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# Environmental research on brine discharge optimization: A case study approach

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**ABSTRACT**

Desalination plants constitute a new way of solving the shortage and degradation of Mediterranean hydric resources by providing a new source of water supply according to local demand, and, at the same time, being climatically independent. Since all desalination plants are located on the shoreline, environmental constraints have to do with water intake and sea outfall discharges. As for brine discharging, a wide range of case-study research is being carried out in order to solve technical uncertainties and provide our projects with preventive measures. The first of these case studies regards the prediction of brine discharge behaviour by using a reduced scale model to simulate the way it is likely to perform in a harbour. The second case-study deals with mixing brine with a thermal effluent in a pipeline to obtain a better dilution that might then minimize its impact on the area. The third case-study is aimed at protecting marine biodiversity by studying into the effects of salinity increase on the growth and survival of the seagrass *Cymodocea nodosa*.

*Keywords*: Desalination; Seawater; Mediterranean sea; Brine discharge; Environmental impact

## 1. Introduction

Desalination in Spain was born as a new alternative to provide quality water from a non-climate dependant source that guaranteed the water supply in the Canary Islands and Mediterranean coastline. These areas have been suffering from intensive agriculture and aggressive urbanism for many years, and they have brought about shortages of hydric resources, mainly ground water sources that are extremely depleted. This phenomenon began in the early 60s, when tourism and intensive irrigation agriculture started to grow at high speed. These facts along with the lack of other water resources obliged the Canary Islands to look for a new water supply system. That is why the first desalination plant was built in the Canary Islands in 1965 [1]; after that, dozens of other desalination plants were built in these islands, and by looking the positive results, other desalination plants were

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built along the Spanish Mediterranean coastline as well.

The technology used in these brand new plants was the evaporation system. In the 80s, the first trials of desalination plants using reverse osmosis (RO) were developed, but it was in the 90s when this technology definitively substituted evaporation systems [1]. Nowadays, there are over 700 desalination plants in Spain which produce more than 5.2 million $m^3$/d and place Spain at the fourth place in terms of desalination after Saudi Arabia, Arab Emirates and the United States [2].

The disposal from a desalination process is considered by the Spanish regulation as an industrial waste; therefore it is affected by several state and local regulations. In the case of the marine RO desalination plants, the discharge can cause a relevant and localized impact over coastal marine ecosystems. Emissions into the sea consist of a brine effluent mainly composed of seawater with a high concentration of salt and other components related to the desalting process such as anticorrosion products, antiscaling and antifouling additives, and oxygen scavengers (sodium sulphite) [3,4], whose potential damage depends on the sensitivity of the ecosystems affected.

Natural dispersion of the brine will depend on the design of the pipe diffuser stretch, the output flow and velocity, the angle of diffusers, and other oceanographic components as waves, currents, depth and so on. A bad design may diminish brine dilution and this hypersaline layer may extend along the mixing zone to the far-field harming the marine ecosystems.

Therefore, the European environmental legislation is becoming stricter constraining those projects which still have not integrated environmental issues, such as maintaining marine water quality and biota conservation, into the decision-making process.

Regulations related to environmental assessment, pollution prevention and control, protected habitats and environmental liability, have made desalination techniques and brine discharge systems evolve in order to achieve the established thresholds and specifications. With regard to pollution prevention and control (IPPC European Directive) and its national transposition (Law 16/2002), it has been define the requirements for a certain industrial process to operate. Moreover, environmental quality standards and emission limit values for coastal waters are also controlled through the 2000/60/EC Water Framework Directive. In addition, associated to the desalination plant operation phase, the European Directive 2004/35/EC on environmental liability with regard to the prevention and remedying of environmental damage, states that operator takes full responsibility for the damages caused by the process. It means that companies must have a risk assessment for their plants and set a financial guarantee in order to cover the potential impacts caused to the environment. This is a new factor taken into account in the planning and designing of desalination projects.

In Spain, the reduction of marine environmental impact of the desalination plants has been focused on the protection of key ecosystems like endemic Mediterranean seagrass *Posidonia oceanica* and *Cymodocea nodosa* from brine discharge. Those are habitats protected by the European ecological Natura 2000 Network. A very restrictive salinity threshold has been established [5] based on extensive scientific research [6–9]. Years of environmental monitoring of brine discharge on *P. oceanica* meadows have demonstrated the effectiveness of the proposed limit [10] to avoid significant impact of brine discharges. However, little information exists on other relevant habitats like the seagrass *Cymodocea nodosa*.

With the aim of solving the hydric problem along the Mediterranean coastline of Spain, Acuamed, as an instrument of the Environment, Rural and Maritime Ministry, is developing a large-scale plan for generating new resources based in two processes: reuse (185 $hm^3$ produced per year) and desalination (479 $hm^3$ produced per year) for industrial, agriculture and human consumption (acuamed personal data). Acuamed is currently designing and building 16 large desalination plants along the Mediterranean Spanish coastline.

Each one of these desalination plants has its own environmental features and difficulties. Therefore a "case-by-case" study is required. Likewise, proceeding require identifying key ecological values of the study area and supplementary research in site-specific examinations, brine mixing behaviour and sensitive coastal biotopes for, eventual, project re-designing. These research projects are the following:

- **Denia desalination plant case study**: study of brine discharge behaviour and evolution into a harbour, using a reduced scale model.
- **Sagunto desalination plant case study**: mixing different discharges (brine and thermal effluents) into a unique pipeline to study the evolution of the hypersaline layers.
- ***Cymodocea nodosa* seagrass case study**: effects of brine discharge salinity variations on the growth and survival of this key species.

In this paper, we will present a general overview of these R&D projects and their results focused on environmental protection.

## 2. Denia desalination plant case study

Denia is a small town located on the Mediterranean coast of Spain. As most Mediterranean coastal towns, the population of Denia rises in summer time; therefore, the water supply demand increases as well. With the aim of satisfying this water demand, the construction of a seawater reverse osmosis desalination plant was projected.

The infralitoral zone of the coast of Denia (Alicante) is covered by a continuous meadow of the endemic seagrass *Posidonia oceanica*. Among the different potential sites, the inner part of Denia Harbour was taken into account to locate the brine disposal. The harbour of Denia has capacity for the entrance of sport, fishing, passengers and cargo vessels. It is made of two protective breakwaters. Between them, an access channel is periodically dredged to ensure the passing of large vessel. The *P. oceanica* meadow shows a good state of conservation at both sides of the channels.

Ports may be considered suitable places for the brine discharge, since no major maritime works are required and the expenses of the project decreases accordingly. In addition that, the waters of the port are already highly modified, the discharge may even contribute to the water renovation rate.

On the other hand, the hydrodynamic conditions of the port waters do not facilitate the brine dilution, which leads to an increase in the salinity that may cause a negative impact in the *Posidonia oceanica* place at both sides of the Denia's harbour channel. Therefore, we studied the brine disposal behaviour considering that the discharge would occur in a bound mass of water like a port. The objective is to try to find out if this way of disposal can be considered a valid option among the different alternatives.

Because of the particularities of harbours, the target was to find a solution which implied the maximum dilution when the effluent reached the bottom of the sea (near-field). The aim of this study was to design a system that implies as less dilution as possible within the near-field and eventually to create a narrow hyperdense layer. Special attention was paid to the thickness of the hyperdense layer at entrance of the harbour in order to verify that *Posidonia* meadow, placed 4 m above both sides of the channel, would not be affected by the density current flowing to deeper waters.

In order to achieve this objective, the Harbour of Denia was reproduced on a physical model in the laboratory for maritime experimentation of CEDEX (Fig. 1).

The project was divided into 2 different phases:

- In a first phase, to carry out an in-depth study on the initial dispersion and dilution phenomenon (near-field), the discharge point and the adjacent area were reproduced at a 1:10 scale.
- In a second phase, to estimate the salinity field (extent, width and bottom dilution) from the discharge point to the entrance of the port as well as the total dilution and thickness at the entrance, the harbour layout was reproduced at a 1:65 scale.

### 2.1. Material and methods

As a consequence of the aimed low initial dilution, the discharge device was designed to obtain the minimum level of turbulence, where the contact of the effluent with the receiving waters occurred. These conditions were achieved with a pit from which the brine was discharged into the receiving waters through twenty nozzles ($D$ = 0.50 m in prototype) placed just above the bottom. This design allowed a very low discharge velocity and almost non-energy at the discharge point.

The experiments were conducted by discharging

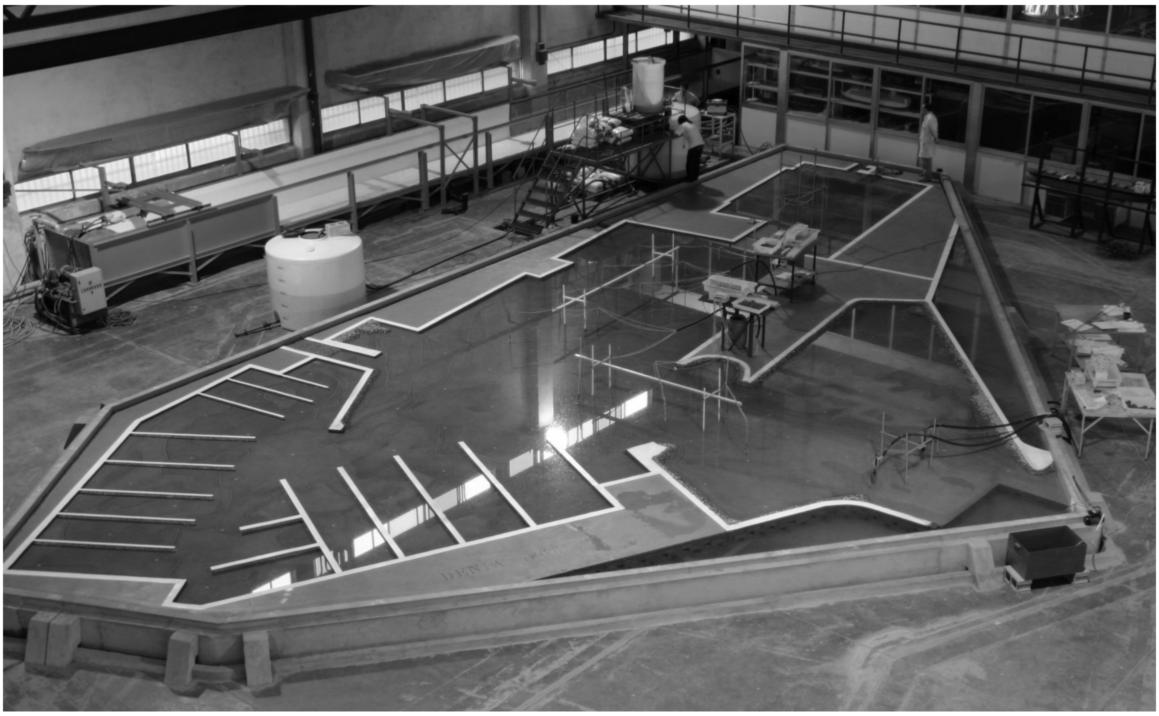

Fig. 1. Physical model of the harbour of Denia at 1:65 scale.

saltwater in two different flumes depending on the scale. These flumes were filled with freshwater. The saltwater solution, traced with Rhodamine WT, was prepared in a nearby mixing reservoir calculating the amount of salt required to produce the density difference required for a given test. During the test, the effluent was discharged into the flumes at a constant flow rate, which was controlled by a valve and monitored with an electromagnetic flow meter.

Once the stationary state was reached, samples located at different points evenly distributed within the model and along the water column were collected with peristaltic pumps. Measurements were made in the laboratory with a high precision conductimeter. Moreover, visual monitoring of the brine track was performed in order to estimate the head plume advance velocity estimation and also the plume shape and thickness.

For the 1:10 scale model, six tests were conducted to examine whether the dilution, the dispersion or the transport phenomena were modified when the discharge conditions were varied. For the model at the 1:65 scales, the discharge conditions projected for the desalination plant of Denia were studied. However since stationary state was not achieved with the project conditions, the test was carried out with a 6 times higher flow. The testing conditions are summarized in Table 1.

### *2.2. Results*

#### *2.2.1. Study on the initial dispersion and dilution phenomenon with the 1:10 scale model*

Independently of the flow regime and the initial concentration applied for each test, the maximum salinity concentration at the sea bottom remains stable all throughout the plume track. Since there is no initial dilution, the bottom concentration of the monitoring points along the track is identical to the discharge salt concentration.

However, even though the dilution of the effluent does not change as a function of the discharge conditions, there is a variation concerning the thickness of the hyperdense layer. Fig. 2 shows, keeping the initial concentration constant, how the thickness of the brine decreases from 0.5 to 0.4 m in prototype dimensions (Fig. 2a), when the flow regime decreases. Likewise, when the flow regime remains constant, the thickness of the brine depends on the effluent concentration. The higher the initial concentration is the less brine thickness results varying from 0.7 to 0.5 m (Fig. 2b). From both figures it is demonstrated that larger Froude number plumes shows less salt concentration at the bottom than the smaller ones. On the contrary, the thickness of the interface increases when the Froude number is enlarged.

Table 1
Summary of testing conditions

| Scale model | Test number | Flow ($m^3/s$) | Density difference $\Delta\rho/\rho_0$ | Densimetric Froude number |
|---|---|---|---|---|
| 1:10 | 1 | 0.4 | 0.0221 | 0.31 |
| | 2 | 0.4 | 0.0117 | 0.43 |
| | 3 | 0.4 | 0.0059 | 0.61 |
| | 4 | 0.2 | 0.0237 | 0.15 |
| | 5 | 0.1 | 0.0237 | 0.08 |
| | 6 | 0.1 | 0.0059 | 0.15 |
| 1:65 | 1 | 0.4 | 0.0221 | 0.31 |
| | 2 | 2.4 | 0.0221 | 1.86 |

#### *2.2.2. Study on the salinity distribution from the discharge point to the entrance of the port with the 1:65 scale model*

When the effluent is discharged, it moves towards the entrance of the port filling firstly the deepest hollows that it finds, and afterwards, it becomes wider, filling also other places where the water depth is less deep, until the moment it reaches the stationary state. At this moment, all the water discharged at the discharge point gets out of the flume at the end of the model and the dilution and brine thickness remain constant over the process.

When the flow was six times the projected one, the stationary state was reached and therefore, the effluent dilution at the bottom could be calculated. Fig. 3 illustrates how shallow areas reach higher dilutions than deeper ones. With regards of the port entrance, after more than 1 km the brine has diluted only two times. In addition, the thickness at that point has also been multiplied almost twice the value it had at the near field. In any case, the hyperdense layer of a thickness of 1.5 m approximately would flow through the access channel without damaging the *Posidonia*.

#### *2.2.3. Conclusion*

The study of the emplacement where the discharge will take place is absolutely crucial for an adequate design of the discharge parameters. All in all, the discharge device is the most important factor limiting the brine dilution. With a discharge device, designed to obtain very low initial velocity, dilutions got at the near field are almost negligible.

If this discharge device favours the dilution, other factors, such as the flow regime or brine concentration, may also contribute to the dilution. On the contrary, if the discharge device contributes to minimize the dilution, these factors only affect the brine thickness. And so, these variables must be taken into account in the project design.

With regards to this project it has been proven that this system may be considered suitable for this specific case. However, due to the negative consequences that it may cause on the marine ecosystems existing in the project area, further studies are strongly recommended.

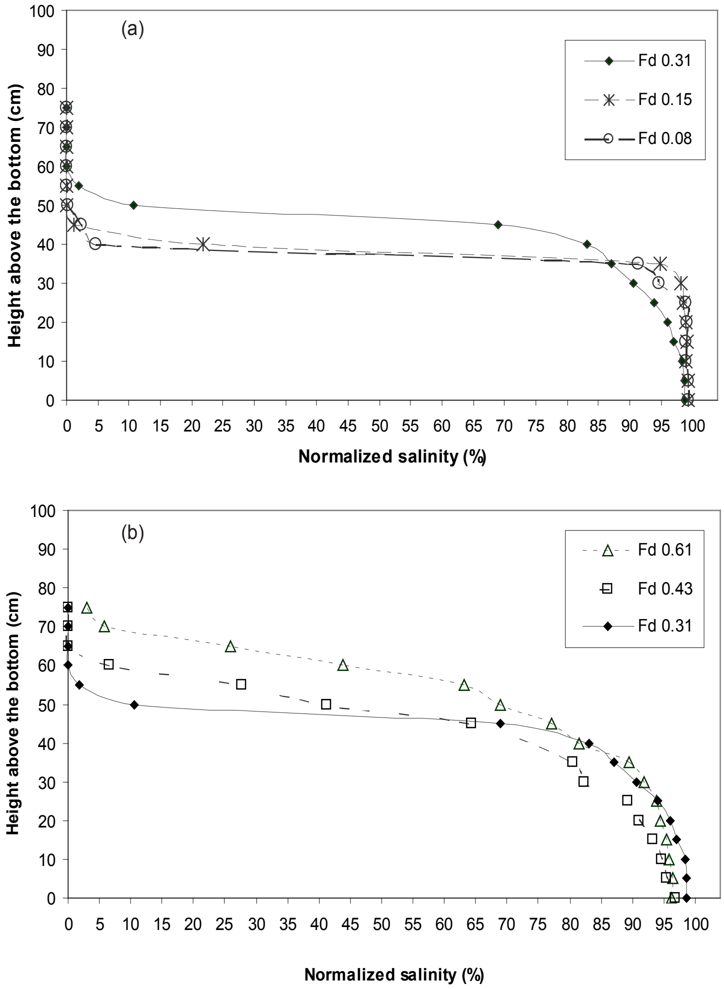


Fig. 2. Thickness of hyperdense layer at 10 m from the discharge point: (a) Analysis of the flow influence; (b) Analysis of the initial concentration influence.

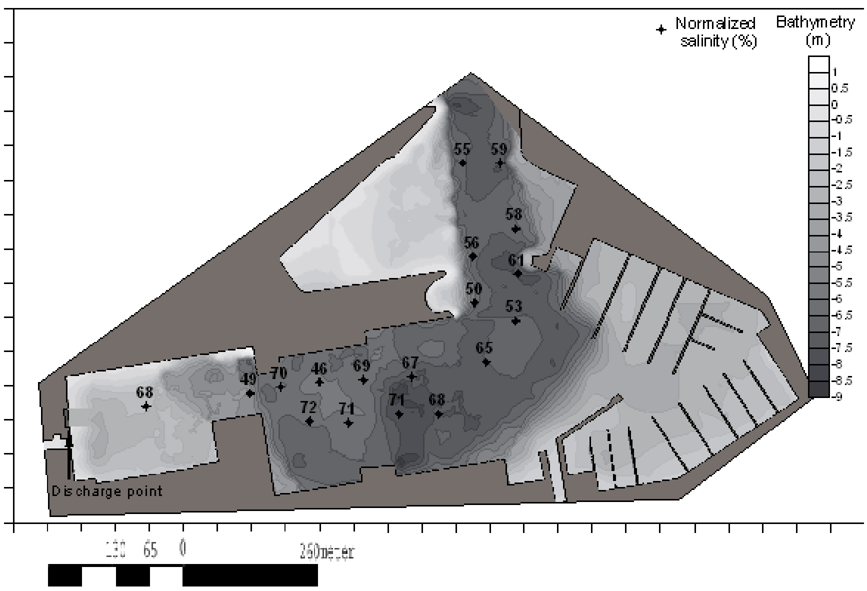


Fig. 3. Salinity distribution at the bottom all through the harbour of Denia.

These studies would consist on the research of the brine behaviour under the action of waves, as this is the main variable that may influence the brine behaviour within the harbour and the brine thickness at the entrance.

## 3. Sagunto desalination plant case study

Desalination plants need to dump the extracted salt of the treated water (brine) into the sea. In this process, it is necessary to control the final salinity of the dumping by reducing it in a mixture of seawater. Acuamed is building a desalination plant near the city of Sagunto (Valencia). Next to the plant, an active cogeneration thermal power station is located. This station has a submarine emissary to return the condenser refrigeration water to the sea. In order to facilitate the brine dilution, the emissary of the desalination plant is connected to the waste piping of the power station, so that both effluents are mixed inside the emissary before discharging into the sea.

The mixture of the effluent with seawater in a single pipe does not give enough guaranties for the salt concentration to be completely homogenized. In this study, the effluent mixture is analyzed by steps taking into account the geometries of the piping joint and the return pipe.

The analysis is aimed at focused on the quantification of the evolution of salinity along the pipe. It is important to point out that the injection of the dump laterally to the pipe (with an angle of 30°) does not mix both effluents because no turbulences are originated. The homogenization must be achieved by diffusion and by the agitation derived from the presence of angles in the piping path.

### *3.1. Material and methods*

In order to fulfil the aim of the study, the model (ANSYS-Desing Modeler 12.0) captures the geometry of the pipe starting at a length of five diameters from the joint, downstream to the first angle and includes 150 m of pipe after it. The path of the emissary is much longer, but it is understood that if an acceptable dilution is achieved in this segment, the obtained result will also be acceptable.

The three-dimensional model includes the geometry of the pipes, its joint, the path throughout the length to be studied and its slope. The fluid domain is discretized by the generation of a finite volumes mesh (ANSYS-ICEM CFD 12.0). In the millions of defined sub-volumes, the fluid mechanics and salt diffusivity equations are solved. Once the model is generated, the working conditions are set, allowing the change of the inflow and salinity of the effluents. The numerical simulation model allows analyzing multiple hypotheses.

Three working hypotheses are analyzed (Table 2):

- *Hypothesis one*: the desalination plant works with one rack and the power station works with one group.
- *Hypothesis two*: the desalination plant works with three racks and the power station works with one group.
- *Hypothesis three*: the desalination plant works with three racks and the power station works with three groups.

For a geometry generation, a three-dimensional model of the joint was created. The model is extended to a minimum of five diameters upstream of the joint, and downstream the first angle is considered, along with a length of pipe of 150 meters downstream from the angle. Due to the requirements of the analysis and the length of the pipe, a hexaedrical mesh was chosen. These types of meshes are the most accurate and allow optimizing the number of finite volumes reducing the computational demand.

### *3.2. Results and conclusions*

The models of particle concentration and diffusivity are applied. Different simulations are carried out, varying the inflows and salt concentrations (ANSYS-CFX 12.0), in order to represent the diverse operation modes. The mixture is analyzed and the salinity homogenization is quantified in the final outflow.

The salinity of the effluent of the desalination plant is placed near the wall of the pipe. Fig. 4 shows how salinity starts to level locally at some points during the first pipe segment before the angle, where diffusion appears because of the different concentration of both effluents. Downstream from the angle, turbulence makes the mixture of the two effluents and the salinity distribution is homogenized. The following graphs show the evolution of salinity along 100 streamlines, which go through the

Table 2
Working hypotheses

| | | Hypothesis 1 | | Hypothesis 2 | | Hypothesis 3 | |
|---|---|---|---|---|---|---|---|
| Pipeline | Diameter (m) | Flow ($m^3/h$) | Salinity (ppm) | Flow ($m^3/h$) | Salinity (ppm) | Flow ($m^3/h$) | Salinity (ppm) |
| Desalination plant | 1.2 | 271.66 | 79,790 | 815 | 79,790 | 815 | 79,790 |
| Power plant | 2 | 1040 | 50,577 | 1040 | 50,577 | 3040 | 50,577 |
| Exit | 2 | 1311.66 | 56,627 | 1855 | 63,412 | 3855 | 56,753 |
| | | | (Theoretical) | | (Theoretical) | | (Theoretical) |

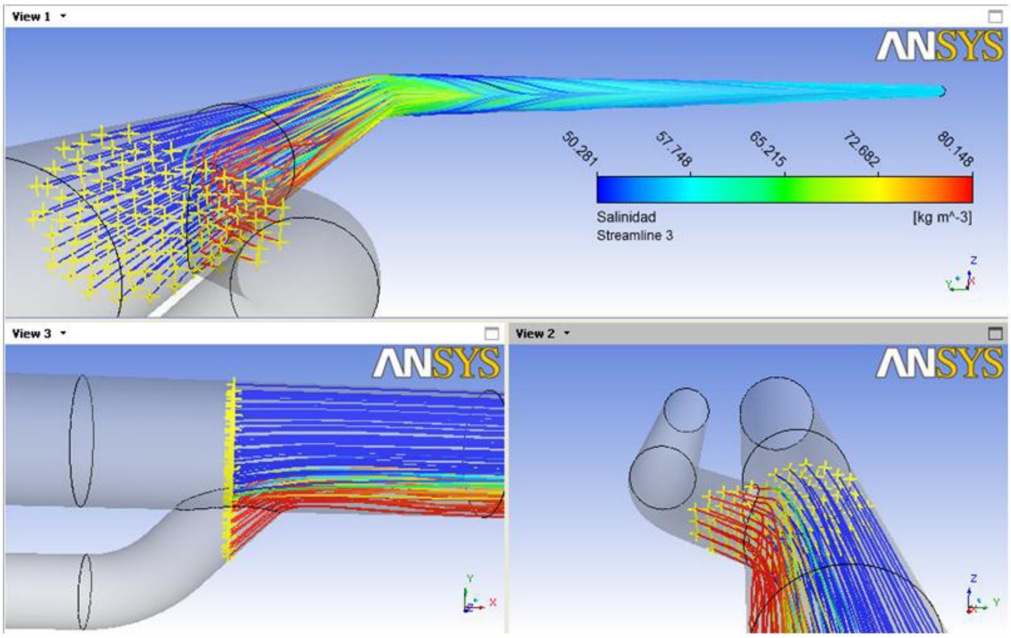


Fig. 4. Graph showing simulation 1. The stream lines are colored to show salinity.

pipe starting from the joint. At the beginning, the streamlines are clearly separated into two different groups, one for each effluent with different salinity. Then, after the first 40 m (Fig. 5) downstream from the first angle, the lines converge rapidly to the expected salinity value. In simulations 1 and 3, this process is very quick, while in simulation 2 convergences is slower due to the increases of the ratio of inflow from the desalination plant to the flow from power station

Table 3 summarizes salinity values at the final section of the simulated model, which is located 150 m downstream from the angle. The small variation of salinity and the exit shows the high homogenization mixture due to the turbulences in the angle. In its complete path before reaching the exit to the sea, the emissary has 4 more angles. Therefore, the complete dilution of brine in the effluent from the power station is achieved.

In conclusion, the presence of angles leads into turbulences that homogenize the salinity of the mixture.

## 4. *Cymodocea nodosa* seagrass case study

In the areas where *Posidonia oceanica* is not present, it is common to find other seagrasses like *Cymodocea nodosa*. *C.nodosa* is a more eurihaline species able to growth in a wider range of salinity regimes, due to its ecological strategy [11]. This species can inhabit in estuarine areas and coastal lagoons with large fluctuations in salinity [12]. Thus, it is frequent to find this species in areas such as river mouths or deltas with lower salinity like Delta del

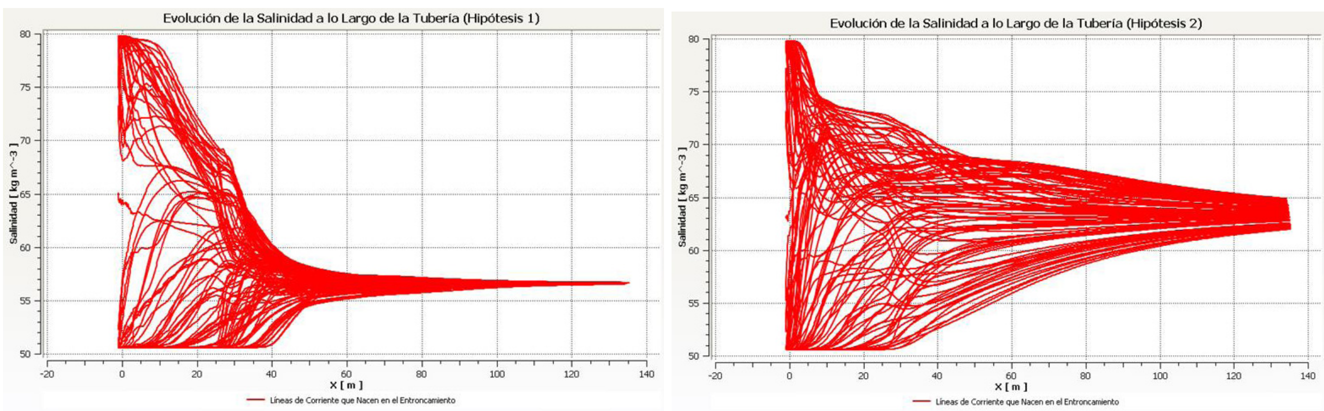


Fig. 5. Evolution of salinity through the 100 analyzed stream lines. Left: simulation 1; right: simulation 2.

Table 3
Final salinity values

| | Theoretical salinity at exit point (ppm) | Medium salinity at exit in simulation (ppm) | Maximum salinity at exit point (ppm) | Minimum salinity at exit point (ppm) | Percentage variation at exit point (%) |
|---|---|---|---|---|---|
| Hypothesis 1 | 56,627 | 56,627 | 56,684 | 56,507 | 0.31 |
| Hypothesis 2 | 63,412 | 63,412 | 64,891 | 61,918 | 4.69 |
| Hypothesis 3 | 56,753 | 56,451 | 56,671 | 56,088 | 1.03 |

Ebro, but it is also present in hypersaline lagoons like the Mar Menor (42–47 psu). When brine discharge may affect *C. nodosa* meadows, Spanish environmental authorities have applied a threshold of 39.5 psu. Nowadays there is some scientific evidence that proof *C. nodosa* may tolerate a higher limit.

### *4.1. Material and methods*

In the present study, mesocosms experiments under controlled conditions were established to estimate the effects of salinity variations on survival and growth of the seagrass *C. nodosa* in order to reduce the impact caused by new desalination plants.

*C. nodosa* shoots were collected by SCUBA diving from two shallow meadows (–2 m) at SE of Spain, Playa de la Almadraba and Cabo de Santa Pola (Alicante). Eight experiments of different time duration were conducted under controlled conditions throughout more than 2 years. For each experiment, ten to twenty shoots were marked using the modified Zieman method [13] and placed in plastic aquariums of 5 l inside 50 l tanks, with an additional overhead fluorescent light (30 μmol quanta $m^{-2}$ $s^{-1}$ of PAR (photosynthetic active radiation, $\lambda$ = 400–700 nm)). Normal light regime was adjusted to 12:12 h (light:dark). Leaf growth and survival of this plant was tested at several periods (1 week, 2 weeks and 4 weeks) and different salinity treatments (ranging from 2 to 72 psu). Increased salinity treatments were made using natural salt produced by Santa Pola saltworks or brine from the Alicante desalination plant. It was also tested the possible interactions of the effect due to salinity and other factors of interest (temperature, photoperiod duration, acclimation, seasonality and plant-population origins).

### *4.2. Results and conclusions*

Results from those experiments indicate that leaf growth and survival of *C. nodosa* were both significantly reduced by water salinity increments. These effects were more marked the greater the increase in salinity and the longer exposure time of the plants (in one, two or four weeks), but they showed significantly from values of 41 psu. Results from the experiment to determine a possible interaction between salinity and temperature showed a significant effect between both factors on the leaf growth of *C. nodosa*, but not on shoot mortality. It was observed that at higher salinities, temperature increases do not enhance leaf growth as had occurred at lower salinity levels. The interaction between salinity and photoperiod time duration also affected plants leaf growth; plants submitted to higher photoperiod times tolerated higher salinities. When the plants were adapted, by gradually increasing the salinity level, it was observed that adaptation improved tolerance to salinity changes. A different response to salinity variations depending on the origin of the plants or the season of the year was also detected. In winter, *C. nodosa* shoots resist the increase in salinity better, as do plants from populations naturally adapted to higher salinities, such as those from the Mar Menor lagoon.

Although these results may indicate that tolerance of *Cymodocea nodosa* meadows may be higher than is currently established in Spain, the current scientific knowledge is insufficient to recommend maintaining or modifying the limit of 39.5 psu that has been applied; and a more extensive research is needed. It is necessary to keep in mind that a very restrictive limit can cause an unnecessary economic cost for the desalination plant, while a too high limit may generate an irreversible damage to the marine ecosystem and the management has to be based on the best scientific evidence.

## 5. Conclusion

The management of desalination plants requires the study of new discharge systems that assure a lesser environmental impact. If this has being a need for the latest decades, the recent Environmental liability legislation obliges plant operators to assume the costs of potential damages of the process. Rules and regulations are increasingly demanding, and it is obvious that we have to take them into account when designing desalination projects. Acuamed has been putting this concept in practice by developing some researching like the three studies developed in this paper.

Denia desalination plant discharge is not a very common case study because the main goal is to achieve a lower dilution level in the near field, when the brine flows through the harbor towards the exit and along a channel, under *P. oceanica* meadows. To reach this objective, the discharge system must be tested bearing in mind variables such as discharge device, flow regime and brine concentration in this particular setting. Some of the benefits related to this option include using an existing infrastructure and avoiding requirements of predilution, which can highly reduced costs during the construction works and the operation phase.

Mixing the brine with an effluent of lower saline concentration in an existing pipeline is another solution, which can be environmentally friendly because a large dilution is expected. However, the possibilities of maximizing the dilution of the brine layer are determined by the current discharge and the pipe characteristics. When using an existing pipeline that does not have a suitable design for a hypersaline discharge, a very common case, it is necessary to ensure that both effluents are totally mixed and homogenized previous to the spill.

Considering these projects and their benefits, other Acuamed desalination works are being designed using the current infrastructures such as channels in river´s mouths or pipelines of wastewater treatment plants.

These discharging systems are designed with the aim of ensuring the protection of seagrasses meadows such as *Cymodecea nodosa*. There are few studies about how this species tolerates changes in salinity values, but it was proven that it adapts better to this variation if it is produced in a progressive way. The thresholds established to protect *Cymodocea nodosa* are the main environmental constraints linked to management phase to some desalination plants. Only by developing more field studies about saline tolerance of these habitats, we may able to change regulations and operation controls in Spanish desalination plants.

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