parcels of 40 × 40 cm where all shoots were marked to determine recruitment and mortality. Echinoderms were monitored as bioindicator species by analyzing their density on rocky bottoms and *P. oceanica* meadows over a 1 × 1 m area with 10 replicates in the brine discharge area and control stations. Annual sediment control was performed along perpendicular transects to the coast at different depths, including granulometric analysis, use of indicator species of infauna, organic matter parameters, pH, and redox potential. An annual revision of submerged diffusers was constructed in the artificial channel. During the first year, fishery catches were monitored using experimental fishing in the effluent area and control stations. Because no negative impacts were observed during these periods, the EMP has been modified to reduce some of the initially included sampling protocols (e.g., fisheries, soft bottom infauna).

No environmental impacts were detected by the EMP from the provisional discharge of the San Pedro del Pinatar SWRO plant operating from May 2005 to January 2006 (Fernández-Torquemada et al., 2007). Similarly, Raventos et al. (2006) found no response of benthic organisms to discharge from the Blanes SWRO plant. However, in some EMPs, changes in marine communities have been observed as a consequence of the effluent, and mitigation measures have been adopted to reverse these impacts. Table 3.2 lists the case studies with adopted measures when potential environmental impacts were detected.

Table 3.2. Mitigation measures adopted when environmental impacts were identified from brine discharge.

SWRO plant	Discharge	Observed impacts	Adopted measures	Result	References
Alicante	Directly to shoreline	Sub-lethal effects on *P. oceanica* meadows, disappearance of echinoderms, and changes in abundance and diversity in infauna communities.	Dilution of brine discharge with by-passing seawater (1.5–5 parts to 1 according to salinity observed in the meadow).	Recovery of echinoderm and soft-bottom communities in the discharge area. No impact on seagrasses.	Del-Pilar-Ruso et al., 2008, 2007; Fernández-Torquemada et al., 2013, 2009, 2005
San Pedro del Pinatar	5-km long outfall at 33-m depth	Plume influence along several km. Soft-bottom community affected.	Single diffuser device at 60º, elevated 4.5 m from seabed. Installed in May 2010.	Salinity was reduced below 38.5 psu. Significant recovery of soft-bottom community richness and diversity and an increase in amphipod abundance.	De-la-Ossa-Carretero et al., 2016c; Del-Pilar-Ruso et al., 2015, 2009; Fernández-Torquemada et al., 2009
Maspalomas II	300-m long submerged pipe at 4-m depth	*C. nodosa* seagrass absent due to influence of brine discharge and observation of dead individuals of soft-bottom characteristic species.	Venturi eductor with Y bifurcation and 90º aperture, reduced outlets of 130-mm diameter and 11 m/s. Installed in 2012.	Salinity was reduced below 37.3 psu. Recovery of *C. nodosa* habitat and associated community. Altered pH and oxygen saturation levels during membrane cleaning operations disappeared.	Portillo et al., 2014b, 2014a, 2013

The SWRO desalination plant of Alicante I began operations in September 2003. The plant had an initial maximum capacity of 50,000 m^3 d^{-1} and enlarged in January 2006 to produce up to 68,000 m^3 d^{-1}. Alicante II began operations in 2008 with a similar capacity.

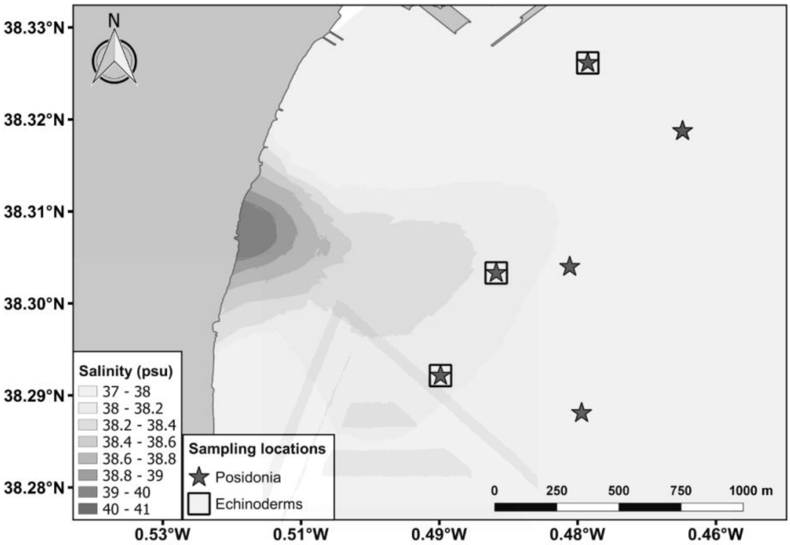

Figure 3.5. Saline plume from discharge of the Alicante SWRO plant in May 2008. The figure shows the salinity distribution on the sea bottom with *Posidonia* meadow localities as stars and echinoderms as squares. Data are from the EMP of the Alicante SWRO plant from the authors.

The results of the EMP of the Alicante SWRO plant between 2003 and 2005 showed a large influence area reaching the nearby *Posidonia* meadow, where sub-lethal effects (reduced growth but no mortality) were observed (Fernández-Torquemada et al., 2005). The disappearance of echinoderms in the area affected by high salinity above natural values was also observed because of their sensitivity to salinity changes (Fernández-Torquemada et al., 2013). Changes in the benthic communities were also observed in areas near the discharge, specifically showing a reduction in the abundance of polychaete assemblages and favoring opportunistic species (Del-Pilar-Ruso et al., 2008, 2007). In view of these impacts and objectives to substantially increase the desalination capacity (e.g., extension of Alicante I plant and construction of Alicante II), effluent dilution with surface seawater was recommended but the dilution level was not constant as in Jávea and depended on the salinity values at the upper limit of the *Posidonia* meadow (Fig. 3.5). Brine discharge dilution reduced the effluent area and recovered the echinoderm densities to values similar to those before the onset of discharge (Fig. 3.6, Fernández-Torquemada et al., 2013). Recovery was also observed for infauna in the discharge area to values similar to the control localities despite higher production (De-la-Ossa-Carretero et al., 2016a).

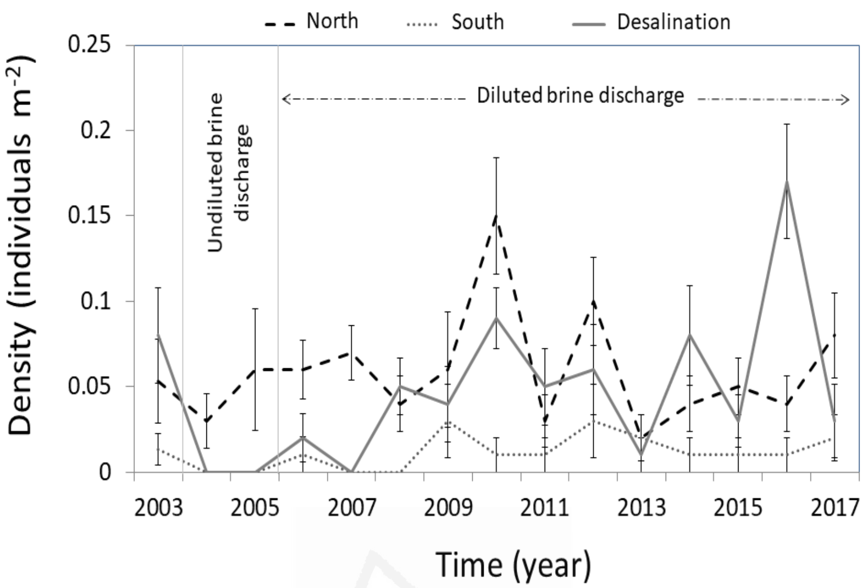

Figure 3.6. Echinoderm abundance as a function of time in the area influenced by brine discharge from the Alicante SWRO plants. The impact area is compared with two control stations (north and south) (modified from Fernández-Torquemada et al. 2013 using unpublished data from the authors).

At the San Pedro del Pinatar SWRO plants, a 5-km-long brine outfall was constructed to protect the *Posidonia* meadows. However, although the meadows were protected, the results of the EMP displayed a large influence area and impoverishment of the diversity and richness of soft-bottom communities (Del-Pilar-Ruso et al., 2009). To increase mixing and reduce the affected area, a single diffuser was installed in 2010 at the end of the outfall at 34.9-m depth (Del-Pilar-Ruso et al., 2015; Loya-Fernández et al., 2018; Table 3.2). After the installation of this diffuser device, the salinity and influenced area were drastically reduced (Fig. 3.7). As consequence, the benthic communities (polychaete and amphipods assemblages) recovered relatively rapidly and the diversity and abundance are now similar to those at the control stations (De-la-Ossa-Carretero et al., 2016c; Del-Pilar-Ruso et al., 2015).

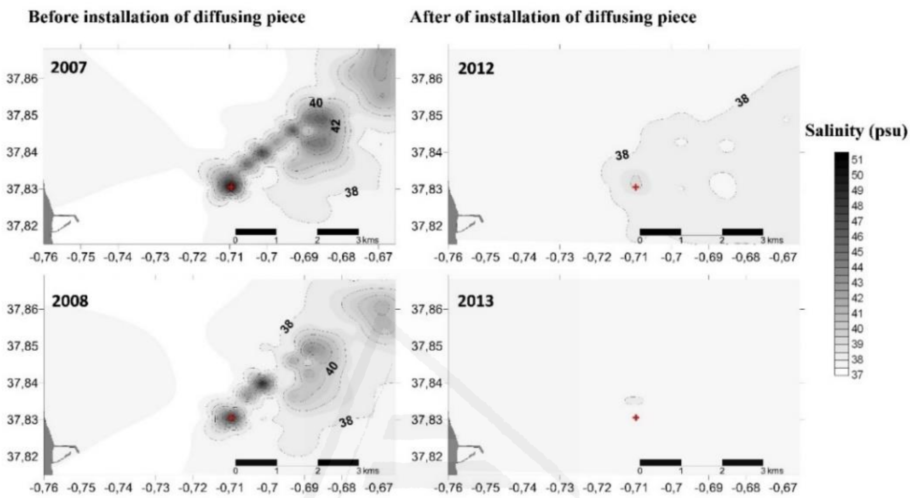

Figure 3.7. Salinity distribution in the area of brine discharge from the San Pedro del Pinatar SWRO plant before and after diffuser installation (unpublished data from the authors).

In the Canary Islands, brine discharge from the Maspalomas II SWRO plant (Fig. 3.1) showed an average salinity of 69.5 psu after dilution with by-passing seawater at a ratio of 1:0.12 (Portillo et al., 2014a, 2013). These characteristics produced a high salinity plume with a significant impact on the physiology, growth, and survival of seagrass *Cymodocea nodosa.* Moreover, it produced toxic effects on fish species *Synodus* and other soft-bottom fishes such as *Bothus podas*, *Microchirus azevia*, and *Trachinus draco* due to low physico-chemical variable values (pH and oxygen saturation) in the brine plume area owing to the addition of sodium metabisulphite during cleaning treatment (Portillo et al., 2014b). To mitigate these impacts on the marine environment, a more efficient Venturi diffuser was installed in the discharge in 2012 (Portillo et al., 2013; Table 3.2). This modification resulted in larger turbulence with higher near field mixing that significantly reduced the salinity near the discharge and maintained an average salinity closer to the mean ambient values compared with the 8-psu increase prior to adopting the diffuser. Thus, the adopted measure reduced the effluent impact on the benthic communities (Portillo et al., 2014b, 2013).

Moreover, appropriately designed EMPs combined with the use of bioindicators to monitor benthic communities or echinoderms allow for distinguishing the impact of desalination from other impacts on the marine environment that may overlap in the same area, such as sewage discharge or aquaculture (De-la-Ossa-Carretero et al., 2016a, 2016b; Del-Pilar-Ruso et al., 2009; Fernández-Torquemada et al., 2013; Ferrero-Vicente et al., 2011).

3.5. Conclusion

Brine discharge can produce a diversity of environmental impacts, mainly on benthic communities, if appropriate dilution is not applied in the discharge mechanism (Belatoui et al., 2017; Fernández-Torquemada et al., 2009; Frank et al., 2019). Cooperation between industry and environmental scientists is highly recommended during the development of new desalination projects to allow the inclusion of scientific recommendations to adapt the discharge to local environmental constraints and prevent negative environmental impacts. EMPs based on the best available scientific knowledge

(Sola et al., 2019b) are useful to assess the effectiveness of adopted measures, ensure that no significant impacts on the marine environment are produced, detect potential negative effects of desalination discharge, and facilitate their mitigation (Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2013). These EMPs should be sufficiently flexible to adapt to new or previous results. The impacts on benthic communities are identified by decreasing abundance, diversity, and richness of some invertebrates (De-la-Ossa-Carretero et al., 2016c; Del-Pilar-Ruso et al., 2015, 2009, 2007; Fernández-Torquemada et al., 2013; Portillo et al., 2014b). These impacts may be reverted by increasing the discharge mixing with diffusers or by-passing seawater. Moreover, the establishment of secure threshold limits has been proven effective to prevent negative impacts on sensitive and protected species such as *Posidonia oceanica*. EMPs should also include bioindicators because they can discriminate between the impacts of different activities that may overlap in the same area and can also produce early warning signals for the application of corrective measures.

The experience in Spain provides a comprehensive approach to minimize the potential impacts of effluent on the environment, which provides useful guidelines for ongoing development of the global desalination sector (Jones et al., 2019; Shahzad et al., 2017). The main recommendations include: i) cooperation with scientists in the adoption of specific measures regarding brine discharge during the development of EIAs or desalination projects; ii) disposal of effluent in areas with lower ecological value when possible; iii) active research on the tolerance of key species to hypersaline discharge when present in the discharge area to establish secure salinity thresholds; iv) adoption of scientifically useful and tested measures, such as dilution with seawater or the installation of diffusers in the outfall to maximize dilution in the discharge area; and v) adoption of properly designed EMPs to assess the effectiveness of measures to prevent the environmental impacts of desalination and identify and correct environmental impacts when produced.

In conclusion, cooperation between industry and environmental scientists has been crucial for understanding and minimizing the environmental impacts of desalination in Spain. To mitigate impacts on the marine environment, it is important to select a discharge outfall configuration that maximizes mixing, which may include diffusers or seawater by-passing and dilution. The experience acquired to date can be applied in other regions where desalination operations are under development to reduce the environmental impact of new desalination projects.

3.6. Author contributions

IS and JS contributed conception and design of the study; JO, IS, YP and YF processed and analyzed the field data from environmental management plans; IS and JS wrote the first draft of the manuscript; IS, JS, DZ and AC wrote sections of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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CHAPTER 4: Evaluating environmental requirements for the management of brine discharges in Spain

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Evaluating environmental requirements for the management of brine discharges in Spain

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ABSTRACT

Desalination activities may have a detrimental impact on the marine environment, caused mainly by hypersaline effluents. The aim of this paper is to assess the quality of Environmental Monitoring Plans (EMPs) of desalination plants in Spain, and the aspects which could be improved to correctly manage brine discharges. A total of 30 desalination projects submitted to Environmental Impact Assessment (EIA) between 1998 and 2009 have been reviewed. Requirements for the monitoring of brine discharges, and their sampling designs, in the EMPs have improved over time. However, this trend is similar for essential and irrelevant descriptors. Furthermore, the presence of protected species in the area of brine discharges showed a significant increase of requirements. Nevertheless, there was no increase of requirements with respect to a major brine discharge production plant. In conclusion, a review of the EIAs would be advisable to unify the monitoring requirements at the national level, and improving their sampling designs, including the essential descriptors when they are absent, and eliminating irrelevant descriptors when they are present. This standardization should be paid attention to desalination plants with higher brine production as they may have a greater influence on the marine environment.

1. Introduction

Ever-increasing demands for freshwater resources in the face of ongoing water scarcity are expected for the foreseeable future, and at a global level [1]. There are different factors impacting upon these increasing water demands, but population and economic growth of the main contributing factors, although others such as climate change are highly likely to have a significant impact also [2,3]. This situation highlights the vitally important role of the desalination industry as an alternative supply method of freshwater in a global water stress context [1,4]. Thus, a substantial increase of desalinated water production is expected, mainly dominated by reverse osmosis (RO) technology [2]. RO technology is the most widely used method due to its lower energy consumption and greater efficiency compared to other technologies [5,6]. In Spain, RO plants provide a significant supply of freshwater due to the negative balance of water resources, specifically in certain Mediterranean coastal regions, such as in the southeast of Spain [7]. Moreover, this water scarcity is exacerbated by the demands of intensive agriculture and tourism [8].

RO desalination plants produce hypersaline discharges which usually are discharged into the sea given their coastal proximity and thus lower economic cost [5]. Brine discharges have a higher density than seawater, so they form a saline plume that tends to follow the bathymetry of the seabed [9]. Furthermore, they may also contain chemical elements due to the use of anti-scalants and coagulants used in the pre-treatment and membrane cleaning treatments, although most of them are effectively consumed by the process. Consequently, it may intensify the toxicity of the brine discharge, and it would thus induce a localized eutrophication and turbidity of the sea water [10–12]. These characteristics of brine discharges impact upon their dispersion mechanisms, which can in turn affect benthic communities such as seagrasses (*Posidonia oceanica* and *Cymodocea nodosa*), or benthic fauna [12–16]. Likewise, recent studies highlight both the short- and long-term impact upon the bacterial activity of benthic bottoms and also the possible impact upon fish larvae [12,17,18].

An Environmental Impact Assessment (EIA) is usually established within the scope of environmental laws as a tool to prevent or correct the environmental impact of a project development or infrastructure, including desalination facilities. EIA is a process includes a set of studies and administrative procedures to analyze the preventive, corrective and monitoring measures of the environmental impact [8].

As part of the EIA process, Environmental Monitoring Plans (EMPs) are established in order to mitigate the impacts of brine discharges upon the marine environment. EMPs are applied to ensure the

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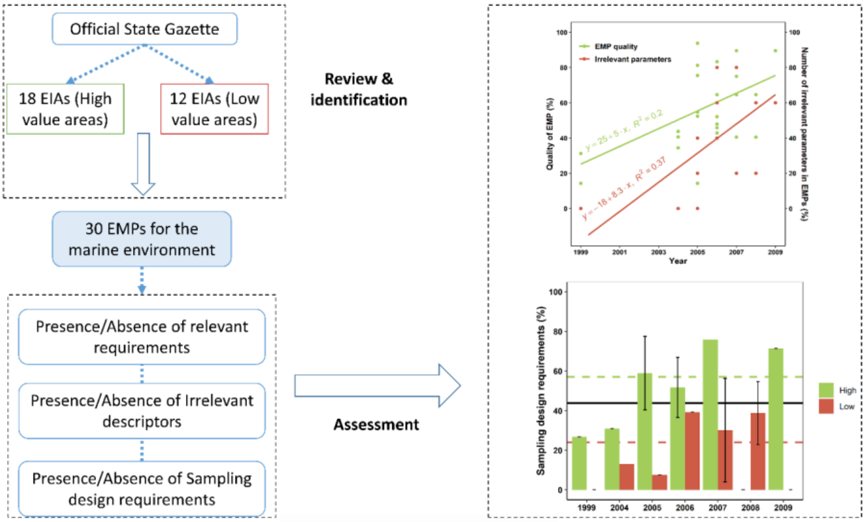
4. EVALUATING ENVIRONMENTAL REQUIREMENTS FOR THE MANAGEMENT OF BRINE DISCHARGES IN SPAIN

Abstract

Desalination activities may have a detrimental impact on the marine environment, caused mainly by hypersaline effluents. The aim of this paper is to assess the quality of Environmental Monitoring Plans (EMPs) of desalination plants in Spain, and the aspects which could be improved to correctly manage brine discharges. A total of 30 desalination projects submitted to Environmental Impact Assessment (EIA) between 1998 and 2009 have been reviewed. Requirements for the monitoring of brine discharges, and their sampling designs, in the EMPs have improved over time. However, this trend is similar for essential and irrelevant descriptors. Furthermore, the presence of protected species in the area of brine discharges displayed a significant increase in requirements. Nevertheless, there was no increase in requirements with respect to a major brine discharge production plant. A review of the EIAs would be advisable to unify the monitoring requirements at the national level, and improving their sampling designs. This standardization should be considered for desalination plants with higher brine production, as they may have a greater influence on the marine environment.



Keywords

Environmental monitoring plan; Brine discharge; Environmental impact; Environmental requirements; Seawater desalination

4.1. Introduction

Ever-increasing demands for freshwater resources in the face of ongoing water scarcity is expected for the foreseeable future and at a global level (Shahzad et al., 2017). There are different factors impacting upon these increasing water demands, but population and economic growth of the main contributing factors, although others such as climate change are highly likely to have a significant impact also (Jones et al., 2019; Qasim et al., 2019). This situation highlights the vitally important role of the desalination industry as an alternative supply method of freshwater in a global water stress context (Gude, 2016; Shahzad et al., 2017). Thus, a substantial increase of desalinated water production is expected, mainly dominated by reverse osmosis (RO) technology (Jones et al., 2019). RO technology is the most widely used method due to its lower energy consumption and greater efficiency compared to other technologies (Mezher et al., 2011; Zarzo and Prats, 2018). In Spain, RO plants provide a significant supply of freshwater due to the negative balance of water resources, specifically in certain Mediterranean coastal regions, such as the south eastern part of Spain (Hernández-Sánchez et al., 2017). Moreover, this water scarcity is exacerbated by the demands of intensive agriculture and tourism (Sadhwani Alonso and Melián-Martel, 2018).

RO desalination plants produce hypersaline discharges which usually are discharged into the sea given their coastal proximity and thus lower economic cost (Mezher et al., 2011). Brine discharges have a higher density than seawater, so they form a saline plume that tends to follow the bathymetry of the seabed (Fernández-Torquemada et al., 2009). Furthermore, they may also contain chemical elements due to the use of anti-scalants and coagulants used in the pre-treatment and membrane cleaning treatments, although most of them are effectively consumed by the process. Consequently, it may intensify the toxicity of the brine discharge, and it would thus induce a localized eutrophication and turbidity of the sea water (Chang, 2015; Petersen et al., 2018a; Portillo et al., 2014b). These characteristics of brine discharges impact upon their dispersion mechanisms and may have abiotic impacts, which can in turn affect benthic communities such as seagrasses (*Posidonia oceanica* and *Cymodocea nodosa*) or benthic fauna, such as echinoderms or amphipod and polychaete assemblages, that are sensitive to this impact in the brine discharge area (De-la-Ossa-Carretero et al., 2016c; Del-Pilar-Ruso et al., 2015, 2008, 2007; Fernández-Torquemada et al., 2013; Kress, 2019b; Petersen et al., 2018a; Roberts et al., 2010; Sánchez-Lizaso et al., 2008). Likewise, recent studies highlight both the short- and long-term impacts upon the heterotrophic bacterial activity of benthic bottoms, the impact on coral reefs (associated bacteria and algae), and also the possible impact upon fish larvae (Belkin et al., 2017; Frank et al., 2017; Lykkebo et al., 2018; Petersen et al., 2018a, 2018b; Röthig et al., 2016).

Sustainable management of brine discharges by conducting proper pre-design can minimize the impact on marine ecosystems (Missimer and Maliva, 2018). Thus, considering the best place to locate brine disposal and adopting previously employed mitigation measures, it is possible to reduce the impact on benthic fauna and illustrate how RO plants can be developed with environmental friendly solutions (Malfeito et al., 2005; Missimer and Maliva, 2018). This concerns should be adopted during the environmental impact assessment (EIA) (Heck et al., 2018). EIA is usually established within the scope of environmental laws as a tool to prevent or correct the environmental impact of a project development or infrastructure, including desalination facilities. EIA is a process including a set of studies and administrative procedures for identifying and analyzing the impacts of RO projects, adopting the preventive, corrective measures and alternatives (such as the brine discharge location or modification to the process), and monitoring measures of the environmental impact (Lattemann and Höpner, 2008; Sadhwani Alonso and Melián-Martel, 2018).

As part of the EIA process, Environmental Monitoring Plans (EMPs) are established in order to mitigate the impacts of brine discharges upon the marine environment. EMPs are applied to ensure the effectiveness of preventive and corrective measures established in the EIAs (Fuentes-Bargues, 2014; Sadhwani Alonso and Melián-Martel, 2018). EMPs can identify marine environmental impacts of brine discharges, and mitigate them when they are identified (De-la-Ossa-Carretero et al., 2016c; Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2013).

In the Spanish case, EIA process is regulated by European regulations outlined in Directive 85/337/EEC (European Union, 1985). This law was supplemented and modified by various subsequent laws, and currently the process is regulated and complemented by Directive 2014/52/EU (European Union, 2014). Moreover, the EIA process is regulated by Spanish laws that transposed the Directive 85/337/EEC (European Union, 1985) by the Royal Decree 1302/86 (Spanish Government, 1986) and were developed by the Royal Decree 1131/88 (Spanish Government, 1988). Currently, the laws developed subsequently have been transposed into a single regulation, stipulated by the law 21/2013 (Spanish Government, 2013). Finally, Autonomous Communities are empowered to adopt their own procedures for the development of EIAs (Fuentes-Bargues, 2014; Sadhwani Alonso and Melián-Martel, 2018; Sadhwani et al., 2005).

Projects subjected to the EIA process are those activities that are listed in Annex I or Annex II, and the environmental authority has decided to submit the project to the EIA process (Spanish Government, 2013). In the case of desalination projects with new (or extension production capacities larger than 3000 m^3/day), they are required to be submitted to the EIA (as specified in Annex II) given that they belong to Group 8, Section E: Water Engineering and Management Projects (Sadhwani Alonso and Melián-Martel, 2018).

The environmental and ecological impacts may represent the main concerns for developing RO plants (Heck et al., 2018, 2016; Liu et al., 2018). Therefore, EIA process should particularly consider these concerns with the adoption of well-designed EMPs to ensure sustainable operation of RO plants with a minimum impact on the environment (Liu et al., 2018; Missimer and Maliva, 2018). The aim of this paper is to assess the quality of EMPs of desalination plants in Spain, and the aspects to be improved to correctly manage brine discharges under defined scientific criteria. This study includes: i) an analysis of the number of projects and production capacity of EIAs evaluated; ii) evolution of environmental requirements over time; iii) analysis of environmental requirements in areas with the presence of protected species; v) influence of brine discharge production on

EMPs; and, vi) identification of irrelevant parameters for the monitoring of brine discharges.

4.2. Materials and methods

An exhaustive analysis of the EMPs defined in the EIAs for the construction of desalination plants in Spain, between 1998 and 2018, has been conducted in this study. EIAs published in the Official State Gazette (*Boletin Oficial del Estado*), and one brine discharge authorization, were analyzed. The first EIA linked to a desalination project was identified in 1999, and the last desalination project conducted for EIA in Spain was identified in 2009. A total of 30 desalination projects with specific EMPs for the marine environment were evaluated (see Table 4.1), all of them using RO technology. Desalination projects evaluated are distributed mainly along the Mediterranean coast and among the Canary Islands. Figure 4.1 shows the maximum freshwater production of projects evaluated and their associated distribution.

Table 4.1. Desalination projects submitted to the EIA and published in the Official State Gazette. *Discharge authorization obtained from Dirección General de Calidad Ambiental de la Conserjería de Territorio y Vivienda de la Comunidad Valenciana.

ID	Desalination projects submitted to EIA	Date	Production (m^3/day)
1	Seawater desalination plant at Nuevo canal de Cartagena (Murcia)	17/12/1999	65000
2	Seawater desalination plant at Carboneras (Almería)	17/12/1999	120000
3	Seawater desalination plant (2nd phase) Telde (Las Palmas de Gran Canaria)	16/01/2004	16000
4	Seawater desalination plant at Campo Cartagena (Murcia)	03/02/2004	160000
5	Seawater desalination plant (2nd phase*)* Mar de Guía (Las Palmas de Gran Canaria)	21/04/2004	5000
6	Seawater desalination plant at Barcelona	06/06/2005	200000
7	Seawater desalination plant at Canal de Alicante	07/06/2005	50000
8	Extension of seawater desalination plant at Tordera (Girona)	07/06/2005	28800
9	Seawater desalination plant at Alcudia (Majorca)	23/06/2005	14000
10	Seawater desalination plant at Ciutadella (Minorca)	23/06/2005	10000
11	Seawater desalination plant at Santa Eulalia (Ibiza)	23/06/2005	10000
12	Seawater desalination plant at Andratx (Majorca)	23/06/2005	14000
13	New seawater desalination plant at Nuevo Canal de Cartagena (Murcia)	17/10/2005	65000
14	Extension of seawater desalination plant at Canal de Alicante	18/10/2005	15000
15	Seawater desalination plant at Tajo-Segura (Alicante)	13/03/2006	180000
16	New seawater desalination plant at Bajo Almanzora (Almería)	24/03/2006	60000
17	New seawater desalination plant at Águilas-Guadalentín. Extension of Águilas (Murcia)	21/04/2006	180000
18	Extension of brackish water desalination plant at El Mojón (Murcia)	08/05/2006	10000
19	Seawater desalination plant at Campo de Dalías (Almería)	22/06/2006	97200
20	Seawater desalination plant at Sagunto (Valencia)	05/09/2006	22900
21	Seawater desalination plant at Marina Alta (Dénia, Alicante)	12/09/2006	24000
22	Extension of seawater desalination plant at Ceuta	16/02/2007	8800
23	Seawater desalination plant at Marina Baja (Alicante)	05/03/2007	80000

24	Seawater desalination plant at Jávea (Alicante)*	06/03/2007	28000
25	Seawater desalination plant at Oropesa del Mar (Castellón)	08/06/2007	65000
26	Seawater desalination plant at Moncófar (Castellón)	31/10/2007	65000
27	Seawater desalination plant at Guía de Isora (Tenerife)	27/12/2007	14000
28	Seawater desalination plant at Costa del Sol (Málaga)	25/01/2008	50000
29	Seawater desalination plant at Granadilla (Tenerife)	28/11/2008	14000
30	Modification of Seawater desalination plant at Santa Eulalia (Ibiza)	26/11/2009	5000

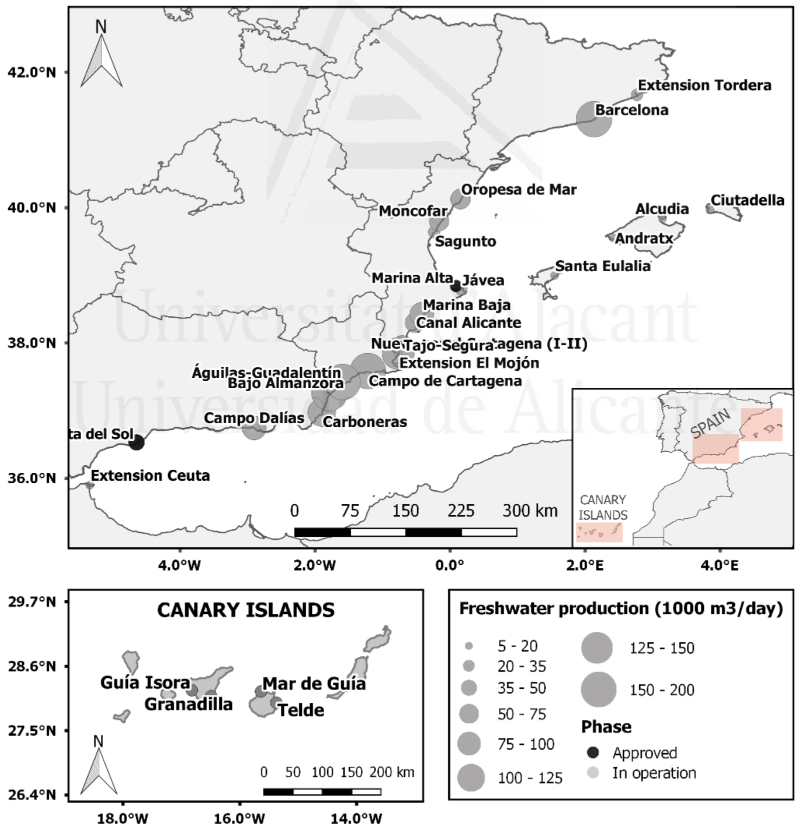


Figure 4.1. Location and production of desalination projects submitted to EIA in Spain between 1998 and 2018.

Maximum capacity of brine discharge production was evaluated using an average conversion rate of 45% for seawater (Palomar and Losada, 2010) and 60 % for brackish water (defined in the EIA of El Mojón desalination plant; ID:18, Table 4.1).

The EMP of each EIA was analyzed, and the requirements established for monitoring the impact of the brine discharges on the marine environment were extracted. The requirements of each EMP were evaluated according to the characteristics of each desalination plant and the environment(s) in which they discharge. EMP quality has been defined according to the presence or absence of the main descriptors that have been considered relevant in the scientific literature up to date for monitoring the potential impact of brine discharges (Fernández-Torquemada et al., 2019; Fernández-torquemada and Sánchez-lizaso, 2007; Lattemann and Höpner, 2008) (Fig. 4.2).

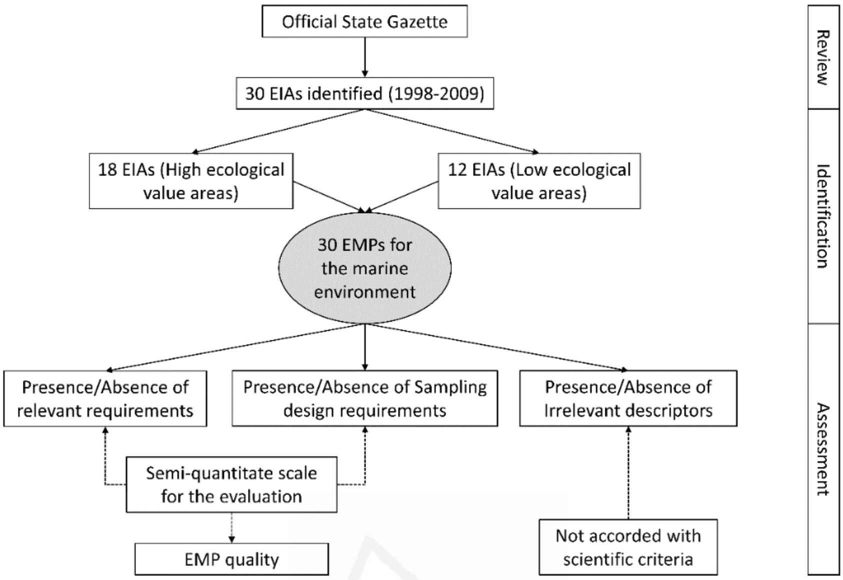


Figure 4.2. Flowchart of the procedure followed for the assessment of EMP quality

Research carried which has been out to date on the different marine environmental impacts of brine discharges highlights the requirements that are important to consider when monitoring brine discharges. These include: i-ii) the analysis of the quantity and **quality** of the **effluent** and **marine environment** including, at least, salinity and nutrients but also substances that come from the pre-treatment and cleaning of membranes and filters, as coagulants and antifouling or organic matter (Lin et al., 2013; Liu et al., 2018; Mezher et al., 2011; Portillo et al., 2014b); iii) the control of the **saline plume** to determine the area potentially affected by the brine discharge (Fernández-Torquemada et al., 2009). For this, it is necessary that the implementation of salinity profiles which reach the bottom are used to determine salinity and temperature in a grid of points that cover the potential area of influence, and with seasonal replication to include different oceanographic conditions (Fernández-Torquemada et al., 2009); iv) to monitor **key** and **protected species** if they are present in the area to ensure they are not affected by the discharge (Petersen et al., 2018a; Sánchez-Lizaso et al., 2008). In Spain, key species include the seagrasses *Posidonia oceanica* or *Cymodocea nodosa* and maërl beds [Directive 92/43/CEE; 31]; v) since discharges are usually on soft bottom sea beds, it is convenient to analyze **sediments** and associated infauna in the discharge area(s) (Del-Pilar-Ruso et al., 2015, 2009, 2007; Lin et al., 2013); vi) the use of salinity-sensitive species of benthic fauna as **bioindicators** has proven to be useful as sentinel species in order to prevent possible impacts on benthic habitats (De-la-Ossa-Carretero et al., 2016b; Fernández-Torquemada et al., 2013) and to discriminate between the effects of desalination and other impacts that may coincide in space (De-la-Ossa-Carretero et al., 2016a; Del-Pilar-Ruso et al., 2009); vii) it is necessary to carry out a structural monitoring of the **submerged outfall** for the early detection of possible fractures (Sadhwani Alonso and Melián-Martel, 2018); viii) in the case of a possible rupture of the outfall (or if the discharge is close to key habitats), the existence of a **protocol of action** with mitigation measures is convenient, given that this may include the increase of dilution, or the reduction of production (Sánchez-Lizaso et al., 2008).

The requirements considered in this study were assessed using a semi-quantitative scale, defined in Table 4.2. Once requirements were assessed, the **quality** of **each EMP** was defined as:

$$\boldsymbol{EMP\ quality_i} = \frac{\sum_i (\boldsymbol{E_{i,e}} + \boldsymbol{ME_{i,e}} + \boldsymbol{SP_{i,e}} + \boldsymbol{PK_{i,e,s}} + \boldsymbol{S_{i,e,s}} + \boldsymbol{B_{i,e,s}} + \boldsymbol{O_{i,e,s}} + \boldsymbol{P_{i,e}})}{\sum_i (\boldsymbol{E_i} + \boldsymbol{ME_i} + \boldsymbol{SP_i} + \boldsymbol{PK_{i,s}} + \boldsymbol{S_{i,s}} + \boldsymbol{B_{i,s}} + \boldsymbol{O_{i,s}} + \boldsymbol{P_i})} \times \mathbf{100}$$

where e is the evaluation of requirements that are important to consider in the monitoring of brine discharges of each EIA i, and s is the necessary or unnecessary control regarding characteristics of each desalination plant and the environment where are located the brine discharge. These characteristics were defined for the control of effluent (E_i) and marine environment (ME_i) quality, saline plume (SP_i), protected and key species (PK_i), the analysis of sediment (S_i), the use of a bioindicator (B_i), control of outfall (O_i), and the existence of protocol of action (P_i).

Table 4.2. Semi-quantitative scale used for the evaluation of environmental requirements of EMPs.

Score	Assessment of environmental requirements of EMPs
4	Control 100% of the parameters in the EMP
3	Sub-optimal control (control of 60–90% of the parameters in the EMP) and identify environmental impact on the marine environment
2	Partial control (control of 40–60% of the parameters in the EMP) and identify environmental impact on the marine environment
1	Insufficient control (control of 10–40% of the parameters in the EMP) and identify environmental impact on the marine environment
0	Absence of control and identify environmental impact on the marine environment

Moreover, this study considered the use of an adequate **sampling design** that allows discernment of the effects of the discharge from the spatial and temporal variability, while avoiding pseudo-replication (Hurlbert, 1984; Stewart-Oaten et al., 1986; Underwood, 1994). Therefore, the **sampling design** for requirements considered for monitoring brine discharges in each EMP was evaluated using the semi-quantitative scale defined in Table 4.2. The assessment of the sampling design was carried out by considering the temporary design; an adequate design with control-impact, and before-after comparison for a correct assessment of the environmental impact; and also, a description of the material or procedure used for carrying out the analysis of the requirements. Table 4.3 summarizes the requirements considered in the analysis of the EMPs.

Furthermore, **irrelevant parameters** were identified as those that do not result in better management of brine discharges to protect marine ecosystems when they are required in the EMPs. Thus, these descriptors are not supported by scientific criteria. Table 4.4 shows the irrelevant parameters identified in the EMPs evaluated.
Areas with **high** and **low** ecological value were established regarding the relevance of the ecosystem where the brine discharge was located. Criteria for defining areas of high ecological value were based on the distribution and presence of the protected species and relevant ecosystems, such as *Posidonia oceanica* or maërl beds (Ruiz et al., 2015). Student's t-tests (unpaired, one-tailed) were performed to compare the means of EMPs requirements and requirements of sampling designs between both areas. Shapiro-Wilk and F-test were conducted to verify the normality distribution and homogeneity of variance for each group. Significant difference was considered when $p<0.05$. Moreover, linear regressions were

conducted to evaluate the temporal evolution of EMPs requirements in both ecological areas and its relation to the production capacity of the desalination plants. Before accepting any model, an analysis of residuals was performed to detect observations with high influence on fitted values of the models. We measured the leverage and the Cook statistic of each sampling unit so that any sampling unit with higher leverage values and influence would be analyzed, and the model would be refitted to ensure uniformity. Statistical analyses and graphs were performed with R software (R Core Team, 2013).

4.3. Results

4.3.1. Desalination projects submitted to EIAs in Spain

A total of 30 desalination projects have been identified and submitted for an EIA, between 1998 and 2009, in Spanish Gazette. These are mainly distributed in the Southeast of the Mediterranean coast, and the Balearic and Canary Islands (Fig. 4.1). The majority of these projects were submitted between 2005 and 2007, and together represent 74% of total projects (Fig. 4.3).

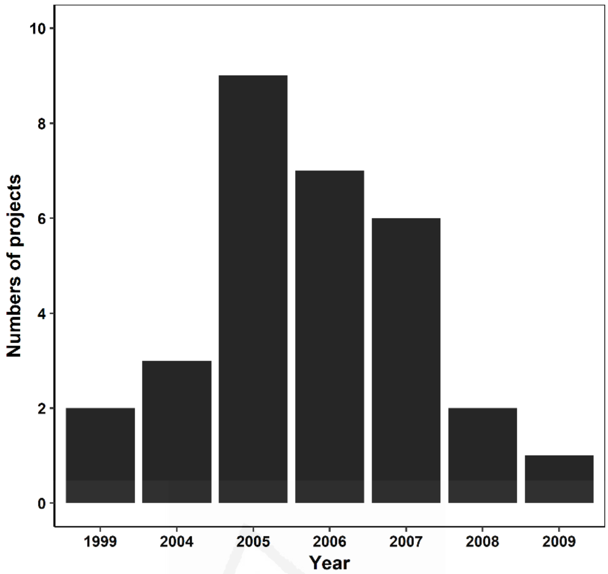


Figure 4.3. Number of desalination projects submitted to EIA each year in Spain.

On the other hand, the maximum freshwater production of the projects evaluated is 1.7 Mm^3/day, which approximately represents a maximum brine discharge production of 2.05 Mm^3/day (Fig. 4.4). Likewise, 74% of total freshwater and brine capacity production was installed between 2005 and 2007.

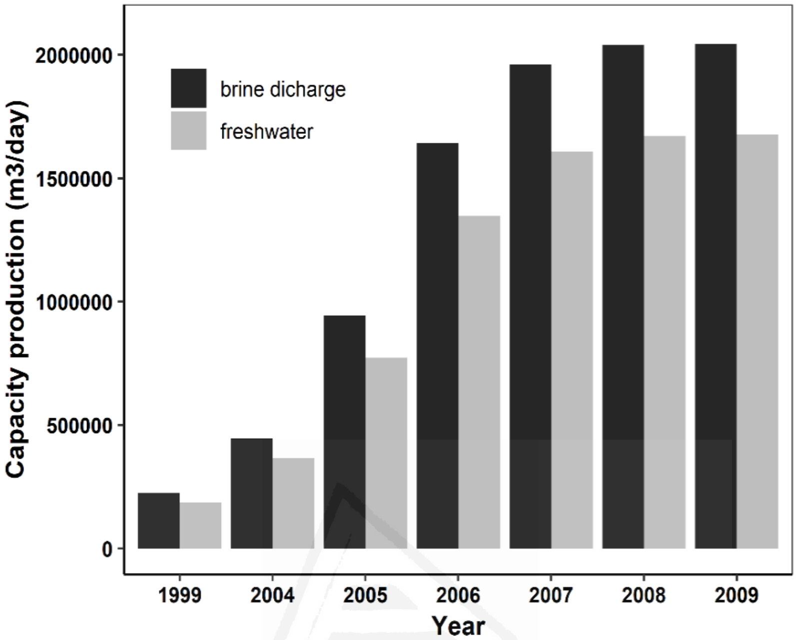


Figure 4.4. Evolution of production capacity and brine discharge volume for projects submitted to EIA.

Within the framework of different regions in Spain (Autonomous Communities), the majority of projects submitted for an EIA were carried out in Valencia (30%), followed by Murcia and the Balearic Islands (16.7%). Regions with the lowest number of projects submitted for an EIA were Catalonia and Ceuta at 6.7% and 3.3% respectively.

4.3.2. Analysis of requirements in EMPs

The results of the 30 EMPs evaluated are presented in Table 4.3. They showed a significant increase of environmental requirements in EMPs over time (Fig. 4.5; p=0.01).

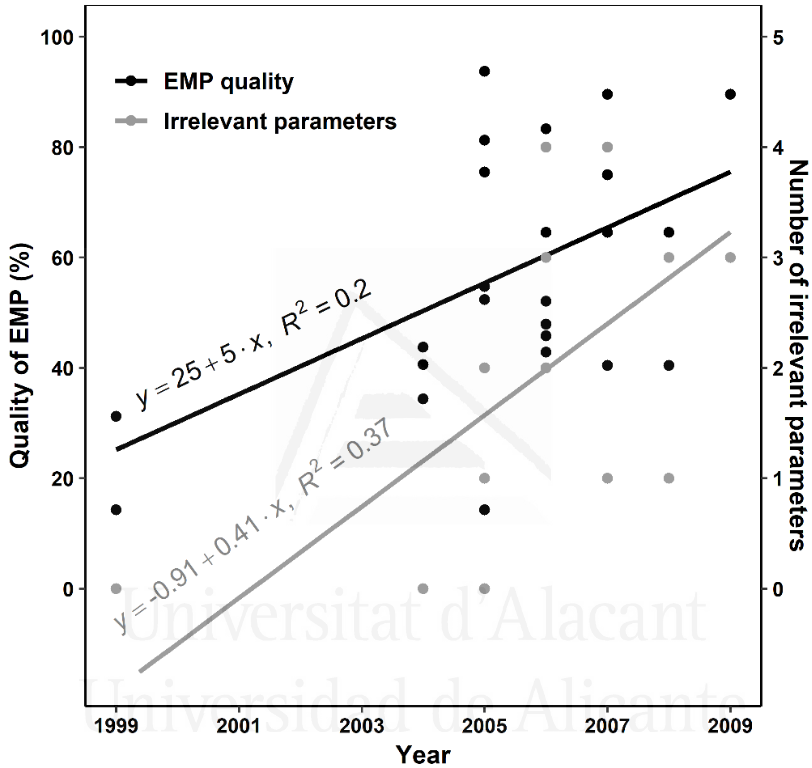


Figure 4.5. Linear regression showing the correlation between environmental requirements of EMPs and the published year of each EIA (black line), and linear regression showing the correlation between the number of irrelevant parameters required in the EMPs and their published year (gray line).

Likewise, EMPs with the lowest requirements were identified in 1999 and 2005 with 14.9% (IDs: 2, 6 and 8; Table 4.3), followed by 31.3% (ID: 1) and 34.4% (ID: 5) in 1999 and 2004 respectively. On the other hand, the EMPs with highest requirements were identified in 2005 with 93.8% (IDs: 9, 11 and 12; Table 4.3), followed by 89.6% in 2009 and 2007 (IDs: 30 and 23) and 83.3% in 2006 (ID:18). The average quality of EMPs analyzed was 57.8%, meaning that 50% of EMPs assessed are below the general average.

Table 4.3. Assessment of the 30 EMPs using the parameters defined for appropriate management of brine discharges into the marine environment.

ID	Protocol of action (P_i)	Key species (PK_i)	Saline plume (SP_i)	Control of outfall (O_i)	Effluent quality (E_i)	Bioindicator (B_i)	Marine environment (ME_i)	Sediment (S_i)	EMP quality	Sampling design	Ecological area
1	0.0	0.5	0.0	0.0	0.0	0.8	0.9	0.3	**31.2**	**26.8**	High
2	0.0	-	0.3	0.0	0.0	0.0	0.7	0.0	**14.3**	**0.0**	Low
3	0.5	0.5	0.3	0.0	0.7	0.3	1.0	0.0	**40.6**	**0.0**	Low
4	0.5	0.5	0.3	0.0	0.7	0.5	1.0	0.0	**43.8**	**31.0**	High
5	0.5	0.0	0.3	0.0	0.7	0.3	1.0	0.0	**34.4**	**26.2**	Low
6	0.5	-	0.3	0.0	0.2	0.0	0.0	0.0	**14.3**	**7.5**	Low
7	1.0	1.0	0.7	-	0.2	1.0	0.0	0.0	**54.8**	**38.9**	High
8	0.5	-	0.3	0.0	0.2	0.0	0.0	0.0	**14.3**	**7.5**	Low
9	1.0	1.0	1.0	1.0	1.0	0.5	1.0	1.0	**93.8**	**66.7**	High
10	1.0	1.0	1.0	0.0	1.0	0.5	1.0	1.0	**81.3**	**64.3**	High
11	1.0	1.0	1.0	1.0	1.0	0.5	1.0	1.0	**93.8**	**85.7**	High
12	1.0	1.0	1.0	1.0	1.0	0.5	1.0	1.0	**93.8**	**71.4**	High
13	1.0	0.9	1.0	1.0	0.2	1.0	0.0	1.0	**75.5**	**52.4**	High
14	1.0	1.0	0.7	-	0.0	1.0	0.0	0.0	**52.4**	**33.3**	High
15	1.0	1.0	1.0	0.0	0.7	0.5	0.0	0.0	**52.1**	**40.5**	High
16	1.0	1.0	1.0	1.0	0.7	0.5	0.0	0.0	**64.6**	**54.8**	High
17	1.0	1.0	1.0	1.0	0.7	0.5	0.0	0.0	**64.6**	**54.8**	High
18	1.0	0.9	1.0	1.0	0.8	1.0	0.0	1.0	**83.3**	**73.8**	High
19	1.0	0.0	1.0	1.0	0.8	0.0	0.0	0.0	**47.9**	**39.3**	Low
20	1.0	0.0	1.0	1.0	0.7	0.0	0.0	0.0	**45.8**	**39.3**	Low

21	1.0	0.5	0.3	-	0.7	0.5	0.0	0.0	**42.9**	**34.7**	High
22	1.0	1.0	1.0	1.0	0.7	1.0	0.0	0.3	**75.0**	**82.1**	High
23	1.0	1.0	1.0	1.0	0.7	0.5	0.0	0.0	**64.6**	**45.2**	High
24	1.0	0.5	1.0	1.0	1.0	1.0	0.7	1.0	**89.6**	**100.0**	High
25	1.0	1.0	1.0	1.0	0.7	0.5	0.0	0.0	**64.6**	**45.2**	Low
26	1.0	1.0	1.0	1.0	0.7	0.5	0.0	0.0	**64.6**	**45.2**	Low
27	0.0	-	0.3	1.0	0.5	0.0	1.0	0.0	**40.5**	**0.0**	Low
28	0.0	-	0.7	1.0	0.2	0.0	0.5	0.5	**40.5**	**27.5**	Low
29	1.0	1.0	1.0	1.0	0.7	0.5	0.0	0.0	**64.6**	**50.0**	Low
30	1.0	1.0	1.0	1.0	0.7	0.5	1.0	1.0	**89.6**	**71.4**	High
Frequency (%)	**78.3**	**77.0**	**75.6**	**66.7**	**57.6**	**47.5**	**39.2**	**30.6**	**57.8**	**43.9**	**60/40**

According to the environmental value of the area where the RO plant effluent was discharged, 18 EIAs were in areas with relevant ecosystems, and 12 were in areas with lower ecological value. The quality of EMPs for high-value areas showed a significant difference, with 69.2% of requirements compared to 40.5% in low-value areas (Fig. 4.6; p<0.001).

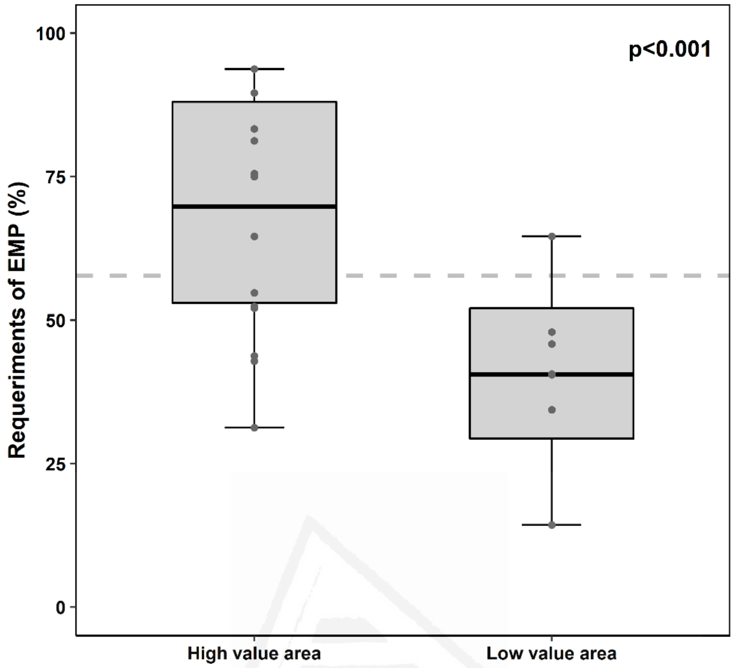


Figure 4.6. Comparison of requirements of EMPs between areas of high and low ecological values. Solid black line in the boxplots represents mean requirements of EMPs in each environmental area. Dashed gray line represents the general mean of EMPs requirements. The box limits in the boxplots represents the interquartile range. P-value is indicated. Means were considered significantly different when $p<0.05$ according to t-test statistical analysis.

Nevertheless, a significant trend to improve the requirements of EMPs over time was observed in both areas (Fig. 4.7; $p<0.05$). Finally, the quality of EMPs evaluated showed higher requirements when brine discharges were located in the regions where protected species are distributed (Fig. 4.8).

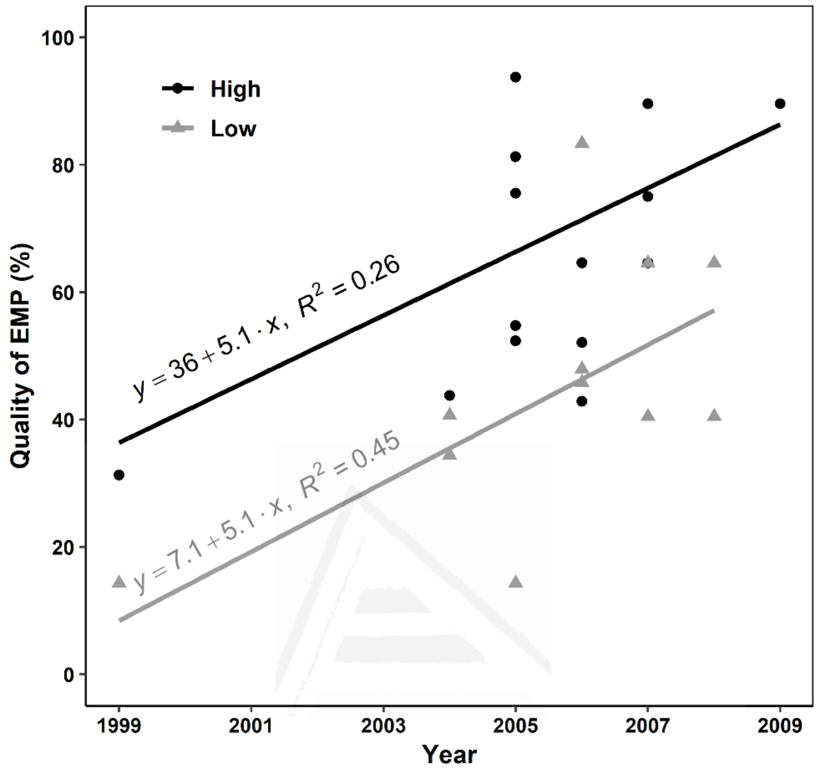


Figure 4.7. Linear regression between the environmental requirements of EMPs evaluated and the published year of each EIA for the two ecological areas defined.

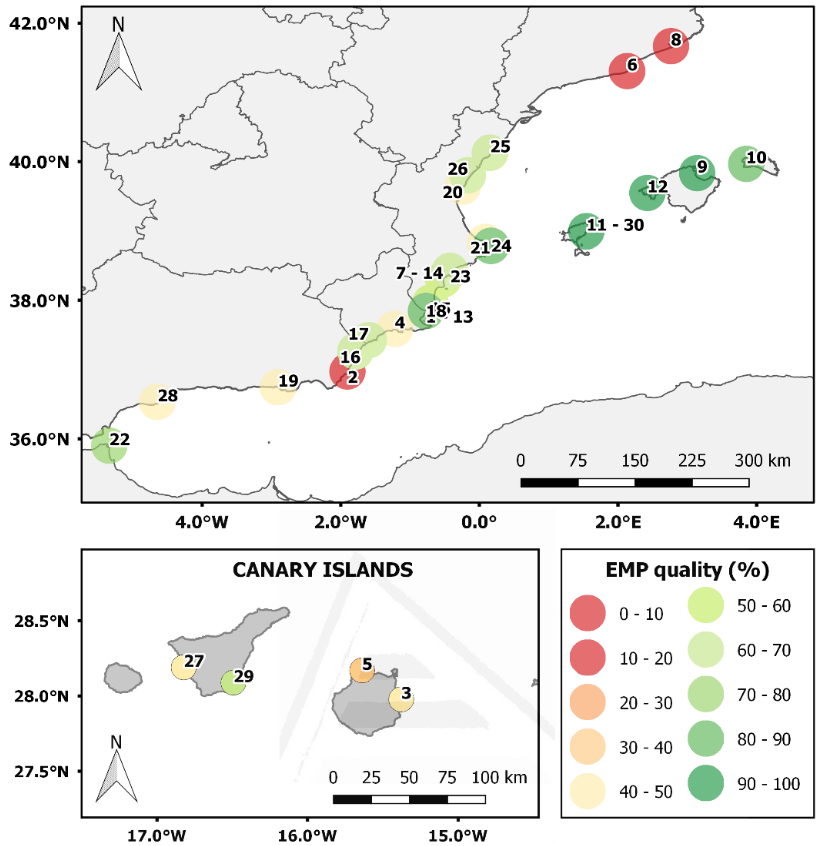


Figure 4.8. Environmental requirements of EMPs evaluated for the distribution of desalination projects submitted to EIA. Green regions show the regions with relevant ecosystems according to protected species (Ruiz et al., 2015).

Regarding the environmental requirements evaluated in EMPs, the requirements most frequently included (see Table 4.3) were the inclusion of a protocol of action (78.3%); the monitoring of key and protected species when they were present in the area of brine discharge (77%); the control of saline plume extension (75.6%); and, the inspection of the submerged outfall when this method of brine discharge was used (66.7%). The least implemented requirements were the control of effluent quality (57.6%); the inclusion of a bioindicator species (47.5%); the control of seawater quality in the area of brine discharge (39.2%); and, the analysis of the sediment (30.6%).

The histogram in Figure 4.9 indicates a general trend in both areas to improve the sampling design defined in EMPs. The overall average of sampling design requirements was 43.9% ± 26.1. However, the mean requirements for sampling designs in high ecological areas was significantly higher with 57.1% ± 21.1 compared to 24% ± 19.8 in low ecological areas ($p<0.05$).

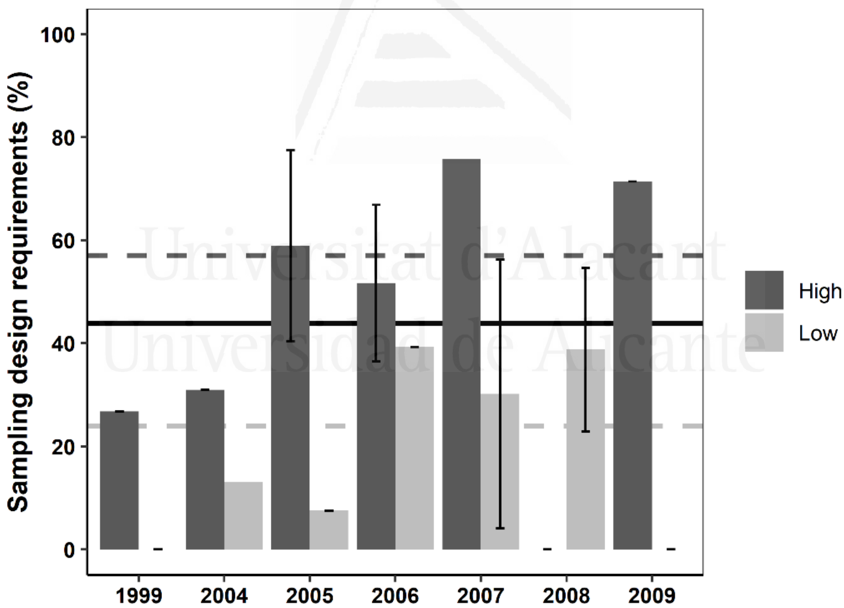


Figure 4.9. Percentage of sampling design requirements of EMPs (bars represent standard deviation). Solid black line indicates the general average of EMPs. Dashed dark-gray line indicates the average for high ecological value areas. Dashed light-gray line indicates the average for low ecological value areas.

Finally, a higher production rate does not imply higher environmental requirements of EMPs. In fact, linear regression showed a significant negative trend between the requirements of EMPs and the brine discharge production rates (Fig. 4.10; P<0.05).

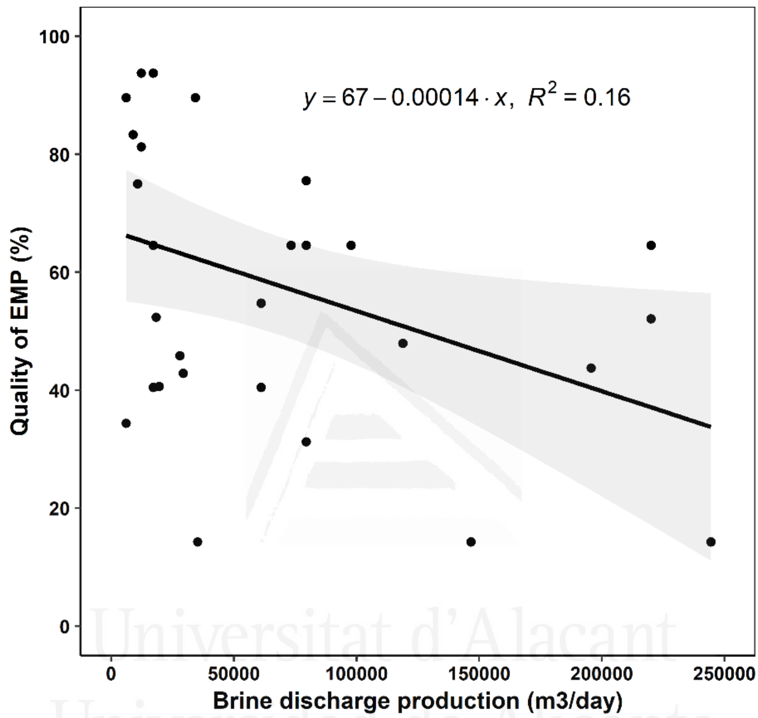


Figure 4.10. Linear regression between the requirements of EMPs and brine discharge production of projects evaluated.

4.3.3. Irrelevant parameters in EMPs

Irrelevant descriptors identified in the EMP analysis, and these are described in Table 4.4. Seven descriptors were identified in the analysis which do not contribute to a better environmental protection of marine environment(s) from discharge effluents. Moreover, a significant tendency to include irrelevant parameters over time has been observed, specifically between 2006–2009, where 84.9% of the total irrelevant parameters were identified (Fig. 4.5). Within the parameters identified, the requirement of sea state reports was the most frequently included parameter in EMPs (53.3%), followed by the monitoring of currents with 43.3%.

Table 4.4. Irrelevant descriptors identified in the EMPs. Requirement of the parameter in the EMP (1). Control of irrelevant descriptors is not needed (-). Salinity thresholds identified for *P. oceanica* not accorded for scientific criteria (Sánchez-Lizaso et al., 2008).

ID	Sea state	Currents monitoring	Flow variables	Salinity thresholds (ppt)	Sensors calibration	Heavy metals	Coastal dynamics
1	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-
7	1	-	-	38.3/39.5	-	-	-
8	-	-	-	-	-	-	-
9	-	-	-	38.3/39.5	-	1	-
10	-	-	-	38.3/39.5	-	1	-
11	-	-	-	38.3/39.5	-	1	-
12	-	1	-	38.3/39.5	-	1	-
13	1	-	-	38.3/39.5	-	-	-
14	1	-	-	38.3/39.5	-	-	-
15	1	1	1	38.5/40.5	-	-	-
16	1	-	1	-	-	-	-
17	1	1	1	-	-	-	-
18	1	1	-	-	-	-	-
19	1	1	1	-	-	-	-
20	1	1	1	-	-	-	-
21	1	1	1	38.5/40.5	1	-	-
22	1	1	1	-	1	-	-
23	1	1	1	-	1	-	-
24	-	-	-	-	-	-	1
25	1	1	1	-	1	-	-
26	1	1	1	-	1	-	-
27	-	-	-	-	-	1	-
28	-	1	-	-	-	-	-
29	1	1	-	-	1	-	-
30	1	-	1	-	1	-	-
Frequency (%)	**53.3**	**43.3**	**36.7**	**36.0**	**23.3**	**16.7**	**3.3**

On the other hand, salinity thresholds in EMPs for *P. oceanica* which differ to those recommended by scientific advice (Sánchez-Lizaso et al., 2008) were also identified. These improper thresholds were present in 36% of the EMPs with established salinity thresholds for *P. oceanica*. Finally, the requirement of calibration and replacement of conductivity sensors not linked with manufacturer's information, or international standards, was observed. It was present in 23% of EMPs.

4.4. Discussion

Currently, Spain has more than 700 desalination plants. Nevertheless, the majority of these represent plants with a low production capacity (AEDyR, 2018; Sadhwani Alonso and Melián-Martel, 2018). EIAs evaluated in this study represent approximately 33.5% of total production capacity in Spain, and the approximately 28% of desalinations plants exceeding 10.000 m^3/day (AEDyR, 2018; Sadhwani Alonso and Melián-Martel, 2018). It would be desirable to know environmental requirements for the discharge of all desalination plants, including smaller ones, and those that were developed before the application of environmental regulations and which are consequently without an environmental assessment (Spanish Government, 1988).

This is the first study to conduct an exhaustive analysis of the environmental requirements established in the EMPs for the management of discharges from RO plants in Spain. In Fuentes (2014), the EIA process for seawater desalination projects in Spain is reviewed, but EMPs from different projects are not evaluated.

EMPs should be designed correctly, and of course based on the best scientific knowledge available (Fernández-torquemada and Sánchez-lizaso, 2007). Given advances in scientific knowledge, it is possible to highlight what environmental impacts may occur in the areas where the brine discharges are located (Petersen et al., 2018a) and, therefore, what requirements are important to consider in EMPs (Fernández-torquemada and Sánchez-lizaso, 2007). High heterogeneity in the environmental requirements of the EMPs evaluated has also been observed. EMPs requirements have increased significantly over time in Spain, and are higher in areas with the presence of protected species in comparison with areas of low ecological value. But no relationship was observed between these requirements and brine discharge production. It would be desirable to pay more attention to plants with higher production during the environmental assessment since they may produce a higher impact upon the marine environment. Moreover, the increase of environmental requirements is not necessarily related to a better knowledge of potential impacts that may be produced by desalination plans since it has been observed that a similar increase in irrelevant parameters- or incorrectly defined descriptors- occurs in EMPs over time. It is not justified to require monitoring for parameters that are not related to the discharge, or that do not improve environmental protection given that these parameters for the management of brine discharges leads to an unnecessary increase in the economic costs of EMPs without increasing the protection of marine ecosystems.

On the other hand, the majority of EMPs evaluated require an improvement in their sampling designs. It is important to consider an adequate sampling design to detect the potential impacts from brine discharges on marine ecosystems. They should include multiple reference locations and replicated sampling before, and after, the brine discharge starts (Roberts et al., 2010). The use of an inadequate sampling design complicates the statistical assessment and furthermore hinders knowledge of the potential effects on marine ecosystems (Roberts et al., 2010; Underwood, 1994). Thus, EMPs with correct sampling design aid in detecting the impacts of desalination plants on marine environment, and they can be mitigated (Del-Pilar-Ruso et al., 2015). We analyzed the requirements established in EMPs, but we have no data to examine whether, in practice, they are implemented correctly, or if they include additional descriptors over the minimum established by EMPs.

On the basis of the results obtained, a review should be desirable and emphasize the initial EMPs developed (IDs: 1-8). As, the majority of requirements evaluated are poorly implemented and the average of the EMP quality reached is 31%, their sampling designs may not detect the environmental impacts on brine discharge area (17.2% of sampling design requirements implemented).

EMPs correctly defined allow sustainable management of RO effluents. Thus, it is possible to identify and mitigate environmental impacts on the marine environment when EMPs are being correctly implemented (Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2013). EMPs demonstrate appropriate pre-designs and effectiveness of measures adopted during the development of EIAs (Clark et al., 2018; Malfeito et al., 2005; Missimer and Maliva, 2018). For instance, the recommendations adopted in Jávea desalination plant (ID: 24) of placing the brine discharge to anoxic channel adopting diffusers and through bypassing seawater revealed the absence of environmental impacts in discharge area (Malfeito et al., 2005). Nevertheless, in the case of Alicante (ID: 7 and 14) and Nueva Canal Cartagena desalinations plants (ID: 1 and 13) the EMPs detected impacts on benthic fauna to adopt measures to revert them (De-la-Ossa-Carretero et al., 2016c; Del-Pilar-Ruso et al., 2015, 2008; Fernández-Torquemada et al., 2013); therefore, EMPs should be flexible in order to adapt to unpredictable scenarios or the best current scientific knowledge. Thus, it is possible that the adoption of mitigation measures accorded to the impacts identified (Kress, 2019b). Further, long-term monitoring systems help in understanding changes in the ecosystem that not associated with the operation of RO plants and with providing information to coastal residents regarding the absence of mitigation impacts when the mitigation measures are adopted (Clark et al., 2018; Fernández-Torquemada et al., 2019; Heck et al., 2018; Missimer and Maliva, 2018).

In this research we analyzed the EMPs as defined in the EIAs. Further research in this field will be necessary to study: i) the environmental licenses approved by the different regions (Autonomous Communities), given that they could include additional or irrelevant requirements; ii) assess the economic costs of monitoring irrelevant parameters in EMPs, and the economic cost of adding relevant requirements when they are absent in EMPs; and, iii) evaluate the implementation EMPs.

4.5. Conclusions

Requirements for the monitoring of brine discharges and their sampling designs in the EIAs have improved over time, but this trend is similar for both essential and irrelevant descriptors. Additionally, the presence of protected species in the area(s) of RO effluents showed a significant correlative effect with greater requirements in the EMPs. Nevertheless, there was no increase of environmental requirements with respect to a major brine discharge production rate.

A high heterogeneity has been observed in EMP, and a review of the EIAs would be advisable to unify the monitoring requirements at the national level. We would also recommend a simultaneous improving of their sampling designs, including the essential descriptors of when they are absent, as well as eliminating irrelevant parameters when they are present. This standardization should be based on the most up-to-date scientific advice, and pay particular attention to desalination plants with higher production rates, as they have a demonstrably greater influence upon the marine environment.

4.6. Acknowledgments

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CHAPTER 5: Assessment of the requirements within the environmental monitoring plans used to evaluate the environmental impacts of desalination plants in Chile

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Assessment of the Requirements within the Environmental Monitoring Plans Used to Evaluate the Environmental Impacts of Desalination Plants in Chile

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Abstract: Seawater desalination represents an alternative solution to face the challenge of water scarcity in Chile. However, the uncertainty toward potential environmental impacts of desalination plants represent a barrier to achieving water sustainability and socioeconomic development in Chile. This study aimed to assess the quality of environmental monitoring plans (EMP) and determine the aspects to be improved within it, in order to enhance the management of desalination plants during the operation phase and guarantee a sustainable development of the activity. The Environmental Impact Assessments (EIAs) and Environmental Impact Studies for seawater desalination projects published in the Environmental Impact Evaluation System (SEIA) in Chile between 1997 and 2018 were reviewed. The results of the brine production from desalination plants showed a significant increase in the last decade (about 1.6 Mm^3 per year estimated according to the projects approved or under implementation). The EMPs data show heterogeneity and increasing requirements over time, which can be attributed to the governmental effort to improve environmental protection. Furthermore, a high frequency of irrelevant descriptors was identified in the current EMPs. The study thus recommended standardizing the environmental requirements included in EMPs based on empiric scientific knowledge to enhance the environmental protection programs in Chile.

Keywords: environmental management plan; seawater desalination; environmental impact; brine discharge; reverse osmosis

1. Introduction

The continuous increase in global freshwater demand highlights the important role played by desalination to address water scarcity [1]. In Latin America, climate change poses critical challenges,

5. ASSESSMENT OF THE REQUIREMENTS WITHIN THE ENVIRONMENTAL MONITORING PLANS USED TO EVALUATE THE ENVIRONMENTAL IMPACTS OF DESALINATION PLANTS IN CHILE

Abstract

Seawater desalination represents an alternative solution to face the challenge of water scarcity in Chile. However, the uncertainty toward potential environmental impacts of desalination plants represents a barrier to achieving water sustainability and socioeconomic development in Chile. This study aimed to assess the quality of Environmental Monitoring Plan (EMP) and determine the aspects to be improved within it, in order to enhance the management of desalination plants during the operation phase and guarantee a sustainable development of the activity. The Environmental Impact Assessment (DIA) and Environmental Impact Studies (EIA) for seawater desalination projects published in the Environmental Impact Evaluation System (SEIA) in Chile between 1997 and 2018 were reviewed. The results of the brine production from desalination plants showed a significant increase in the last decade (about 1.6 Mm^3 per year estimated according to the projects approved or under implementation). The EMPs data show heterogeneity and increasing requirements over time, which can be attributed to the governmental effort to improve environmental protection. Furthermore, a high frequency of irrelevant descriptors was identified in the current EMPs. The study thus recommended standardizing the environmental requirements

included in EMPs based on empiric scientific knowledge to enhance the environmental protection programs in Chile.

Keywords: environmental management plan; seawater desalination; environmental impact; brine discharge; reverse osmosis

5.1. Introduction

The continuous increase in global freshwater demand highlights the important role played by desalination to address water scarcity (Shahzad et al., 2017). In Latin America, climate change poses critical challenges, among which water scarcity is one of the most important (Mata-Torres et al., 2017). In Chile, which is highly affected by climate change (Ancapichun, 2015; Bonelli et al., 2014), desalination of seawater using reverse osmosis has been proven to improve the social and economic sustainability of the country, because it can provide water for both human consumption and industrial activities. The industries in Chile, especially the copper and lithium mining industries, require very large quantities of water. In addition, Chile faces a critical challenge in providing water for the cities near to the Atacama Desert, which is considered the driest desert in the world. Owing to the geographic characteristics of Chile, with 6400 km of coastline and an average width of 180 km, seawater desalination is considered the best alternative to solve current and future challenges regarding water scarcity in the country (Mineria, 2012; Molinos-Senante and González, 2018).

The salinity of brine discharges from reverse osmosis plants is up to double that of seawater. In addition, they often contain chemicals used in the pretreatment and membrane cleaning processes. Some of these chemicals may be toxic to marine organisms (Portillo et al., 2014b). Brine tends to accumulate on the benthic area near the outfall, due to its high density with respect to seawater, and it then moves toward deeper waters following the bottom bathymetry (Fernández-Torquemada et al., 2009). Therefore, it can induce stress responses in marine organisms, mainly benthic communities near the brine discharge (De-la-Ossa-Carretero et al., 2016b; Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2013; Petersen et al., 2018a; Portillo et al., 2014b; Roberts et al., 2010). Thus, these uncertainties regarding the environmental impacts of desalination on coastal systems represent a barrier to Chile's water sustainability and socioeconomic development.

In Chile, the environmental impact assessment process is perceived as an important legal instrument to pursue environmental protection, sustainable development, and marine conservation (Lacy et al., 2017). It is considered the most powerful management tool controlling environmental impacts from seawater reverse osmosis (SWRO) plants. However, normative and protocols related to SWRO plants are still under consideration. The environmental assessment process for the development of desalination plants in Chile began in 1997 through the Environmental Impact Evaluation System (*Servicio de Evaluación de Impacto Ambiental*, SEIA). Desalination projects submitted to SEIA could be assessed in two types of environmental assessment regarding the characteristics of these projects, as their specific effects or circumstances. Thus, projects with less involvement are being assessed through the Environmental Impact Assessment (*Declaración de Impacto Ambiental*, DIA), and projects with more involvement are being assessed through the Environmental Impact Study (*Estudio de Impacto Ambiental*, EIA) (de la Maza, 2001; Lacy et al., 2017). In [15], there are additional details about the environmental assessment process in Chile. Environmental monitoring plans (EMPs) ensure the effectiveness of the preventive and corrective measures established in DIAs or EIAs to protect marine environments (Sadhwani Alonso and Melián-Martel, 2018). EMPs can identify potential negative environmental impacts of desalination discharges and mitigate them by adopting adequate measures (Del-Pilar-Ruso et al., 2015).

However, the weaknesses and gaps within the DIA or EIA frameworks must be fully understood and addressed. This study aims to assess the quality of EMPs and identify the process aspects that need improvement to achieve sustainable operation of desalination plants in Chile. This information can be used to conduct critical analyses to achieve the followings: (a) propose key environmental parameters that should be measured to identify the impacts of brine discharges, and (b) recognize the strengths and weaknesses within the current DIAs and EIAs frameworks in order to protect marine ecosystems from potential detrimental effects of the desalination industry.

5.2. Materials and Methods

A review of the DIAs and EIAs related to the construction and expansion of desalination projects in Chile was carried out based on the data compiled in the SEIA between 1997 and 2018 (http://seia.sea.gob.cl). A total of 24 desalination projects were identified, with three SWRO plants (IDs: 1, 7, and 15 in Table 5.1) that did not present EMPs for evaluation. Figure 5.1 shows the location of the desalination projects identified. Therefore, 21 EMPs for discharging brine effluents from SWRO plants were evaluated.

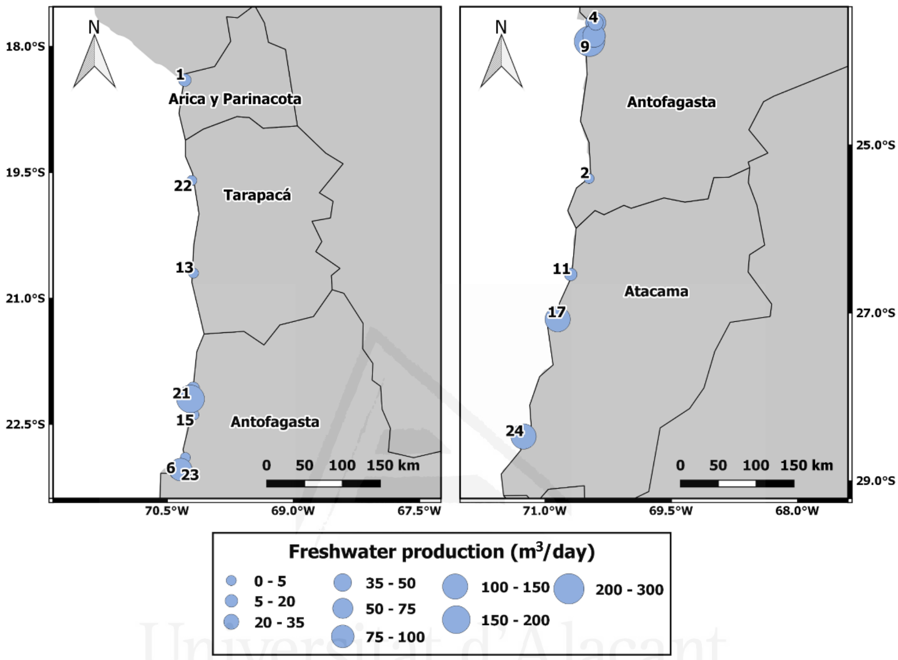

Figure 5.1. Location of desalination projects and their maximum production capacity (m^3/day) submitted to the Environmental Impact Evaluation System (SEIA) between 1997 and 2018 in Chile.

Table 5.1. Publications of desalination projects approved by Chile's SEIA.

ID	Projects Approved or in Operation Submitted to Chile's SEIA	Date	Typology	Region	Fresh water Production (m^3/day)	Time Project (days)
1	*Arica* desalination plant	16/09/1997	EIA	XV	17798	347
2	*Taltal* submarine emissary	02/12/1998	EIA	II	432	182
3	*Antofagasta II Región* desalination plant	18/05/1999	DIA	II	79920	253
4	*Agua de Mar Antofagasta* desalination plant	27/09/2001	DIA	II	51840	118
5	*Lixiviación de Sulfuros*	29/08/2003	EIA	II	86400	242
6	Desalination plant implementation	07/10/2004	DIA	II	375	169
7	Piloto desalination plant	18/10/2004	DIA	II	45360	73
8	*Angamos* Thermoelectric plant	07/09/2007	EIA	II	4800	319
9	Complementary Supply of Desalinated Water for *Minera Escondida*	12/06/2009	EIA	II	276480	280
10	*Hornitos* desalination plant	27/12/2010	DIA	II	375	207
11	Desalinated Water Supply for *Mantoverde*	13/05/2011	DIA	III	10368	358
12	Planta Desalinizadora *Minera Candelaria*	24/06/2011	EIA	III	43200	330
13	Rural freshwater system. *Chanavayita* desalination plant	09/03/2012	DIA	I	775	123
14	*Sur Antofagasta* desalination plant	07/09/2012	DIA	II	86400	352
15	*Mantos de la Luna* second modification	14/06/2013	DIA	II	750	231
16	Update and Expansion of *La Chimba* Desalination Plant	07/07/2014	DIA	II	21600	336
17	*Bahía Caldera* desalination plant	13/07/2015	DIA	III	8000	581
18	*Tocopilla* desalination plant	13/05/2016	DIA	II	17280	449
19	*Región de Atacama, Provincias de Copiapó y Chañaral* desalination plant	17/08/2016	EIA	III	103680	392

20	Extension of *Angamos* Thermoelectric plant	18/08/2016	EIA	II	13680	622
21	*Pisagua* desalination plant	12/07/2017	DIA	I	345.6	567
22	Desalination plant and industrial water supply	15/06/2017	DIA	II	86400	685
23	Adaptation of the Desalination Plant *RT Súlfuros*	09/03/2018	DIA	II	168998	198
24	*Guacolda* desalination plant	24/01/2018	DIA	III	120956	225

The possible environmental impacts of each case were analyzed in order to perform adequate management of the brine discharges based on scientific criteria and achieve sufficient environmental protection. Thus, EMP requirements were specified according to the characteristics of the SWRO desalination plants and the marine ecosystem at the location of the brine effluent discharge.

The EMP requirements for monitoring the effects on marine ecosystems during the operation phase were identified. This approach also identifies the requirements for correct management of brine discharges (Sola et al., 2019b) and some considerations related to the characteristics related the Chilean environment for sustainable management of SWRO desalinations plants during the operation phase. The important requirements highlighted by this approach include: (i,ii) analysis of the composition of the effluent water and seawater is advisable to control the substances present in the effluents—in particular, those caused by the pretreatment or cleaning of membranes, such as coagulants, antifouling compounds, and nutrients; (iii) determination of the saline plume extension, because it can help in specifying the area potentially affected by the discharge; (iv) using salinity-sensitive species as bio-indicators, which was proven to be useful, because they can provide information on possible impacts on benthic habitats and allow a discrimination between the effects of desalination and other impacts that may coincide in space, such as the effects of sewage discharges; (v) analysis of the ecological and chemical qualities of the sediments in order to quantify the impact on the benthic in the discharge area; (vi) conducting a structural monitoring of the submerged outfall for the early detection of possible fractures and leaks; and (vii) implementing a contingency plan that includes mitigation measures to control and correct the identified detrimental effects in cases when negative effects on benthic communities, such as infauna or sensitive species, are evidenced (De-la-Ossa-Carretero et al., 2016b; Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2009; Mezher et al., 2011; Petersen et al., 2018a; Sadhwani Alonso and Melián-Martel, 2018).

Additional considerations were included in this approach to adopt it within the Chilean environmental legislation according to the specific characteristics of the Chilean environment and marine communities. Firstly, (viii) the potential effects of seawater intake on plankton communities were incorporated. The effects of the brine effluent on plankton communities is unknown; nevertheless, plankton cannot survive during the seawater intake (Petersen et al., 2018a). (ix) Moreover, toxicity testing is included in order to evaluate the effects of chemicals used in the pretreatment or membrane cleaning on the endemic species around the outfall area (Kress, 2019a). Finally, no protected species, such as *P. oceanica* in Spain or *P. australis* in Australia, were identified in the outfall area; hence, the evaluation of how the effluents affect them was not considered a requirement in the EMPs (Roberts et al., 2010; Sánchez-Lizaso et al., 2008).

The requirements extracted of each EMP were assessed using a semiquantitative scale (Table 5.2) following the method proposed by (Sola et al., 2019b).

Table 5.2. Semiquantitative scale used for evaluating the environmental requirements of environmental monitoring plans (EMPs).

Score	Assessment of environmental requirements of EMPs
-	Absence of control, without environmental impact for its necessary control
4	Control 100% of the parameter in the EMP
3	Suboptimal control (control of 60–90% of the parameters in the EMP). Identified environmental impact on the marine environment
2	Partially control (control of 40–60% of the parameters in the EMP). Identified environmental impact on the marine environment
1	Insufficient control (control of 10–40% of the parameters in the EMP). Identified environmental impact on the marine environment
0	Absence of control, identified environmental impact on the marine environment

Finally, the quality of each EMP was estimated using Equation as follows:

$$\boldsymbol{EMP\ quality_i} = \frac{\sum_i \left(\boldsymbol{E_{i,e}} + \boldsymbol{SW_{i,e}} + \boldsymbol{SP_{i,e}} + \boldsymbol{S_{i,e,s}} + \boldsymbol{B_{i,e,s}} + \boldsymbol{O_{i,e,s}} + \boldsymbol{CP_{i,e}} + \boldsymbol{PK_{i,e,s}} + \boldsymbol{T_{i,e}}\right)}{\sum_i \left(\boldsymbol{E_i} + \boldsymbol{SW_{i,}} + \boldsymbol{SP_i} + \boldsymbol{PK_{i,s}} + \boldsymbol{S_{i,s}} + \boldsymbol{B_{i,s}} + \boldsymbol{O_{i,s}} + \boldsymbol{CP_i} + +\boldsymbol{PK_{i,s}} + \boldsymbol{T_i}\right)} \times \mathbf{100}$$

where e is the evaluation of requirements considered for managing desalination plants during the operation phase of each EMP i, and s is the necessary or unnecessary control parameters determined according to the characteristics of each desalination plant and the environment at the brine discharge location. The following parameters were considered according to these characteristics: the analysis of effluents and seawater quality (E_i, SW_i), saline plume (SP_i), analysis of sediment (S_i), use of bio-indicators (B_i), structural monitoring of the submerged outfall (O_i), existence of contingency plan (CP_i), analysis of plankton communities in the seawater intake area PK_i, and use of toxicological studies (T_i).

Furthermore, sampling designs of each EMP were evaluated. Sampling process design is defined according to the spatial and temporal variability to avoid pseudo-replication and allow the detection of significant differences among samples (Hurlbert, 1984; Underwood, 1994). Therefore, the following requirements were considered important for an adequate sampling design: (i) the spatial–temporal characteristics of the sampling design; (ii) the correct description of the procedure to carry out the analysis of requirements; (iii) and the inclusion of before-after-control-impact (BACI) to understand the environmental impacts of SWRO desalination plants on marine ecosystems (Roberts et al., 2010).

In addition, irrelevant requirements were also evaluated. They are defined as those requirements that do not result in better control of the desalination plants during the operation phase and/or those with insignificant effects on the environment. These requirements are typically not based on scientific criteria and are not useful for managing SWRO plants during the operation phase (Sola et al., 2019b). Finally, linear regressions were performed to assess the incorporation of EMP requirements, irrelevant parameters and sampling design requirements over time, and relationships between

EMP requirements and the production capacity of SWRO plants. Significant levels were set at $p < 0.05$. R software was used to conduct statistical analyses and prepare graphs (R Core Team, 2013).

5.3. Results

5.3.1. Current State of Desalination in Chile

A total of 32 new constructed projects were submitted to DIA or EIA in Chile's SEIA from 1997 to 2018. A total of 75% of these projects were approved, 18.8% were not accepted or desisted, and only 6.3% are currently under assessment (Fig. 5.2).

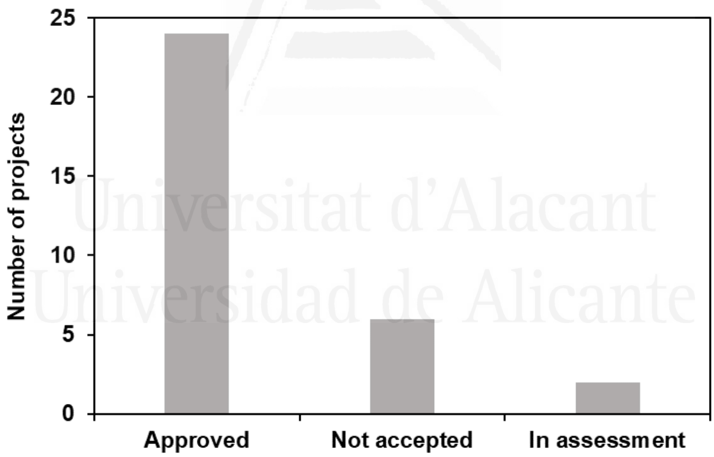

Figure 5.2. Number of desalination projects submitted to SEIA in Chile between 1997 and 2018 categorized by their status (approved, not accepted, and under assessment).

A total of 24 of the approved projects, which represent 62.5% of all approved projects between 2011 and 2018, were compiled (Fig. 5.3). Among these, projects submitted to DIA and EIA represented 66.7% and 33.3%, respectively, of the total (Table 5.1). The majority of these projects (66.7%) have been installed in the Antofagasta Region (Second region), while 20.8% of the approved projects are located in the Atacama (Third region). Currently, the extension of desalination to the central regions is under study.

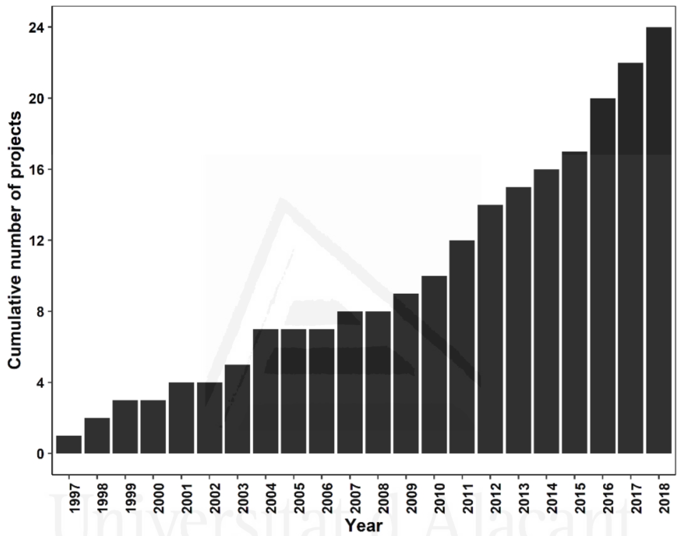

Figure 5.3. Cumulative number of desalination projects approved per year in Chile between 1997 and 2018.

The desalination sector in Chile is expanding at an increasing rate. This increase is divided between the private and public sectors (Fig. 5.4). Desalination for public use started in 1997 and significantly increased from 2012. By contrast, desalination for industrial use started growing in 2003, which until 2011 represented 53% of water production capacity for the industry, and continued to increase afterwards (Fig. 5.4).

The maximum production capacity among the projects evaluated was approximately 1.26 Mm^3/day, which represents a maximum brine discharge capacity of nearly 1.57 Mm^3/day, assuming an average plant conversion rate of 45% when brine production was not specified in the DIA or EIA (Meneses et al., 2010).

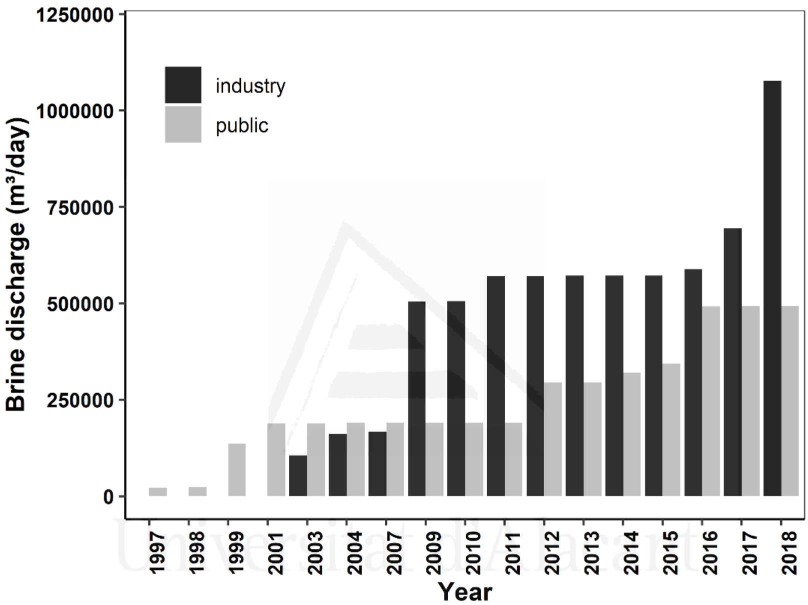

Figure 5.4. Assessment of the accumulated brine discharge production (m^3/day) in the Chilean industrial and public sectors.

Furthermore, the increasing development in the desalination industry in Chile caused an increase in the duration of environmental assessments. Thus, results showed a significant increase in the duration of the environmental assessment process over time in Chile ($p < 0.01$, Fig. 5.5). No significant differences were observed in the duration of the environmental assessment related with the different administrative procedure (DIA or EIA).

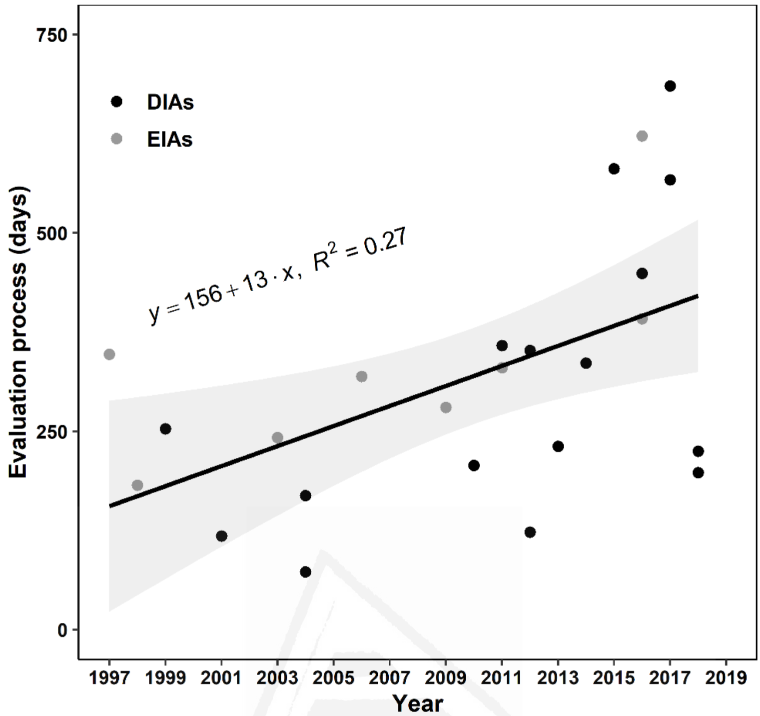

Figure 5.5. Linear regression between the period of the evaluation process (days) of projects and the publishing year in the SEIA.

5.3.2. Environmental Requirements in the EMPs of Chile's Desalination Plants

The results of the EMPs assessment show a high heterogeneity in the EMP requirements. Table 5.3 shows the analysis of EMP requirements for each project and the quality of the 21 EMPs evaluated.

Table 5.3. Assessment of the 21 EMPs using the parameters defined for the correct control and mitigation of the impacts caused by SWRO plants on the marine environment.

ID	Saline Plume	Bio-Indicator	Plankton	Sediment	Water Quality	Effluent Quality	Bio-Toxicity	Contingency Plan	Outfall Inspection	EMP Quality
1	-	-	-	-	-	-	-	-	-	-
2	0.67	0.00	0.00	0.83	1.00	0.17	0.00	0.00	0.00	29.63
3	0.67	0.75	0.00	0.00	0.33	0.00	1.00	0.00	0.00	30.56
4	0.67	0.75	0.00	0.00	0.33	0.17	0.00	0.00	0.00	21.30
5	1.00	1.00	0.00	0.00	0.00	0.58	0.00	0.00	0.00	28.70
6	1.00	0.00	0.00	1.00	1.00	0.54	1.00	0.00	0.00	50.46
7	-	-	-	-	-	-	-	-	-	-
8	1.00	0.50	1.00	0.67	0.33	0.00	0.00	0.00	0.00	38.89
9	1.00	1.00	1.00	0.33	0.67	0.58	0.00	0.00	0.00	50.93
10	0.67	0.50	0.00	0.33	0.00	0.58	0.00	0.00	0.00	23.15
11	1.00	1.00	1.00	1.00	0.67	0.54	1.00	0.50	0.25	77.31
12	1.00	0.75	1.00	0.67	0.33	0.17	0.00	0.00	0.50	49.07
13	1.00	0.50	1.00	1.00	1.00	0.58	0.00	0.00	0.00	56.48
14	1.00	0.50	0.00	0.33	0.33	0.17	0.00	0.25	0.00	28.70
15	-	-	-	-	-	-	-	-	-	-
16	1.00	1.00	1.00	0.33	0.50	0.17	1.00	0.25	0.00	58.33
17	1.00	1.00	0.50	1.00	0.00	0.58	0.00	0.00	0.00	45.37
18	1.00	1.00	1.00	0.33	0.33	0.92	1.00	0.75	1.00	81.48
19	1.00	1.00	1.00	0.33	0.67	0.33	1.00	0.00	1.00	70.37
20	1.00	1.00	1.00	0.67	0.33	0.00	0.00	0.00	0.00	44.44
21	1.00	0.50	0.00	0.67	1.00	0.58	0.00	1.00	0.00	52.78
22	1.00	1.00	1.00	0.33	0.75	0.33	0.00	1.00	1.00	71.30
23	1.00	1.00	1.00	0.33	0.33	0.17	0.00	0.50	0.00	48.15
24	1.00	0.50	1.00	1.00	0.33	0.54	0.00	0.75	-	64.06
Freq. (%)	**93.65**	**72.62**	**59.52**	**53.17**	**48.81**	**36.71**	**28.57**	**23.81**	**18.75**	**48.64**

The results of this study show a significant increasing trend in the environmental requirements within Chile's EMPs over time ($p < 0.01$; Fig. 5.6). The highest environmental requirements reached 81.5% in 2016 (ID: 18; Table 5.2), followed by those in 2011 (ID 11), 2017 (ID 22), and 2016 (ID 19, equivalent to more than 70% of requirements), respectively. By contrast, the lowest environmental requirements were identified in ID 4 (2001) with 21% of the requirements, followed by ID 10 (2010), ID 14 (2012), ID 5 (2003), and finally ID 2 (1998) with less than 30% of the requirements. The EMPs assessed were found to have an average quality of 48.64%. Furthermore, the relationship between maximum production capacity of SWRO plants and the requirements of EMPs was found to have high heterogeneity. This shows that there is no trend or relationship between plant capacity and environmental control requirements ($p > 0.05$).

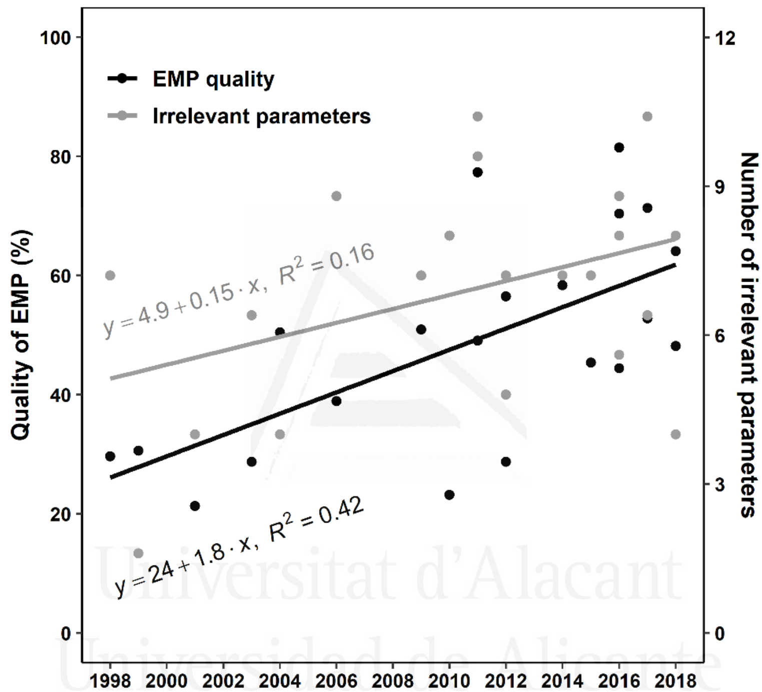

Figure 5.6. Linear regression between the number of environmental requirements in Chile's EMPs and the publishing year in the SEIA (black line) as well as the linear regression between the number of irrelevant parameters in EMPs and their publishing year (gray line).

In addition, a high heterogeneity was observed between the parameters included in the EMPs (Table 5.3). The parameters most frequently included in EMPs were the control of saline plume; bio-indicators; plankton; and sediment analyses, which were applied in

93.7%, 72.6%, 59.5%, and 53.2% of the EMPs, respectively. The parameters that were less frequently included in the EMPs were the analysis of seawater; assessment of effluent quality; development of bio-toxicological analysis of endemic species around the brine discharge area; a contingency plan for the brine discharge; and inspection of the submerged outfall, which were applied in 48.8%, 36.7%, 28.6%, 23.8%, and 18.8% of the EMPs, respectively.

The results of EMPs distribution for each project evaluated showed that the Atacama Region had the highest requirements in the EMPs (61.2%) followed by the Taracapá Region (54.6%). Figure 5.7 shows the quality of EMPs based on the distribution of desalination plants in Chile.

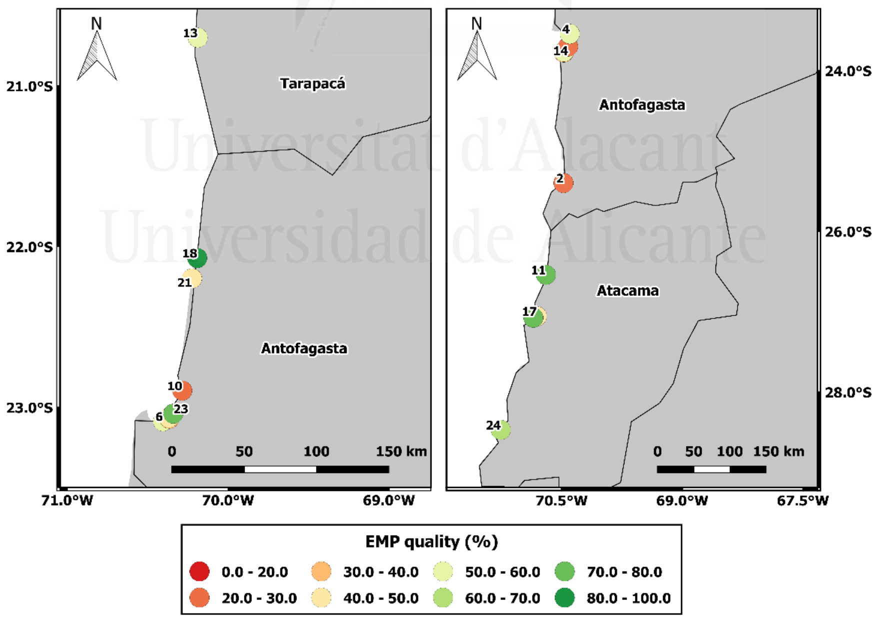

Figure 5.7. EMP quality assessed based on the distribution of desalination projects in Northern Chile.

In general terms, sampling designs defined in Chile's EMPs were found to be correctly established, since a 76% ± 14.9 general average was reached (Fig. 5.8). In addition, linear regression between the sampling design requirements and the publishing year of each DIA/EIA showed a significant trend of improving in the EMP sampling designs over time ($p < 0.01$).

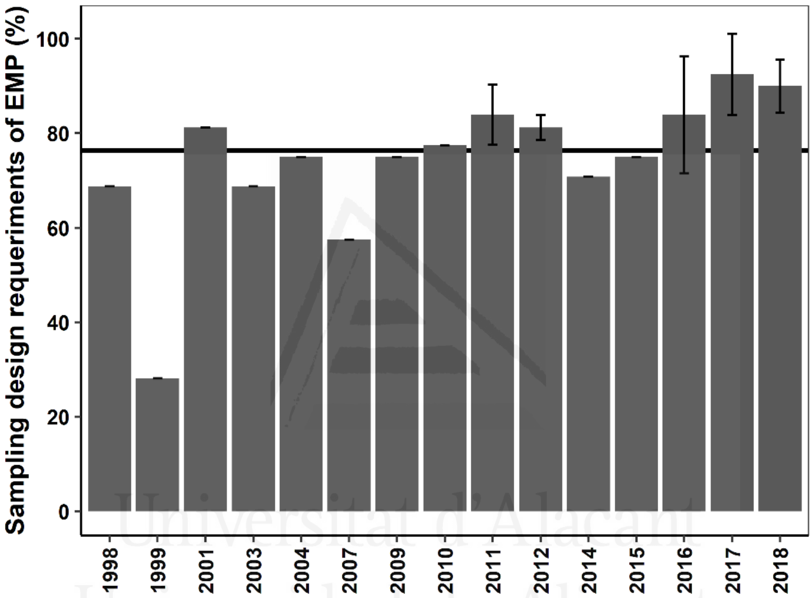

Figure 5.8. Mean values of sampling design requirements for each EMP assessed (bars represent standard deviation and solid black line indicates the general average).

5.3.3. Irrelevant Parameters Identified in EMPs

The improvement in environmental requirements was found to be associated with a slightly increasing trend in irrelevant parameters in EMPs, although this trend was not significant ($p = 0.07$; Fig. 5.6). Table 5.4 shows the irrelevant parameters identified, i.e., those parameters that do not contribute to an accurate environmental diagnosis and protection. The average number of irrelevant parameters of EMPs reached seven.

The maximum number of descriptors found within the irrelevant parameters identified after the assessment of the quality of the effluent represented 46.6% of the total. These parameters are mainly associated with the analysis of fats and oils, hydrocarbons, metals, and coliforms. A 30.8% of the irrelevant parameters determined in seawater were found to be associated with of the concentration of metals, coliforms, hydrocarbons, foaming power, etc., while 10.3% of the irrelevant parameters were related to monitoring intertidal and littoral communities and associated sediments. Finally, 8.9% of the total irrelevant parameters corresponded to physicochemical description of sediments (e.g., concentration of metals, hydrocarbons, sulfur content, and surface carbon particles), and the other 3.4% were associated with the monitoring of other parameters, such as oceanographic and atmospheric characterization near the brine discharge (refer to Table 5.A to 5.E in Appendix 5.8).

Table 5.4. Irrelevant parameters identified in EMPs for each requirement.

ID	Effluent	Seawater	Biological	Sediment	Others	Total
1	0	0	0	0	0	0
2	0	6	2	0	0	8
3	0	1	1	0	0	2
4	4	-	-	0	0	4
5	6	0	0	0	0	6
6	1	1	1	0	1	4
7	0	0	0	0	0	0
8	0	4	0	3	0	7
9	6	0	1	0	0	7
10	6	0	1	0	1	8
11	0	5	3	2	1	11
12	4	5	1	1	0	11
13	5	2	0	0	0	7
14	3	0	1	0	0	4
15	0	0	0	0	0	0
16	3	2	0	2	0	7
17	6	0	1	0	0	7
18	6	2	0	0	0	8
19	0	4	1	0	2	7
20	0	4	0	3	0	7
21	6	3	1	1	0	11
22	4	2	1	0	0	7
23	4	0	0	0	0	4
24	4	4	0	1	0	9
Total	**68**	**45**	**15**	**13**	**5**	**146**

5.4. Discussion

The analysis of projects submitted to SEIA provided a perspective of the brine production expected from the operative and projected SWRO plants in Chile. In the last decade, the production capacity of desalinated water in the country has notably increased, representing 77% of the total production of freshwater, and used for different applications (Valdés-Pineda et al., 2014). However, this significant development results in huge brine effluents delivered to the marine environment. Desalination is considered an important solution to solve the problem of water scarcity in Chile, especially for semiarid and arid areas (Central and Northern Chile). Moreover, 68% of the total production capacity evaluated is aimed at the industrial sector. However, there has been a marked increase in the production of desalinated water for the public sector since 2012. Water supplies in the semiarid and arid zones are intensified by the huge freshwater demand for industrial applications, especially in the mining industry (Valdés-Pineda et al., 2014). Moreover, the number of desalination projects is expected to increase toward the south as a result of the accompanied climate change-driven displacement of the Atacama Desert (Mata-Torres et al., 2017). The investigations conducted in this study demonstrate that about 88% of the projects in the Antofagasta and Atacama Regions have been submitted to SEIA, which include those approved or currently subjected to evaluation.

This increase in desalinated water production may cause negative impacts on the marine ecosystems with incorrect environmental management of the SWRO plants operation as a result of the brine discharges (Petersen et al., 2018a; Roberts et al., 2010). The results show that the brine discharge production in Chile was about 1.6

Mm^{3}/day from all desalination projects currently operating or under the SEIA consideration. Thus, there is an urgent need for correct implementation of EMPs for desalination projects in order to ensure the environmental protection of the locations, where the currently operating plants discharge their effluents, facilitate the installation of new SWRO projects, and increase their economic viability through only focusing on the parameters that are environmentally relevant.

The significant increasing trend in the control requirements within EMPs over time in all 21 EMPs evaluated reflects an awareness of the local authorities (led by the Ministry of the Environment of Chile) to solve the water scarcity crises through environmentally sustainable practices. However, environmentally relevant parameters in current EMPs reached only 48.6% of the total requirements. Thus, improvements, especially related to monitoring the seawater and brine qualities by including biological tools for environmental diagnosis, are necessary (e.g., assessment of bio-indicators, biomarkers, and/or stress responses) using local species; contingency plans to apply mitigation measures when environmental impacts are identified; and frequent outfall inspection for the early detection of possible leaks or fractures. These are highlighted as the main considerations for future EMPs, because they are only considered in 50% of the current EMPs.

Similar results were obtained in the study conducted by (Sola et al., 2019b), which showed a significant trend in improving the environmental requirements and sampling designs in Spain’s EMPs; however, the majority of EMPs in Spain displayed less appropriate sampling designs compared to the Chilean EMPs. A good sampling design allows better detection of potential negative effects on the marine environment, so that they can be mitigated and controlled (Del-Pilar-Ruso et al., 2015). To address the latter, it is essential to increase spatial/temporal variabilities in the environmental requirements of the assessment conducted in the affected area of the brine discharge and in control locations (Roberts et al., 2010).

Although DIA is a relative brief procedure compared with EIA [14], no significant differences were found between them in the period of evaluation or in requirements included in EMPs for desalination projects analyzed.

A number of disadvantages have been identified in the assessment of EMPs in Chile. For instance, no relation was found between the environmental requirements and the increase in the brine discharge from SWRO plants. However, an increase in the brine production may lead to creation of saline plumes and an increase in the affected area (Fernández-Torquemada et al., 2009). Similarly, an increase in the freshwater production is related to an increase in the seawater intake capacity, which could affect the surrounding plankton communities (Petersen et al., 2018a). On the other hand, the irrelevant parameters (77.4% of the total) are better suited to other types of effluents, such as sewage and wastewaters from agriculture (Aguilera et al., 2019), but not from the SWRO plant operation.

In terms of biomonitoring, it is important to adopt requirements that focus on species with high probability of occurrence in the affected area. SWRO plants evaluated in this study use submerged outfalls as discharge method; thus, monitoring the intertidal and littoral communities, which are unlikely to be affected, has little value to the environmental diagnosis (Fernández-Torquemada et al., 2009; Loya-Fernández et al., 2018). Including these irrelevant parameters in the assessment increases the cost of EMPs and does not offer valuable information.

There are a lot of relevant studies in the literature documenting impacts from desalination discharges. However, the available published information is of little use in the evaluation of impacts on Chilean coastal systems. Model species, for which impacts are examined in these studies, have a completely different ecological structure and potential tolerance thresholds compared to the marine communities of the Humboldt system dominant in the Chilean coastline. Therefore, it is difficult to envision recommendations for sustainable and biologically nonthreatening operation to be incorporated in the EMPs, due to the absence of toxicological assessments on local species and communities. Considering that only 28.5% of the EMPs assessed implement these analyses, further investigations are required to generate basic information on biological effects of brines on Chilean coastal communities, which are valuable information for the development of up-to-date biomonitoring protocols to achieve accurate and reliable environmental diagnosis. These actions are essential to keep up with the fast growth of the SWRO industry in Chile that is expected to further increase due to climate change. However, according to the international experience in Spain and Australia, negative impacts of SWRO discharges on the marine environment caused by the development in desalination sector can be efficiently mitigated (Clark et al., 2018; De-la-Ossa-Carretero et al., 2016c; Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2013; Petersen et al., 2018a).

Research has proven that marine macrophytes are a suitable species for biomonitoring that can reflect the impacts of the desalination industry—for example, marine angiosperms including *Posidonia oceanica* found in the Mediterranean Sea (Marín-Guirao et al., 2013; Sánchez-Lizaso et al., 2008; Sandoval-Gil et al., 2012) or *Posidonia australis* found in Australia (Cambridge et al., 2017). In addition, the authors of (Sola et al., 2019b) showed that areas with protected species, such as *P. oceanica,* indicated greater environmental requirements in their EMPs for monitoring the effect of brine effluents on marine ecosystems. This, added to their ecological relevance as a base of trophic networks, suggests that macroalgae and kelp forests, since they are dominant in Chilean coastal ecosystems, would make good candidates for future eco-toxicological assessments regarding brine discharge impacts in Chile (Wernberg et al., 2019).

5.5. Conclusions

The assessment of the requirements stated in the Chilean EMPs revealed a high heterogeneity between projects and indicates that it needs to be improved and updated according to sound scientific evidence. The significant increasing trend in the control requirements within EMPs over time reflects an increasing awareness of the local authorities to solve the water scarcity crises through environmental sustainability. However, a review of EMPs is necessary to include all relevant requirements when they are absent and eliminate irrelevant descriptors that are not related to better protection of marine ecosystems. This will ensure real environmental protection and avoid unnecessary economic losses due to the study of irrelevant, and sometimes costly, descriptors. Finally, special consideration should be taken of EMPs for plants with high water production, which are the most likely to induce environmental impacts.

5.6. Author Contributions

Conceptualization, J.L.S.L., D.Z., and C.A.S..; methodology, I.S.; formal analysis, I.S. and J.L.S.L.; investigation, I.S., P.T.M. and E.G.B.; data curation, I.S.; writing—original draft preparation, I.S.; writing—review and editing, all authors; supervision, C.A.S. and J.L.S.L..; funding acquisition, D.Z. and C.A.S.

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The authors declare no conflict of interest.

5.8. Appendix. Irrelevant parameters by monitoring area

Table 5.A. Irrelevant descriptors identified in the effluent monitoring.

ID	Fat/oils	Hydrocarbons	Metals	Coliforms	Phenols	Chloroethenes/ Methanes	Total
1	-	-	-	-	-	-	-
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	1	1	1	0	1	0	4
5	1	1	1	1	1	1	6
6	1	0	0	0	0	0	1
7	-	-	-	-	-	-	-
8	0	0	0	0	0	0	0
9	1	1	1	1	1	1	6
10	1	1	1	1	1	1	6
11	0	0	0	0	0	0	0
12	1	1	1	0	1	0	4
13	1	1	1	1	1	0	5
14	1	1	0	1	0	0	3
15		-	-	-	-	-	
16	1	1	0	1	0	0	3
17	1	1	1	1	1	1	6
18	1	1	1	1	1	1	6
19	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
21	1	1	1	1	1	1	6
22	1	1	1	0	1	0	4
23	1	1	1	0	1	0	4
24	1	1	1	1	0	0	4
Total	**15**	**14**	**12**	**10**	**11**	**6**	**68**

Table 5.B. Irrelevant descriptors identified in the seawater monitoring.

ID	Metals	Coliforms	Foaming Power	Hydrocarbons	Fat / Oils	Phenols	Chlorophyll	HAT/ Color	Carbon/ Organic Matter	Total
1	-	-	-	-	-	-	-	-	-	-
2	1	1	1	1	1	0	0	1	0	6
3	1	0	0	0	0	0	0	0	0	1
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	1	0	0	0	0	1
7	-	-	-	-	-	-	-	-	-	-
8	1	1	0	0	0	0	0	1	1	4
9	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0
11	1	0	1	1	1	1	0	0	0	5
12	1	0	1	1	1	1	0	0	0	5
13	0	1	0	0	1	0	0	0	0	2
14	0	0	0	0	0	0	0	0	0	0
15	-	-	-	-	-	-	-	-	-	-
16	1	0	0	0	0	0	1	0	0	2
17	0	0	0	0	0	0	0	0	0	0
18	0	1	1	0	0	0	0	0	0	2
19	0	0	1	1	0	1	1	0	0	4
20	1	1	0	0	0	0	0	1	1	4
21	1	1	0	0	0	0	1	0	0	3
22	1	0	0	1	0	0	0	0	0	2
23	0	0	0	0	0	0	0	0	0	0
24	1	1	1	1	0	0	0	0	0	4
Total	**10**	**7**	**6**	**6**	**5**	**3**	**3**	**3**	**2**	**45**

Table 5.C. Irrelevant descriptors identified in the monitoring of biological parameters.

ID	Intertidal Communities	Littoral Communities	Intertidal Sediments	Littoral Sediments	Total
1	-	-	-	-	-
2	1	0	1	0	2
3	1	0	0	0	1
4	0	0	0	0	-
5	0	0	0	0	0
6	0	1	0	0	1
7	-	-	-	-	-
8	0	0	0	0	0
9	1	0	0	0	1
10	1	0	0	0	1
11	1	1	0	1	3
12	1	0	0	0	1
13	0	0	0	0	0
14	1	0	0	0	1
15	-	-	-	-	-
16	0	0	0	0	0
17	1	0	0	0	1
18	0	0	0	0	0
19	1	0	0	0	1
20	0	0	0	0	0
21	1	0	0	0	1
22	1	0	0	0	1
23	0	0	0	0	0
24	0	0	0	0	0
Total	**11**	**2**	**1**	**1**	**15**

Table 5.D. Irrelevant descriptors identified in the sediment monitoring.

ID	Metals	Hydrocarbons	Sulphurus	Surface Carbon Particles	Total
1	-	-	-	-	-
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	0	0	0	0
7	-	-	-	-	-
8	1	0	1	1	3
9	0	0	0	0	0
10	0	0	0	0	0
11	1	1	0	0	2
12	0	1	0	0	1
13	0	0	0	0	0
14	0	0	0	0	0
15	-	-	-	-	-
16	1	1	0	0	2
17	0	0	0	0	0
18	0	0	0	0	0
19	0	0	0	0	0
20	1	0	1	1	3
21	0	1	0	0	1
22	0	0	0	0	0
23	0	0	0	0	0
24	1	0	0	0	1
Total	**5**	**4**	**2**	**2**	**13**

Table 5.E. Others irrelevant descriptors identified.

ID	Current Monitoring	Sea State/Wind	Total
1	-	-	-
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	1
7	-	-	-
8	0	0	0
9	0	0	0
10	0	1	0
11	1	0	1
12	0	0	0
13	0	0	0
14	0	0	0
15	-	-	-
16	0	0	0
17	0	0	0
18	0	0	0
19	1	1	2
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0
24	0	0	0
Total	**3**	**2**	**5**

CHAPTER 6: Sustainable desalination: long-term monitoring of brine discharge in the marine environment

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Sustainable desalination: Long-term monitoring of brine discharge in the marine environment

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ABSTRACT

The environmental impact of desalination is the most important concern related to its sustainable development. We present the results of a long-term environmental plan to monitor brine discharge (BD) from a desalination plant located in a high environmental value area in Spain. Generalized additive models were used to analyze the biological parameters of biological communities. Results of 17 years of BD monitoring show how its environmental impact can be minimized through well-planned decision-making between scientists and industry. The brine dilution prior to its discharge into an artificial channel of low ecological value significantly reduced the brine influence area. *P. oceanica* shoot production and echinoderms abundances were relatively stable across historical series and similar values in control and impacts locations were observed. Conversely, there was a higher abundance and species richness of fishes in the BD area. The important findings reported here should be considered for future applications in similar projects.

1. Introduction

Given the increased global demand for freshwater, desalination technology has become a feasible alternative to standard freshwater procurement methods and may help to address global water scarcity. Population growth and economic development are the key drivers of global water scarcity, but climate change is also likely to alter hydro-climatic conditions and thereby increase water scarcity (Hejazi et al., 2014; Hoekstra, 2014; Sun et al., 2019). In the last decade, the number of desalination projects has substantially increased in all major regions worldwide; however, the majority of freshwater production primarily takes place on the Mediterranean coast, Arabian Gulf, and around the Red Sea (Jones et al., 2019). In Spain, the Mediterranean peninsular coast and Balearic and Canary Islands are areas of high water stress mainly due to tourism, population growth, and intensive agriculture; in these areas, the desalination industry plays an important role in mitigating water scarcity (Hernández-Sánchez et al., 2017; Sadhwani Alonso and Melián-Martel, 2018).

Currently, reverse osmosis (RO) is the most commonly used technology in desalinated water production due to its efficiency and lower economic costs relative to those of other technologies (Jones et al., 2019; Mezher et al., 2011; Zarzo and Prats, 2018). The RO process produces a brine discharge (BD) that is commonly discharged into seawater (Missimer and Maliva, 2018). BDs are mainly characterized by a high salinity concentration that can double seawater salinity depending on the intake water salinity and recovery rate of the RO process (Abessi, 2018; Fernández-Torquemada et al., 2019; Mezher et al., 2011). When released into seawater, BDs form a high-density plume that follows the bottom bathymetry. Saline plume dispersion varies significantly depending on effluent characteristics, such as desalination plant production, and BD disposal method (Fernández-Torquemada et al., 2019; Fernández-Torquemada et al., 2009; Loya-Fernández et al., 2018; Petersen et al., 2019; Portillo et al., 2014a). In addition, BDs may contain the chemicals that are commonly used in desalination during pre-treatment and in the membrane and filter cleaning processes; these may include antiscalants, coagulants, antifouling agents, biocides, and antifoaming agents, which are all subsequently discharged with the BD (Lattemann and Höpner, 2008; Liu et al., 2013; Mezher et al., 2011; Portillo et al., 2014b). The characteristics of BDs may therefore have environmental impacts on the marine environment when they are

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6. SUSTAINABLE DESALINATION: LONG-TERM MONITORING OF BRINE DISCHARGE IN THE MARINE ENVIRONMENT

Abstract

The environmental impact of desalination is the most important concern related to its sustainable development. We present the results of a long-term environmental plan to monitor brine discharge (BD) from a desalination plant located in a high environmental value area in Spain. Generalized additive models were used to analyze the biological parameters of biological communities. Results of 17 years of BD monitoring show how its environmental impact can be minimized through well-planned decision-making between scientists and industry. The brine dilution prior to its discharge into an artificial channel of low ecological value significantly reduced the brine influence area. *P. oceanica* shoot production and echinoderms abundances were relatively stable across historical series and similar values in control and impacts locations were observed. Conversely, there was a higher abundance and species richness of fishes in the BD area. The important findings reported here should be considered for future applications in similar projects.

Keywords: sustainable desalination; environmental monitoring plan; brine discharge; environmental impact; seawater reverse osmosis

6.1. Introduction

Given the increased global demand for freshwater, desalination technology has become a feasible alternative to standard freshwater procurement methods and may help to address global water scarcity. Population growth and economic development are the key drivers of global water scarcity, but climate change is also likely to alter hydro-climatic conditions and thereby increase water scarcity (Hejazi et al., 2014; Hoekstra, 2014; Sun et al., 2019). In the last decade, the number of desalination projects has substantially increased in all major regions worldwide; however, the majority of freshwater production primarily takes place on the Mediterranean coast, Arabian Gulf, and around the Red Sea (Jones et al., 2019). In Spain, the Mediterranean peninsular coast and Balearic and Canary Islands are areas of high water stress mainly due to tourism, population growth, and intensive agriculture; in these areas, the desalination industry plays an important role in mitigating water scarcity (Hernández-Sánchez et al., 2017; Sadhwani Alonso and Melián-Martel, 2018).

Currently, reverse osmosis (RO) is the most commonly used technology in desalinated water production due to its efficiency and lower economic costs relative to those of other technologies (Jones et al., 2019; Mezher et al., 2011; Zarzo and Prats, 2018). The RO process produces a brine discharge (BD) that is commonly discharged into seawater (Missimer and Maliva, 2018). BDs are mainly characterized by a high salinity concentration that can double seawater salinity depending on the intake water salinity and recovery rate of the RO process (Abessi, 2018; Fernández-Torquemada et al., 2019; Mezher et al., 2011). When released into seawater, BDs form a high-density plume that follows the bottom bathymetry. Saline plume dispersion varies significantly depending on effluent characteristics, such as desalination plant production, and BD disposal method (Fernández-Torquemada et al., 2019, 2009; Loya-

Fernández et al., 2018; Petersen et al., 2019; Portillo et al., 2014a). In addition, BDs may contain the chemicals that are commonly used in desalination during pre-treatment and in the membrane and filter cleaning processes; these may include antiscalants, coagulants, antifouling agents, biocides, and antifoaming agents, which are all subsequently discharged with the BD (Lattemann and Höpner, 2008; Liu et al., 2013; Mezher et al., 2011; Portillo et al., 2014b). The characteristics of BDs may therefore have environmental impacts on the marine environment when they are improperly managed (Fernández-Torquemada et al., 2019; Kress, 2019; Petersen et al., 2018; Sharifinia et al., 2019).

BDs may produce on marine environment a reduction of abundance and diversity of benthic communities in which BDs become situated (De-la-Ossa-Carretero et al., 2016c; Del-Pilar-Ruso et al., 2009, 2008; Petersen et al., 2018a). They may have a potential effect particularly on organisms most sensitive to salinity increases such as echinoderms (Fernández-Torquemada et al., 2013) or seagrasses (Cambridge et al., 2017; Garrote-Moreno et al., 2014; Marín-Guirao et al., 2013; Sánchez-Lizaso et al., 2008; Sola et al., 2020b). They may also be used as bioindicators to prevent the environmental impacts from BDs (De-la-Ossa-Carretero et al., 2016b; Fernández-Torquemada et al., 2013). Recent studies show that BDs may also have negative effects on the bacterial activity of benthic bottoms, zooplankton and fish larvae (Frank et al., 2019, 2017; Petersen et al., 2018a). When impacts on the marine environment are observed it is usually due to a low dilution of the BD and they may be reverted increasing the BD dilution with diffusers of with seawater by-passing (Belatoui et al., 2017; De-la-Ossa-

Carretero et al., 2016c; Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2013).

In addition, the impingement and entrainment of seawater through submerged pipelines or open intakes on the shoreline potentially affects fish eggs and small marine organisms such as plankton and larvae, which are removed from the seawater during the desalination process due to their small size and lack of (or limited) swimming ability (Missimer and Maliva, 2018; Petersen et al., 2018a; Sharifinia et al., 2019). Likewise, these seawater intake systems collect organic matter, nutrients, and microorganisms that require the use of aggressive pre-treatments as additional chemical additives, and higher filter and membrane cleaning frequencies, the products of which are subsequently discharged with the BD (Fernández-Torquemada et al., 2019).

Given that the collective characteristics of desalination effluents can produce negative effects on marine ecosystems if proper mitigation measures are not applied (De-la-Ossa-Carretero et al., 2016b; Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2013), Environmental Monitoring Plans (EMPs) are typically established to monitor the effectiveness of mitigation measures and ensure the sustainable operation of desalination technology without environmental impacts from BDs (De-la-Ossa-Carretero et al., 2016b; Petersen et al., 2019; Sadhwani Alonso and Melián-Martel, 2018; Sola et al., 2019b). Indeed, environmental impact is the most important concern for the sustainable development of desalination (Ibrahim et al., 2018). The uncertainty in various countries surrounding the environmental impact of desalination may represent a barrier for desalinated water production (Sola et al., 2019a).

With the aim of allaying this uncertainty, our study presents 17 years of data from an EMP designed to monitor the brine effluent from Javea SWRO plant in Spain. Here, we evaluate the measures adopted during the development of a project in which industry and environmental science collaborated to effectively achieve a long-term sustainable operation with low impact on the surrounding marine environment.

6.2. Material and methods

6.2.1. Case study of Javea SWRO plant

The Javea SWRO plant, which began operations in June 2002, is located on the Spanish Mediterranean coast in an area of high environmental value due mainly to the presence of *Posidonia oceanica* seagrass meadows (Fig. 6.1); the area is protected by habitat Directive 92/43/CEE (EU, 1992) and national regulations (Spanish Government, 1986).

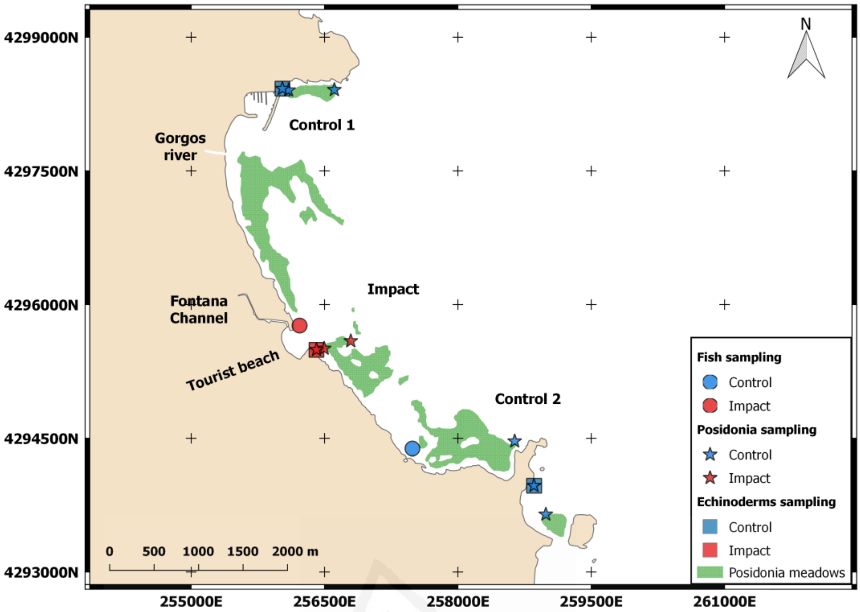

Figure 6.1. The location of the Javea SWRO (Sea Water Reverse Osmosis) plant and sampling study areas for monitoring biological communities. Shown are the Gorgos river (the previous location of the brine discharge), Fontana Channel (current brine discharge location established through recommendations), and *Posidonia oceanica* seagrass meadow distribution.

The Javea SWRO plant has four lines that can produce 6720 m^3 of freshwater per day; thus, its maximum freshwater production capacity is 26800 m^3 per day with a recovery rate of 44.8%. However, its production varies seasonally, with more lines used in summer (2-4) than in winter (0-1).

During the construction phase of the plant, a preliminary study of possible initiatives to minimize the environmental effects from BD was carried out (Malfeito et al., 2005). In the initial plan, the Gorgos River, close to where the plant is located, was targeted as the BD disposal site (Fig. 6.1). However, due to the presence of *P. oceanica* meadows close to the river (within 80 m), an alternative disposal location was recommended: an artificial channel called the "Fontana Channel," which is 700 m long, 20 m wide, about 1 m deep, previously anoxic, and discharges close to a tourist beach (Fig. 6.1). Since conditions in the channel are not favorable for the dilution of the brine, it was proposed that the brine effluent was diluted 4:1 with seawater to achieve a salinity below 44 psu and that the discharge took place through 16 horizontal diffusers to increase dilution in the Fontana Channel (Malfeito et al., 2005; Sola et al., 2020b).

At the Javea SWRO plant, seawater is taken in through 10 deep beach wells at a depth of 200 m; this eliminates the impingement and entrainment of marine organisms and reduces the levels of organic matter in the water, thereby negating the use of aggressive pre-treatments and further chemical additives (Fernández-Torquemada et al., 2019; Mezher et al., 2011).

An EMP was established for monitoring the brine plume behavior in the marine environment and biological communities were used as bioindicators to identify potential environmental changes induced by the brine effluent (Sánchez Lizaso et al., 2004, Sola et al., 2020).

6.2.2. Sampling

The dispersion of saline plumes was monitored 2-4 times per year. Vertical profiles of salinities were completed in a grid of approximately 30 equidistant stations, ranged between 1 m and 7 m depth, distributed in the area of the BD with a CTD. From 2008, the brine effluent composition was monitored monthly after the RO process in the SWRO plant and after dilution with seawater in the diffuser discharge.

Monitoring of *P. oceanica* meadows was carried out annually at three sampling locations: two control locations and one location near the discharge area (Fig. 6.1) (Underwood, 1994). As shown in Figure 6.1, the control locations are separated but both are approximately 2 km from the BD area, ensuring that the seagrass in these locations is sufficiently similar and unaffected by impacts other than the operation of the SWRO plant. Within each location, three stations were established at 3, 7, and 15 m depths with four permanent parcels. At each permanent parcel, four 40 x 40 cm squares were established within which all the shoots of *P. oceanica* were marked to evaluate population dynamics. Marked shoots were monitored annually to estimate shoot recruitment and mortality rates.

Echinoderms are extremely sensitive to changes in seawater salinity and consequently have previously been used as bioindicators for the impacts of desalination (De-la-Ossa-Carretero et al., 2016b; Fernández-Torquemada et al., 2013). In the present study, echinoderms were monitored using the same procedure applied for *P. oceanica*, i.e., establishing two control locations and one impact location but at a 3 m depth (Fig. 6.1). Within each location, two stations were established: one on the rocky bottom and the other in the *P. oceanica* meadow, where 10 quadrats of 1 m^2 were sampled and the echinoderms within the quadrats were identified and counted.

Fish communities were monitored using underwater visual census method. This technique is ideally suited to monitoring the abundance of fish as it allows for the collection of community level data without the disturbance inherent in other more destructive sampling techniques (Harmelin-Vivien et al., 1985; Sale and Douglas, 1981). For fish monitoring, a control location and an impact location were established, and two stations were established within each location (Fig. 6.1). At each station, the abundance and size (total length in classes of 2 cm) of each fish species was recorded by a SCUBA diver within four random replications of areas 25 m long and 5 m wide were sampled; thus, 16 samples/replicates of 125 m^2 were obtained per year. The surveys were done always in the same season (summer) to reduce the natural variance between replicates thus providing better evidence of spatial patterns of distribution. The warm season is the most suitable period for visual counts in the Mediterranean, as fish communities are more diverse and stable during this period (Harmelin, 1987).

6.2.3. Statistical analysis and spatial representation

The salinity data obtained from each sampling survey were analyzed using the kriging spatial interpolation technique to obtain a real representation of the saline plume in the space. In the kriging method, the sampled data points are used to estimate salinity values over a continuous spatial area. The applied model is based on the work of Fernández-Torquemada et al. (2009). The spatial representation and model cross-validation were conducted using the Geostatistical Analyst extension in ArcGIS© v.9.0 software (Johnston et al., 2001)

In addition, generalized additive models (GAMs) were used to analyze the trends in biological parameters (e.g., the abundance or density of individuals) as smooth splines of time between the control and impact locations. GAMs can estimate non-linear trends in many ecological processes (e.g. the annual natural fluctuations of populations themselves) and are used to identify whether significant temporal changes, such as the effects of an impact during a particular period, have occurred (Fisher et al., 2018; Simpson, 2018). GAM analysis was conducted using the “mgcv” package in R (R Core Team, 2017). The degrees of freedom and the amount of smoothness for each spline regression were determined internally during the model fitting for each variable analyzed (Wood and Scheipl, 2016). However, smoothing regression was not applied to functions for which linear patterns were detected with the variable analyzed.

6.3. Results

6.3.1. Plant production and brine characteristics

The total freshwater produced at the Javea SWRO plant between 2002 and 2019 was 57.3 Hm^3, which represented a total volume of approximately 70 Hm^3 BD discharged into the marine environment (Fig. 6.2). The maximum freshwater production, produced between 2014 and 2016, was 26.5% of the total freshwater and brine produced. These results suggest that the demand for desalinated water slightly increased in the last decade.

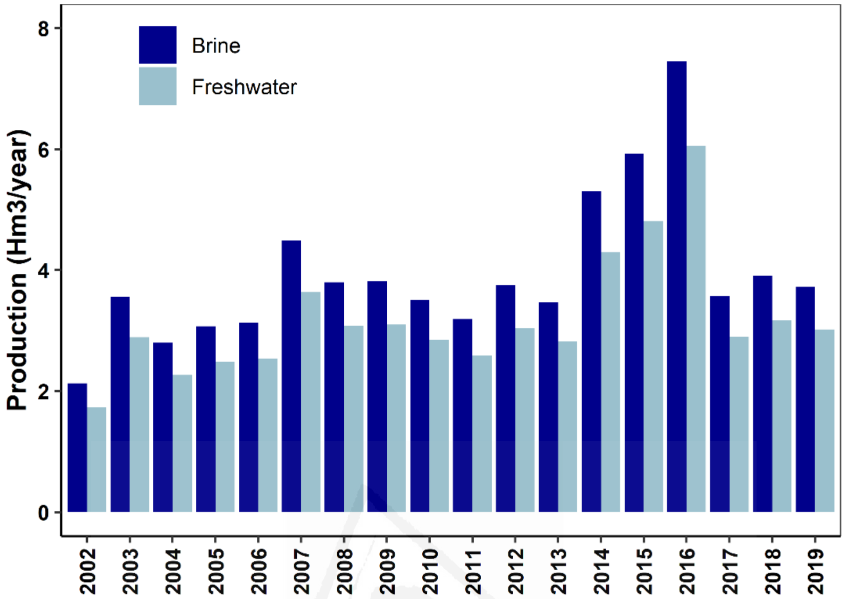

Figure 6.2. Annual production of freshwater and brine discharge by the Javea SWRO (Sea Water Reverse Osmosis) plant between 2002 and 2019.

The average energy consumption of the SWRO plant was 4.6 Kw/m^3 and the energy consumed by the brine dilution process represented approximately 2.2% of the total energy consumed by the SWRO plant.

From 2008 to 2019, the salinity of the brine was on average 68.2 ± 4.4 psu, with slight annual variability shown during certain years (Fig. 6.3). Seawater by-passing produced a significant reduction in the salinity of the brine before its discharge (an average of 42.4 ± 2.9 psu after the dilution process).

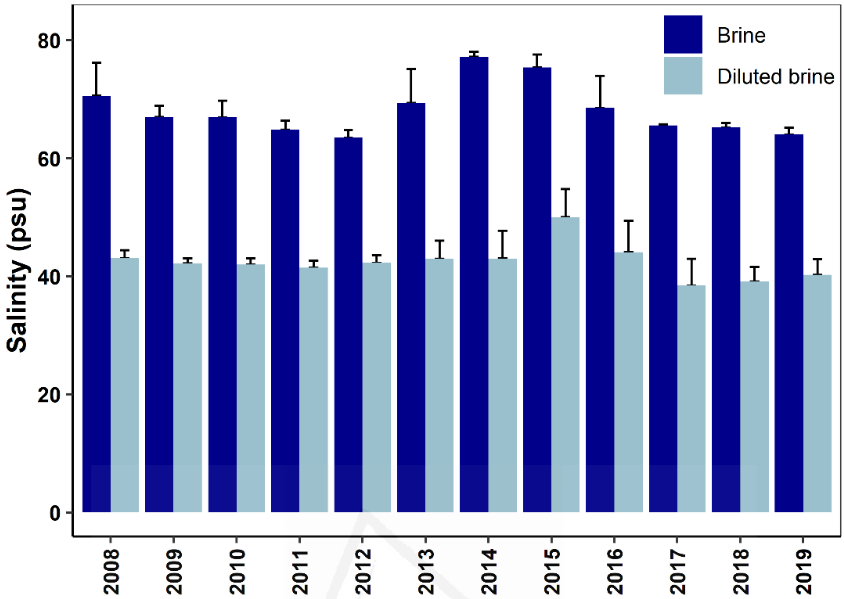

Figure 6.3. Average annual salinity values of brine discharge after the SWRO (Sea Water Reverse Osmosis) process and after dilution with seawater from 2008 to 2019. Error bars indicate standard deviation (SD).

The average salinity values of BD were constant throughout the year with a monthly average of 68 psu (Fig. 6.4). However, the salinity of diluted BD slightly increased during the summer due to lower rainfall in this season.

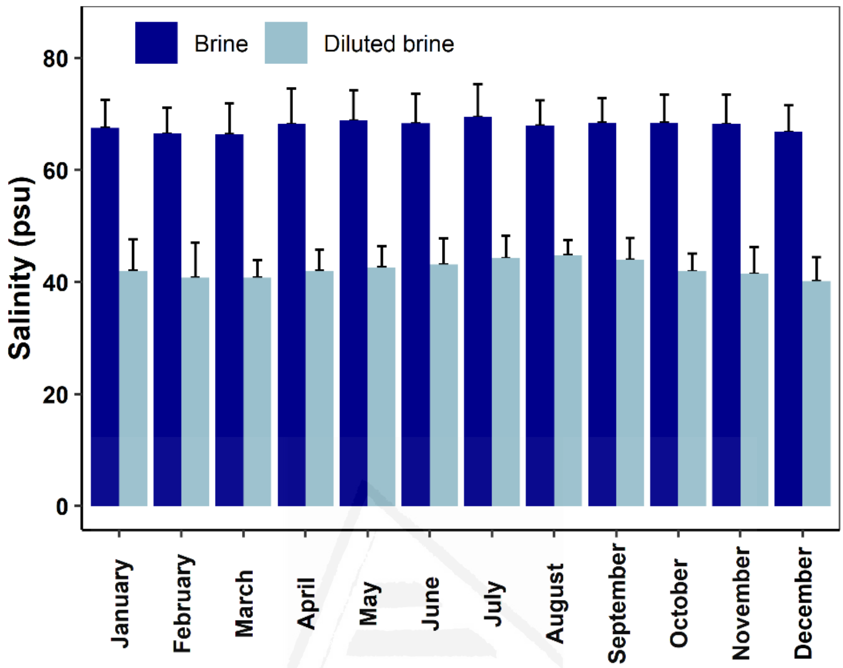

Figure 6.4. Average monthly salinity values of brine discharge after SWRO (Sea Water Reverse Osmosis) process and after dilution with seawater from 2008 to 2019. Error bars indicate standard deviation (SD).

The temperature of the BD was relatively constant throughout the year (average monthly temperature: 20.1 ± 1.1 ºC) because the seawater was taken in through beach wells. After its dilution with superficial seawater, the temperature of BD approached the natural conditions in the area, with maximum values in the summer and minimum values in the winter (Fig. 6.5).

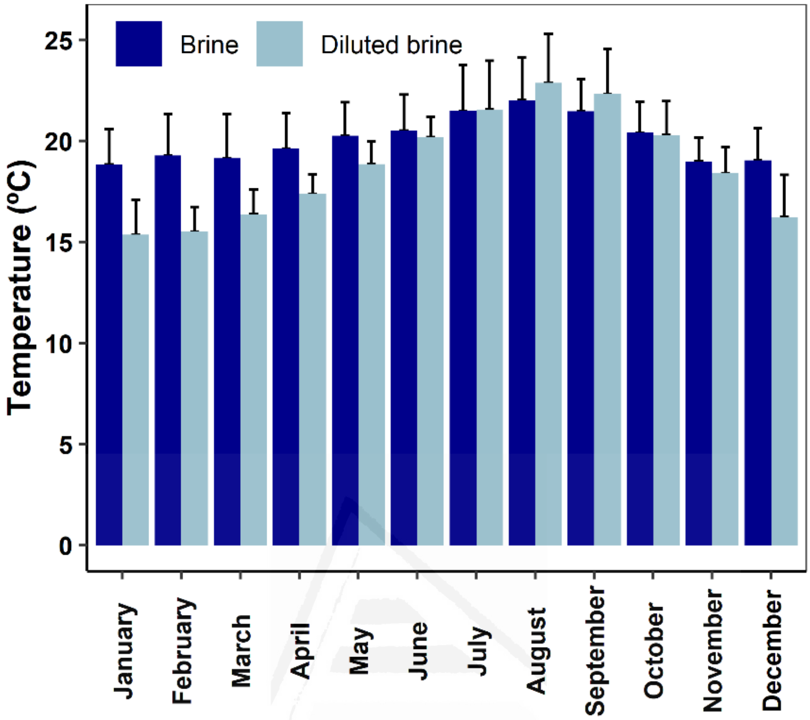

Figure 6.5. Monthly temperature values of brine discharge after SWRO (Sea Water Reverse Osmosis) process and after dilution with seawater from 2008 to 2019. Error bars indicate standard deviation (SD).

The BD in the Fontana Channel increased the water renewal and oxygen content of the channel, which was previously anoxic (Fig. 6.6).

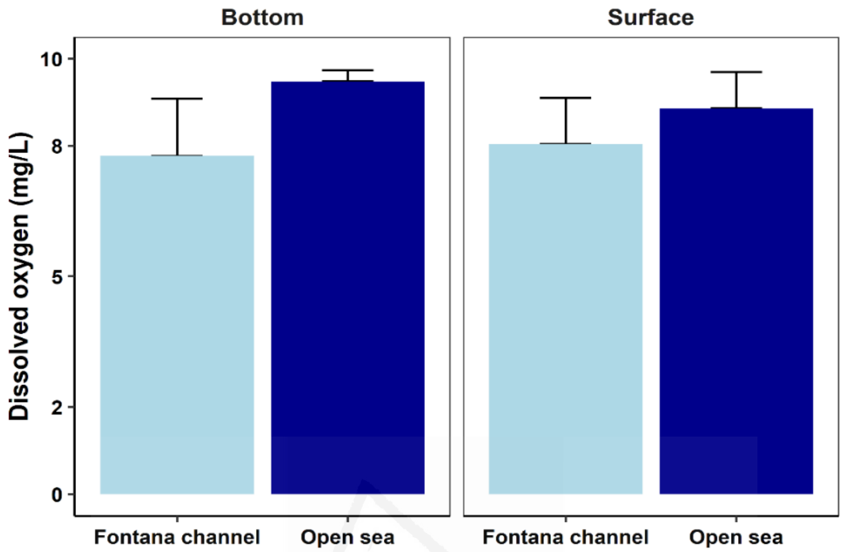

Figure 6.6. Average dissolved oxygen values at the bottom and surface of the Fontana Channel and open sea in 2004. Error bars indicate standard deviation (SD).

6.3.2. Salinity plume

Figure 6.7 shows the dispersion of the plume in a selection of surveys in contrasting environmental conditions. Results show that the behavior of the plume salinity from the Javea brine effluent was similar across the 17 years of monitoring. In addition, the salinity in the Fontana Channel was <44 psu, indicating that the BD has been effectively diluted by seawater by-passing. The salinity on the surface water was rapidly diluted. The bottom salinity had a spatial distribution related to the bathymetry within the discharge area.

The saline plume also showed strong seasonal behavior. For example, during summer, the saline plume area could extend to a distance of about 300 m from the channel outfall (Fig. 6.7: A.2 to D.2). The highest salinity values on the bottom, 38-43 psu, were observed around the channel outfall. During winter, when there was lower freshwater production, the saline plume's area of influence was substantially reduced (Fig. 6.7: A.1 to D.1).

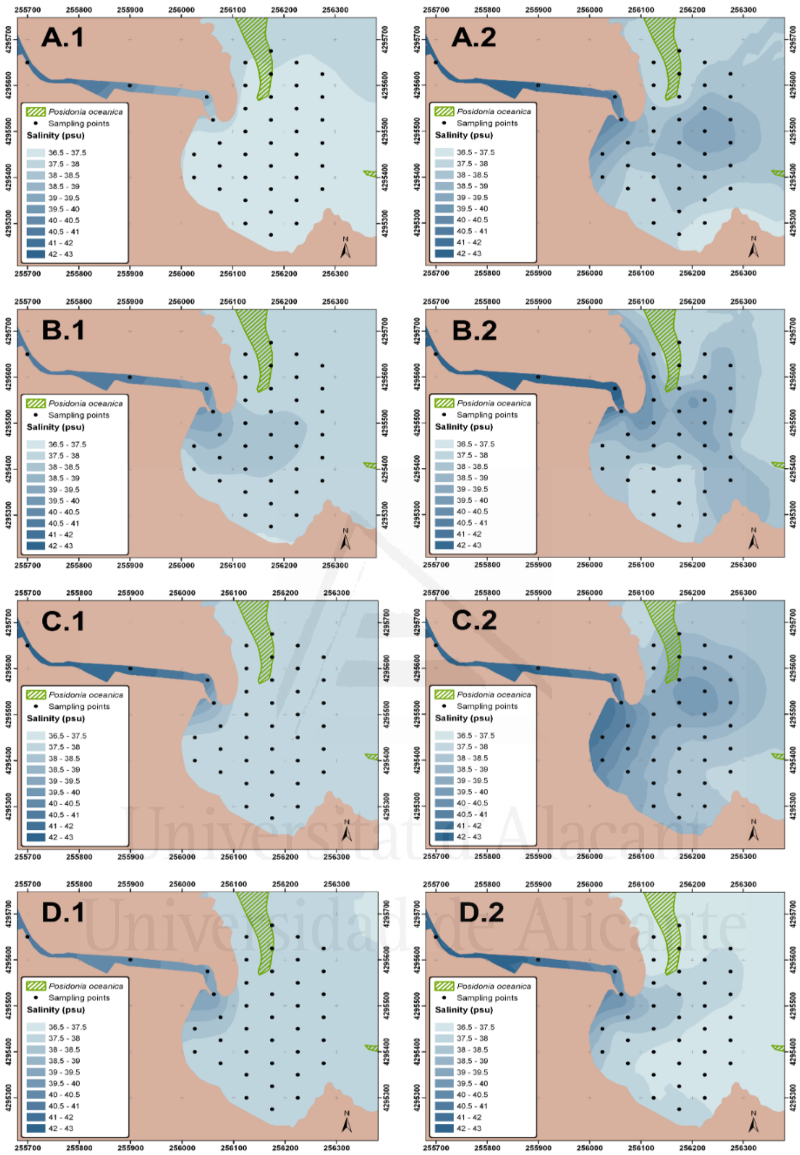

Figure 6.7. Spatial representation of the saline plume on the water bottom around the Fontana Channel outfall area. Data were obtained during winter in 2003 (A.1), 2008 (B.1), 2013 (C.1), and 2018 (D.1), and during summer in 2003 (A.2), 2008 (B.2), 2013 (C.2), and 2018 (D.2).

6.3.3. Monitoring of biological communities

Results showed similar temporal trends of *P. oceanica* meadows in the control and impact locations, with annual oscillations but a stable pattern from 2003 to 2019. From 2003 to 2007, in the locations closest to the coast (3 m), there was a temporal trend for higher shoot production rates in the meadows located in the impact area relative to those in the control area (Fig. 6.8). However, from 2008 onwards, shoot production values were similar in the control and impact areas, with a balance between recruitment and mortality that was close to zero over the historical series.

At the deeper stations (7 and 15 m), there were no major differences in shoot production rates between the control and impact locations. In general, annual fluctuations in shoot production were observed at both the control and impact stations; however, the locations within the 7 m station showed slightly higher rates in the impact area than in the control stations, which had values close to zero. At the 15 m depth, from 2003 to 2005, lower shoot production rates were observed in the meadows located in the impact area; however, from 2006 onwards, the shoot production in this area was very similar to that at the control stations.

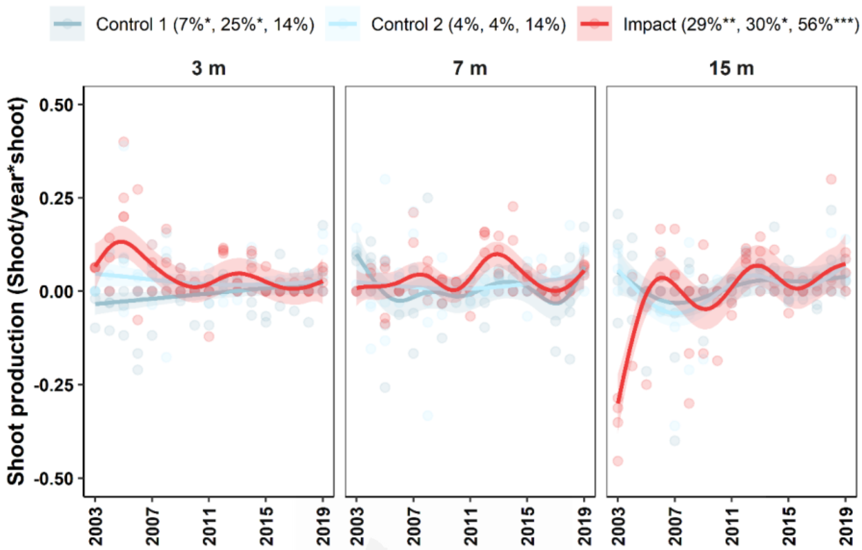

Figure 6.8. Temporal trends in *P. oceanica* shoot production at the three stations analyzed (3, 7, and 15 m depth). Fitted lines from generalized additive models are presented with 95% confidence intervals. The total percentage of deviance explained by the models is presented in the legend with its significance level (*p-value <0.05; ** p-value <0.01; *** p-value <0.001).

BD apparently had no effect on echinoderms from 2003 to 2019 (Fig. 6.9); indeed, echinoderm abundance was relatively stable across the historical series. In the *P. oceanica* meadows, there was a higher abundance of echinoderms at the impact location than at the control locations, but all *P. oceanica* locations showed high fluctuations in echinoderm abundance during the historical series. In contrast, there was a higher average abundance of echinoderms in one of the control areas at the rocky bottoms, but all rocky bottom locations showed relatively stable abundances over the historical series.

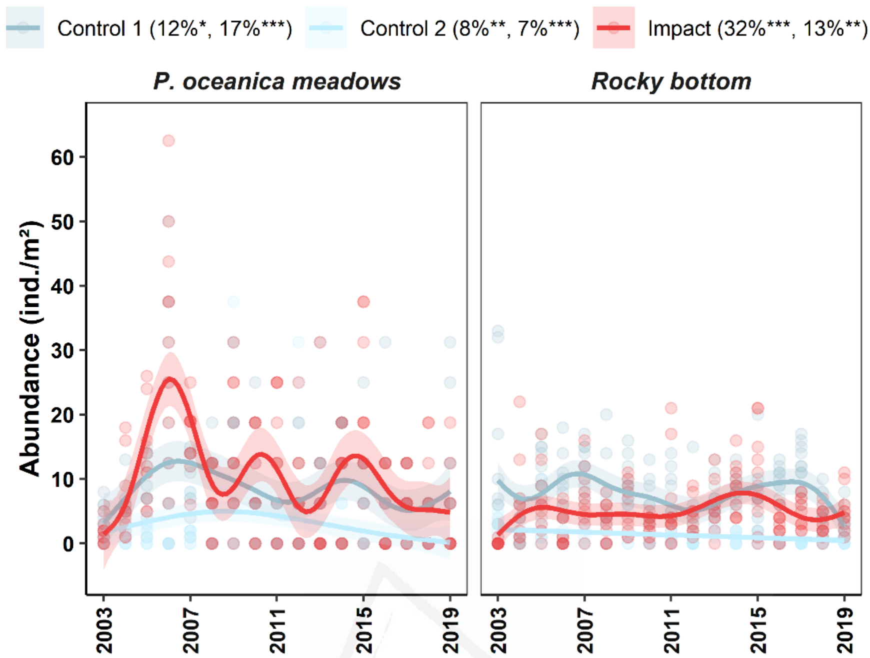

Figure 6.9. Temporal trends in echinoderm abundance at three locations analyzed at both the *P. oceanica* meadows and rocky bottoms. Fitted lines from generalized additive models are presented with 95% confidence intervals. The total percentage of deviance explained by the models is presented in the legend with its significance level (*p-value <0.05; ** p-value <0.01; *** p-value <0.001).

From 2003 to 2019, there was a higher abundance of fish at the impact location than at the control location (Fig. 6.10). However, results showed a substantial decrease in average fish abundance within the impact area from 2012. A similar negative trend was also observed within the control location, although both locations showed a slight increase in fish abundance from 2017.

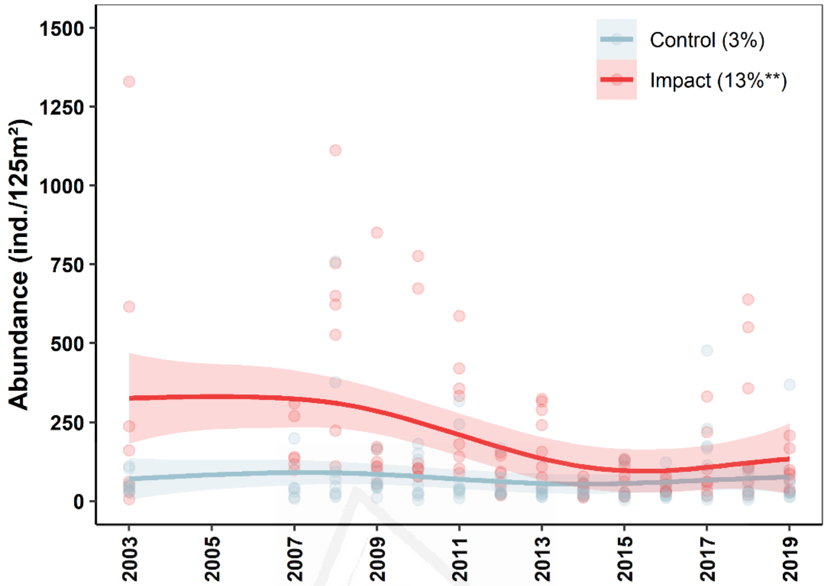

Figure 6.10. Temporal trends in fish abundance at the two locations. Fitted lines from generalized additive models are presented with 95% confidence intervals. The total percentage of deviance explained by the models is presented in the legend with its significance level (** p-value <0.01).

In addition, from 2003 to 2019, there was a higher number of fish species present in the impact area relative to the control area (Fig. 6.11). Although the number of fish species within the impact area fluctuated annually, the values remained around the initial monitoring value recorded in 2003.

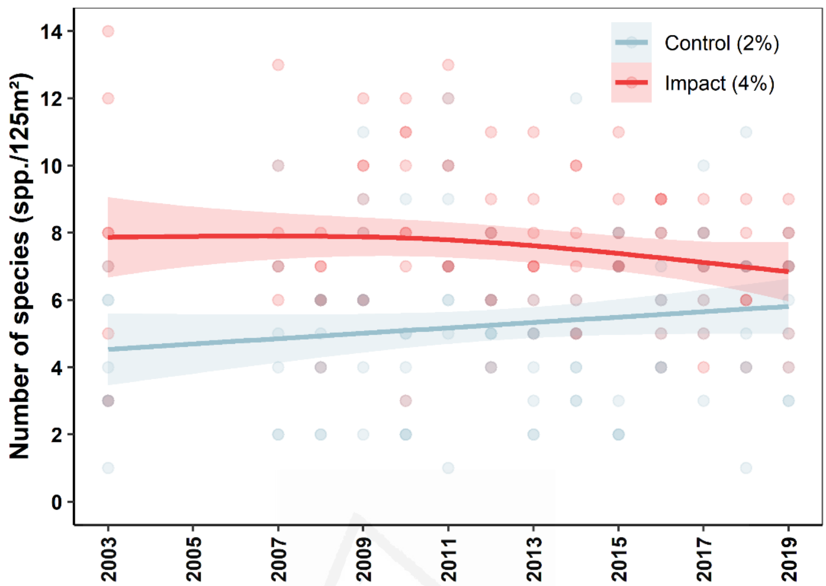

Figure 6.11. Temporal trends in fish species in the two locations. Fitted lines from generalized additive models are presented with 95% confidence intervals. The total percentage of deviance explained by the models is presented in the legend with its significance level.

6.4. Discussion

Data from long-term monitoring shows that the collaboration between industry and environmental science has ensured the sustainable operation of the Javea SWRO desalination plant (Sola et al., 2020b). This study confirms that desalination could be a “win-win solution” to combating water scarcity with no apparent long-term impact on the marine environment, as has been previously been proposed by Pistocchi et al. (2020).

Seawater intake through beach wells prevents the impingement and entrainment of small marine organisms with limited swimming abilities that typically occurs in open seawater intakes (Missimer and Maliva, 2018; Petersen et al., 2018a; Sharifinia et al., 2019). Moreover, beach wells provide feed water with more consistent and homogeneous physical and chemical characteristics and smaller amounts of organic matter and nutrients, i.e., seawater of better quality, than open intakes, which reduces the need for chemical additives and aggressive pre-treatments (Fernández-Torquemada et al., 2019). In the present study, the homogenous characteristics of feed water are reflected in the low annual temperature oscillation of BD prior to its dilution with sea water.

In the present study, changing the discharge location to the previously anoxic Fontana Channel using seawater by-passing to dilute the brine and applying diffusers, all combined, ensured rapid effluent dilution and conservation of protected habitats (Fernández-Torquemada et al., 2004). The diluted BD from the Javea SWRO plant was shown to have an average salinity of <44 psu and the rapid dilution of effluent reduced the area affected by the salinity plume to ≤300 m from the mouth channel. This dilution is much faster than that observed in other desalinations plants where the salinity plumes have reached several kilometers from the discharge point (Fernández-Torquemada et al., 2009; De-la-Ossa-Carretero et al., 2016c) thereby impacting benthic communities (De-la-Ossa-Carretero et al., 2016c; Del-Pilar-Ruso et al., 2015; Kress, 2019c; Petersen et al., 2018a). However, fast dilution of brine has also been observed in other plants with higher production capacities than Javea SWRO plant that use seawater by-passing (Fernández-

Torquemada et al., 2009; 2013; Zarzo et al., 2009), mix the effluent with cooling water from a power plant (Petersen et al., 2019), or use different types of diffusers (Portillo et al., 2013; Loya et al., 2018; Belatoui et al., 2017). Furthermore, the BD from the Javea SWRO plant improved the environmental conditions in the previously anoxic artificial channel; it increased water circulation and promoted the recovery of faunal communities within the channel (Malfeito et al., 2005). The dilution system of the Javea SWRO plant also has a low energy consumption (<3% of the plant's total energy consumption). These energy costs can be assumed by the plant and they address the environmental issues related to BD. However, this energy consumption could be reduced with the development of SWRO plants that utilize renewable energies (Shahzad et al., 2017).

Long-term monitoring showed no apparent effect of BD on biological communities, which was likely due to the rapid dilution of the effluent. Several studies have reported the widespread regression of *P. oceanica* meadows over recent decades due to the cumulative effects of various natural and anthropogenic disturbances (Guillen et al., 2012; de los Santos et al., 2020). However, *P. oceanica* meadows are stable at the Javea SWRO plant, both in the area close to the discharge and in control meadows. Moreover, higher abundances of echinoderms observed close to the discharge also indicate the positive effects of rapid effluent dilution: echinoderms are sensitive to salinity changes and have previously been used as sentinel species for desalination impacts on benthic communities (De-la-Ossa-Carretero et al., 2016b; Fernández-Torquemada et al., 2013).

A higher abundance fish and more species were observed in the impact area relative to the control area. We cannot determine whether the effluent attracts some fish species or whether there is higher habitat diversity in the discharge area because we have no similar data from before the plant began operating. However, Kelaher et al. (2020) recently reported an increase in local fish abundance and species richness related with the BD of a SWRO plant in Australia. In the present study, we also identified a decrease in fish abundance in both study areas from 2012 that could not be attributed to the discharge. Instead, this decrease may be due to other factors such as local fishing activity since the area has become popular for recreational and artisanal fishing of target species since the oxygen levels in the channel improved.

Taken together, the results of this study highlight the benefits of a well-defined, long-term EMP for monitoring the effects of BD on the marine environment and for discriminating the effects of other local impacts that may overlap in the BD area (Sola et al., 2019b). Other studies have demonstrated how science-based EMPs enable discrimination between the effects of BD and other impacts such as sewage discharges and aquaculture (De-la-Ossa-Carretero et al., 2016a; Del-Pilar-Ruso et al., 2009).

The long-term monitoring reported here shows that it is possible to achieve the sustainable management of a SWRO plant through an adequate environmental assessment process (Sola et al., 2020b). Indeed, long-term EMPs are essential for understanding the behavior and potential negative impacts of BD in marine environment and ecosystems (Petersen et al., 2018a). Our results, which represent the longest historical series of BD monitoring published to date, provide robust evidence to support future desalination projects and reduce their impact on the environment. However, the current lack of long-term studies highlights the need for more comprehensive research in this field (Clark et al., 2018; De-la-Ossa-Carretero et al., 2016b; Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2013; Kress et al., 2020). Nevertheless, the present research provides a model example of a sustainable SWRO plant that can act as a reference as the use of RO technology to produce freshwater increases globally (Jones et al., 2019; Shahzad et al., 2017).

Finally, based on the findings of this long-term monitoring project, we make the following recommendations for addressing the environmental effects of BD: (1) a rigorous environmental assessment process must determine the best location to discharge the effluent and the best possible mitigation measures; (2) both engineers and environmental scientists must collaborate during the environmental assessment processes in order to adapt the project to the local characteristics and mitigate the impact of effluents; (3) wherever possible, the brine should be diluted prior to its discharge into the sea (although seawater by-passing may slightly increase the plant’s energy consumption, the use of diffusers or mixing with cooling water is also effective (Loya-Fernández et al., 2018; Portillo et al., 2013)); and (4) a long-term EMP should be designed and implemented to ensure that the measures adopted during the environmental assessment process are carried out correctly, that the sustainable operation of the SWRO plant is guaranteed, that the environmental impacts caused by BD are either eliminated or that mitigation measures are adopted if negative impacts on the marine environment are detected, and finally that it is possible to discriminate between the effects of BD and those other impacts that may overlap in the discharge area (Underwood, 1994).

6.5. Conclusions

According to this research, it is possible to achieve the long-term sustainable operation of a SWRO plant through well-planned and executed collaborative decision-making between scientist and industry. With an adequate environmental assessment process that includes analysis of feasible alternatives for seawater intake and brine effluent disposal, the environmental impacts of desalination activities on marine ecosystems can be minimized. Moreover, with a science-based monitoring system, negative impacts on the environment can be eliminated or detected and dealt with swiftly. The Javea SWRO plant can act as an example for future SWRO plants, which will produce freshwater without substantially impacting the marine environment.

6.6. Acknowledgments

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6.7. Author statement

IS and JS contributed conception and design of the study; YF, AF, CV and IS processed the field data; IS presented and analyzed the field data; YF, AF, CV, YP, JG and IS contributed to the field sampling surveys of environmental management plans; IS wrote the first draft of the manuscript; IS and JS wrote sections of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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ARTÍCULOS NO PUBLICADOS

CHAPTER 7: Evaluating Environmental and Socio-Economic Requirements for Improving Desalination Development

Sola, I., Sáez, C., Sánchez-Lizaso, J.L., Under review. Evaluating Environmental and Socio-Economic Requirements for Improving Desalination Development. Under Review.

7. EVALUATING ENVIRONMENTAL AND SOCIO-ECONOMIC REQUIREMENTS FOR IMPROVING DESALINATION DEVELOPMENT

Abstract

The continuous increase in global freshwater demand highlights desalination technology as one of the most feasible options for addressing global water scarcity. This increase has occurred more rapidly in certain countries owing to certain factors that can influence the development of desalination projects. An international survey of desalination experts was carried out to evaluate the main requirements and most limiting factors for the development of desalination projects in different countries based on a semi-quantitative analysis. The obtained results showed high heterogeneity of environmental and socio-economic requirements across different countries. The main barriers identified for desalination development were the cost of produced water, low financial support, and stringent environmental requirements. We observed that social acceptance of desalination projects is normally high and does not represent a limiting factor for their development. However, low levels of environmental requirements and/or public involvement have been identified as issues and these should be improved in some countries. The knowledge obtained in this research may be used to inform scientific advice and advance toward the sustainable development of desalination projects.

Keywords

Desalination development; Sustainable desalination; Requirements; Limiting factors; Environmental assessment;

7.1. Introduction

The continuous increase in global freshwater demand highlights the important role played by desalination technology as one of the most feasible options for addressing global water scarcity. There are currently more than 17,000 desalination plants around the world, representing a capacity of more than ~97 million m^3/day (Eke et al., 2020; Jones et al., 2019). Desalination production capacity has increased significantly in the last decade, representing a continuous increase of about 7% per year since year 2010 until the end of 2019. Therefore, a substantial increase in desalinated water production is expected, dominated mainly by reverse osmosis technology due to its lower energy consumption and higher efficiency compared to other technologies (Shahzad et al., 2017; Zarzo and Prats, 2018). Although the scale of this development differs across countries despite the global lack of freshwater. Much freshwater production through desalination is concentrated in the Middle East, representing 39% of the total production capacity installed (Eke et al., 2020; Jones et al., 2019).

Among the main factors relating to the development of desalination plants are (i) the complexity and requirements of national laws, (ii) the economic and energy costs of water production, (iii) government commitment to the technology as a complement to its water matrix policy, (iv) the legal certainty of the country, (v) the management of brine discharges, (vi) public/private financing for the development of desalination plants, (vii) the requirements established during environmental impact assessments (EIAs), and (viii) social acceptance of the projects (Eke et al., 2020; Ibrahim et al., 2018; Kress, 2019a; Miller et al., 2014; Sadhwani Alonso and Melián-Martel, 2018; Shemer and Semiat, 2017; Sola et al., 2019b). These uncertainties, which vary among countries, may represent a threat to desalinated water production and socioeconomic development (Shemer and Semiat, 2017).

The start-up financial costs for implementing desalination plants and/or the water production costs represent major obstacles to implementation in some countries since non-governmental organizations without public support are not always able to cover these costs and the citizens are unable to pay the entire production costs (Shemer and Semiat, 2017). In addition, environmental impact is one of the most important issues limiting the sustainable development of desalination projects. Highly stringent environmental requirements are not always justified based upon empirical scientific criteria and may represent an obstacle to the development of desalination plants in some countries (Navarro Barrio et al., 2021; Petersen et al., 2019; Sola et al., 2019a). The most important tool for managing and minimizing the impacts of desalination projects is the Environmental Impact Assessment (EIA). EIAs include studies and administrative procedures aimed at identifying the potential environmental impacts of project development (i.e., desalination) and provide corrective measures to minimize and mitigate these impacts (Elsaid et al., 2020b; Fuentes-Bargues, 2014; Sadhwani Alonso and Melián-Martel, 2018; Sola et al., 2019b, 2019a). EIAs assess whether a project's impacts are in line with environmental norms and authorities' guidelines; ultimately, projects not complying with these may be rejected or cancelled (Elsaid et al., 2020b).

Environmental monitoring plans (EMPs) are programs that impose monitoring and corrective measures arising from the EIA process, ensuring sustainable development during the operational phase of the project. In the case of desalination, EMPs are mainly related to identifying possible negative impacts associated with brine discharges on marine environments and adopting proper mitigation measures when such impacts are identified (De-la-Ossa-Carretero et al., 2016b; Del-Pilar-Ruso et al., 2015; Fernández-Torquemada et al., 2013).

The aim of this research was to study the main requirements (economic, environmental, legal certainty, and social aspects) and most limiting factors for the successful development of desalination projects in several countries. This was achieved using a survey of global experts in the desalination field. The knowledge gained from this research may be used to (i) improve EIAs and EMPs in countries with high installed desalination capacities, (ii) facilitate an increase in the development of desalination projects in countries with high need and potential, and (iii) identify potential improvements to ensure the environmentally sustainable development of desalination projects worldwide.

7.2. Materials and methods

7.2.1. Survey analysis

A survey of desalination experts was structured into two major components (Fig. 7.1). First, the main *requirements* related to desalination project development were defined, including socio-economic and environmental aspects. The requirements were defined according to the published literature and were summarized into six main requirements to reduce the survey's complexity and thus obtain higher response rates. These included (i) the legal certainty to ensure the successful development of a desalination project; (ii) the presence or absence of the EIA process required for desalination project installation, and the environmental requirements of the EIA; (iii) the presence or absence of EMPs for the operation phase, and the number of environmental requirements within the EMPs; (iv) social acceptance of desalination projects among the population; (v) public involvement in the development of desalination projects; and (vi) financial support of the construction and operation of desalination projects to complement the hydric matrix (Al-Karaghouli and Kazmerski, 2013; Eke et al., 2020; Heck et al., 2018, 2016; Mezher et al., 2011; Miller et al., 2014; Mohammadi et al., 2020; Shemer and Semiat, 2017; Sola et al., 2019a, 2019b). Within each requirement, no sub-factors were considered; thus minimizing the survey's complexity, which reduced the time demand for completion and facilitated a high number of surveys responses from leading experts. Increasing the complexity of the survey would have resulted in a lower response rate, which would have negatively impacted the accuracy of the results and led to subsequent misrepresentation of the data (Ibrahim et al., 2018).

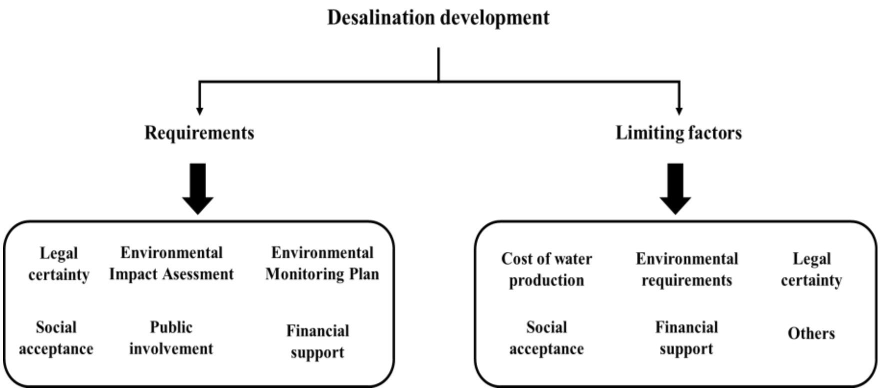

Figure 7.1. Summary of requirements and limiting factors used to assess desalination development across different countries.

The requirements were evaluated using a semi-quantitative scale where 1 represented the lowest degree and 5 the highest degree for each requirement (Table 7.1). In addition, the number of years of processing and/or authorization of desalination projects in the survey for each country was compiled through a free value response. Furthermore, it was assessed whether countries required an EIA process for desalination project development and/or if they implemented an EMP for the operational phase of desalination plants. Likewise, data on the nationality, number of years working in the desalination sector, working sector (e.g. water management and treatment companies, scientists, and academics), and number of countries worked in were collected for each desalination expert interviewed.

Table 7.1. Semi-quantitative scale used for requirements evaluation by survey respondents.

Score	Semi-quantitative scale for requirements evaluation
1	Represents the lowest legal certainty; lowest number of requirements in EIAs; lowest number of requirements within EMPs; lowest social acceptance of desalination projects; lowest involvement in project development; lowest funding availability
2	Represents a low degree for each requirement
3	Represents a medium degree for each requirement
4	Represents a high degree for each requirement
5	Represents the highest degree for each requirement

The second group identified the most *limiting factors* for desalination development in each country (Fig. 7.1). These were defined according to published literature and summarized as five main factors, i.e., (i) the cost of desalinated water produced, (ii) the number of environmental requirements, (iii) social acceptance among the population, (iv) legal certainty of the country; and (v) financial availability for the desalination projects (Al-Karaghouli and Kazmerski, 2013; Eke et al., 2020; Heck et al., 2018, 2016; Mezher et al., 2011; Miller et al., 2014; Mohammadi et al., 2020; Shahzad et al., 2019, 2018; Shemer and Semiat, 2017; Sola et al., 2019a, 2019b). Within each most limiting factor, no sub-factors were considered; thus minimizing the survey's complexity and increasing the response numbers (Ibrahim et al., 2018). The limiting factors were evaluated through a semi-quantitative scale (Table 7.2).

Table 7.2. Semi-quantitative scale used for limiting factors evaluation by survey responders.

Score	Semi-quantitative scale for limiting factors evaluation
1	Represents a very low limiting factor
2	Represents a slightly limiting factor
3	Represents a more limiting factor
4	Represents a strongly limiting factor
5	Represents an extremely limiting factor

Once the assessments were collected for each country, only those with a minimum of two surveys returned by different experts were considered in the analysis. This allowed us to compare the experts' assessments based on the different factors and requirements considered, and to reduce any potential bias derived from the non-objective personal perception of each of the experts regarding their local desalination realities. The median measure was used to compare the results obtained from the surveys.

7.2.2. Desalination survey of experts

The survey was aimed at desalination experts with strong and long-term backgrounds in the desalination field. To facilitate a multidisciplinary approach and obtain accurate results, the surveys involved experts from water management and treatment companies, constructors and/or operators' companies, workers in research and development in the water industry, scientists and academics, and workers in international consulting companies (among others). For this purpose, face-to-face surveys were carried out during the International Desalination Association (IDA) Congress, which took place in Dubai from October 20th to 24th, 2019. In addition, the survey was disseminated through board members of the IDA and Spanish Desalination and Reuse Association (AEDyR), as well as to researchers and scientists around the world with strong backgrounds in desalination. The online survey was carried out using the google docs platform (*https://docs.google.com*), with the survey link disseminated to experts via email. A total of 34 desalination experts were interviewed, which resulted in a total of 69 evaluations with which to analyze the most limiting factors and requirements for each country. Each survey was filled out anonymously. An example of the disseminated survey is presented in the Supplementary Material (S1).

7.3. Results

7.3.1. Desalination surveys

A total of 34 interviews were compiled, with the results showing respondents with a general average of 17.7 years working in the desalination sector and an average of more than 4.2 countries in which they have conducted associated activities (Table 7.3). It should be noted that 76.5% of the surveys compiled were obtained from experts in the industrial sector. The experts from the desalination industry sector showed averages of 19 years working in the field and operations in 5.1 countries, compared with 12.6 years and 1.7 countries for experts from the scientific sector (Table 7.3).

An expert from the law sector was also surveyed but was not included in the global analysis since using only one respondent would have been misrepresentative of the sector.

Table 7.3. Summary of survey numbers, average years in desalination, and average countries worked by sector for the different survey interviewees.

Sector	Number of surveys	Average years in desalination sector	Average number of countries worked in
Industry	26	19.0	5.1
Research	7	12.6	1.7
Law	1	20.0	1.0
Total	34	17.7	4.2

A total of 13 nationalities were present in the data, although the largest numbers of surveys were obtained from Spanish, American, and Australian experts, accounting for 41%, 12% and 9% of total surveys, respectively (Fig. 7.2A). The respondents of most nationalities showed an average of more than 10 years of experience in the desalination sector and more than two countries where they had worked in the field (Fig. 7.2B and 7.2C).

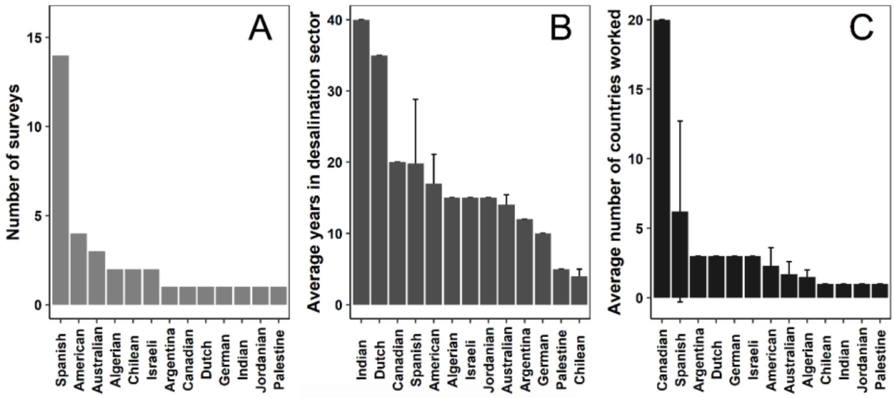

Figure 7.2. Number of surveys (A), average years in the desalination sector (B), and average number of countries worked in (C) by nationality of survey experts.

A total of 69 evaluations were obtained to analyze the requirements and limiting factors for each country (Fig. 7.3). This resulted in 23 countries being evaluated, of which 11 countries were analyzed since they met the requirement of having more than two experts per country. Spain, Australia, USA, Algeria and Chile accounted for 10–13% of the total number of evaluations obtained.

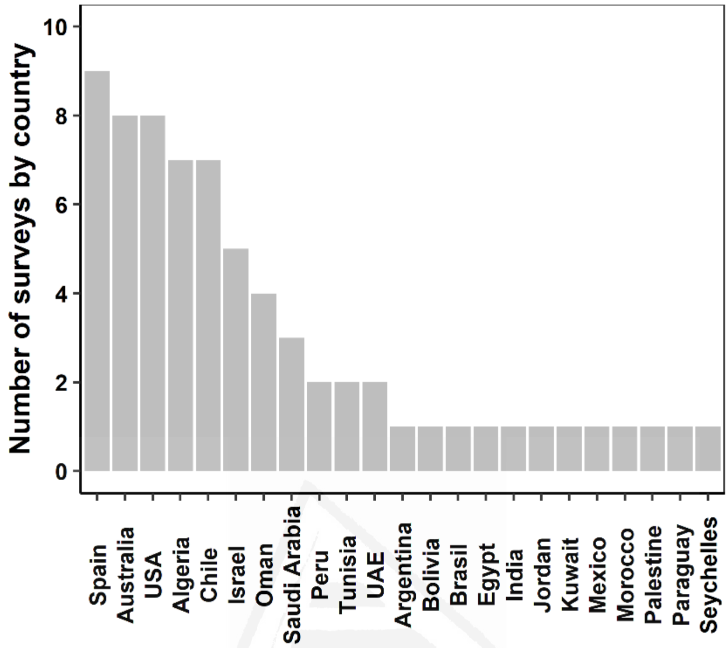

Figure 7.3. Country evaluations obtained to evaluate the requirements and limiting factors of desalination development

7.3.2. Authorization years for the development of desalination projects

The results showed marked differences in the authorization time required for desalination projects among the different countries analyzed. The USA showed the longest authorization time, with an average of 13.6 ± 6.2 years, followed by Peru and Israel, with averages of 7.5 ± 4.5 and 5.3 ± 1.4 years, respectively. Saudi Arabia and Algeria showed the shortest authorization times, with averages of 2 ± 0.7 and 2.3 ± 1.4 years, respectively. For the remainder of the assessed countries, the average authorization time ranged from 2.4 to 3.1 years.

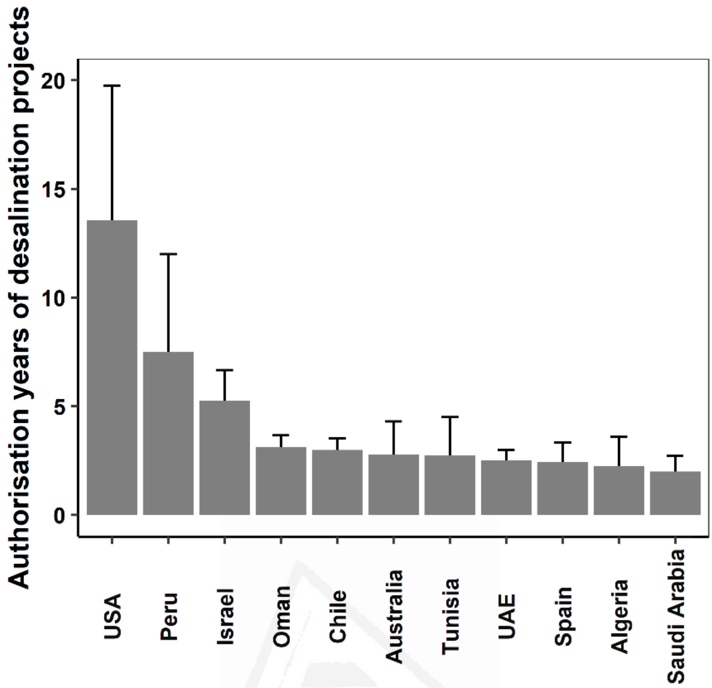

Figure 7.4. Average authorization time required for a desalination project in each country based on the results obtained from the different desalination experts surveyed. Error bars indicate standard deviation.

7.3.3. Requirements of countries where desalination projects have been developed

Within the environmental regulation of the countries analyzed, according to results obtained from desalination experts, most countries demonstrated that they require an EIA to develop a desalination project. However, 50%, 33.3%, and 20% of total surveys conducted for Peru, Saudi Arabia, and Israel, respectively, indicated that they do not require an EIA; and 50%, 25%, and 14% of total surveys for Tunisia, Oman, and Algeria, respectively, indicated that EIAs are only required in certain cases.

The results showed significant heterogeneity in the requirements for EMPs among the different countries analyzed. For Spain, Australia, and the USA, the results show that these countries always require an EMP. For Chile, Israel, and Saudi Arabia, 87.5%, 80%, and 66.7% of the total surveys, respectively, indicated that an EMP would be required. In contrast, for Tunisia, United Arab Emirates (UAE), Oman, and Algeria, 100%, 100%, 75%, and 57.2% of the total surveys, respectively, indicated that these countries do not require EMPs and/or these are only applied in certain cases.

Table 7.4. Percentage of the total number of surveys conducted for the existence of environmental regulations for each country arising from expert responses. EIA: environmental impact assessment; EMP: environmental monitoring plan.

Country	Environmental regulation	Yes	Sometimes	No
Algeria	EIA	85.7	14.3	0.0
	EMP	42.9	42.9	14.3
Australia	EIA	100.0	0.0	0.0
	EMP	100.0	0.0	0.0
Chile	EIA	100.0	0.0	0.0
	EMP	87.5	12.5	0.0
Israel	EIA	80.0	0.0	20.0
	EMP	80.0	20.0	0.0
Oman	EIA	75.0	25.0	0.0
	EMP	25.0	50.0	25.0
Perú	EIA	50.0	0.0	50.0
	EMP	0.0	0.0	100.0
Saudi Arabia	EIA	66.7	0.0	33.3
	EMP	66.7	0.0	33.3
Spain	EIA	100.0	0.0	0.0
	EMP	100.0	0.0	0.0
Tunisia	EIA	50.0	50.0	0.0
	EMP	0.0	100.0	0.0
UAE	EIA	100.0	0.0	0.0
	EMP	0.0	50.0	50.0
USA	EIA	100.0	0.0	0.0
	EMP	100.0	0.0	0.0

The “requirements” assessment related to socio-economic and environmental aspects of desalination development is presented in Figure 7.5. According to the EIA requirements assessment, the results showed that Australia and USA impose the highest number of requirements in EIAs, followed by Chile, Spain and Peru, which each impose a high number of requirements. In contrast, Saudi Arabia impose a low number of requirements.

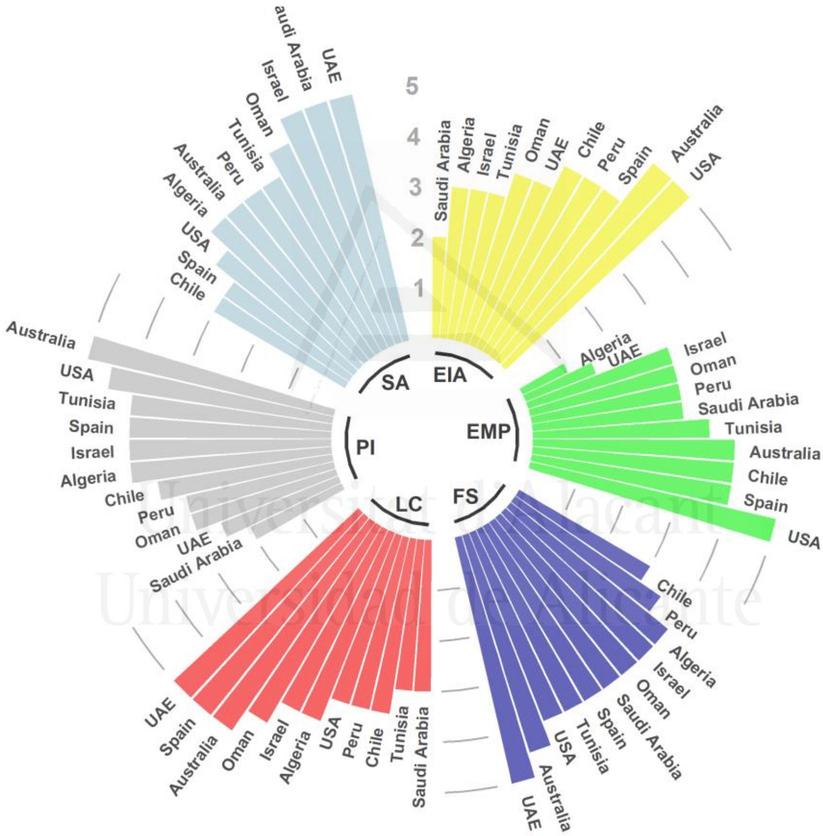

Figure 7.5. Conceptual summary of median values for “requirements”, as evaluated by desalination experts for each country analyzed. Requirements were evaluated using a semi-quantitative scale (1–5), where 1 represents a lowest number of

requirements and 5 a highest number of requirements. EIA: environmental impact assessment requirements; EMP: environmental monitoring plan; FS: financial support; LC: legal certainty; PI: public involvement; SA: social acceptance.

Regarding the EMP requirements assessment, the USA imposes the highest number of requirements, followed by Australia, Chile, and Spain, which impose a high number of requirements. Algeria and UAE impose the lowest number of EMP requirements.

In addition, most countries analyzed show significant financial support for desalination plant development, with UAE showing the highest funding level. Chile showed a medium capability to obtain good financial support.

Most countries analyzed showed a high degree of legal certainty to facilitate the development of desalination projects. The results showed highest legal certainty for Australia, Spain, and UAE. Saudi Arabia and Tunisia showed a medium degree of legal certainty to facilitate desalination development.

Most countries analyzed showed a high level of social acceptance of desalination projects among their population, with highest levels seen for UAE, Saudi Arabia, and Israel. Chile, Spain, and USA showed a medium degree of acceptance for desalination projects.
Regarding the public involvement assessment, the results showed highest involvement for Australia, followed by USA, Tunisia, Spain, Israel, and Algeria, each with high involvement. UAE and Saudi Arabia showed low public involvement.

7.3.4. Limiting factors for desalination development

The “limiting factors” assessment for desalination project development is presented in Figure 7.6. Within this evaluation, the cost of desalinated water production showed as a strongly limiting factor for desalination plant development in most countries analyzed. In Saudi Arabia, this factor presented as a slightly limiting factor.

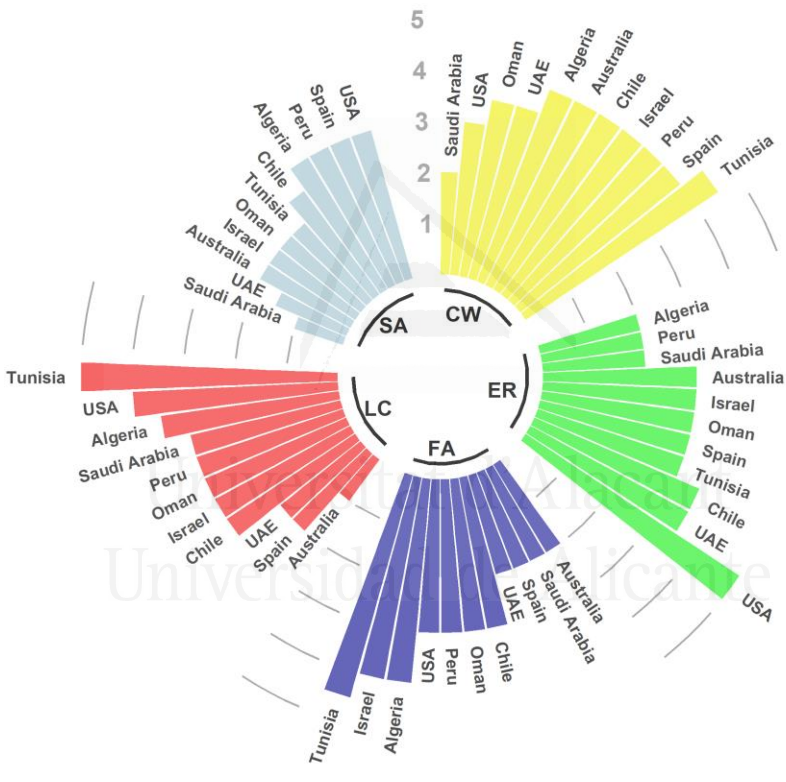

Figure 7.6. Conceptual summary of median values for limiting factors evaluated by desalination experts for each country analyzed. Limiting factors were evaluated using a semi-quantitative scale (1–5), where 1 represents a very low limiting factor and 5 represents an extremely limiting factor. CW: cost of desalinated water produced;

ER: environmental requirements; FA: financial availability; LC: legal certainty; SA: social acceptance.

The environmental requirements were generally moderately limiting factors for project development in most countries. However, in the USA, the results showed that these requirements represented an extremely limiting factor. In Saudi Arabia, Peru, and Algeria, these requirements presented as a slightly limiting factor.

In terms of financial availability, the results showed that this is a highly limiting factor for Tunisia, Algeria, and Israel. The results indicated this is a slightly limiting factor for Saudi Arabia, Australia, UAE, and Spain.

Legal certainty typically presented as a moderately limiting factor in most countries. This factor represented an extreme barrier and strongly limiting factor for Tunisia and USA, respectively. The results showed that it represents a very low limiting factor for Australia, UAE, and Spain.

Compared with the others limiting factors analyzed, social acceptance was the least significant. For Spain, Peru, Algeria, and USA this presented as a moderately limiting factor.

Figure 7.7 shows the totals of the limiting factors by country. The results show higher levels of limiting factors for Tunisia, USA, Algeria, Israel, and Chile, whereas Saudi Arabia, Australia, and UAE present the lowest levels of limitations for desalination project development.

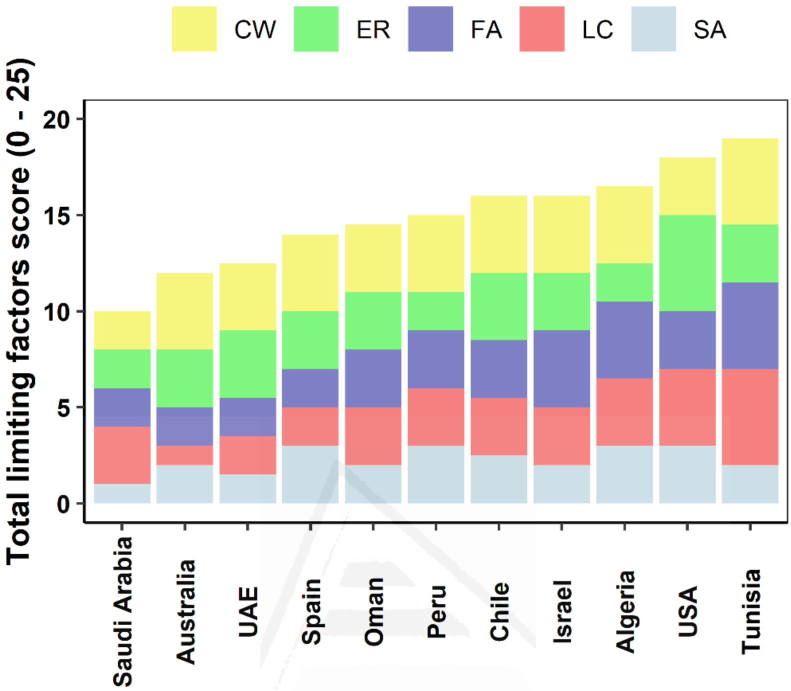

Figure 7.7. Total limiting factors evaluated by desalination experts for each country analyzed. Limiting factors were evaluated using a semi-quantitative scale (1–5), where 1 represents a very low limiting factor and 5 represents an extremely limiting factor. CW: cost of desalinated water produced; ER: environmental requirements; FA: financial availability; LC: legal certainty; SA: social acceptance.

7.4. Discussion

The results presented in this research represent a first approach to assess how different socio-economic and environmental factors impact desalination development in different countries. An accurately understanding of these factors provides highly relevant information for moving toward sustainable desalination development and addressing increasing freshwater global demand (Eke et al., 2020; Jones et al., 2019; Shahzad et al., 2017).

From the survey analysis carried out in this study, we show that the surveyed experts have an average experience of more than 17 years in the desalination sector and have worked in at least two or three different countries. The information obtained from global desalination experts is relevant to evaluating the pros and cons of the main factors involved in desalination development. Other studies such as Ibrahim et al. (Ibrahim et al., 2018) also used the experience of desalination experts to assess the sustainability of thermal distillation and reverse osmosis technologies. However, our research is the first to use information gained from desalination experts to assess desalination development worldwide.

Our results show marked heterogeneity in the requirements and limiting factors among the different countries evaluated, showing a close relationship with the authorization time for project development. USA showed the longest authorization time, followed by Peru and Israel, although Peru showed a high standard deviation from the average value, suggesting different responses among the desalination experts. Likewise, USA and Israel presented as having high levels of limiting factors compared with the other countries assessed; these factors were mainly related to environmental requirements in USA and economic factors in Israel. However, most countries analyzed showed an average authorization time of less than three years.

We identified that the **cost of producing desalinated water** is a highly limiting factor in many of the countries analyzed, e.g., Tunisia, Algeria, Spain, and Australia. However, in Saudi Arabia and the USA, this factor represented only a slight limiting factor. The cost of desalinated water production is highly complex because it depends on many factors such as the technology used, energy costs, plant location, feedwater quality, capital costs, water intake and brine discharge costs, regulatory requirements, and maintenance and financial costs (among others) (Al-Karaghouli and Kazmerski, 2013; Eke et al., 2020; Kettani and Bandelier, 2020; Mezher et al., 2011; Mohammadi et al., 2020; Shahzad et al., 2019, 2018; Shemer and Semiat, 2017). The energy costs represent the highest costs for most technologies used in seawater desalination, e.g., for thermal distillation and membrane desalination technologies, the energy costs are 60% and 44%, respectively, of the total water costs (Al-Karaghouli and Kazmerski, 2013). Therefore, seawater desalination is commonly more efficient and more sustainable when using reverse osmosis than when using thermal desalination owing to the lower energy consumption and desalinated water costs (Eke et al., 2020; Zarzo and Prats, 2018). Likewise, the results obtained are in accordance with the energy costs published by Eke et al. (Eke et al., 2020), showing higher energy costs for Spain and Algeria (21% and 24% of total energy cost, respectively) than for UAE and USA (14% and 18% of total energy cost, respectively), indicating that the economic costs of desalinated water production are more limiting in some countries than in others (Fig. 7.6). Also, the high economic costs of desalinated water production, which limit desalination development in Australia, can be attributed to the use of energy from renewable sources and expensive designs for water intake and brine discharge infrastructure (Shemer and Semiat, 2017).

The results show that **environmental requirements** associated with the EIAs and EMPs required for managing the environmental impacts of desalination plants were very low in countries such as Saudi Arabia, Algeria, and UAE, as compared with the others countries assessed. Moreover, these countries do not require an EMP or would impose an EMP with very low requirements, limiting the potential to (i) evaluate if measures adopted during the EIA are adequate and/or (ii) identify potential environmental impacts of brine discharge to facilitate their mitigation (De-la-Ossa-Carretero et al., 2016b; Del-Pilar-Ruso et al., 2015; Elsaid et al., 2020b; Fernández-Torquemada et al., 2013; Lattemann and Höpner, 2008; Petersen et al., 2018b; Sadhwani Alonso and Melián-Martel, 2018; Sola et al., 2019a). EIA is the most important tool for adopting specific mitigation measures to address the environmental impacts of desalination plants. Therefore, in countries where an environmental assessment has not been properly carried out, the ecological value of a desalination plant location or brine discharge areas associated with the construction and/or operation phase of the plant may become deteriorated (Cambridge et al., 2017; De-la-Ossa-Carretero et al., 2016a; Elsaid et al., 2020b, 2020a; Heck et al., 2018; Liu et al., 2013; Petersen et al., 2018a; Roberts et al., 2010; Sadhwani Alonso and Melián-Martel, 2018). However, even in countries where the environmental regulation requirements are low, desalination plants can operate without producing impacts on the marine environment when adequate measures are adopted by desalination operators. For instance, in Algeria, where two SWRO plants with capacities of 200,000 m^3 operate without an EMP, the potential impact of brine discharge from one plant was minimized through a proper dilution system using multiport diffuser devices (Belatoui et al., 2017; Loya-Fernández et al., 2018; Portillo et al., 2013), whereas in the other plant (with the same characteristics), brine discharge resulted in a large saline plume distribution with high salinity values and slight detrimental effects on benthic communities around the brine discharge area (Belatoui et al., 2017).

USA, Australia, Spain, and Chile presented as having high environmental regulation requirements. Our results are in line with the environmental requirements imposed in the EIAs for brine discharge management in Spain and Chile, as published by Fuentes-Bargues (2014) and Sola et al. (2019a; 2019b); although the EIA of both countries has some requirements that should be improved. High environmental requirements have not been a severe problem for desalination development in Spain, Australia, or Chile (Molinos-Senante and González, 2018; Sola et al., 2020b, 2019a). However, the results showed that environmental requirements are the most limiting factor for project development in USA, indicaitng an average of 13.6 years for authorizing a project compared with an overall average of 4.3 years across all countries. The development of desalination of projects with higher production capacities is limited in some parts of Europe and the Americas owing to rigid environmental protection laws in these regions (Eke et al., 2020). The enforcement of stringent environmental laws is not always justified scientifically and can delay the development of desalination projects, representing a barrier to the production of desalinated water for homes and industry. The experience obtained to date shows it is possible to ensure the long-term sustainable operation of desalination plants without environmental impacts on the marine environment when an appropriate environmental assessment process is carried out and mitigation measures are adopted (Abessi, 2018; Fernández-Torquemada et al., 2019; Kelaher et al., 2020; Pistocchi et al., 2020; Sola et al., 2020a).

The results showed a high degree of **financial support** in most of the countries evaluated, with UAE presenting the highest level financial support. However, this is a very limiting factor in Tunisia, Algeria, and Israel. According to the results of Eke et al., the Middle East Bank sponsors a large number of global desalination projects, which is a key factor responsible for the high production capacity of countries from this region, i.e., UAE or Saudi Arabia. Nevertheless, European and North African banks finance desalination projects due to the high freshwater demand in regions where water is scarce (Eke et al., 2020; Jones et al., 2019). However, some countries experiencing financial difficulties may be supported by strong government involvement in desalination projects, such as in Algeria and Israel (Drouiche et al., 2011; Kress et al., 2020).

According to the **legal certainty** factor, Australia, Spain, and UAE showed the highest legal certainty degree among the countries assessed. However, this factor presented as a high limiting factor for Tunisia and USA, and the most limiting factor for desalination development in Tunisia (followed by the cost of water production and financial support).

Regarding **public involvement** requirements in desalination development, our results showed that most countries have a high degree of public involvement. Nevertheless, Saudi Arabia and UAE showed a low involvement degree, although this would be offset by the high degree of financial support in these countries. Appropriate government involvement in desalination development is relevant to integrated water management. For instance, this requirement would offset water desalination costs and the price of water sold through public subsidies, which may affect 20–30% of the estimated cost of water desalination. Similarly, government involvement may provide subsidies to integrate renewable energies in desalination projects to amortize the short-term costs; thus reducing energy costs and aiding sustainable desalination development (Al-Karaghouli and Kazmerski, 2013; Kettani and Bandelier, 2020; Pistocchi et al., 2020; Shahzad et al., 2017).

In this research we also explored the influence of **social factors**. As evidenced by our results, social acceptance may be the least relevant limiting factor (compared with the other factors) in desalination development. In addition, most countries showed a high potential acceptance of desalination projects. Desalination is an essential tool to adress global freshwater demand for irrigation, tourism, industrial purposes such as power plants or mining, drinking water, etc., providing significant benefits for homes and industries as such countries work toward socio-economic development (Eke et al., 2020; Hernández-Sánchez et al., 2017; Jones et al., 2019).

Table 7.5 summarizes the general recommendations for countries where the requirements for desalinination development are very low and/or the limiting factors are very high. For instance, for the USA, the limiting factor is scientific advice for sustainable desalination without producing environmental impacts on the marine environment when environmental requirements are a significant barrier to desalination plant development. For other countries (e.g., Tunisia, Spain, and Israel) the limiting factor is carrying out highly cost-effective projects through the proper analysis and design of desalination projects (within each country's context) aimed at reducing the costs of desalinated water production (Al-Karaghouli and Kazmerski, 2013; Mezher et al., 2011; Pistocchi et al., 2020).

Table 7.5. General summary of recommendations to improve desalination sustainable development in countries where requirements are very low and/or limiting factors are very high.

Country	Requirements	Limiting factors
Algeria	Improve the number of EMP requirements	Carry out highly cost-effective projects to reduce costs of desalinated water produced. Improve financial availability. Improve legal certainty.
Australia	-	Carry out highly cost-effective projects to reduce costs of desalinated water produced
Chile	-	Carry out highly cost-effective projects to reduce costs of desalinated water produced. Scientific advice to facilitate environmental assessment process.
Israel	-	Carry out highly cost-effective projects to reduce costs of desalinated water produced. Improve financial availability.

Saudi Arabia	Improve the number of EIA and EMP requirements. Improve public involvement.	-
Perú	-	Carry out highly cost-effective projects to reduce costs of desalinated water produced.
Oman	-	Carry out highly cost-effective projects to reduce costs of desalinated water produced.
Spain	-	Carry out highly cost-effective projects to reduce costs of desalinated water produced.
Tunisia	-	Carry out highly cost-effective projects to reduce costs of desalinated water produced. Improve financial availability. Improve legal certainty.
UAE	Improve the number of EIA and EMP requirements. Improve public involvement.	Carry out highly cost-effective projects to reduce costs of desalinated water produced. Scientific advice to facilitate environmental assessment process.
USA	-	Scientific advice to facilitate environmental assessment process. Improve legal certainty.

Promoting the development of adequate environmental regulations in countries where the environmental requirements are very low, such as in Saudi Arabia or Algeria, would help correctly manage the environmental impacts of desalination. The application of EMPs with specific environmental requirements according to plant location would help assess whether measures adopted during the EIAs are appropriate and allow monitoring of the potential effects of desalination plants during the operation phase, e.g., in UAE or Algeria (Belatoui et al., 2017; Elsaid et al., 2020b; Hoepner, 1999; Lattemann and Höpner, 2008; Liu et al., 2013; Navarro Barrio et al., 2021; Sola et al., 2019b, 2019a).

Improving government involvement to support desalination projects is also an important factor, e.g., in UAE and Saudi Arabia, as is increasing financial availability for desalination projects, e.g., as Algeria, Israel and Tunisia. Improving legal certainty in those countries that protect the builders and/or operators of desalination plants, e.g., in Tunisia, USA, or Algeria, is also recommended (Al-Karaghouli and Kazmerski, 2013; Drouiche et al., 2011; Eke et al., 2020; Pistocchi et al., 2020; Shemer and Semiat, 2017).

The experience gained to date shows that it is possible to achieve a long-term sustainable desalination when adequate measures and proper requirements are implemented (Fernández-Torquemada et al., 2019; Pistocchi et al., 2020; Sola et al., 2020a). Further, through an appropriate analysis of the pros and cons of desalination technologies it is possible to maximize the benefits and design of desalination projects within the context of reducing the energy costs of the water produced under an expected increase in the development of global desalination efforts (Al-Karaghouli and Kazmerski, 2013; Kettani and Bandelier, 2020; Mezher et al., 2011; Miller et al., 2014; Pistocchi et al., 2020; Shahzad et al., 2017; Zarzo and Prats, 2018).

Future evaluations can bring a larger sampling effort. This study obtained surveys from 23 countries; however, assessment was only possible for 50% of the countries when requiring replication. In future, this study could be extended to compare these factors across a greater number of countries, including other global regions where desalination is developing significantly, e.g., Asia or Oceania. Our results present a first approach to understanding which factors mainly affect desalination development globally based on a semi-quantitative analysis. For future research, data could be compiled from each country for quantitative assessment and comparison with the requirements evaluated in this study.

7.5. Conclusions

The results show large heterogeneity in terms of the requirements and limiting factors for desalination development across different countries. Special attention should be given to countries where strong limiting factors would represent a barrier to desalination development. In addition, environmental and/or socio-economics requirements should be improved where very low requirements have been identified. The knowledge obtained in this research could be used to enhance scientific advice, advance toward sustainable desalination development, and address global water demand challenges.

7.6. Funding

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7.7. Acknowledgements

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DISCUSIÓN GENERAL

8. DISCUSIÓN

Las investigaciones presentadas en esta Tesis aportan una visión holística sobre cómo se pueden abordar adecuadamente los efectos negativos de los vertidos de salmuera de las plantas desalinizadoras en los ecosistemas marinos, con el fin de asegurar una operación y desarrollo sostenible a largo plazo. Se abordaron los diferentes aspectos ambientales relacionados con el proceso de evaluación ambiental y la fase de operación de las plantas de desalación a través de: i) una revisión de los estudios y medidas de mitigación llevadas a cabo en España para la gestión de los vertidos de salmuera, mostrando soluciones testadas científicamente para permitir un desarrollo de la industria de la desalación sin producir impactos significativos en los ecosistemas marinos (Sola et al., 2020b, 2020a); ii) un análisis exhaustivo de los requerimientos exigidos en los EMPs para los vertidos de salmuera de España y Chile, y como se deberían mejorar para asegurar una correcta monitorización e identificación de posibles impactos (Sola et al., 2019b, 2019a); iii) un análisis de un EMP a largo plazo como ejemplo de desarrollo sostenible de un SWRO tras llevar a cabo un riguroso proceso de evaluación ambiental en colaboración con científicos, demostrando un buen estado de los indicadores biológicos a largo plazo (Sola et al., 2020a); iv) una evaluación de cómo se están abordando los requerimientos en las normativas ambientales, y que factores son más limitantes en el desarrollo de proyectos de desalación a nivel global (capítulo 7).

España es de unos los países pioneros en el desarrollo de la desalación que comenzó el inicio de la desalación en las Islas Canarias con su primera desaladora en 1964 (Cabrera et al., 2019; Downward and Taylor, 2007; Gómez-Gotor et al., 2018). Actualmente, se presenta como referencia a nivel mundial como uno de los principales países en cuanto a su capacidad de producción de agua desalinizada instalada para solventar problemas de escasez hídrica para diferentes usos (AEDyR, 2018; Cabrera et al., 2019). Sin embargo, uno de los principales factores que limitaba el desarrollo de la desalación en el país era la incertidumbre ante los efectos producidos por los vertidos de salmuera en el medio marino (Cabrera et al., 2019).

Ante el esperado desarrollo de la desalación en España, las autoridades competentes impulsaron un proyecto en cooperación entre la industria y los científicos, para estudiar los efectos de los vertidos de salmuera sobre uno de los ecosistemas claves del Mediterráneo, las praderas de *P. oceanica* (Buceta et al., 2003; Sánchez-Lizaso et al., 2008). Los resultados permitieron establecer unos umbrales de salinidad seguros para gestionar el potencial impacto del desarrollo significativo de plantas SWRO en la costa mediterránea (AEDyR, 2018; Sánchez-Lizaso et al., 2008; Sola et al., 2019b). En la presente tesis se revisaron los estudios y medidas llevadas a cabo en España para abordar la gestión de los vertidos de salmuera, que permitieron el desarrollo de la desalación sin impactar significativamente en el medio ambiente marino o, cuando se han identificado efectos negativos, diseñar estrategias para revertirlos o minimizarlos. La experiencia obtenida en España como país pionero en la desalación es crucial para entender y minimizar los impactos de la desalación en otros países donde la desalación es emergente (Sola et al., 2020b).

En la presente investigación se evalúan por primera vez los requerimientos que son exigidos por las autoridades competentes en los EMPs para la monitorización de los vertidos de salmuera de las plantas desalinizadoras, tomando como referencia a España (Cabrera et al., 2019; Gómez-Gotor et al., 2018; Sola et al., 2019b). Este estudio permitió desarrollar una metodología útil para evaluar de manera estandarizada los requerimientos que deberían estar presentes en los EMPs para la monitorización e identificación de los efectos producidos por los vertidos de salmuera en el medio marino. La metodología fue contrastada empleando los EMPs de Chile, que se trata de un país en pleno desarrollo de la industria de la desalación empleando la tecnología de RO (Molinos-Senante and González, 2018; Sola et al., 2019a). Para ello, se consideraron las especificidades y necesidades ambientales de Chile. Por un lado, y a diferencia de España, Chile no disponía de especies claves o protegidas en las que se han establecido umbrales de salinidad para la protección ante vertidos de salmuera, como está implementado en España en las praderas marinas de *Posidonia oceanica* o *Cymodocea nodosa*, y por tanto, es un requerimiento que no se podía considerar para la evaluación (Sánchez-Lizaso et al., 2008).

Estos resultados evidencian la necesidad de establecer unos límites de salinidad para la protección de los ecosistemas marinos en Chile, que podrían implementarse mediante umbrales de salinidad obtenidos del estudio de la tolerancia al incremento de salinidad de ecosistemas claves como las macroalgas o bosques de Kelp, tomando como referencia la experiencia adquirida en España con las praderas de *P.* oceanica, o con *Posidonia australis* en Australia (Berenguel-Felices et al., 2020; Navarro Barrio et al., 2021; Sánchez-Lizaso et al., 2008; Sola et al., 2020b).

Por otro lado, se consideró relevante entre las especificidades de la regulación ambiental de Chile, incluir como requerimiento los bioensayos de toxicidad para monitorizar posibles efectos tóxicos sobre las especies presentes en el área de vertido; que pueden estar mediados por el estrés osmótico y/o elementos químicos usados para el pretratamiento y/o limpieza de membranas (Tabla 2.2) (Agus and Sedlak, 2010; Portillo et al., 2014b; Voutchkov, 2017). Adicionalmente, se incluyó un requerimiento para el control de los efectos de la captación de agua de mar, considerando la monitorización del impacto de la succión sobre las comunidades de plancton (Petersen et al., 2018a; Sharifinia et al., 2019).

Los resultados obtenidos en España y Chile (Sola et al., 2019b, 2019a) muestran una tendencia significativa a incluir mayores requerimientos en los EMPs con el paso del tiempo para garantizar una mayor protección del medio marino. Sin embargo, ambos países mostraron que existe una alta heterogeneidad en los requerimientos exigidos entre proyectos de similares características, mostrando la necesidad de establecer una regulación ambiental específica para vertidos de salmuera, que esté apoyada por el mejor criterio científico conocido hasta la fecha. Ambos países mostraron EMPs que presentaban requerimientos no acordes al control de un vertido de salmuera, y que más bien parecían responder al control de descargas de otro tipo de industrias (ej. vertido de una planta de aguas residuales), o requerimientos que respondían más bien a una fase de proyecto diferente a la de operación (ej. fase de construcción o estudios previos). Específicamente, Chile se apoya en la norma D.S. Nº90, que establece requerimientos generales para vertidos industriales a cuerpos acuáticos; en el contexto de la desalación, considera un gran número de requerimientos irrelevantes para un vertido de salmuera y sus potenciales consecuencias ambientales (Sola et al., 2019a, 2019b; Valdés-Pineda et al., 2014).

Acorde a los resultados obtenidos en la presente tesis, se recomienda revisar los requerimientos exigidos en los EMPs de España y Chile, incluyendo descriptores esenciales para la vigilancia de los efectos de los vertidos de salmuera en el medio marino cuando no están presentes en los EMPs, y eliminando los descriptores innecesarios que generan costes económicos añadidos sin aportar herramientas efectivas para el diagnóstico ambiental. La definición de estos requerimientos debe ir de la mano de una adecuada definición de los diseños de muestreo de estos requerimientos (Roberts et al., 2010; Underwood, 1994). Además, los EMPs definidos de manera rigurosa permiten discriminar de otros impactos antrópicos que se solapan en el área de influencia de un vertido de salmuera, como pueden ser los efectos añadidos de un vertido de una planta de aguas residuales o la ampliación de un puerto (De-la-Ossa-Carretero et al., 2016a). En Sola et al., (2020a) se observa cómo los resultados del EMP de la SWRO de Jávea han permitido demostrar que la pérdida de abundancia y riqueza de especies de peces presentes en el área de vertido de salmuera, son por el contrario más atribuibles a otros impactos antrópicos locales (ej. pesca profesional o recreativa). La experiencia obtenida en esta tesis podría emplearse para que las autoridades competentes de los países donde se desarrolla la desalación establezcan regulaciones ambientales acorde a las características específicas de los vertidos de salmuera (Fuentes-Bargues, 2014; Sadhwani Alonso and Melián-Martel, 2018).

Acorde a los resultados obtenidos, se demuestra que es posible alcanzar una desalación sostenible a largo plazo cuando se adopta un proceso riguroso y en cooperación entre el sector de la industria y academia (Sola et al., 2020b). En la presente tesis, se ha demostrado con el caso de estudio de la SWRO de Jávea (España), que llevando a cabo una adecuada evaluación del proceso de evaluación ambiental, se puede operar una planta SWRO a largo plazo sin producir impactos ambientales significativos; incluso en esta zona de alto valor ecológico (Clark et al., 2018; Miller et al., 2014; Missimer and Maliva, 2018; Sola et al., 2020b; Zarzo et al., 2009). Los resultados obtenidos tras 17 años de seguimiento ambiental con el EMP de la desaladora de Jávea, han demostrado impactos negativos poco significativos en especies sensibles o protegidas presentes en el área de vertido, como las praderas de *P. oceanica* y equinodermos (Sola et al., 2020a).

Además, se ha demostrado que llevar una adecuada gestión del vertido de salmuera, adoptando medidas de prevención y mitigación, pueden incluso aportar beneficios en algunas especies (Kelaher et al., 2020). En este contexto, los resultados obtenidos en Sola et al., (2020a) demostraron una mayor abundancia, riqueza y diversidad de especies de peces con valor socio-económico (ej. *Dicentrarchus labrax* o *Diplodus sargus*) en el área de vertido de la planta SWRO de Jávea respecto al área control. Recientemente, Kelaher et al., (2020) obtuvieron resultados similares para el seguimiento ambiental de un vertido de salmuera de una SWRO en Australia, observándose que cuando se adoptan infraestructuras bien diseñadas para minimizar el impacto de los vertidos de salmuera, también se puede mejorar la abundancia y riqueza de especies de peces locales con interés para la pesca comercial y recreativa.

La metodología llevada a cabo en España y Chile permitió evaluar de manera muy detallada los requerimientos establecidos en los EMPs (Sola et al., 2019b, 2019a). Sin embargo, la complejidad y tiempo necesario para llevar a cabo estos análisis eran un limitante para diagnosticar los requerimientos exigidos en la regulación ambiental en todos los países donde se está desarrollando la desalación. Por ello, a través de una encuesta a nivel global a expertos en el área, se evaluó mediante un análisis semi-cuantitativo el número de requerimientos exigidos en los procesos de evaluación ambiental en los países donde se está desarrollando la industria de la desalinización (Capítulo 7). Los resultados permitieron obtener una primera aproximación del número de exigencias requeridas en los procesos de regulación ambiental acorde al país evaluado. Las resultados mostraron que hay países que podrían presentar EIAs o EMPs con requerimientos muy bajos, o incluso, donde la ley no los exige (Kämpf and Clarke, 2013; Kress, 2019a; Sadhwani Alonso and Melián-Martel, 2018). Aunque la preocupación ambiental en algunos países puede ser baja, se abre la oportunidad de realizar un asesoramiento científico-técnico que incremente su interés en estrategias de proyección y conservación ambiental, que no es necesariamente vinculante a un menor desarrollo económico (Lattemann et al., 2009; Sadhwani Alonso and Melián-Martel, 2018).

Por otro lado, los resultados obtenidos en la presente Tesis mostraron que hay ciertos países que presentan un alto interés en torno a los impactos ambientales, presentando un número alto de requerimientos exigidos durante el proceso de EIA y/o en la implementación de un EMP. Asimismo, los resultados mostraron que los aspectos ambientales junto a los costes económicos de la producción de agua desalada, representan los factores más limitantes en el desarrollo de un proyecto de desalación (Heck et al., 2018; Ibrahim et al., 2018). La incertidumbre en torno al impacto ambiental de la desalinización podría representar un problema en algunos países para el desarrollo de plantas de desalación. Los resultados mostraron que USA presenta un tiempo de autorización de proyectos mucho mayor a la media de los países evaluados, causado principalmente por la alta exigencia de requerimientos ambientales (Heck et al., 2018, 2016; Liu et al., 2018).

En conclusión, es importante llevar a cabo un riguroso **proceso de evaluación ambiental** para gestionar de manera sostenible los efectos producidos de los vertidos de salmuera en el medio marino (Kress, 2019a; Sadhwani Alonso and Melián-Martel, 2018). Este debería incluir: un estudio del área más óptima para la disposición del vertido de salmuera, seleccionando áreas de bajo valor ecológico o zonas previamente degradadas por otras actividades antrópicas (ej. puertos u otros vertidos industriales) cuando sea posible (Sola et al., 2020b; Zarzo et al., 2009). Un estudio previo de la dilución del vertido en el medio marino empleando softwares adecuados de simulación, para adoptar la mejor configuración del vertido (Loya-Fernández et al., 2012; Palomar et al., 2012). Establecer límites o umbrales de salinidad para la protección de especies protegidas o ecosistemas claves presentes en el área de vertido cuando no han podido evitarse (Sánchez-Lizaso et al., 2008). La implementación de medidas de mitigación testadas científicamente como el uso de difusores y/o la dilución del vertido con agua de mar u otras fuentes, para maximizar la dilución y reducir el área de influencia del vertido; que suponen un consumo energético adicional pero asumible para llevar a cabo una correcta protección ambiental y cumplir con la regulación ambiental establecida (Navarro Barrio et al., 2021; Sola et al., 2020a).

Asimismo, es importante la implementación de un **EMP** correctamente diseñado, que: i) incorpore los requerimientos esenciales para evaluar la eficacia de las medidas adoptadas durante el proceso de evaluación ambiental; ii) asegure que las plantas de desalación operen de manera correcta sin realizar cambios a los definidos durante el proceso de evaluación ambiental; iii) sea diseñado en cooperación con científicos y permita cierta flexibilidad para adaptarse al mejor conocimiento científico presente; iv) se evite el uso de descriptores irrelevantes en el contexto de desalación; v) permita identificar y minimizar los impactos ambientales cuando estos se produzcan (Sola et al., 2019a, 2019b). Finalmente, se debe prestar especial atención a los países donde los requerimientos exigidos durante el proceso de evaluación ambiental y desarrollo de EMP son bajos o inexistentes, para garantizar un desarrollo global sostenible de la desalación (Capítulo 7).

La industria de la desalación sigue experimentando un desarrollo importante a nivel global para el suministro de agua potable y para otros usos, más aun considerando el contexto actual de cambio climático (Eke et al., 2020; Jones et al., 2019; Sun et al., 2019). Las evidencias científicas obtenidas en la presente Tesis, pueden servir como ejemplo para el desarrollo de proyectos de desalación en los países que requieran una mejora del conocimiento de gestión de los aspectos ambientales relacionados con los vertidos de salmuera sobre ecosistemas marinos y llevar a cabo una desalación sostenible (Pistocchi et al., 2020; Sola et al., 2020b).

CONCLUSIONES

9. CONCLUSIONES

A continuación, se presentan las conclusiones obtenidas de esta Tesis doctoral:

1. La experiencia obtenida en España para la gestión de los vertidos de salmuera ofrece un enfoque integral para minimizar los potenciales efectos de los efluentes de las plantas SWRO en otras regiones, donde el sector de la desalinización se encuentra en vías de desarrollo (Capítulo 3).

2. La cooperación entre el sector de la industria y científicos durante el proceso de evaluación ambiental de un nuevo proyecto de desalación permite adoptar recomendaciones con base científico/técnica, para minimizar y prevenir los efectos significativos de los vertidos de salmuera (Capítulos 3 y 7).

3. La implementación de umbrales de salinidad con base científica ha garantizado la protección de especies sensibles y protegidas, como las praderas de *Posidonia oceanica* (Capítulo 3).

4. Los requerimientos establecidos en los EMPs para la vigilancia de los vertidos de salmuera en el medio marino y sus diseños de muestreo han mejorado con el tiempo en las EIAs de España y Chile. Sin embargo, esta tendencia es similar para la inclusión de descriptores innecesarios que no garantizan una mayor protección del medio marino y generan costes económicos añadidos (Capítulos 4 y 5).

5. La presencia de especies protegidas como *Posidonia oceanica* o *Cymodocea nodosa* en el área de vertido de las plantas de SWRO en España favorece la implementación de EMPs con mayores requerimientos esenciales (Capítulos 4).

6. Los EMPs de España y Chile muestran una alta heterogeneidad en los requerimientos establecidos para la vigilancia de vertidos de salmuera de plantas SWRO con similares características, y no existe una relación de mayores requerimientos en las plantas con mayor capacidad de producción (Capítulos 4 y 5).

7. La implementación de un riguroso proceso de evaluación ambiental en la SWRO de Jávea ha permitido lograr una operación sostenible a largo plazo en una zona de alto valor ecológico, minimizando los impactos asociados a la

captación de agua de mar y vertido de salmuera (Capítulos 3 y 6).

8. El área de vertido de salmuera de la SWRO de Jávea (España) mostró una mayor abundancia y diversidad de peces gracias a la correcta planificación y diseño del vertido de salmuera (Capítulo 4).

9. La dilución de un vertido de salmuera con agua de mar en la proporción adecuada a la salinidad de ésta, es una solución efectiva para lograr una dilución adecuada de un vertido de salmuera, e implica un consumo de energía relativamente bajo respecto al consumo de energía total de una SWRO (Capítulos 3 y 6).

10. Los requerimientos y factores limitantes ambientales y socio-económicos involucrados en el desarrollo de proyectos de desalación, muestran una alta heterogeneidad entre diferentes países (Capítulo 7).

11. La implementación de requerimientos ambientales muy estrictos durante los procesos de evaluación ambiental para un proyecto de desalación, puede implicar un obstáculo o mayor tiempo de autorización en ciertos países, como Estados Unidos (Capítulo 7).

12. El coste económico de la producción de agua desalinizada representa un factor muy limitante para el desarrollo de la desalinización, sobre todo en aquellos países sub- o en vías de desarrollo (Capítulo 7).

13. Se ha identificado que los requerimientos ambientales asociados al proceso de evaluación ambiental y seguimiento ambiental de los vertidos de salmuera para un proyecto de desalación, presentan requerimientos muy bajos o no son exigidos en ciertos países (Capítulo 7).

14. La mayoría de los países muestran una alta aceptación social del desarrollo de proyectos de desalación para solventar problemas de escasez hídrica (Capítulo 7).

BIBLIOGRAFÍA

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Abessi, O., 2018. Brine Disposal and Management—Planning, Design, and Implementation. Sustain. Desalin. Handb. 259–303. https://doi.org/10.1016/B978-0-12-809240-8.00007-1

AEDyR, 2018. Desalación en España en primera persona: de hitos pioneros, a referente internacional (in Spanish). https://historiadesalacion.es

Aguilera, M.A., Aburto, J.A., Bravo, L., Broitman, B.R., García, R.A., Gaymer, C.F., Gelcich, S., López, B.A., Montecino, V., Pauchard, A., Ramos, M., Rutllant, J.A., Sáez, C.A., Valdivia, N., Thiel, M., 2019. Chile: Environmental Status and Future Perspectives. World Seas an Environ. Eval. 673–702. https://doi.org/10.1016/B978-0-12-805068-2.00046-2

Agus, E., Sedlak, D.L., 2010. Formation and fate of chlorination by-products in reverse osmosis desalination systems. Water Res. 44, 1616–1626. https://doi.org/10.1016/J.WATRES.2009.11.015

Al-Karaghouli, A., Kazmerski, L.L., 2013. Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. Renew. Sustain. Energy Rev. 24, 343–356. https://doi.org/https://doi.org/10.1016/j.rser.2012.12.064

Alshahri, F., 2017. Heavy metal contamination in sand and sediments near to disposal site of reject brine from desalination plant, Arabian Gulf:

Assessment of environmental pollution. Environ. Sci. Pollut. Res. 24, 1821–1831. https://doi.org/10.1007/s11356-016-7961-x

Ancapichun, S., 2015. Variability of the Southeast Pacific Subtropical Anticyclone and its impact on sea surface temperature off north-central Chile. Ciencias Mar. 41, 1–20. https://doi.org/10.7773/cm.v41i1.2338

Areiqat, A., Mohamed, K.A., 2005. Optimization of the negative impact of power and desalination plants on the ecosystem. Desalination 185, 95–103. https://doi.org/10.1016/J.DESAL.2005.04.038

Baalousha, H., 2006. Desalination status in the Gaza Strip and its environmental impact. Desalination 196, 1–12. https://doi.org/10.1016/J.DESAL.2005.12.009

Barbera, C., Sánchez-Jerez, P., Sánchez-Lizaso, J.L., 2001. Test agudo de ecotoxicidad para estimar el efecto combinado de la salinidad y temperatura en la mortalidad del misidáceo *Leptomysis posidoniae* Wittmann, 1986 (Crustacea), in: Congreso Nacional AEDyR. Alicante.

Belatoui, A., Bouabessalam, H., Hacene, O.R., De-la-Ossa-Carretero, J.A., Martinez-Garcia, E., Sanchez-Lizaso, J.L., 2017. Environmental effects of brine discharge from two desalinations plants in Algeria (South Western Mediterranean). Desalin. Water Treat. 76, 311–318. https://doi.org/10.5004/dwt.2017.20812

Belkin, N., Rahav, E., Elifantz, H., Kress, N., Berman-frank, I., 2017. The effect of coagulants and antiscalants discharged with seawater desalination brines on coastal microbial communities: A laboratory and in situ study from the southeastern Mediterranean. Water Res. 110, 321–331. https://doi.org/10.1016/j.watres.2016.12.013

Berenguel-Felices, F., Lara-Galera, A., Muñoz-Medina, M.B., 2020. Requirements for the Construction of New Desalination Plants into a Framework of Sustainability. Sustainability. https://doi.org/10.3390/su12125124

Bonelli, S., Vicuña, S., Meza, F.J., Gironás, J., Barton, J., 2014. Incorporating climate change adaptation strategies in urban water supply planning: the case of central Chile. J. Water Clim. Chang. 5, 357–376. https://doi.org/10.2166/wcc.2014.037

Boudouresque, C., Meinesz, A., 1982. Découverte de l ’ herbier de Posidonies. Parc Natl. Port-Cros 4, 1–79.

Buceta, J.L., Fernández-Torquemada, Y., Gacía, E., Invers, O., Mas, J., Romero, J., Ruiz, J.M., Ruiz-Mateo, A., Sabah, S., Sánchez-Lizaso, J.L., 2003. Investigación conjunta sobre la tolerancia de *Posidonia oceanica* a incrementos de la salinidad. Ing. Civ. 111–116.

Cabrera, E., Estrela, T., Lora, J., 2019. Desalination in Spain. past, present and future. Houille Blanche 2019-Janua, 85–92. https://doi.org/10.1051/lhb/2019011

Cambridge, M.L., Zavala-Perez, A., Cawthray, G.R., Mondon, J., Kendrick, G.A., 2017. Effects of high salinity from desalination brine on growth, photosynthesis, water relations and osmolyte concentrations of seagrass *Posidonia australis*. Mar. Pollut. Bull. 115, 252–260. https://doi.org/10.1016/J.MARPOLBUL.2016.11.066

Chang, J.S., 2015. Understanding the role of ecological indicator use in assessing the effects of desalination plants. Desalination 365, 416–433. https://doi.org/10.1016/j.desal.2015.03.013

Clark, G.F., Knott, N.A., Miller, B.M., Kelaher, B.P., Coleman, M.A., Ushiama, S., Johnston, E.L., 2018. First large-scale ecological impact study of desalination outfall reveals trade-offs in effects of hypersalinity and hydrodynamics. Water Res. 145, 757–768. https://doi.org/10.1016/J.WATRES.2018.08.071

Costanza, R., d’Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O’Neill, R. V, Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world’s ecosystem services and natural capital. Nature 387, 253–260. https://doi.org/10.1038/387253a0

De-la-Ossa-Carretero, J.A., Del-Pilar-Ruso, Y., Giménez-Casalduero, F., Sánchez-Lizaso, J.L., 2016a. Amphipoda assemblages in a disturbed area (Alicante, Spain, Western Mediterranean). Mar. Ecol. 37, 503–517. https://doi.org/10.1111/maec.12264

De-la-Ossa-Carretero, J.A., Del-Pilar-Ruso, Y., Loya-Fernández, A., Ferrero-Vicente, L.M., Marco-Méndez, C., Martinez-Garcia, E., Giménez-Casalduero, F., Sánchez-Lizaso, J.L., 2016b. Bioindicators as metrics for environmental monitoring of desalination plant discharges. Mar. Pollut. Bull. 103, 313–318. https://doi.org/10.1016/j.marpolbul.2015.12.023

De-la-Ossa-Carretero, J.A., Del-Pilar-Ruso, Y., Loya-Fernández, A., Ferrero-Vicente, L.M., Marco-Méndez, C., Martinez-Garcia, E., Sánchez-Lizaso, J.L., 2016c. Response of amphipod assemblages to desalination brine discharge: Impact and recovery. Estuar. Coast. Shelf Sci. 172, 13–23. https://doi.org/10.1016/j.ecss.2016.01.035

de la Maza, C.L., 2001. NEPA's influence in developing countries: the Chilean case. Environ. Impact Assess. Rev. 21, 169–179. https://doi.org/10.1016/S0195-9255(00)00073-1

de los Santos, C.B., Krause-Jensen, D., Alcoverro, T., Marbà, N., Duarte, C.M., van Katwijk, M.M., Pérez, M., Romero, J., Sánchez-Lizaso, J.L., Roca, G., Jankowska, E., Pérez-Lloréns, J.L., Fournier, J., Montefalcone, M., Pergent, G., Ruiz, J.M., Cabaço, S., Cook, K., Wilkes, R.J., Moy, F.E., Trayter, G.M.-R., Arañó, X.S., de Jong, D.J., Fernández-Torquemada, Y., Auby, I., Vergara, J.J., Santos, R., 2019. Recent trend reversal for declining European seagrass meadows. Nat. Commun. 10, 3356. https://doi.org/10.1038/s41467-019-11340-4

Del-Pilar-Ruso, Y., De-la-Ossa-Carretero, J.A., Giménez-Casalduero, F., Sánchez-Lizaso, J.L., 2008. Effects of a brine discharge over soft bottom Polychaeta assemblage. Environ. Pollut. 156, 240–250. https://doi.org/10.1016/j.envpol.2007.12.041

Del-Pilar-Ruso, Y., Jose Antonio, D. la O.C., Angel, L.F., Luis Miguel, F.V., Francisca, G.C., Jose Luis, S.L., 2009. Assessment of soft-bottom Polychaeta assemblage affected by a spatial confluence of impacts: Sewage and brine discharges. Mar. Pollut. Bull. 58, 776–782. https://doi.org/10.1016/j.marpolbul.2009.03.002

Del-Pilar-Ruso, Y., la Ossa Carretero, J.A. De, Casalduero, F.G., Lizaso, J.L.S., 2007. Spatial and temporal changes in infaunal communities inhabiting soft-bottoms affected by brine discharge. Mar. Environ. Res. 64, 492–503. https://doi.org/10.1016/j.marenvres.2007.04.003

Del-Pilar-Ruso, Y., Martinez-Garcia, E., Giménez-Casalduero, F., Loya-Fernández, A., Ferrero-Vicente, L.M., Marco-Méndez, C., de-la-Ossa-Carretero, J.A., Sánchez-Lizaso, J.L., 2015. Benthic community recovery from brine impact after the implementation of mitigation measures. Water Res. 70, 325–336. https://doi.org/10.1016/j.watres.2014.11.036

Downward, S.R., Taylor, R., 2007. An assessment of Spain's Programa AGUA and its implications for sustainable water management in the province of Almería, southeast Spain. J. Environ. Manage. 82, 277–289. https://doi.org/10.1016/J.JENVMAN.2005.12.015

Drouiche, N., Ghaffour, N., Naceur, M.W., Mahmoudi, H., Ouslimane, T., 2011. Reasons for the Fast Growing Seawater Desalination Capacity in Algeria. Water Resour. Manag. 25, 2743–2754. https://doi.org/10.1007/s11269-011-9836-8

Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I., Marbà, N., 2013. The role of coastal plant communities for climate change mitigation and adaptation. Nat. Clim. Chang. 3, 961.

Eke, J., Yusuf, A., Giwa, A., Sodiq, A., 2020. The global status of desalination: An assessment of current desalination technologies, plants and capacity. Desalination 495, 114633. https://doi.org/https://doi.org/10.1016/j.desal.2020.114633

Elsaid, K., Kamil, M., Sayed, E.T., Abdelkareem, M.A., Wilberforce, T., Olabi, A., 2020a. Environmental impact of desalination technologies: A review. Sci. Total Environ. 748, 141528. https://doi.org/10.1016/j.scitotenv.2020.141528

Elsaid, K., Sayed, E.T., Abdelkareem, M.A., Baroutaji, A., Olabi, A.G., 2020b. Environmental impact of desalination processes: Mitigation and control strategies. Sci. Total Environ. 740, 140125. https://doi.org/10.1016/j.scitotenv.2020.140125

European Union, 2014. Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014, on the assessment of the effects of certain public and private projects on the environment, Off. J. Eur. Union L124, 1–18.

European Union, 1992. Directive 92/43/CEE of 21th May on the conservation of natural habitats and of wild fauna and flora, Off. J. Eur. Union, L26, 7-50.

European Union, 1985. Directive 85/337/EEC of the Council of June 27th 1985, on the assessment of the effects of certain public and private projects on the environment, Off. J. Eur. Union, L175, 40-48.

Fernández-torquemada, Y., Carratalá, A., Luis, J., Lizaso, S., 2019. Impact of brine on the marine environment and how it can be reduced. Desalin. Water Treat. 167, 27–37. https://doi.org/10.5004/dwt.2019.24615

Fernández-Torquemada, Y., Gónzalez-Correa, J.M., Loya, A., Ferrero, L.M., Díaz-Valdés, M., Sánchez-Lizaso, J.L., 2009. Dispersion of brine discharge from seawater reverse osmosis desalination plants. Desalin. Water Treat. 5, 137–145. https://doi.org/10.5004/dwt.2009.576

Fernández-Torquemada, Y., González-Correa, J.M., Sánchez-Lizaso, J.L., 2013. Echinoderms as indicators of brine discharge impacts. Desalin. Water Treat. 51, 567–573. https://doi.org/10.1080/19443994.2012.716609

Fernández-Torquemada, Y., Loya-Fernández, A., Múgica, Y., Sánchez-Lizaso, J.L., Templado, J., Calvo, M., Antoranz, A., Cortés, J.M., 2007. Monitoring the brine discharge from a desalination plant in the Mediterranean, in: IDA World Congress. Maspalomas (Gran Canaria) - Spain.

Fernández-torquemada, Y., Sánchez-lizaso, J.L., 2007. Monitoring of brine discharges from seawater desalination plants in the Mediterranean. Int. J. Health 1, 449–461. https://doi.org/10.1504/IJENVH.2007.017870

Fernández-Torquemada, Y., Sánchez-Lizaso, J.L., 2013. Effects of salinity on seed germination and early seedling growth of the Mediterranean seagrass *Posidonia oceanica* (L.) Delile. Estuar. Coast. Shelf Sci. 119, 64–70. https://doi.org/10.1016/j.ecss.2012.12.013

Fernández-Torquemada, Y., Sánchez-Lizaso, J.L., 2011. Responses of two Mediterranean seagrasses to experimental changes in salinity. Hydrobiologia 669, 21–33. https://doi.org/10.1007/s10750-011-0644-1

Fernández-Torquemada, Y., Sánchez-Lizaso, J.L., 2005. Effects of salinity on leaf growth and survival of the Mediterranean seagrass *Posidonia oceanica* (L.)

Delile. J. Exp. Mar. Bio. Ecol. 320, 57–63. https://doi.org/10.1016/j.jembe.2004.12.019

Fernández-Torquemada, Y., Sánchez-Lizaso, J.L., González-Correa, J.M., 2005. Preliminary results of the monitoring of the brine discharge produced by the SWRO desalination plant of Alicante (SE Spain). Desalination 182, 395–402. https://doi.org/10.1016/j.desal.2005.03.023

Ferrero-Vicente, L.M., Loya-Fernández, Á., Marco-Méndez, C., Martínez-García, E., Sánchez-Lizaso, J.L., 2011. Soft-bottom sipunculans from San Pedro del Pinatar (Western Mediterranean): Influence of anthropogenic impacts and sediment characteristics on their distribution. Anim. Biodivers. Conserv. 34, 101–111.

Fisher, R., Langlois, T.J., Wilson, S.K., Sin, T.M., Lee, A.C., 2018. A simple function for full subsets multiple regression in ecology with R. Ecol Evol. 8, 6104–6113. https://doi.org/10.1002/ece3.4134

Frank, H., Fussmann, K.E., Rahav, E., Bar Zeev, E., 2019. Chronic effects of brine discharge from large-scale seawater reverse osmosis desalination facilities on benthic bacteria. Water Res. 151, 478–487. https://doi.org/10.1016/J.WATRES.2018.12.046

Frank, H., Rahav, E., Bar-Zeev, E., 2017. Short-term effects of SWRO desalination brine on benthic heterotrophic microbial communities. Desalination 417, 52–59. https://doi.org/10.1016/j.desal.2017.04.031

Fuentes-Bargues, J.L., 2014. Analysis of the process of environmental impact assessment for seawater desalination plants in spain. Desalination 347, 166–174. https://doi.org/10.1016/j.desal.2014.05.032

Gacia, E., Invers, O., Manzanera, M., Ballesteros, E., Romero, J., 2007. Impact of the brine from a desalination plant on a shallow seagrass (*Posidonia oceanica*) meadow. Estuar. Coast. Shelf Sci. 72, 579–590. https://doi.org/10.1016/J.ECSS.2006.11.021

Garrote-Moreno, A., Fernández-Torquemada, Y., Sánchez-Lizaso, J.L., 2014. Salinity fluctuation of the brine discharge affects growth and survival of the seagrass *Cymodocea nodosa*. Mar. Pollut. Bull. 81, 61–68. https://doi.org/10.1016/J.MARPOLBUL.2014.02.019

Gheorghe, S., Stoica, C., Vasile, G.G., Nita-Lazar, M., Stanescu, E., Lucaciu, I.E., 2017. Metals toxic effects in aquatic ecosystems: modulators of water quality. Water Qual. Intech. https://doi.org/10.5772/65744

Giwa, A., Dufour, V., Marzooqi, F. Al, Kaabi, M. Al, Hasan, S.W., 2017. Brine management methods: Recent innovations and current status. Desalination 407, 1–23. https://doi.org/10.1016/j.desal.2016.12.008

Gómez-Gotor, A., Del Río-Gamero, B., Prieto Prado, I., Casañas, A., 2018. The history of desalination in the Canary Islands. Desalination 428, 86–107. https://doi.org/https://doi.org/10.1016/j.desal.2017.10.051

González-Correa, J.M., Torquemada, Y.F., Sánchez Lizaso, J.L., 2008. Long-term effect of beach replenishment on natural recovery of shallow *Posidonia oceanica* meadows. Estuar. Coast. Shelf Sci. 76, 834-844. https://doi.org/10.1016/j.ecss.2007.08.012

Gude, V.G., 2016. Desalination and sustainability – An appraisal and current perspective. Water Res. 89, 87–106. https://doi.org/10.1016/J.WATRES.2015.11.012

Guillén, J.E., Sánchez Lizaso, J.L., Jiménez, S., Martínez, J., Codina, A., Montero, M., Triviño, A., Soler, G., Zubcoff, J.J., 2013. Evolution of *Posidonia oceanica* seagrass meadows and its implications for management. J. Sea Res. 83, 65–71. https://doi.org/10.1016/J.SEARES.2013.04.012

Heck, N., Paytan, A., Potts, D.C., Haddad, B., 2016. Predictors of local support for a seawater desalination plant in a small coastal community. Environ. Sci. Policy 66, 101–111. https://doi.org/10.1016/j.envsci.2016.08.009

Heck, N., Paytan, A., Potts, D.C., Haddad, B., Lykkebo Petersen, K., 2018. Management preferences and attitudes regarding environmental impacts from seawater desalination: Insights from a small coastal community. Ocean Coast. Manag. 163, 22–29. https://doi.org/10.1016/J.OCECOAMAN.2018.05.024

Hejazi, M.I., Edmonds, J., Clarke, L., Kyle, P., Davies, E., Chaturvedi, V., Wise, M., Patel, P., Eom, J., Calvin, K., 2014. Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies. Hydrol. Earth Syst. Sci. 18, 2859–2883. https://doi.org/10.5194/hess-18-2859-2014

Hemminga, M.A., Duarte, C.M., 2000. Seagrass Ecology. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511525551

Hernández-Sánchez, J.C., Boluda-Botella, N., Sánchez-Lizaso, J.L., 2017. The role of desalination in water management in southeast Spain. Desalin. Water Treat. 76, 71–76. https://doi.org/10.5004/dwt.2017.20657

Hoekstra, A.Y., 2014. Water scarcity challenges to business. Nat. Clim. Chang. 4, 318–320. https://doi.org/10.1038/nclimate2214

Hoepner, T., 1999. A procedure for environmental impact assessments (EIA) for seawater desalination plants. Desalination 124, 1–12. https://doi.org/https://doi.org/10.1016/S0011-9164(99)00083-1

Hurlbert, S.H., 1984. Pseudoreplication and the Design of Ecological Field Experiments. Ecol. Monogr. 54, 187–211. https://doi.org/10.2307/1942661

Ibrahim, Y., Arafat, H.A., Mezher, T., AlMarzooqi, F., 2018. An integrated framework for sustainability assessment of seawater desalination. Desalination 447, 1–17. https://doi.org/10.1016/J.DESAL.2018.08.019

Johnston, K., Ver Hoef, J.M., Krivoruchko, K., Lucas, N., 2001. ArcGIS 9. Using ArcGIS Geostatistical Analyst.

Jones, E., Qadir, M., van Vliet, M.T.H., Smakhtin, V., Kang, S., 2019. The state of desalination and brine production: A global outlook. Sci. Total Environ. 657, 1343–1356. https://doi.org/10.1016/j.scitotenv.2018.12.076

Kämpf, J., Clarke, B., 2013. How robust is the environmental impact assessment process in South Australia? Behind the scenes of the Adelaide seawater desalination project. Mar. Policy 38, 500–506. https://doi.org/10.1016/j.marpol.2012.08.005

Kelaher, B.P., Clark, G.F., Johnston, E.L., Coleman, M.A., 2020. Effect of Desalination Discharge on the Abundance and Diversity of Reef Fishes. Environ. Sci. Technol. 54, 735–744. https://doi.org/10.1021/acs.est.9b03565

Kettani, M., Bandelier, P., 2020. Techno-economic assessment of solar energy coupling with large-scale desalination plant: The case of Morocco. Desalination 494, 114627. https://doi.org/10.1016/j.desal.2020.114627

Kress, N., 2019a. Policy and Regulations for Seawater Desalination. Mar. Impacts Seawater Desalin. 135–163. https://doi.org/10.1016/B978-0-12-811953-2.00007-4

Kress, N., 2019b. Theoretical Analysis of the Potential Impacts of Desalination on the Marine Environment. Mar. Impacts Seawater Desalin. 53–69. https://doi.org/10.1016/B978-0-12-811953-2.00004-9

Kress, N., 2019c. Actual Impacts of Seawater Desalination on the Marine Environment Reported Since 2001. Mar. Impacts Seawater Desalin. 81–133. https://doi.org/10.1016/B978-0-12-811953-2.00006-2

Kress, N., Gertner, Y., Shoham-Frider, E., 2020. Seawater quality at the brine discharge site from two mega size seawater reverse osmosis desalination plants in Israel (Eastern Mediterranean). Water Res. 171, 115402. https://doi.org/10.1016/J.WATRES.2019.115402

Lacy, S.N., Meza, F.J., Marquet, P.A., 2017. Can environmental impact assessments alone conserve freshwater fish biota? Review of the Chilean experience. Environ. Impact Assess. Rev. 63, 87–94. https://doi.org/10.1016/J.EIAR.2016.12.006

Lattemann, S., Höpner, T., 2008. Environmental impact and impact assessment of seawater desalination. Desalination 220, 1–15. https://doi.org/10.1016/j.desal.2007.03.009

Lattemann, S., Kennedy, M.D., Schippers, J.C., Amy, G., 2009. Global desalination situation, in: Escobar, I., Schäfer, A. (Eds.), Sustainable Water for the Future: Water Recycling versus Desalination. Elsevier Ltd, pp. 7–39.

Lin, Yung Chang, Chang-Chien, G.P., Chiang, P.C., Chen, W.H., Lin, Yuan Chung, 2013. Potential impacts of discharges from seawater reverse osmosis on Taiwan marine environment. Desalination 322, 84–93. https://doi.org/10.1016/j.desal.2013.05.009

Liu, T.-K., Sheu, H.-Y., Tseng, C.-N., 2013. Environmental impact assessment of seawater desalination plant under the framework of integrated coastal management. Desalination 326, 10–18. https://doi.org/10.1016/j.desal.2013.07.003

Liu, T.K., Weng, T.H., Sheu, H.Y., 2018. Exploring the environmental impact assessment commissioners' perspectives on the development of the seawater desalination project. Desalination 428, 108–115. https://doi.org/10.1016/j.desal.2017.11.031

Lloret-Oltra, M.P., Sánchez-Lizaso, J.L., 2001. Bioensayo para la evaluación de los efectos producidos por un incremento de la salinidad sobre la supervivencia del erizo de mar *Paracentrotus lividus* (Lamarck, 1816), in: Congreso Nacional AEDyR. Alicante.

Loya-Fernández, Á., Ferrero-vicente, L.M., Marco-méndez, C., Martínez-garcía, E., Jacobo, J., Sánchez-lizaso, J.L., 2018. Quantifying the efficiency of a mono-port diffuser in the dispersion of brine discharges 431, 27–34. https://doi.org/10.1016/j.desal.2017.11.014

Loya-Fernández, Á., Ferrero-Vicente, L.M., Marco-Méndez, C., Martínez-García, E., Zubcoff, J., Sánchez-Lizaso, J.L., 2012. Comparing four mixing zone models with brine discharge measurements from a reverse osmosis desalination plant in Spain. Desalination 286, 217–224. https://doi.org/10.1016/J.DESAL.2011.11.026

Lykkebo, K., Paytan, A., Rahav, E., Levy, O., Silverman, J., Barzel, O., Potts, D., Bar-zeev, E., 2018. Impact of brine and antiscalants on reef-building corals in the Gulf of Aqaba e Potential effects from desalination plants. Water Res. 144, 183–191. https://doi.org/10.1016/j.watres.2018.07.009

Malfeito, J.J., Díaz-Caneja, J., Fariñas, M., Fernández-Torrequemada, Y., González-Correa, J.M., Carratalá-Giménez, A., Sánchez-Lizaso, J.L., 2005. Brine discharge from the Javea desalination plant. Desalination 185, 87–94. https://doi.org/10.1016/j.desal.2005.05.010

Marín-Guirao, L., Sandoval-Gil, J.M., Bernardeau-Esteller, J., Ruíz, J.M., Sánchez-Lizaso, J.L., 2013. Responses of the Mediterranean seagrass *Posidonia oceanica* to hypersaline stress duration and recovery. Mar. Environ. Res. 84, 60–75. https://doi.org/10.1016/j.marenvres.2012.12.001

Mata-Torres, C., Escobar, R.A., Cardemil, J.M., Simsek, Y., Matute, J.A., 2017. Solar polygeneration for electricity production and desalination: Case studies in Venezuela and northern Chile. Renew. Energy 101, 387–398. https://doi.org/10.1016/J.RENENE.2016.08.068

Meneses, M., Pasqualino, J.C., Céspedes-Sánchez, R., Castells, F., 2010. Alternatives for reducing the environmental impact of the main residue from a desalination plant. J. Ind. Ecol. 14, 512–527. https://doi.org/10.1111/j.1530-9290.2010.00225.x

Mezher, T., Fath, H., Abbas, Z., Khaled, A., 2011. Techno-economic assessment and environmental impacts of desalination technologies. Desalination 266, 263–273. https://doi.org/10.1016/j.desal.2010.08.035

Miller, S., Shemer, H., Semiat, R., 2014. Energy and environmental issues in desalination. Desalination 366, 2–8. https://doi.org/10.1016/j.desal.2014.11.034

Mineria, M. de Consumo de agua en la minera de cobre. 2012, 1–36. Available online: http://www.aih-cl.org/articulos/Consumo-de-agua-en-la-mineria-del%20cobre-COCHILCO-(2011).pdf (accessed on 20 April 2019).

Missimer, T.M., Maliva, R.G., 2018. Environmental issues in seawater reverse osmosis desalination: Intakes and outfalls. Desalination 434, 198–215. https://doi.org/10.1016/j.desal.2017.07.012

Mohammadi, F., Sahraei-Ardakani, M., Al-Abdullah, Y., Heydt, G.T., 2020. Cost-Benefit Analysis of Desalination: A Power Market Opportunity. Electr. Power Components Syst. 48, 1091–1101. https://doi.org/10.1080/15325008.2020.1829188

Molinos-Senante, M., González, D., 2018. Evaluation of the economics of desalination by integrating greenhouse gas emission costs: An empirical application for Chile. Renew. Energy 1–11. https://doi.org/10.1016/J.RENENE.2018.09.019

Navarro Barrio, R., Sola, I., Blanco-Murillo, F., del-Pilar-Ruso, Y., Fernández-Torquemada, Y., Sánchez-Lizaso, J.L., 2021. Application of salinity thresholds in Spanish brine discharge regulations: Energetic and environmental implications. Desalination 501, 114901. https://doi.org/https://doi.org/10.1016/j.desal.2020.114901

Palomar, P., Lara, J.L., Losada, I.J., Rodrigo, M., Alvárez, A., 2012. Near field brine discharge modelling part 1: Analysis of commercial tools. Desalination 290, 14–27. https://doi.org/10.1016/j.desal.2011.11.037

Palomar, P., Losada, I.J., 2010. Desalination in Spain: Recent developments and recommendations. Desalination 255, 97–106. https://doi.org/10.1016/j.desal.2010.01.008

Panagopoulos, A., Haralambous, K.-J., 2020. Environmental impacts of desalination and brine treatment - Challenges and mitigation measures. Mar. Pollut. Bull. 161, 111773. https://doi.org/https://doi.org/10.1016/j.marpolbul.2020.111773

Panagopoulos, A., Haralambous, K.-J., Loizidou, M., 2019. Desalination brine disposal methods and treatment technologies - A review. Sci. Total Environ. 693, 133545. https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.07.351

Petersen, K.L., Frank, H., Paytan, A., Bar-Zeev, E., 2018a. Impacts of Seawater Desalination on Coastal Environments. Sustain. Desalin. Handb. 437–463. https://doi.org/10.1016/B978-0-12-809240-8.00011-3

Petersen, K.L., Heck, N., Reguero, B.G., Potts, D., Hovagimian, A., Paytan, A., 2019. Biological and Physical Effects of Brine Discharge from the Carlsbad Desalination Plant and Implications for Future Desalination Plant Constructions. Water (Switzerland) 11, 208. https://doi.org/10.3390/w11020208

Petersen, K.L., Paytan, A., Rahav, E., Levy, O., Silverman, J., Barzel, O., Potts, D., Bar-Zeev, E., 2018b. Impact of brine and antiscalants on reef-building corals in the Gulf of Aqaba – Potential effects from desalination plants. Water Res. 144, 183–191. https://doi.org/10.1016/j.watres.2018.07.009

Pistocchi, A., Bleninger, T., Breyer, C., Caldera, U., Dorati, C., Ganora, D., Millán, M.M., Paton, C., Poullis, D., Herrero, F.S., Sapiano, M., Semiat, R., Sommariva, C., Yuece, S., Zaragoza, G., 2020. Can seawater desalination be a win-win fix to our water cycle? Water Res. 182. https://doi.org/10.1016/j.watres.2020.115906

Portillo, E., Louzara, G., Ruiz de la Rosa, M., Quesada, J., Gonzalez, J.C., Roque, F., Antequera, M., Mendoza, H., 2013. Venturi diffusers as enhancing devices for the dilution process in desalination plant brine discharges. Desalin. Water Treat. 51, 525–542. https://doi.org/10.1080/19443994.2012.694218

Portillo, E., Ruiz de la Rosa, M., Louzara, G., Quesada, J., Ruiz, J.M., Mendoza, H., 2014a. Dispersion of desalination plant brine discharge under varied hydrodynamic conditions in the south of Gran Canaria. Desalin. Water Treat. 52, 164–177. https://doi.org/10.1080/19443994.2013.795349

Portillo, E., Ruiz de la Rosa, M., Louzara, G., Ruiz, J.M., Marín-Guirao, L., Quesada, J., González, J.C., Roque, F., González, N., Mendoza, H., 2014b. 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. Mar. Pollut. Bull. 80, 222–233. https://doi.org/10.1016/j.marpolbul.2013.12.048

Qasim, M., Badrelzaman, M., Darwish, N.N., Darwish, N.A., Hilal, N., 2019. Reverse osmosis desalination: A state-of-the-art review. Desalination 459, 59–104. https://doi.org/10.1016/J.DESAL.2019.02.008

R Core Team, 2017. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

R Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria.

Raventos, N., Macpherson, E., García-Rubiés, A., 2006. Effect of brine discharge from a desalination plant on macrobenthic communities in the NW Mediterranean. Mar. Environ. Res. 62, 1—14. https://doi.org/10.1016/j.marenvres.2006.02.002

Roberts, D.A., Johnston, E.L., Knott, N.A., 2010. Impacts of desalination plant discharges on the marine environment: A critical review of published studies. Water Res. 44, 5117–5128. https://doi.org/10.1016/j.watres.2010.04.036

Rodríguez-Rojas, F., López-Marras, A., Celis-Plá, P.S.M., Muñoz, P., García-Bartolomei, E., Valenzuela, F., Orrego, R., Carratalá, A., Sánchez-Lizaso, J.L., Sáez, C.A., 2020. Ecophysiological and cellular stress responses in the cosmopolitan brown macroalga *Ectocarpus* as biomonitoring tools for assessing desalination brine impacts. Desalination 489, 114527. https://doi.org/https://doi.org/10.1016/j.desal.2020.114527

Röthig, T., Ochsenkühn, M.A., Roik, A., Van Der Merwe, R., Voolstra, C.R., 2016. Long-term salinity tolerance is accompanied by major restructuring of the coral bacterial microbiome. Mol. Ecol. 25, 1308–1323. https://doi.org/10.1111/mec.13567

Ruiz, J.M., Guillén, J.E., Ramos Segura, A., Otero, M.M., 2015. Atlas de las praderas marinas de España. IEO/IEL/UICN, Murcia-Alicante-Málaga. https://doi.org/10.1109/INFCOMW.2009.5072203

Ruíz, J.M., Marín-Guirao, L., Sandoval-Gil, J.M., 2009. Responses of the Mediterranean seagrass *Posidonia oceanica* to in situ simulated salinity increase. Bot. Mar. 52, 459–470. https://doi.org/10.1515/BOT.2009.051

Sadhwani Alonso, J.J., Melián-Martel, N., 2018. Environmental Regulations—Inland and Coastal Desalination Case Studies. Sustain. Desalin. Handb. 403–435. https://doi.org/10.1016/B978-0-12-809240-8.00010-1

Sadhwani, J.J., Veza, J.M., Santana, C., 2005. Case studies on environmental impact of seawater desalination. Desalination 185, 1–8. https://doi.org/10.1016/J.DESAL.2005.02.072

Sánchez-Lizaso, J.L., 2012. Programas de vigilancia ambiental y reducción de los impactos ambientales la desalación, in: Congreso Internacional AEDyR - Asociación Española de Desalación y Reutilización. Madrid - Spain.

Sánchez-Lizaso, J.L., Romero, J., Ruiz, J., Gacia, E., Buceta, J.L., Invers, O., Fernández Torquemada, Y., Mas, J., Ruiz-Mateo, A., Manzanera, M., 2008. Salinity tolerance of the Mediterranean seagrass *Posidonia oceanica*: recommendations to minimize the impact of brine discharges from desalination plants. Desalination 221, 602–607. https://doi.org/10.1016/j.desal.2007.01.119

Sandoval-Gil, J.M., Marín-Guirao, L., Ruiz, J.M., 2012. Tolerance of Mediterranean seagrasses (*Posidonia oceanica* and *Cymodocea nodosa*) to hypersaline stress: Water relations and osmolyte concentrations. Mar. Biol. 159, 1129–1141. https://doi.org/10.1007/s00227-012-1892-y

Shahzad, M.W., Burhan, M., Ang, L., Ng, K.C., 2017. Energy-water-environment nexus underpinning future desalination sustainability. Desalination 413, 52–64. https://doi.org/10.1016/j.desal.2017.03.009

Shahzad, M.W., Burhan, M., Ng, K.C., 2019. A standard primary energy approach for comparing desalination processes. npj Clean Water 2, 1–7. https://doi.org/10.1038/s41545-018-0028-4

Shahzad, M.W., Burhan, M., Soo Son, H., Jin Oh, S., Choon Ng, K., 2018. Desalination processes evaluation at common platform: A universal performance ratio (UPR) method. Appl. Therm. Eng. 134, 62–67. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2018.01.098

Sharifinia, M., Afshari Bahmanbeigloo, Z., Smith, W.O., Yap, C.K., Keshavarzifard, M., 2019. Prevention is better than cure: Persian Gulf biodiversity vulnerability to the impacts of desalination plants. Glob. Chang. Biol. 25, 4022–4033. https://doi.org/10.1111/gcb.14808

Shemer, H., Semiat, R., 2017. Sustainable RO desalination – Energy demand and environmental impact. Desalination 424, 10–16. https://doi.org/10.1016/J.DESAL.2017.09.021

Short, F.T., Wyllie-Echeverria, S., 1996. Natural and human-induced disturbance of seagrasses. Environ. Conserv. 23, 17–27. https://doi.org/DOI: 10.1017/S0376892900038212

Simpson, G.L., 2018. Modelling Palaeoecological Time Series Using Generalised Additive Models. Front. Ecol. Evol. 6, 1–21. https://doi.org/10.3389/fevo.2018.00149

Sola, I., Fernández-Torquemada, Y., Forcada, A., Valle, C., Del-Pilar-Ruso, Y., González-Correa, J.M., Sanchez-Lizaso, J.L., 2020a. Sustainable desalination: long-term monitoring of brine discharge in the marine environment. Mar. Pollut. Bull. 161, 111813. https://doi.org/10.1016/j.marpolbul.2020.111813

Sola, I., Sánchez-Lizaso, J.L., Muñoz, P.T., García-Bartolomei, E., Sáez, C.A., Zarzo, D., 2019a. Assessment of the requirements within the environmental monitoring plans used to evaluate the environmental impacts of desalination plants in Chile. Water (Switzerland) 11, 1–17. https://doi.org/10.3390/w11102085

Sola, I., Zarzo, D., Carratalá, A., Fernández-Torquemada, Y., de-la-Ossa-Carretero, J.A., Del-Pilar-Ruso, Y., Sánchez-Lizaso, J.L., 2020b. Review of the management of brine discharges in Spain. Ocean Coast. Manag. 196, 105301. https://doi.org/10.1016/j.ocecoaman.2020.105301

Sola, I., Zarzo, D., Sánchez-lizaso, J.L., 2019b. Evaluating environmental requirements for the management of brine discharges in Spain. Desalination 471, 114132. https://doi.org/10.1016/j.desal.2019.114132

Spanish Government, Act 21/2013, of the 9th of December, on Environmental Impact Assessment, Bol. Oficial Estado 296 (2013) 98151–98227.

Spanish Government, Royal Decree 1131/1988, on the 30th of September, that develops the EIA regulation on RD 1302/1986, Bol. Oficial Estado 239 (1988) 28911–28915.

Spanish Government, Royal Decree 1302/1986, of the 28th of June, on Environmental Impact Assessment, Bol. Oficial Estado 155 (1986) 23733–23736.

Stewart-Oaten, A., Murdoch, W.W., Parker, K.R., 1986. Environmental Impact Assessment: “Pseudoreplication” in Time? Ecology 67, 929–940. https://doi.org/10.2307/1939815

Sun, S., Fu, G., Bao, C., Fang, C., 2019. Identifying hydro-climatic and socioeconomic forces of water scarcity through structural decomposition analysis: A case study of Beijing city. Sci. Total Environ. 687, 590–600. https://doi.org/10.1016/J.SCITOTENV.2019.06.143

Underwood, A.J., 1994. On Beyond BACI: Sampling Designs that Might Reliably Detect Environmental Disturbances. Ecol. Appl. 4, 3–15. https://doi.org/10.2307/1942110

Unsworth, R.K.F., Nordlund, L.M., Cullen-Unsworth, L.C., 2019. Seagrass meadows support global fisheries production. Conserv. Lett. 12, e12566. https://doi.org/10.1111/conl.12566

Valdés-Pineda, R., Pizarro, R., García-Chevesich, P., Valdés, J.B., Olivares, C., Vera, M., Balocchi, F., Pérez, F., Vallejos, C., Fuentes, R., Abarza, A., Helwig, B., 2014. Water governance in Chile: Availability, management and climate change. J. Hydrol. 519, 2538–2567. https://doi.org/10.1016/J.JHYDROL.2014.04.016

Vassallo, P., Paoli, C., Rovere, A., Montefalcone, M., Morri, C., Bianchi, C.N., 2013. The value of the seagrass *Posidonia oceanica*: A natural capital assessment. Mar. Pollut. Bull. 75, 157–167. https://doi.org/10.1016/J.MARPOLBUL.2013.07.044

Voutchkov, N., 2017. Pretreatment for Reverse Osmosis Desalination. Elsevier.

Wernberg, T., Krumhansl, K., Filbee-Dexter, K., Pedersen, M.F., 2019. Status and Trends for the World's Kelp Forests. World Seas an Environ. Eval. 57–78. https://doi.org/10.1016/B978-0-12-805052-1.00003-6

Wood, S., Scheipl, F., 2016. gamm4: Generalized Additive Mixed Models using 'mgcv' and 'lme4'. R package version 0.2-4. https://cran.r-project.org/package=gamm4

Zarzo, D., García, C., Sánchez-Lizaso, J.L., Deudero, S., Box, A., 2009. Environmental protection strategies in the Bahia de Alcudia project (Spain), in: Desalination for the Environment. Baden-Germany.

Zarzo, D., Prats, D., 2018. Desalination and energy consumption. What can we expect in the near future? Desalination 427, 1–9. https://doi.org/10.1016/j.desal.2017.10.046

Zhou, J., Chang, V.W.-C., Fane, A.G., 2013. An improved life cycle impact assessment (LCIA) approach for assessing aquatic eco-toxic impact of brine disposal from seawater desalination plants. Desalination 308, 233–241. https://doi.org/https://doi.org/10.1016/j.desal.2012.07.039