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Boosting sustainable water production by upstream integration of desalination with saltworks in the Mediterranean region

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ABSTRACT

SEArcularMINE is an EU project that is focused on mineral extraction from saltwork bitterns, adopting a circular approach. Within this context, this work shows the possibility of completing the circular scheme with an upwind integration of seawater desalination that can provide freshwater to the local community but also use the brine reject to feed the saltwork in order to increase its productivity. In this study, a specific case of a natural saltwork in Trapani (Italy) is presented, assuming to place a desalination plant very close to the saltworks, so that the brine can be sent there without an additional energy input. After choosing the best desalination technology, demonstrating that Reverse Osmosis (RO) is more suitable than thermal processes from both economic and environmental point of view, the details of the RO design are presented. Then, preliminary calculations using a simple model for the saltwork ponds have been performed, showing that the brine feed can either increase the salt productivity by more than 50% or that the ponds surface can be reduced by more than 40%. Finally, evaporation experiments on desalination brines have been performed to demonstrate that no changes in salt quality occur compared to the standard seawater feed.

1. Introduction

During the last years, several efforts have been made to reach the goal of minerals recovery from seawater or desalination brines [1,2]. In the EU, several projects have been funded [3–5] with the aim of assessing the potential market and develop suitable technologies.

The H2020 SEArcularMINE project is a remarkable attempt of achieving these ambitious targets to extract valuable minerals from the residual stream after sea salt production in saltworks, namely the bittern [4]. The project wants to drive the development of innovative, sustainable and cost-effective technologies that will contribute to securing European access to Magnesium (Mg) [6], Lithium (Li) [7] and other Trace Elements (Rb, Sr, Cs, Ga, Ge, Co) [5], through a circular processing of the abundant bittern resources coming from saltworks (Fig. 1).

An interesting aspect of the circular concept of the aforementioned EU project is the proposition of the possibility of building desalination plants close to saltworks, in order to use the desalination brine to feed the process (Fig. 2).

Saltworks are generally made of artificial ponds organized in series that in time have become host of evaporitic ecosystems [8]. Depending on the design of the saltworks, the first pond can be a “preliminary pond”, which has a role of regulating the flow of water and clarifying the seawater. The increase in salinity is usually negligible. The main salinity increase starts in the “Cold” or first entry pond where seawater (generally with a density ≈3.5°Bé,[1] in the Baumé scale for specific gravity measurement, typically used in saltworks, corresponding roughly to a salinity 35–40 g/l) flows in during high tide or by using pumps and faces a density increase up to 5–6°Bé. The next pond is the “driving” pond where the salinity rises to 9–11°Bé, followed by the

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Abbreviations: CF, Concentration factor; DMPF, Dual media pressure filter; DOC, Dissolved organic carbon; ERD, Energy recovery device; GOD, Gained output ratio; MED, Multi-effect distillation; MSF, Multistage flash; RO, Reverse osmosis; SEC, Specific energy consumption; SW, Seawater; TDS, Total dissolved solids

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[1] °Bé = 144.32–144.32/d, where d is the solution density [g/cm3]

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Nomenclature

A_{pond}	Pond area [m^2]
C_{sat}	Saturation concentration [g/l]
m_{inlet}	Inlet solids mass flowrate [kg/d]
m_{outlet}	Outlet solids mass flowrate [kg/d]
$m_{product}$	Precipitated product mass flowrate [t/d]
Q_{evap}	Evaporation volume flowrate [m^3/d]
Q_{inlet}	Inlet volume flowrate [m^3/d]
Q_{outlet}	Outlet volume flowrate [m^3/d]
r_{evap}	Evaporation rate [mm/d]

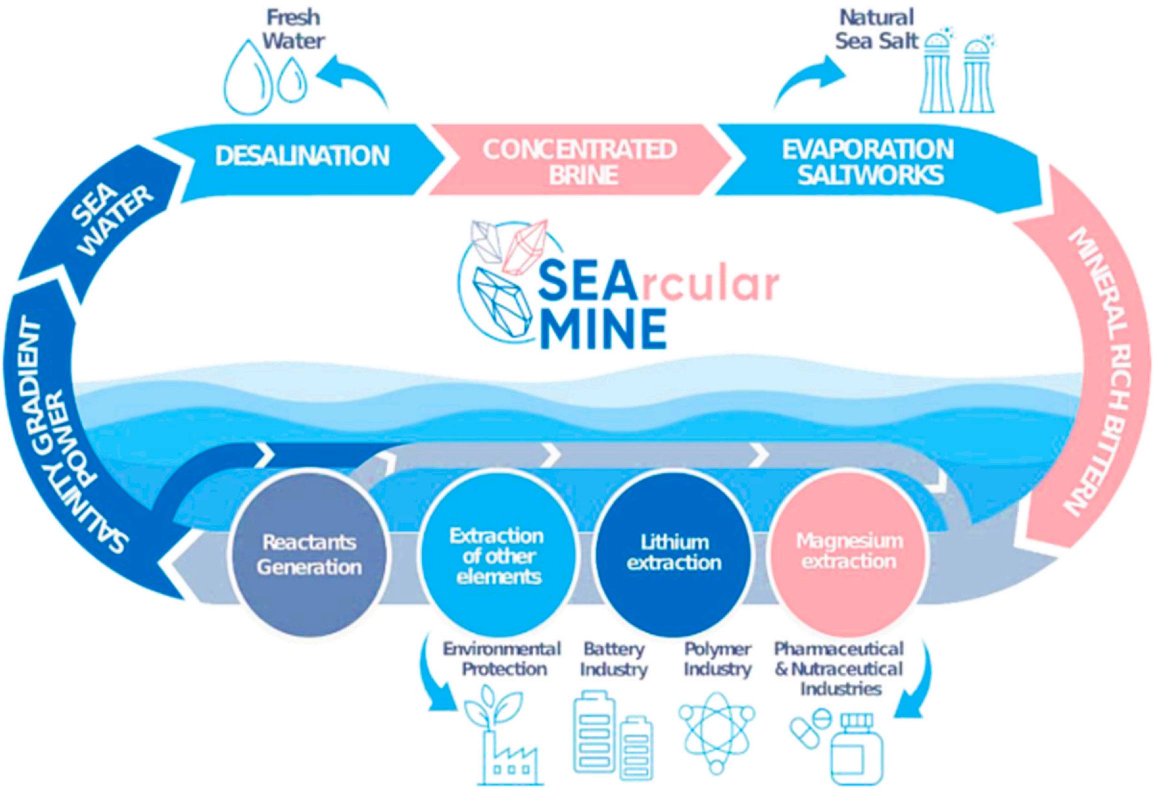


Fig. 1. Schematics of the EU project SEArcularMINE, where the desalination integration with saltworks is shown (up left part of the scheme).

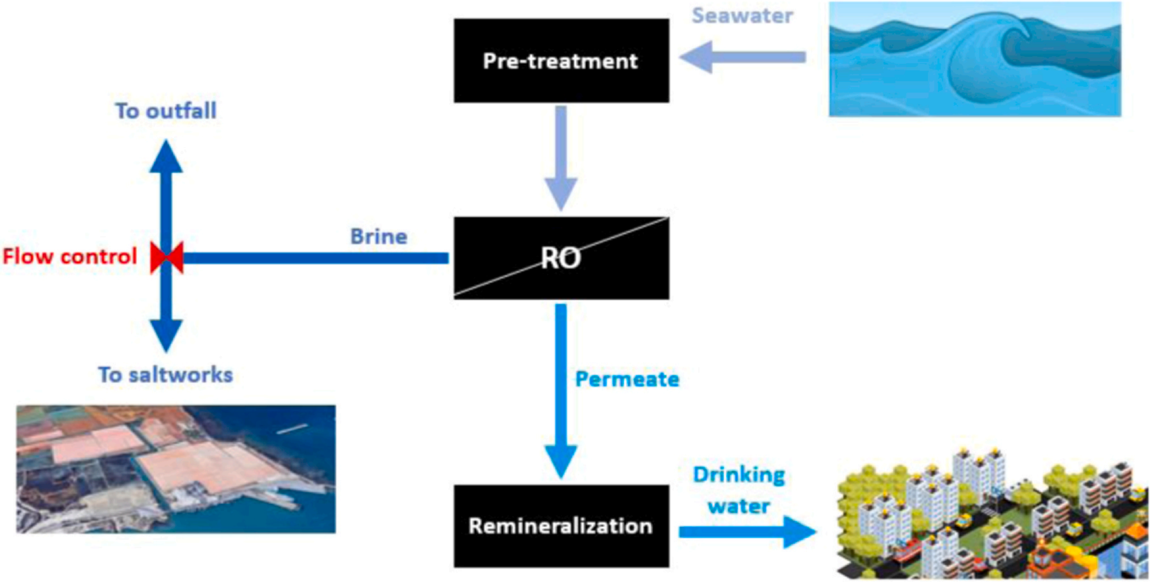


Fig. 2. RO desalination plant schematics including the option of feeding a saltworks with part of the brine generated in the plant.

"hot" ponds (or evaporative ponds), where the water reaches the saturation point of sodium chloride (25.7°Bé). Finally, there are the serving and the crystallizing ponds.

Several potential advantages are associated to this coupling approach, including the possibility of producing drinking water for local communities [9]. In fact, it is not unusual to have saltworks in very hot regions where water scarcity is present or it is very likely to arise in the upcoming years [10].

Other advantages are related to the possibility of reducing brine discharge to the sea (especially during saltwork's peak months) and increase salt productivity. The latter advantage can be easily understood by looking at the layout of a saltwork. In modern desalination plants, the brine can have a density of around ≈ 7–8°Bé , which falls within the range of the driving pond, suggesting that a positive impact is potentially achievable by using brine instead of seawater as a feed.

Despite the interesting foreseen advantage, other aspects must be taken into account, such as the importance of maintaining the equilibrium of saltwork ecosystem [11–13] and the impact that the brine would have in general on the final salt quality [14].

1.1. Desalination market overview

In recent years, a boom in Reverse Osmosis technology has been observed in the desalination market [15] (Fig. 3). This is mainly driven by:

- An increasing market demand in municipal, industrial and agricultural sectors, as well as in different geographical areas (Middle East, Asia, Australia, others…);
- Improvements in the RO process, such as better RO element performances (salt rejection: 5 to 10-fold, and permeability: two-fold);
- An increase in the maturity of the process and a strong confidence in the technology;

- Decreasing costs of high-tech equipment (Membrane cost divided by 2, Pumps, instrumentation);
- Increasing plant sizes (up to 1 000 000 m^3/d now);
- Decreasing cost of OPEX / energy consumption (from 10 kWh/m^3 to 2.5 – 4 kWh/m^3).

Fig. 4, there is a clear dominance of membrane-based desalination in the European Mediterranean region, especially for large-scale plants.

1.2. Work objectives

Within the context of the project, a preliminary technical assessment was performed with the aim of exploring the concept of upwind integration of a desalination plant to saltworks with the goal to increase this latter's productivity.

In particular, the work focused on a case study of existing natural saltworks located in Trapani, Italy, directly next to the sea. We

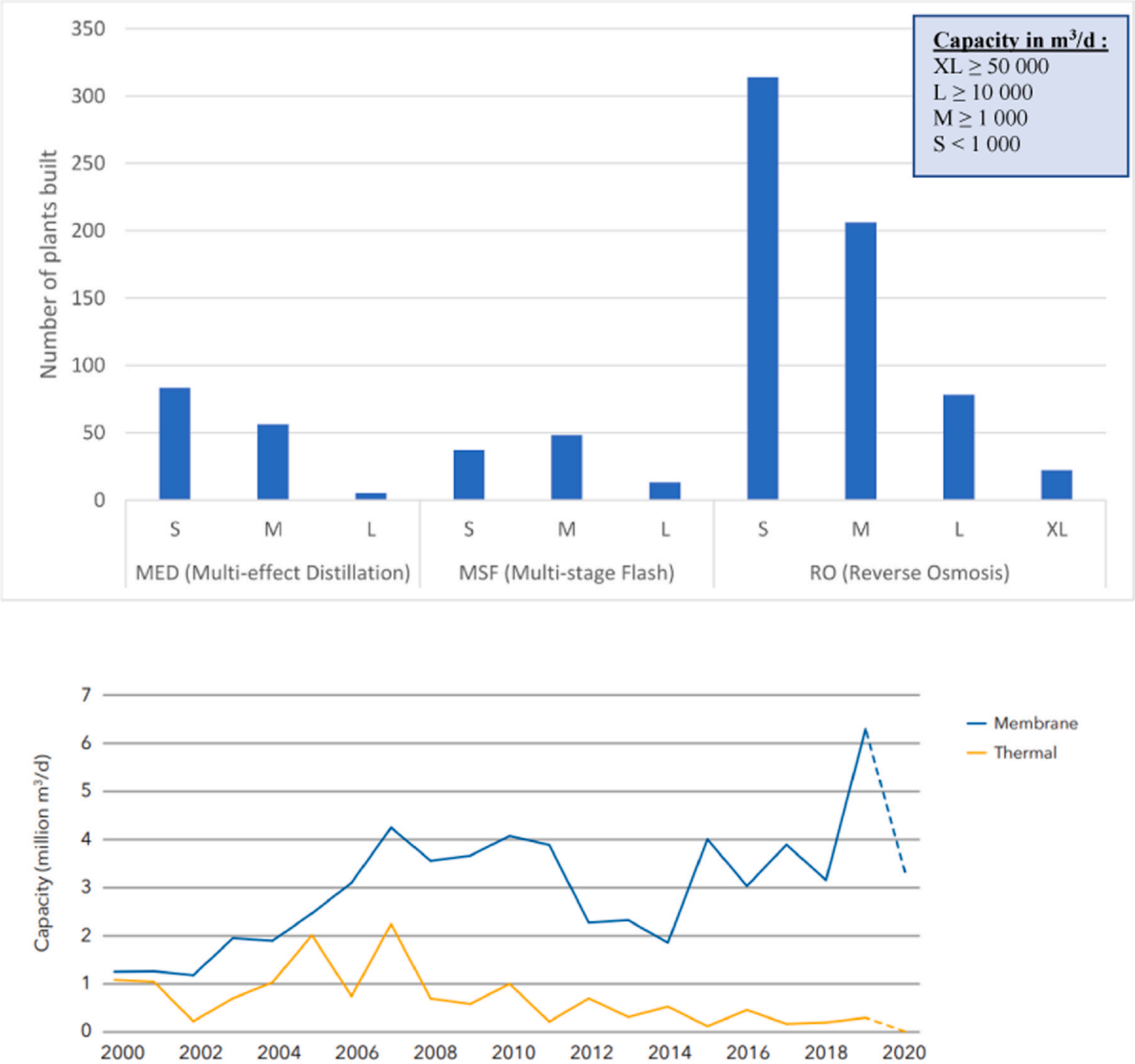


Fig. 3. World Desalination market, contracted capacity [15] – Source: Desaldata 2022.

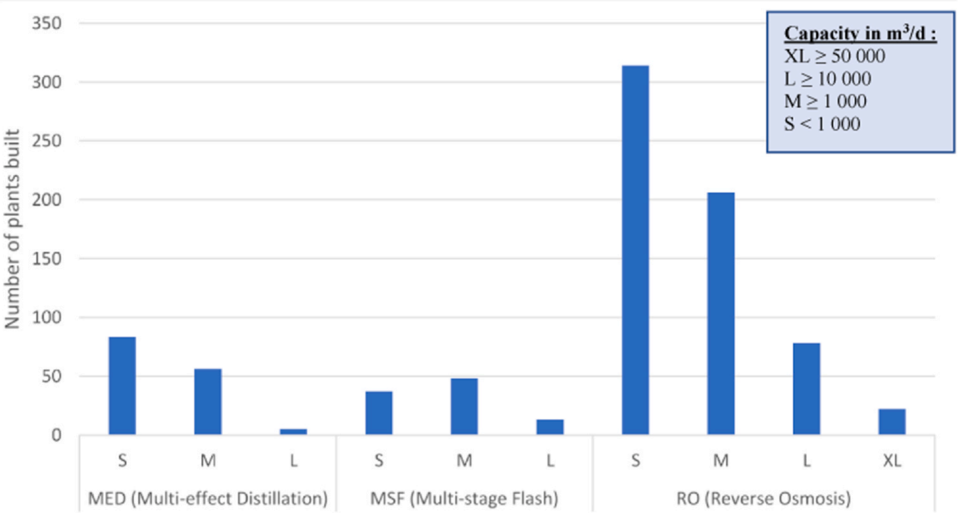


Fig. 4. Desalination plants by size and type [15] -
Source: Desaldata 2022.

assumed that a desalination plant can be built in the immediate proximity of the saltworks, by readapting some pre-existing facilities of an old Multi-Effect Distillation (MED) plant, so that a direct connection of the brine outlet line to the saltworks inlet can be envisaged, without the need of additional equipment. On this basis, the aim was to analyse:

- The impact of brine feeding on final salt quality;
- The choice of the proper desalination technology (thermal vs membrane);
- The design of the chosen desalination treatment line;
- The effect of brine feeding on the saltwork productivity.

2. Methodology

2.1. Crystallization experiments with desalination brines

Crystallisation experiments have been performed on real Tunisian desalination brines from thermal and RO desalination units located in Gabes-Tunisia. The aim is to explore the opportunity of integrating desalination ahead of saltworks. The samples have been concentrated at a laboratory scale emulating the natural evapo-concentration of seawater in saltworks but with a much faster rate.

The laboratory experimental set-up for the desalination brines concentration is shown in Fig. 5.

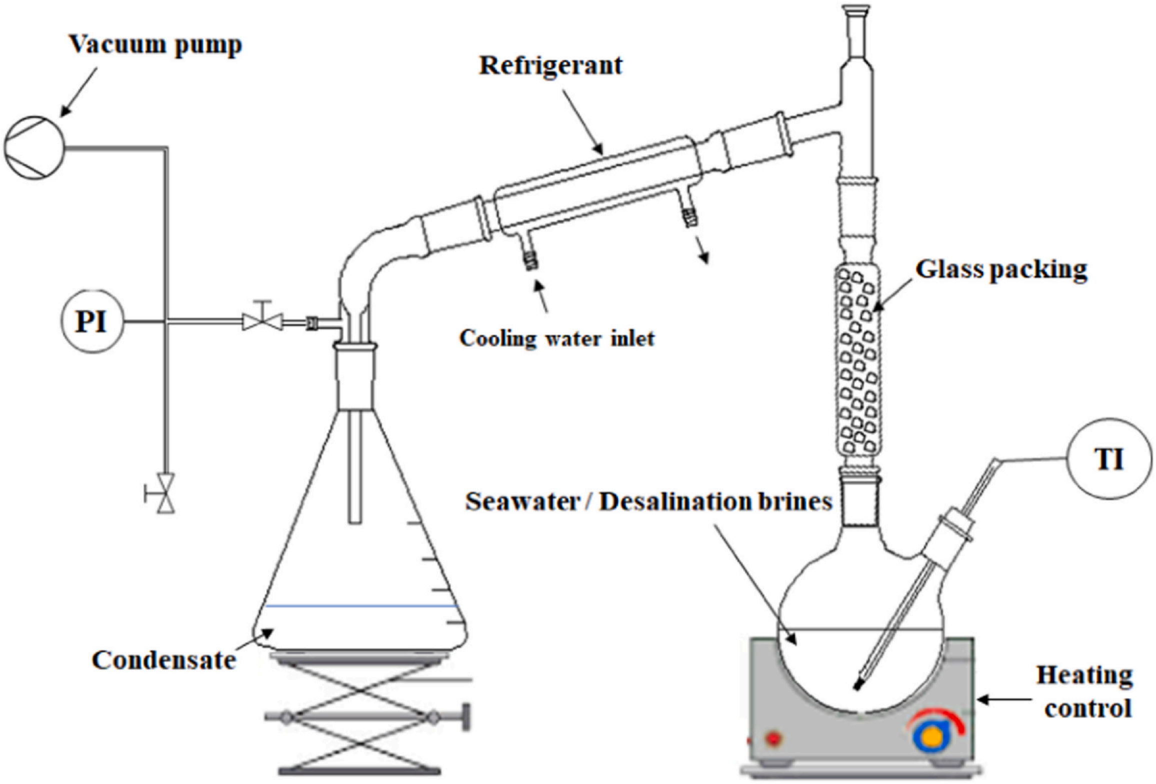


Fig. 5. Experimental setup for desalination brines concentration.

The thermal desalination brine was collected from a Multi Effect Distillation (MED) thermal desalination unit, with just two effects at an overall Gained Output Ratio (GOR) of 5 permitting a recovery rate approaching 20%. Feed seawater undergoes a gross filtration before getting mixed with antiscalant ahead of the first effect. The unit has a distilled water production capacity of 25 m^3/h. The SWRO brine was collected from an industrial RO plant operating within a power station, with a recovery rate of about 38%. The feed water is pre-treated in a coagulation/flocculation and filtration unit. The nominal feed water flow rate is 50 m^3/h. Antiscalant is used to prevent scaling in the RO process.

In the evaporation process, brines concentration was gradually increased by evaporating water at 50–55 °C under reduced pressure of about − 670 ± 15 mmHg. For each concentration step increase, several batches were performed. The Concentration Factors (CF) were chosen in order to have dominant single salt crystallization domains as recognized in saltworkers extended practices and corroborated by simulations using PhreeQC [16]. At any concentration level, the CF is defined as the ratio of the initial seawater and the brine weights:

$$CF_{Brine} = m_{SW}/m_{Brine} \tag{1}$$

Where: m_{SW} and m_{Brine} are the weights of initial seawater and the obtained brine, respectively. The CF domains are 1–2.5, 2.5–5 and 5- 12 corresponding to calcium carbonate, calcium sulphate and sodium chloride salts precipitation, respectively.

After each concentration step, brine, precipitated salt and distillate were collected and weighed. Before separating the precipitate by filtration, the brines were allowed to settle for a long period of time allowing to reach a pseudo-equilibrium with respect to salt precipitation, i.e. reaching near saturation conditions. Brines and distillates conductivities were systematically assessed. After reaching the targeted CF, all collected brines were later mixed to obtain representative samples before further concentrating the solutions in small batches. Almost pure water is recovered as distillate with conductivities ranging between 5 µS/cm and 12 µS/cm with and without rectification columns, respectively. For all batches, the overall balance was holding within ± 1%. For the sake of comparison, the same experiments were performed feeding the system with seawater.

2.2. Modelling of saltworks evaporation and Trapani saltwork specifics

Each pond has been simulated using a simplified steady state mass balances as suggested in the scheme of Fig. 6.

In particular, the main assumption is that no transfer of dissolved salts occurs within a pond, leading to

$$m_{inlet} = m_{outlet} \tag{2}$$

Where m_{inlet} is the mass flowrate of dissolved solids at the inlet of the pond and m_{outlet} is the mass flowrate of dissolved solids at the outlet of the pond.

In addition, water mass balance is described by

Table 1
Evaporation rates for Trapani saltwork on 01/08/2020.

Brine density	3.5°Bé	7°Bé	30°Bé
Evaporation rates in mm/d	11,1	11,0	8,9

$$Q_{inlet} - Q_{outlet} = Q_{evap} \tag{3}$$

Where Q_{inlet} is the volume flowrate entering the pond, Q_{outlet} is the volume flowrate exiting the pond and Q_{evap} (m^3/d) is the evaporation flow rate calculated as

$$Q_{evap} = \frac{r_{evap} * A_{pond}}{1000} \tag{4}$$

Where A_{pond} is the pond area and r_{evap} (mm/d) is the evaporation rate.

In literature there are correlations that can be used to estimate the evaporation rate. In particular, the method described by Akridge [17] is based on the density of the fluid, as well as wind velocity, solar radiation geographical location and dates. However, for the case of Trapani saltworks actual recordings of the solar radiation coming from a weather station were used, referring to the 1st of August 2020. The obtained evaporation rates for 3 different densities are reported in Table 1.

With an increasing density, we can observe that the change of evaporation rates is low, especially between 3.5°Bé and 7°Bé , which are approximately the salinities of seawater and SWRO brine. As we get closer to the to the saturation point of sodium chloride, the decrease of evaporation rates becomes larger.

The saturation is assumed to be reached at 358.8 g/l. At this point, as the water evaporates the salt precipitates while the concentration in the water stream remains constant. Assuming to have only NaCl in the stream, the amount of salt produced could be roughly estimated by using the following equation:

$$m_{product} = \frac{Q_{evap} \quad C_{sat}}{1000} \tag{5}$$

Where $m_{product}$ is the amount of salt produced expressed in t/d and C_{sat} is the saturation concentration.

In addition to the measured evaporation rates, the following data have been used to perform the estimations:

- Seawater density: 3.5 Bé
- SWRO Brine density: 7 Bé
- Surface area of the saltwork: 7 000 000 m^2
- Saltworks layout:
  o Preliminary ponds: 12.5%
  o Cold pond: 25%
  o Driving pond: 25%
  o Hot pond: 20%
  o Serving pond: 7.5%
  o Crystallization pond: 10%

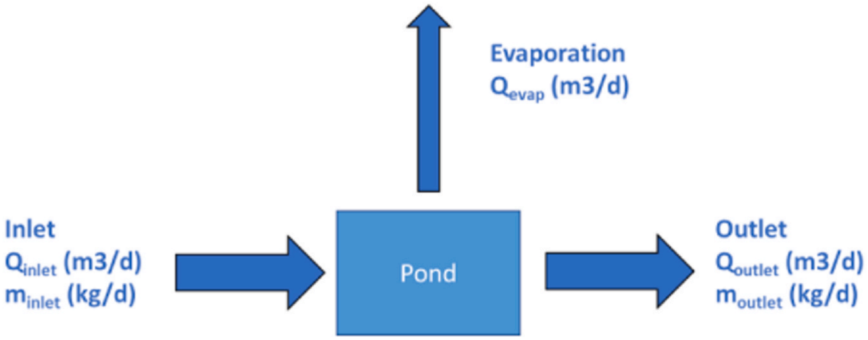


Fig. 6. Schematics of the simplified pond model.

3. Results and discussion

3.1. Choice of the desalination technology

There are two main aspects that should be looked at when comparing thermal and membrane technologies in the context of saltworks integration. The first is related to the desalination economical performances, while the other one is more related to the quality of the brine that can be produced, both in terms of salt concentration and potential chemical impurities contents.

The first aspect can be assessed by looking at the CAPEX that, on average, is lower than €1000/(m^3/d) of produced water for RO while being higher than €1700/(m^3/d) of produced water for thermal processes.

Another aspect is the typical Specific Energy Consumption (SEC) of the two types of plants and it is summarized Table 2. Here it can be seen how RO is usually less energy intensive that thermal processes, and only Multi-Effect Distillation (MED) can get close.

Another advantage is that higher recoveries are associated with RO (Table 3), meaning that it can produce more drinking water starting from the same feed, but also more concentrated brine, with a more beneficial impact on saltworks (as will be discussed in Section 3.3.2).

As anticipated above, another critical aspect of the desalination technologies for integration with saltworks is the chemicals residuals in the brines. The main chemicals that can be used are shown in Table 4.

The available data about chemical residues is very sparse. For the RO plants, a few published data mention the coagulant dosing rate upstream of the pre-treatment (1–1.6 ppm as Fe), but they do not state what are the residuals after the filters. The only real guidelines available to estimate the maximum allowable concentration in the brine is by using the limits stated by the membrane manufacturers. For example, Dupont's guidelines for feedwater quality for ferric iron is < 0.05 ppm. According to Suez's experience the iron residual is typically below 0.02 ppm as Fe after dual media filters (around the same value as naturally occurring iron in seawater).

Generally speaking, in the Mediterranean Sea RO plants operating with a stable pre-treatment do not require high doses of chemicals. Low dosing rates of coagulant upstream of the pre-treatment and of antiscalant upstream of the RO membranes is usually sufficient. The coagulant residual in the brine is usually very low because it is consumed by the pre-treatment.

MED typically requires antiscalant, antifoam and oxidants (to provide free chlorine). The chemical residuals at the outfall are usually very low because they are diluted even further when the temperature of the brine is decreased. In our application, the brine would most probably be sent to the saltworks without cooling down. We must therefore estimate that the chemicals would not be diluted.

Antifoaming agents (polyglycols and fatty acids) are surface active chemical agents applied mainly to thermal desalination processes to reduce surface tension and disperse foam causing organics in the water-air interface. They are considered non-toxic and they are readily decomposed in the marine environment. It is nevertheless hard to estimate the potential impact of the additional Dissolved Organic Carbon (DOC) sent to the saltworks (no data available).

Regarding the antiscalant, the available data show dosing rates of phosphonates of around 1–1.2 ppm for RO membranes, and around 1–3 ppm of polymer based or phosphonate based for MED. However, these values are not necessarily realistic because plants have, in the last years, started to reduce their dosing rates as per the manufacturers recommendations. Furthermore, there is also only little information on the type of antiscalant used and none about the real residuals in the brine. The two main impacts to consider about the use of antiscalants on saltworks are the potential hindering of crystallization of NaCl and the addition of phosphorus or polymers into the saltworks basins. The former will be addressed in chapter 3.3.2, and the latter was recently shown to have only a moderate effect, shifting calcium salts crystallization to higher degree of concentration [19]. However, at the typically used doses, the effect is so marginal that it can be considered of minimum concern.

Table 3
Desalination technologies recovery rates.

Technology	MSF	MED-tvc	SWRO
Recovery rates	10-15%	25-35%	40-50%

The chlorine used in MED plants may be expected to create slight problems with the biological life in the first saltworks basins, though some experimental investigation was performed in the past, showing negligible effects of this type [6]. Further studies should be done to estimate its impact on the saltworks when fed with MED brine, but it can be anticipated that the combination of the chlorine demand in the ponds, the brine temperature and the environmental conditions may accelerate its phase change.

Overall, the chemicals used in RO are generally fewer and at lower dosing rates than for MED. Therefore, RO plants have numerous advantages over MED, both with respect to the freshwater production objective and looking at the potential integration with saltworks. In particular:

1. Lower TOTEX;
   1. Lower CAPEX;
   2. Higher recovery, thus higher salt concentration in the waste brines;
   3. Lower energy requirements;
2. Lower environmental impact
   1. Less chemicals and lower dosing rates, thus with limited effect on saltworks;

The most suitable desalination technology for integration with saltworks is therefore reverse osmosis. Moreover, RO technology is taking over the desalination market. Most, if not all, new plants will use RO membranes, and many old thermal plants are being converted to RO plants.

Details on the design and costs associated to the RO plant for the Trapani case is gives in Section 3.2.

3.2. RO detailed design and economics

A desalination plant upstream of a saltworks has to be able to provide:

1. Fresh water to the end user, whether it is for agricultural or drinking water purposes;

Table 2
Energy consumption of desalination technologies. Multi-Stage Flash distillation (MSF), Multi-Effect Distillation (MED) and RO.

Technology	MSF (**)	MED (**)	SWRO
Electrical energy (kWh/m^3)	2.5-4	1.5-2	2.5 - 4 (***)
Equivalent Thermal energy* (kWh/m^3)	7.5-12	4-7	0
Total equivalent SEC (kwh/m^3)	**10-16**	**5.5-9**	**2.5 - 4**

(*) Expressed in electrical equivalent energy, (**) Taken from [18], (***) depending on Seawater TDS

Table 4
Chemicals used in RO and MED plants.

Chemical	RO		MED	
	Is it used?	*Maximum residual in the brine*	*Is it used?*	*Maximum residual in the brine*
Antiscalant	Yes *unless seawater has low salinity*	1,5-2 ppm	Yes	4-5 ppm
Antifoam	No		Yes	0,3-0,5 ppm
Free Chlorine	Only if shock chlorination is used at the intake	0 ppm It is neutralized by Sodium bisulfite	Very often Can be continuous or by shock	1-1,5 ppm free chlorine
Sodium Bisulfite	Only if shock chlorination is used at the intake	Generally null, but if present, it should be less than 1 ppm	No	
Coagulant (Fe)	Yes	0,04-0,1 ppm	No	
Coagulant aid	Rarely used in the Mediterranean area		No	
Acid	Rarely used in the Mediterranean area	Not compatible with saltworks	Rarely	

2. Concentrated brines to the first pond of the saltworks with adjustable flowrates.

Saltworks generally do not need a constant flowrate of seawater during the whole day. The flow into the ponds is regulated by the saltworker. Thus, it is critical that the desalination plant is able to provide a variable quantity of brine, while being able to produce 100% of its drinking water capacity.

In particular, Trapani saltworks can operates for more than 6 months per year, with an operational peak in July-August. To address the variability, a flow control system must be included in the brine outlet of the plant, so that part of the brine can be supplied to the saltworks and the rest is sent to the outfall. With this respect, the flow can be controlled based on average solar radiation data coming from weather stations and re-adjusted for the desired salt production (easily estimated through models and/or previous saltworks real data).

For the winter months when the saltworks are not operating, all the brine must be discarded. Therefore, the desalination plant outfall must be designed to accept 100% of the brine when it is at 100% capacity.

Trapani is characterized by a pre-existing MED plant, that is not in use anymore. For this reason, the site already presents intake and outfall Therefore, SWRO design is presented below and at the end some comparison figures are presented as well.

According to [20], the Trapani plant intake has the following characteristics (Fig. 7):

- Two separate intakes:
  - o #1 is 24 m deep, 4500 m from the shoreline
  - o #2 is 12 m deep, 2100 m from the shoreline
  - o Both intakes can provide in total a flowrate of up to 9000 m^3/h of seawater
- The seawater temperature at the intake has a range from 10-22 °C (design temperature)

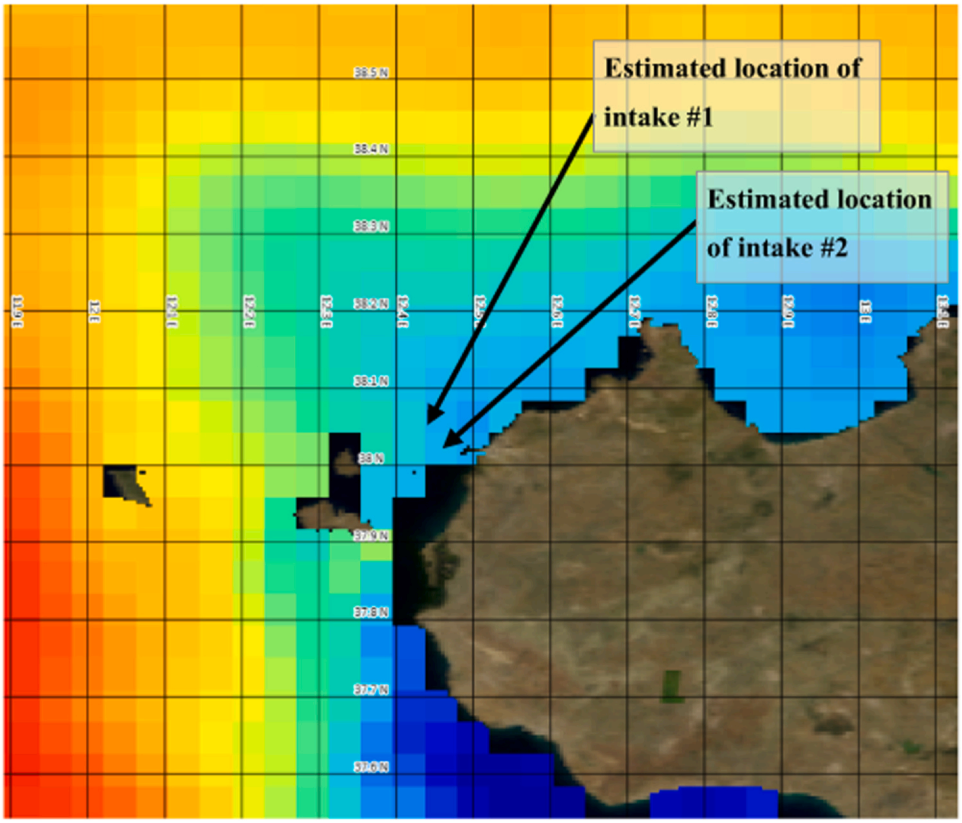


Fig. 7. Location used for the measurement of temperatures on Copernicus [21].

- There is a sand removal and filtration facility and 4 + 1 centrifugal pumps (2100 m^3/h each) to feed the plant.

The maximum feed flowrate is therefore the capacity of the pumping station, thus being 8400 m^3/h.

Seawater quality in the Mediterranean Sea is generally good. The main reasons for potential problems with the feed water quality could be linked to pollution, either from waste, dredging activities or hydrocarbons. However, these specific issues are not expected to be common, and are not considered in this study, especially because the intakes are located at depths of 24 and 12 m. As most coasts in the region, there should not be any algae bloom events, or frequent jelly fish influxes.

The plant design is mainly dependent on the water quality. Therefore, it is crucial to identify the main parameters for our study case.

On average, the Trapani seawater characteristics are as follows:

- Salinity: 36.8 g/L
- Temperature: 15-27 °C
- Turbidity: 1.5-2.5 NTU
- TSS: 2.5-3.5 ppm
- TOC: 1-1.6 ppm
- SDI_3: 20-22
- Algae: No blooms

The surface temperature off the coast of Trapani varies on average from 14.6 to 26.5 °C, but it can reach a peak of 28.2 °C (Fig. 8 and Fig. 9). However, as the intakes are located at 12 and 24 m of depth, the actual plant feedwater would be colder.

Fig. 9 shows increases up to 23.4 °C at − 22.4 m and 26.3 °C at − 10.5 m. Furthermore, as we do not know the distribution of flow between the first and second intakes, we assumed that each would provide 50% of the feed flowrate. Therefore, we assumed that the maximum monthly average temperature is 24.9 °C, and the maximum and minimum peak temperatures is 27 °C and 15 °C.

To have an accurate measurement of the TDS for the case analysis, the element concentrations were taken from an analysis of the water inside the Trapani saltworks within the SEArcularMINE project [23]. The ion distribution is shown in Table 5.

Given the water conditions described above, the following design has been adopted, starting from the intake screening:

- Intake:
  The best choice would be a coarse screening of 50 mm followed by fine screening of 5 mm.
  The maximum intake flowrate is estimated at 8 400 m^3/h.
- Filtration:
  With the given data for turbidity, and with the information known about the Mediterranean Sea, the recommended pre-treatment is a dual media filter.
  The Dual Media Pressure Filters (DMPF) would be designed as follows:

1. Number of units: 12 + 1
2. Dimensions: 55 m^2, 4 m diameter, 12.5 m long
3. Media: Sand and Anthracite (with gravel as support)
4. Up to 3% water losses from backwashing
5. Dosing rate of Ferric Chloride: up to 2 ppm as Fe
   The backwash water is sent to a sludge thickener, followed by sludge dewatering. The dried sludge is then disposed.
   Iron residuals after a DMPF are typically below 0.02 ppm, which is within the range of naturally occurring iron in seawater. No negative impacts of the iron residual on saltworks should be expected.

- RO protection

To protect the RO membranes from DMPF disfunction or from damage to pipes or equipment between the DMPF and the RO membranes, cartridge filters are used. The recommended design consists of 8 filters, with each 1800 elements. The filters would have a 5 µm cut-off.

- RO unit

For Mediterranean seawater, Suez usually recommends using a single pass, single stage configuration. However, the design must be validated by a simulation software. In this case, WAVE by Dupont [24] was used to find the best configuration. The target is to maximize the recovery while keeping fluxes at an acceptable level and boron concentrations ≤ 0.8 ppm.

The results from the simulations are shown in Table 6, while the schematics of the RO plant can be found in Fig. 10. The maximum brine TDS that was obtained with 1 stage is 70.8 g/L for case 1b (15 °C). Brine flowrates can reach 4282.2 m^3/h or 102773 m^3/day, which is much higher than the assumed peak flowrate to feed the TP-IT saltworks (about 65000 m^3/day). The flow is nevertheless low enough to be able to be fully discharged through the plant outfall.

It is also interesting to compare the results of this design with the actual performances of the old MED plant in Trapani.

As previously indicated in Section 3.1, in MED, the energy consumption is separated in two parts, namely the electrical energy and the thermal

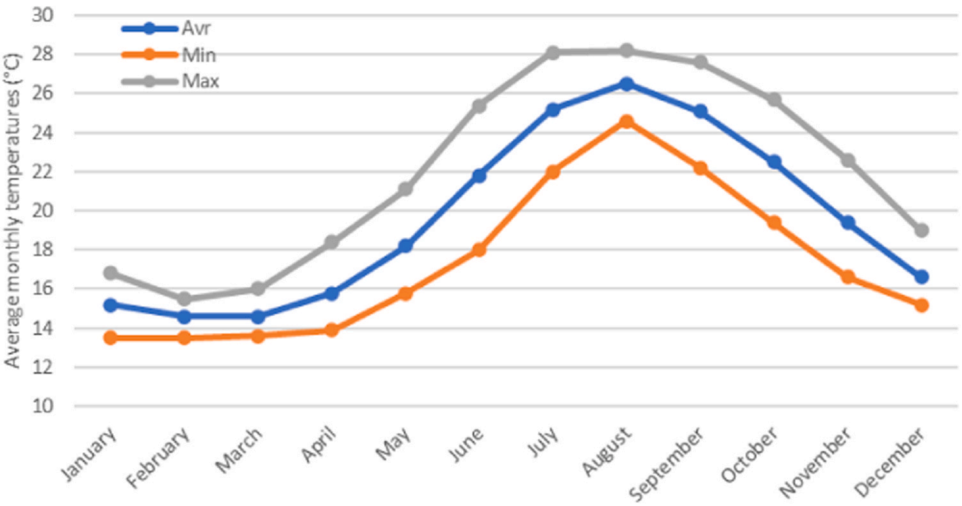


Fig. 8. Trapani average seawater surface temperatures [22].

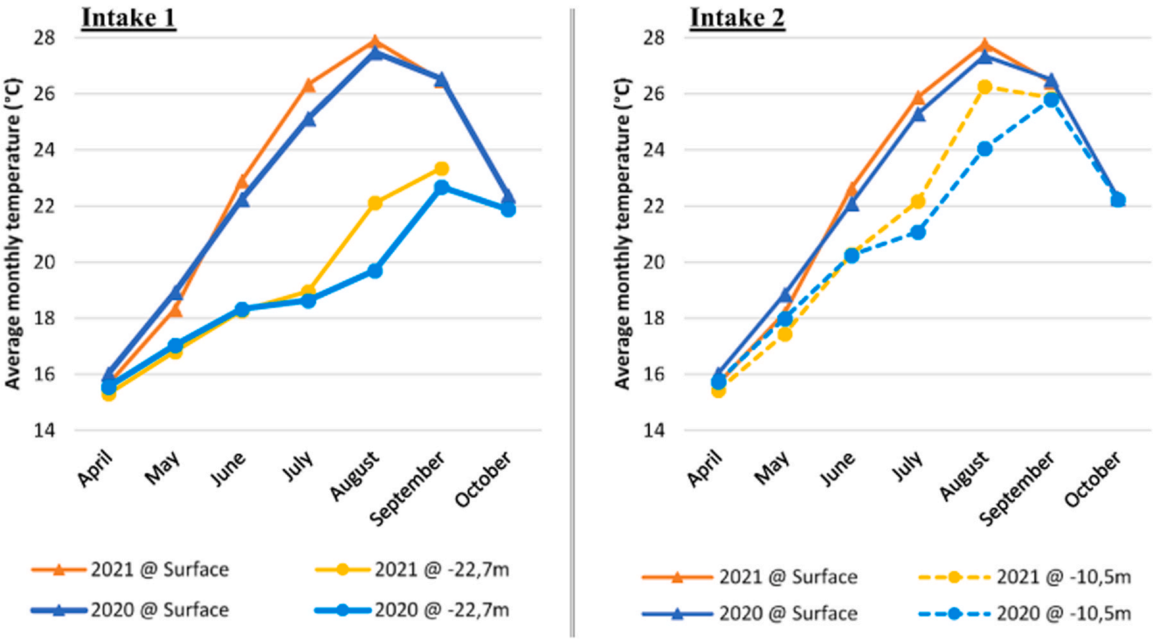


Fig. 9. Average surface and intake level temperatures for 2020 and 2021 [21].

Table 5
Ionic composition of seawater. For the energy recovery device (ERD) an increase in TDS of 2.4% is assumed.

Ions [mg/l]	Seawater	Adjusted due to ERD TDS increase*
Ca	444,48	455,15
Mg	1504	1540
Na	10536	10789
K	427	437
Ba	0	0
Sr	8219	8417
total cations	12919	13229
HCO_3	120	123
CO_3	0	0
Cl	20523	21016
Br	71	73
SO_4	2997	3069
total anions	23712	24281
B	4,37	4,47
TDS	36635	37514
Energy Recovery Device (ERD) TDS increase 2,40%		

Table 6
RO simulations results.

Simulation 36.8 g/L @ 14lmh flux		#1a	#1b
Membrane types		**DOW FILMTEC 4xXHR440 + 3xXLE440**	
Temperature	°C	27	15
Recovery	%	48%	48%
Brine TDS	ppm	70738	70804
Permeate TDS	ppm	201	101
Boron	ppm	0,78	0,4
Elements	u	7000	
Brine flowrate	m^3/h	4282,2	
Permeate Flowrate	m^3/h	3952,8	
SEC	kWh/m^3	1,91	2,06
ERD units	u	252	252

energy. The electrical energy consists in the pumps and utilities, while the thermal energy is the energy requirements to produce the steam.

According to [20] and [25], the plant:

1. Requires between 1-1.5 kWh/m^3 of electrical energy (without seawater intake pumps)
2. Consumes 5.5-6 Nm^3 of methane in the boiler, which is the equivalent of 55-61 kWh/m^3

Even considering the lowest range of consumption for MED specific cost of energy (without the intake pump) for the RO is much lower (Table 7). Considering the average prices for the period 2016–2021 of 0.032 €/kWh for gas, and 0.176 €/kWh for electricity (Eurostat source), The RO energy cost would be 0.539 €/m^3 while the MED would be 1957 €/m^3 which represents more than a 3.5-fold increase.

Regarding the CAPEX, it was already discussed in previous paragraphs that for RO would be below €1000/(m^3/d) of produced water while being lower than €1700/(m^3/d) of produced water for MED. Therefore, the convenience is from both points of view.

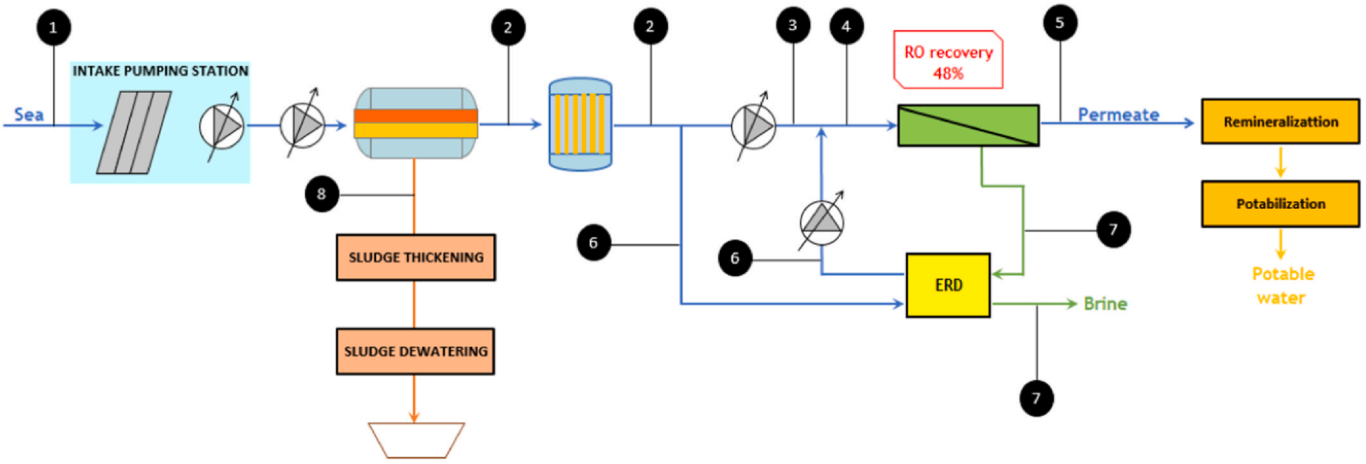
3.3. Brine impact assessment on saltwork

3.3.1. Brine evaporation and concentration experiments

As explained in the methodology section, seawater, MED brine and RO brine have been compared in order to assess the behaviour upon evaporation. Fig. 11 shows the evolution of brine density for the three feed water qualities. Big markers correspond to mean samples for each CF for any feed quality. Clearly, all water qualities have almost the same behaviour regardless of the origin. This result is further corroborated with near infinite dilution conductivities shown on Fig. 12. The results suggest that desalination brines could be integrated into saltworks without any significant quantitative effects on saltworks operating procedures. Moreover, the sodium chloride yield is expected to substantially increase.

3.3.2. Saltworks productivity

In order to assess the impact of the RO brine on saltwork productivity, three cases were simulated by considering the overall saltwork surface area of 7 000 000 m^2 divided according to the distribution described in the methodology section. In each case, the fixed parameter was the outlet flow concentration of the serving pond set at 358,8 g/L or 30°Bé and the evaporation rates are taken from the data of Table 1. while the inlet flowrate (i.e. the amount of seawater or brine that the saltwork can process given a specific meteorological condition) is the calculated variable. It is predicted using the simple modelling approach described in Section 2.2. The three cases were as follows:



		1	2	3	4	5	6	7	8
Flowrate	m3/day	201 600	197 640	95 895	197 640	94 867	101 745	102 773	3 960
	m3/h	8 400	8 235	8 235	3 996	3 953	4 239	8 235	165

Fig. 10. Flow chart of RO plant.

Table 7
SWRO and MED plant energy consumption (without seawater pumps). The energy consumption of RO includes the contribution of pre-treatments assumed 1kWh/m3. MED methane consumption is taken 5.5 Nm^3/m^3 of distillate and electrical consumption 1 kWh/m3.

Case	Recovery	Thermal Energy	Electrical Energy	Energy cost @ 0.176€/ kWh
		kWh/m³	*kWh/m³*	*€/m³*
RO	48%	0	3,06	0539
MED	29%	55,7	1	1957

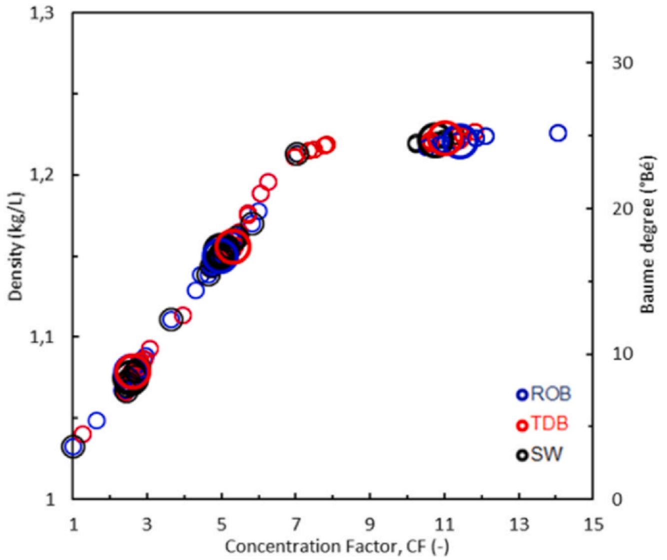


Fig. 11. Evolution of brine density with increasing Concentration Factor (CF) for: Seawater (SW), Thermal Desalination Brine (TDB) and Seawater Reverse Osmosis Brine (ROB).

1. Case#1 Benchmark: the saltworks was simulated by feeding seawater through the cold pond.
2. Case#2 Productivity increase: The cold pond is fed with RO brine at the same flowrate as the seawater in benchmark case.
3. Case#3 Surface reduction: The cold pond is bypassed and RO brine is fed directly to the driving pond in order to obtain the same outlet flowrate and concentration in the serving pond as for case 1.

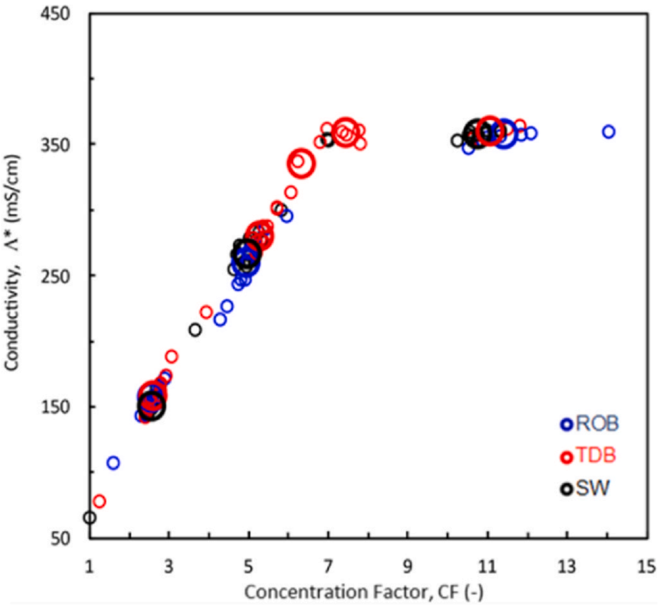


Fig. 12. Evolution of brine conductivity at near infinite dilution with increasing Concentration Factor (CF) for: Seawater (SW), Thermal Desalination Brine (TDB) and Seawater Reverse Osmosis Brine (ROB).

Table 8 shows that using RO brines can provide significant benefits. In case #3, for the same serving pond outlet flowrate as case #1, the cold pond can be bypassed and the driving pond inflow can be reduced by about 20% (from 45 670 m^3/day to 36 400 m^3/day). In addition, the hot pond surface area can be reduced from 20% to 10% of the total surface area. The saltworks surface could therefore operate with a total surface area representing less than 53% of the original area.

In case #2, feeding the whole saltwork with RO brine (same flowrate as for seawater) results in the achievement of the saturation at the outlet of the hot pond. Therefore, the serving pond can act as additional crystallization surface. In addition, an increased outflow of about 78% (from 6 340 m^3/day to 11 320 m^3/day) is obtained. It is then possible to estimate the salt productivity in case 1 and 2 through Eq. (5) showing a productivity increase of nearly 75%.

Table 8
Estimated parameters of the cold, driving, hot and serving ponds.

CASE #1	[Cold]	[Driving]	[Hot]	[Serving]
% of total surface area	*25%*	*25%*	*20%*	*7.5%*
Q_{inlet} $[m^3/d]$	65 000	45 670	26 340	11 000
C_{inlet} $[g/L]$	35,0	49,8	86,4	206,9
Q_{outlet} $[m^3/d]$	45 670	26 340	11 000	**6 340**
C_{outlet} $[g/L]$	49,8	86,4	206,9	358,8
CASE #2				
% of total surface area	*25%*	*25%*	*20%*	*7.5%*
Q_{inlet} $[m^3/d]$	65 000	45 830	26 660	-
C_{inlet} $[g/L]$	**62,5**	88,6	152,3	-
Q_{outlet} $[m^3/d]$	45 830	26 660	**11 320**	**-**
C_{outlet} $[g/L]$	88,6	152,3	358,8	-
CASE #3				
% of total surface area	*0%*	*25%*	*10%*	*7.5%*
Q_{inlet} $[m^3/d]$	-	**36 400**	20 300	11 000
C_{inlet} $[g/L]$	-	**62,5**	112,1	206,3
Q_{outlet} $[m^3/d]$	-	20 300	11 000	**6 340**
C_{outlet} $[g/L]$	-	112,1	206,3	358,8

Even if a more detailed study could be required to assess the full potential of the abovementioned solution, it seems reasonable to state that an enhancement of more than 50% of the productivity of the saltworks could be expected to be reached for saltworks fed with SWRO brine.

4. Conclusions

The aim of this work was to assess the impact of an RO desalination plant coupled with the saltworks in Trapani, Sicily, Italy.

Firstly, a design for the case of the Trapani Saltworks is proposed. The study of the Trapani desalination plant with RO was completed. In this specific case, the results show that the pre-existing MED plant's specific cost of energy was at least 3.5-fold higher than the RO one, while producing a brine 25% less concentrated. This confirmed the choice of RO as the best technology for the application thanks to its higher recovery rate, lower costs and lower chemical dosing rates.

Moreover, preliminary laboratory experiments with real desalination brines by ENIG showed that RO (and MED) brines can be integrated into saltworks without issues with the crystallization of salts, despite the use of antiscalants.

Finally, the simulations of the Trapani saltworks fed with desalination brines have revealed that, at least in the peak months, the saltwork could operate with less than 53% of the original area. Alternatively, it could theoretically enhance its salt productivity of more than 70%. This means that, generalising the specific case study, an enhancement of about 50% of productivity can likely be expected for most saltworks during the whole year.

Data Availability

The data that has been used is confidential.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Antonino Campione reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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