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Research paper

A spatial decision framework for sustainable desalination: Mapping optimal sites for zero liquid discharge in Europe

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ABSTRACT

Water scarcity is an increasingly critical global issue, driven by population growth, industrial development, and the effects of climate change. Desalination has become a weighty strategy to ensure freshwater supply, particularly in arid and water-stressed regions. However, deploying desalination plants presents challenges such as high energy demands, environmental impact, and the need for sustainable site selection. This study proposes an integrated spatial analysis method that combines geographic data with multi-criteria decision-making to identify suitable locations for desalination facilities. The approach evaluates factors such as land availability, climatic conditions, energy costs, environmental risks, brine discharge, and eutrophication potential. A decision-analysis technique was used to balance competing objectives and produce suitability maps. The proposed method also incorporates strategies to minimize environmental impacts, including technologies that eliminate liquid waste and use renewable energy sources. A case study was conducted across the European continent. The analysis identified 3,309 suitable sites for desalination plants, located in both coastal and inland areas, covering approximately 10% of the continent's land surface. These results demonstrate the feasibility of implementing advanced desalination systems beyond traditional coastal zones. The resulting framework offers a scalable and adaptable model for sustainable water resource management in diverse environmental and geographic contexts.

1. Introduction

Water is at the core of sustainable development and plays a critical role in socioeconomic development, healthy ecosystems, energy, and food production. Although Earth's water resources are estimated to be around 1.4 billion km^3, 97.5% is ocean water, which is not suitable for most human activities due to high salt concentrations, and only 2.5% is freshwater, the majority of which is locked in ice and glaciers [1]. Of the freshwater available, only 1.20% is surface water, and much of this is not technically exploitable or highly polluted, reducing the annual global exploitable volume to a mere 89,840 km^3 [2]. The increase in the global population, coupled with industrialization and agricultural demands, has significantly reduced the usable amount of freshwater in the early 21st century. This fact was accentuated by climatic change, characterized by higher average temperatures, which has led to a sharp decline in net water reserves and a degradation of water quality [3]. Currently, around four billion people live in regions that experience severe water stress, and one in four large cities is already facing water scarcity, with the projection of increasing water demand by 55% by 2050 [4]. In response to these challenges, the General Assembly of the United Nations established the Sustainable Development Goals (SDGs) in 2015 [5]. The Sixth Goal focuses on ensuring the availability and sustainable management of water and sanitation for all, addressing every aspect of the water cycle and sanitation systems. Achieving this goal is crucial for progress in health, education, economy, and the environment [6]. Due to the global scarcity of freshwater, the use of unconventional water resources is increasingly being explored. Reclaimed water can be obtained through the advanced treatment of effluents that are initially unsuitable for agricultural or domestic use. These sources include municipal and industrial wastewater, as well as saline and seawater. Among the technologies available for

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the treatment of saltwater and seawater, desalination stands out as a widely implemented solution [7]. Desalination technology is widely used in regions with dry climates, scarce potable water, and access to seawater or brackish water. Desalination involves the extraction of fresh water from saltwater to address the increasing demand for freshwater due to human, industrial, and agricultural needs. The technology separates saline feed water into two streams: permeate freshwater and concentrated brine, effectively reducing the total dissolved solids (TDS) below 500 mg/L [8]. Desalination technologies are categorized into membrane-based and thermal-based processes. In 2024, there were more than 21,000 operational desalination plants worldwide, producing approximately 99 million cubic meters of freshwater per day [9].

According to the International Desalination Association, global desalination capacity is expected to nearly double by 2050, reflecting the increasing dependence on this technology [10]. Despite its increasing implantation, desalination presents significant environmental challenges, particularly the disposal of brine into marine environments and groundwater [11]. Brine, which has at least 1.6 times the salinity of seawater, may contain pretreatment chemicals, nutrients, microbes, and heavy metals [12]. To address this issue, minimal or zero liquid discharge (MLD or ZLD) strategies have been developed. These treatments eliminate brine discharge by recovering the liquid fraction of freshwater and valuable compounds, such as salts, achieving more than 95% freshwater recovery [13]. Typically, brine is first concentrated using membrane systems, followed by thermal processes to recover salts through precipitation and crystallization. These methods are environmentally friendly, do not produce greenhouse gases, and often incorporate renewable energy sources [14]. The site selection process for ZLD desalination plants requires the consideration of socio-economic, environmental, and technical variables to ensure global reproducibility and local community acceptance. Geographic information systems (GIS) and Multi-Criteria Decision Making (MCDM) provide a suitable structured framework to evaluate potential sites. Recent studies have successfully coupled GIS with the Entropy method, analytic hierarchy process (AHP), and the Vlsekriterijumska Optimizacija I KOmpromisno Resenje (VIKOR) algorithm to rank desalination locations at a regional scale, for example in Crete [15], Chile [16], Morocco [17].

GIS enhances the process by integrating spatial data, enabling multiscale analysis, and visualizing geographically specific evaluation units [18]. MCDM complements this by systematically prioritizing alternatives based on weighted criteria [19]. Entropy Method: Assigns weights to uncertainty-based criteria, ensuring balanced importance for factors such as cost, environmental impact, and community needs. VIKOR method is ideal for site selection, it balances conflicting objectives (e.g., cost vs. sustainability) and, combined with GIS, generates dynamic maps and actionable insights [20]. Unlike the AHP, VIKOR offers nuanced solutions tailored to diverse geographic and climatic contexts, making it highly effective in selecting the site of the ZLD desalination plant [21].

Water distribution across Europe exhibits significant spatial variability, with remarkable disparities in the Mediterranean region, where anthropogenic activities have exacerbated existing challenges. The Mediterranean climate is characterized by arid summers prone to recurrent droughts, contrasted with intense precipitation events during the fall and winter months, further complicating the management of water resources [22]. This region faces high variability in precipitation and temperatures. Long-standing water scarcity issues have been exacerbated by increased consumption due to tourism and other anthropogenic factors, leading to desertification and saltwater intrusion in coastal aquifers. Water shortages are most severe in southern Europe but are also present across the continent. Since 1976, many EU countries have experienced droughts, with several reporting ongoing water scarcity and over-exploited aquifers [23]. Research indicates that around 11% of the European Union (and UK) population, live in water-scarce regions [24]. This fact significantly affects countries such as Spain, Italy, Greece and Portugal, where a large proportion of the population faces water scarcity [25]. During summer, the use of water in the Mediterranean often reaches 100%, depleting the available freshwater resources [26]. Despite the imperative need for new technologies to overcome water stress in Mediterranean regions of southern Europe, finding optimal locations for implementing ZLD-desalination plants is crucial to ensure their efficient operation, environmental sustainability, and economic viability [27] not only in coastal areas, but also in inland areas. Although full-scale ZLD schemes have not yet been widely deployed inland, the number of brackish groundwater desalination facilities is rapidly increasing, where reject brine is not always reinjected into wells, but also is discharged to nearby wetlands and shallow aquifers. Recent studies report sharp increases in salinity and electrical conductivity that displace the native population of organisms, while the nutrient-rich brine accelerates eutrophication [28], evidence that supports the need for true ZLD trains in interior basins.

Developing predictive solutions based on well-defined criteria for selecting suitable sites is essential. The success of desalination projects depends on several factors: topography, proximity to power sources, access to input seawater and output freshwater pipelines to minimize costs, closeness to consumers to reduce transmission and distribution expenses, and avoiding impacts on biological sanctuaries and surrounding environments. Additionally, the integration of renewable energy sources is a significant consideration. Challenges in site selection include limited coastal areas due to urbanization, high land costs, disposal of treated sewage effluent near intake points, and the distance of some power plants from the sea. Conventional desalination plants also need to meet environmental standards for brine discharge. However, this issue is overcome by the new ZLD-desalination plants, making it a more versatile technology [29].

The methods proposed in this study integrate climatic factors such as relative humidity and wind speed, considered critical to evaluate evaporation efficiency in ZLD systems. Indeed, this framework ensures objective prioritization of criteria by incorporating entropy weighting. In addition, the proposed GIS-MCDM-VIKOR approach addresses challenges such as brine discharge and eutrophication, common issues in conventional desalination. This innovative framework not only mitigates environmental impacts but also leverages renewable energy potential, offering a replicable, multiscale model for sustainable water resource management. Water stress in Europe's coastal regions and the inland areas of the Iberian Peninsula is examined as a case study to inform decision-making processes aligned with EU sustainability objectives, including the SDGs and the zero pollution action plan. The framework's adaptability to diverse regional and environmental contexts emphasizes its strategic importance in addressing global water scarcity, a challenge increasingly intensified by the impacts of climate change.

The remainder of the paper is structured as follows. Section 2 describes the proposed methods for optimizing ZLD desalination locations and the description of the case study. The results are provided in Section 3, and discussion in Section 4. Finally, conclusions are given in Section 5.

2. Materials and methods

This section presents the structured approach adopted to assess and identify optimal locations for the implementation of desalination plants along the European coastline. The section first introduces the concept of ZLD desalination, describing technological components, environmental significance, and relevance in the context of sustainable water resource management. Subsequently, details the methodological framework proposed to carry out the spatial and multi-criteria analysis are discussed. The case study area focuses on selected coastal regions of Europe, chosen for their potential strategic importance and

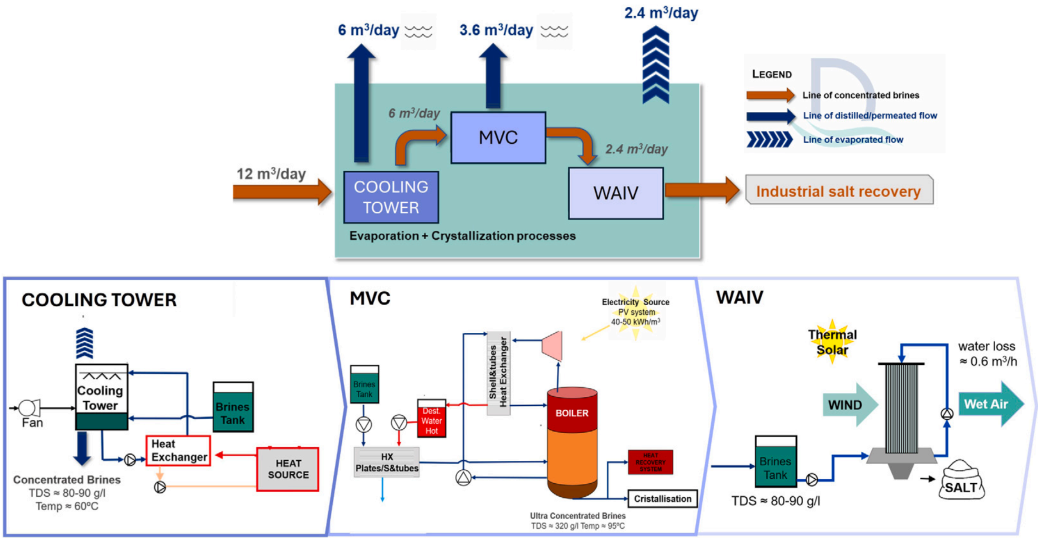


Fig. 1. Block diagram of the proposed ZLD-desalination plant configuration.
Source: Adapted and modified from Prado et al. (2022) [30], with permission.

variability in geographical and socio-environmental conditions. The analysis incorporates a series of restriction layers to remove areas that are not suitable for development, based on topographic limitations, environmental protection zones, social and urban constraints, and economic feasibility. This spatial filtering process ensures that only viable candidate zones are considered for further evaluation. The evaluation criteria used to assess the suitability of the remaining areas are also included, covering aspects such as proximity to existing infrastructure, environmental impact, land use compatibility, and potential for energy integration. Finally, an MCDM model is applied that synthesizes the selected criteria to prioritize and rank the most appropriate sites for the deployment of the ZLD desalination plant. This integrative approach ensures a comprehensive, objective, and reproducible method for site selection on a regional scale.

2.1. Preliminaries: Zero liquid discharge desalination plant

The ZLD-desalination plant is an advanced brine reduction system designed to eliminate liquid brine discharge by promoting total water recovery and salt crystallization, thereby mitigating environmental impacts and enabling the valorization of recovered solids. ZLD configurations typically integrate membrane-based concentration with successive thermal processes. In the proposed configuration, based on Prado et al. 2022 [30], three key thermal technologies are considered (Fig. 1). First, a cooling tower (CT) thermal unit, which achieves further brine concentration and partial evaporation, reducing brine volume by 50% and increasing salinity up to 80 g NaCl L^{-1}. Recovered water is free of salts and pathogens, making it suitable for reuse. Key operational parameters include brine temperature, flow rate, and air flow. Second, a mechanical vapour compression (MVC), a vacuum-based crystallization technology, that uses compressed vapour as the heat source to evaporate the brine. The system operates at 80 °C and concentrates the brine up to 320 g TDS L^{-1}. The recovered distillate is of high quality and the latent heat is reused through heat exchange, enhancing energy efficiency. Third, a wind-aided intensified evaporation (WAIV) is used, a passive, land-efficient alternative to evaporation ponds. It consists of vertical geotextile structures that enhance brine evaporation by wind exposure. WAIV increases the evaporation rate by 50%–90% compared to conventional ponds, while enabling salt recovery with low energy input due to its passive aeration mechanism. To enhance evaporation rates, the brine is heated above ambient temperature using a biomass boiler that relies on renewable energy sources such as wood pellets and forest residues, ensuring sustainable heat production

Critical environmental parameters, including air temperature, brine temperature, wind speed, and relative humidity, significantly affect the system's evaporative efficiency [27]. The ZLD system offers environmentally sustainable advantages by addressing key technological challenges, including the reduction of brine discharge, the recovery of valuable resources, the minimization of environmental pollution, and the integration of renewable energy and energy-efficient processes [31]. By integrating renewable energy sources, it mitigates the high energy costs typically associated with desalination processes. Moreover, it eliminates the discharge of high-salinity brine, preventing ecological damage to marine ecosystems. Consequently, the system can be deployed across a broader range of locations, safeguarding aquatic environments and preventing issues such as eutrophication [32].

2.2. Proposed methods

The proposed methods include a geospatial multi-criteria evaluation decision model to optimize the process for selecting optimal sites to implement desalination plants incorporate the ZLD strategy. Unlike previous studies, this model considers criteria directly related to thermal processes and evaporation efficiency, enabling the achievement of zero brine discharge. This approach allows ZLD-desalination plants to be installed in locations where discharges are not allowed due to environmental or socio-political reasons. The model is validated within a broad study area, as shown in Fig. 3, covering both coastal regions of Europe and groundwater areas within the Iberian Peninsula. The methods, outlined in Fig. 2, include four sequential stages: first, site selection and restriction criteria are identified, focused on European locations within 50 km of the coast and areas experiencing water stress. The second step involves the selection of the parameters of the criteria. A total of 7 parameters were selected based on the literature and the authors' criteria: land cover surface availability, distance to water resources (sea saltwater and groundwater), relative humidity, wind velocity, ground surface temperature, eutrophication, and thermal energy price. Third stage: MCDM methods were used to assign weights and prioritize the relative importance of each criterion, as well as to rank the different alternatives. Two complementary methods were used in this process. Firstly, the entropy weighting method was applied to objectively derive the weights of each criterion based on the degree of variability (i.e., information entropy) present in the data. According to this method, criteria with greater variability across the set of alternatives provide more information, and they are thus assigned higher weights. The procedure involves the following steps: given a

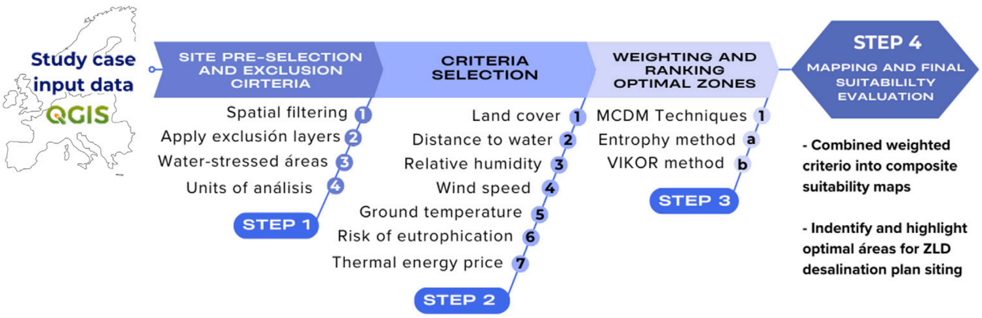


Fig. 2. Proposed methods.

decision matrix $X = [x_{ij}]$, with m alternatives and n criteria, the data are initially normalized as:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}. \tag{1}$$

The entropy of each criterion j is then calculated by using:

$$e_j = -k \sum_{i=1}^{m} p_{ij} \ln(p_{ij}), \quad \text{where } k = \frac{1}{\ln(m)}. \tag{2}$$

The degree of divergence, which represents the information contribution of each criterion, is computed as:

$$d_j = 1 - e_j. \tag{3}$$

Finally, the normalized weight w_j of each criterion is given by:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}. \tag{4}$$

This method allows for a data-driven, objective assignment of weights to each criterion without requiring subjective judgment [33]. Secondly, the VIKOR method [34] was used to rank the 3064 alternatives by integrating the weighted criteria. The VIKOR method is a compromise ranking method that identifies solutions closest to the ideal (best possible) and farthest from the anti-ideal (worst possible) performance. For each alternative i, the utility measure S_i and the regret measure R_i are computed as:

$$S_i = \sum_{j=1}^{n} w_j \cdot \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \tag{5}$$

$$R_i = \max_j \left[w_j \cdot \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right], \tag{6}$$

where f_j^* and f_j^- are the best and worst values of criterion j, respectively. The final compromise ranking index Q_i is determined as:

$$Q_i = v \cdot \frac{S_i - S^*}{S^- - S^*} + (1 - v) \cdot \frac{R_i - R^*}{R^- - R^*}, \tag{7}$$

where $v \in [0, 1]$ is the weight of the decision-making strategy (usually $v = 0.5$), and S^*, S^-, R^*, R^- are the minimum and maximum values of S_i and R_i across all alternatives. This method enables a structured comparison of alternatives in complex decision-making scenarios involving trade-offs among criteria. Finally, the results of this process are translated into suitability maps by using GIS tools, identifying the most appropriate locations for the ZLD desalination plant installation.

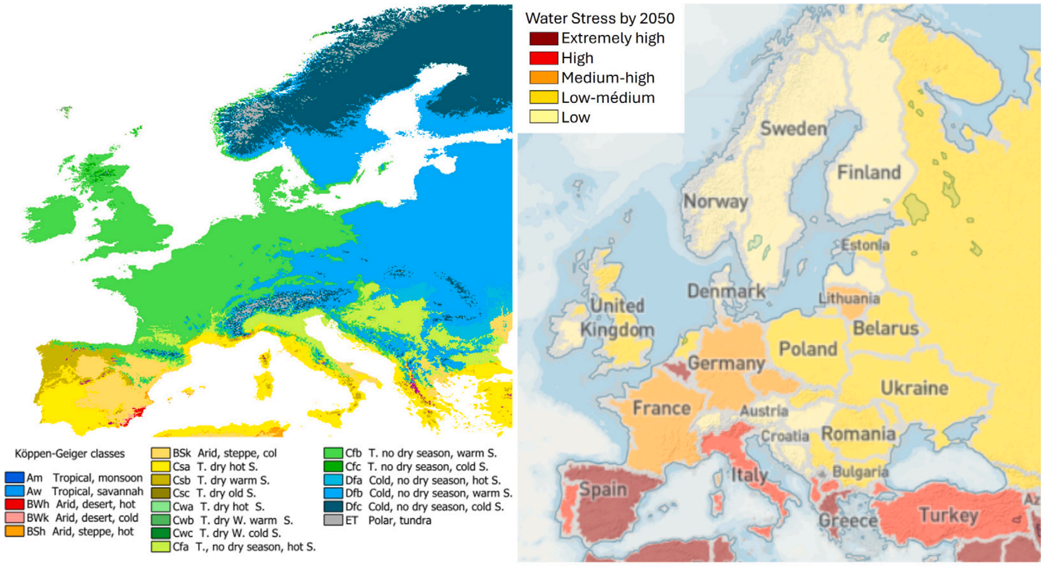
2.3. Case study. Description of the area

The study focuses on the European coastline and the groundwater aquifers of the Iberian Peninsula (Fig. 3a), which spans a range of climates from the temperate, rainfall-abundant Atlantic coast to the drier Mediterranean regions in the south. Northern and western Europe experience milder temperatures and higher rainfall, averaging 15 °C to 25 °C in summer and 5 °C to 10 °C in winter, and 1000 to 2000 mm per year. In contrast, southern Europe faces hot, dry summers (temperatures range from 20 °C to 30 °C) and mild, wet winters (5 °C to 15 °C), with annual precipitation as low as 300 to 600 mm, contributing to water scarcity [35]. Water stress is a growing issue, particularly in southern Europe, where increasing demand, climate change, and over-extraction of groundwater intensify the problem [4]. The World Resources Institute projects that by 2050, 33% of countries will face high or extremely high water stress, with Spain, Portugal, and Italy among the most affected (Fig. 3b). This highlights the critical need for the implementation of desalination plants, particularly with ZLD technology, to ensure long-term water security in these vulnerable regions.

The Iberian Peninsula, with its numerous aquifers, was selected as a focal point for studying groundwater usage due to its high water stress and reliance on groundwater for agriculture and human consumption. These aquifers, located across various hydrological basins, are influenced by the region's topography and climate [36]. Groundwater plays a critical role in supporting ecosystems and providing water in regions where surface water is limited. These aquifers have shown optimal suitability for integration with desalination plants due to their moderate depth, groundwater potential, and moderate salinity levels, making them key to managing water scarcity effectively. With climate models predicting increasing stress on these water resources, the integration of desalination plants and ZLD technology in these regions becomes crucial to ensure water quality by removing contaminants and salts, supporting economic development by facilitating agriculture and tourism and promoting long-term water security in the face of climate change.

2.4. Layers of restrictions. Selecting suitable areas

The analysis involves a preliminary assessment to identify areas unsuitable for ZLD-desalination plants due to topographic, social, environmental, and economic constraints. Regions located more than 50 km from the coast were excluded from further consideration, as distance from saltwater sources is a key limiting factor. In coastal areas within 50 km of the coast, both seawater and groundwater from littoral aquifers can be utilized as input sources, with groundwater being accessed through vertical wells or boreholes [38]. Expanding the study area to include regions up to 50 km from the coast enhances water independence, addressing accessibility challenges for inland communities. This also helps mitigate the effects of poor groundwater quality, which is often impacted by nutrient pollution from fertilizers and saline intrusion, despite the adequate quantity of these aquifers. Additionally, areas affected by topographic constraints, such as mountains, deserts, and cliffs, were removed. Urban and industrial zones, including roads, towns, cities, construction sites, and airports, were also excluded from the analysis, although was considered a 1 km buffer from the continuous and discontinuous urban fabric. Also, salines, water bodies, coastal lagoons, and estuaries areas were removed, and only a 1 km buffer from



(a)

(b)

Fig. 3. (a) Study area map: European bioclimatic regions. Source: World Map of the Köppen–Geiger climate classification [3] (b) Projected ratio of water stress level (human water demand to water availability) in 2050.
Source: World Resources Institute [37].

Table 1
Description of the thematic classes.

Thematic class	Objective and calculation
111 – Continuous urban fabric	Assess the potential space for desalination plants class to urban areas
112 – Discontinuous urban fabric	
422 – Salines	
512 – Water bodies	Only 1 km buffer from them is considered and the area is removed
521 – Coastal lagoons	
522 – Estuaries	
422 – Salines	
121 – Industrial and commercial units	The area is completely considered
131 – Mineral extraction sites	
212 – Permanent irrigated land	
213 – Rice fields	
221 – Vineyards	
222 – Fruit trees and berry crops	
241 – Annual associated with permanent crops	
242 – Complex cultivation patterns	

them was considered, see Table 1. Endangered ecosystems and natural forests were not included in this study due to their environmental sensitivity. All of these restriction layers were consolidated into a single exclusion layer, shown in Fig. 4, which also displays the study area's division into work units, with the polygons resulting from the criteria of individual watersheds within a country.

2.5. Evaluation criteria

In this section, the criteria for site selection of ZLD-desalination plants along the European coastline and the Iberian Peninsula are evaluated, incorporating environmental, economic, and technical factors essential for determining the most suitable locations. The criteria are grouped into four categories: (i) land suitability, which identifies available areas based on characteristics like land cover availability and distance to water resources; (ii) climatic factors, which assess the influence of parameters on evaporative efficiency such as relative humidity, wind velocity, and ground surface temperature; (iii) environmental impact, considering the risk of eutrophication in nearby aquatic ecosystems; and (iv) economic viability, estimating energy costs to ensure the economic sustainability of the facilities. These comprehensive criteria aim to guarantee operational efficiency, minimize environmental impact, and align with the sustainability goals of ZLD-desalination plants in the region.

2.5.1. Land cover and use

Land cover and use are essential environmental factors for selecting optimal sites. Land use refers to how people utilize land, including its activities and infrastructure, while land cover describes the physical material present on the surface, such as vegetation, water bodies, urban areas, or barren lands. This study uses data from the CORINE Land Cover 2018 dataset (vector/raster 100 m). The dataset has a minimum mapping unit of 25 hectares for areal phenomena and a minimum mapping width of 100 m for linear features. The dataset is available in both vector and raster formats, covering the reference year 2018. The CORINE Land Cover dataset categorizes Europe into 44 thematic classes based on their suitability for development. These classes can be grouped into several main categories. Urban and built-up areas, continuous and discontinuous urban fabric, industrial units, and transport infrastructure like airports and ports. Agricultural land, including non-irrigated and irrigated arable land, fruit plantations, olive groves, and vineyards. Natural land and forests include broad-leaved, coniferous, and mixed forests. Finally, water bodies. as wetlands, coastal lagoons, and estuaries. The most suitable locations for ZLD-desalination plants are areas classified as industrial and urban. These areas are often less restricted by environmental or urban development laws and offer easier access to essential infrastructure, minimizing ecological disruption. Additionally, agricultural areas, such as fruit tree plantations, may also provide suitable spaces for development due to their high water demand.

2.5.2. Surface availability

Surface availability must be calculated to determine the adequacy of each alternative land cover for hosting a ZLD desalination plant. In this context, surface availability is calculated as the ratio between the area of suitable land cover and the total surface area of each alternative. The surface land cover ratio has been estimated by identifying and summing up the spatial extent of land cover classes deemed suitable for ZLD plant development (e.g., industrial and urban areas, or agricultural zones with high water demand) and dividing this by the total area under consideration for each alternative. This ratio provides a quantitative metric that reflects the proportion of each alternative's surface area that meets the criteria for development. The calculation is conducted using GIS tools, leveraging vector or raster data from the CORINE Land Cover 2018 dataset.

2.5.3. Distance to the water source

Regarding the distance to the sea, the closer the plant is to the sea, less than 0.5 km from the coast, the less energy is required to pump water, minimizing pressure losses and operational costs. An average distance of 0.5 to 3 km is the most common, balancing accessibility to seawater and reducing environmental risks [39]. Distances beyond 3 km significantly increase costs and project complexity due to longer pipelines and higher pumping energy consumption, making the process less efficient [40]. While there is no specific legal requirement for distance, environmental regulations and impact assessments ensure the plant's location minimizes environmental impact and meets sustainability standards. Therefore, proximity to the sea is a key criterion in site selection to ensure both operational efficiency and economic feasibility.

Groundwater availability is also a key factor in the site selection of ZLD-desalination plants in the Iberian Peninsula. Desalination is particularly effective where brackish groundwater is available in sufficient quantities, ensuring continuous operation during dry seasons and supplementing limited surface water supplies. Low salinity aquifers are ideal, as higher salinity levels increase the complexity and cost of desalination. Strategically locating desalination plants near groundwater sources can enhance operational efficiency, reduce environmental stress, and provide resilience against climate-induced water scarcity. This also helps balance water extraction needs across agriculture, industry, and domestic use, making groundwater availability a vital consideration for sustainable desalination site selection. Additionally, areas with a high density of existing wells offer economic advantages by reducing the need for new well construction and lowering operational costs.

Distance to the water source for potential use in ZLD-desalination plants is systematically identified in a GIS environment, distinguishing between coastal and inland regions. For coastal zones, seawater was considered the primary resource, while groundwater from aquifers was the targeted resource for inland areas. A maximum distance of 3 km was set as a feasible limit for water extraction by desalination plants. Accordingly, a 3 km buffer zone was delineated from the coastline, encompassing areas within this boundary. For inland sources, spatial identification of water bodies was conducted, followed by the application of a similar 3 km buffer around aquifer locations. The layers representing desalination alternatives were then overlain with these buffered regions to pinpoint overlapping zones. To quantify accessible water coverage across each alternative, the ratio of overlapping area to the total area of each desalination option was calculated, providing the percentage of accessible water surface relative to the overall area of each alternative.

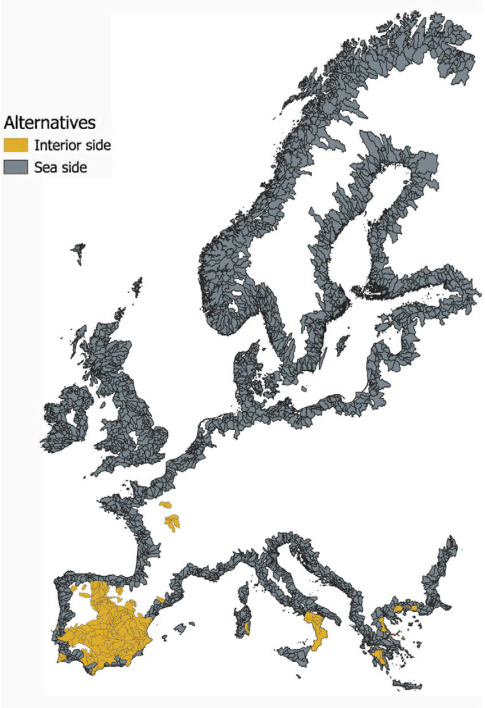


Fig. 4. Alternatives.

2.5.4. Relative humidity

The relative humidity (RH) is another important factor in brine removal systems, especially in processes involving evaporation and crystallization to concentrate or eliminate brine [29]. Low RH accelerates water evaporation, as dry air has a greater capacity to absorb moisture, making brine removal faster and more efficient. Conversely, high RH reduces the air's ability to absorb water vapour, slowing down the evaporation process. This is particularly relevant in thermal evaporation systems, where high humidity can decrease the efficiency of CT or heat exchangers, as humid air is less effective in extracting heat, thus increasing the energy cost of the process [27]. When considering location, brine removal systems that depend on natural evaporation, such as those in arid regions, perform best in climates with low RH. In coastal or tropical areas with high humidity, these systems may require more space or time to operate efficiently [14].

2.5.5. Wind speed

Wind speed is a critical parameter in assessing the feasibility of ZLD-desalination plants, particularly those employing wind-aided intensified evaporation (WAIV) systems [41] or CTs for brine evaporation. In ZLD systems, natural wind energy facilitates water evaporation and brine concentration, thereby decreasing overall energy demands. Elevated wind speeds optimize this mechanism by expediting the removal of water vapor molecules from the diffusion boundary layer, thereby establishing a pronounced vapor pressure gradient between the brine surface and the surrounding air, which significantly enhances the evaporation rate. Leveraging wind energy for brine evaporation enables ZLD-desalination plants to achieve lower operational costs and reduced environmental impact, positioning wind speed as a pivotal factor in site selection and system design.

2.5.6. Ground surface temperature

The ground surface temperature (GST) is closely linked to both the temperature of the brine and the salt or brackish water to be treated, making it a crucial factor in the decision-making process. The GST directly impacts the efficiency and performance of brine evaporation processes and desalination methods such as reverse osmosis (RO) and thermal distillation. In RO, the temperature of the brine affects both water viscosity and osmotic pressure. Higher temperatures reduce water viscosity, allowing it to flow more easily, which improves permeate flow and enhances the overall performance of the process. Conversely, at lower temperatures, increased water viscosity raises the osmotic pressure, resulting in higher energy consumption and a greater amount of brine produced. In thermal distillation or evaporation systems — such as the one described in this article, which employs a CT for brine concentration via evaporation — brine temperature is critical. At higher temperatures, evaporation occurs more readily, boosting brine removal in ZLD-systems. The importance of brine inlet temperature has been underscored in several experimental studies, such as Prado et al. [14]. Furthermore, the operating parameters of CT systems, as examined in Bueso et al. [27], showed that brine inlet temperature was the most significant variable influencing evaporation efficiency in CT.

2.5.7. Eutrophication

ZLD-desalination plants are particularly advantageous in areas vulnerable to eutrophication, where traditional desalination methods with brine discharge are not environmentally sustainable. These conventional systems can introduce high nutrient loads into coastal ecosystems, exacerbating eutrophication and triggering issues such as algal blooms and oxygen depletion. By eliminating brine discharge, ZLD-systems mitigate these environmental risks, making them the preferred option for regions where aquatic ecosystem protection is critical. In our analysis, the risk of eutrophication is a key environmental criterion, assessed using the HEAT+ classification method [42]. This method involves a stepwise approach, starting with grouping the indicators into nutrient levels, direct effects, and indirect effects, followed by calculating the corresponding eutrophication ratio (ER) for each indicator based on monitoring data and target values. The average ER is then determined for each group, and eutrophication status is classified as non-problem areas for values ≤ 1.0 or problem areas for values >1.0. By applying this classification, we ensure that our ZLD-desalination systems are aligned with environmental priorities and offer a sustainable solution for desalination in ecologically sensitive areas.

2.5.8. Thermal energy price

Thermal energy price is an important factor in ZLD desalination systems, particularly when using CT systems, where where brine evaporation efficiency is highly dependent on the inlet temperature of the brine, according with Prado et al. [14]. In CT-ZLD systems, thermal energy plays a central role in forced evaporation, which maximizes water evaporation and minimizes the volume of liquid waste until complete elimination is achieved. However, these processes are energy-intensive due to the need to balance heat transfer and brine concentration. The cost of thermal energy directly impacts the operational expenses and overall feasibility of such systems. High prices of thermal energy can limit the adoption of ZLD systems in the case of industries or agronomics exploitations that do not dispose of free or cheap thermal energy to use. Conversely, competitive energy costs encourage the wider implementation of ZLD technologies, making them more financially sustainable and accessible for various sectors. Moreover, energy efficiency in ZLD systems based on cooling towers is key to optimizing the process. This involves designing highly efficient heat exchangers, integrating renewable or low-cost energy sources, and recovering waste heat whenever possible. Ensuring affordable and stable thermal energy prices not only enhances the economic viability of ZLD systems but also reduces their environmental footprint, promoting more sustainable water management practices in water-scarce regions.

2.6. Multi-criteria evaluation decision modeling

To determine the optimal conditions for ZLD-desalination plants within the European context, MCDM methods are utilized. The process begins with the development of a matrix, as depicted in Fig. 2, which encapsulates the relationship among evaluation criteria and the alternatives under study—sub-watersheds in this case. Various alternatives have proven effective in classifying these alternatives [43]. The approach typically involves assigning weights to criteria to reflect their relative importance and ranking the alternatives accordingly [44]. One notable method for determining the weights of the criteria in the MCDM is the entropy method, rooted in information theory. This technique provides an objective framework for assigning significance to criteria by leveraging the inherent information within the data [45]. Its primary objective is to ensure an equitable and unbiased assignment of weights to criteria. A concise summary of this process is available in [46], which highlights the systematic integration of these methodologies for robust decision-making.

1. Normalization of data: The values of the criteria are standardized to ensure comparability, thereby eliminating discrepancies due to differences in scale or units.
2. Estimation of entropy: The entropy for each criterion is determined by using Shannon's entropy formula. Entropy serves as a quantitative measure of uncertainty or dispersion within the values of a given criterion. A higher entropy value indicates greater uncertainty or variability in the criterion's data distribution.
3. Relative information calculation: The relative significance of each criterion is determined by calculating its proportionate entropy. This is achieved by dividing the entropy of an individual criterion by the total entropy across all criteria. This ratio provides an objective measure of the relative importance of each criterion within the overall decision-making framework.
4. Weight assignment: The weights of the criteria are determined based on their determined relative information values. Criteria exhibiting lower entropy — indicative of reduced uncertainty — are assigned higher weights, reflecting their greater significance in the decision-making process.
5. Weight normalization: The weights are normalized to ensure their sum equals 1, thereby achieving a proper and proportional distribution of the criterion importance.

The VIKOR method, short for multi-criteria compromising optimization, is a decision-making technique designed to rank alternatives by evaluating their performance relative to both the ideal and anti-ideal solutions [47]. This approach balances the trade-offs between criteria to identify a compromise solution that is closest to the ideal while minimizing the distance from the least favorable alternative. The procedural steps can be summarized as follows [48]:

1. Normalization of data: The values of the criteria are normalized to remove scale disparities, enabling a standardized basis for direct comparison across all criteria.
2. Weight estimation: Weights are allocated to the criteria based on their relative significance in the decision-making process. These weights may be determined through expert judgment or calculated using analytical techniques, such as the entropy method.
3. Alternative score estimation: For each alternative, a score is computed by applying a weighted aggregation of the normalized criteria values, utilizing the corresponding assigned weights to reflect their relative importance.
4. Anti-ideal and ideal solution identification: The corresponding alternatives for each criterion are identified based on their normalized values. The ideal solution represents the alternative that achieves the highest benefit and lowest cost, while the anti-ideal solution corresponds to the alternative with the lowest benefit and highest cost.

5. Distance estimation to the anti-ideal and ideal solution: The proximity of each alternative to both the ideal and anti-ideal solutions is quantified using a distance metric, typically the Euclidean distance. This calculation evaluates how closely each alternative aligns with the ideal scenario and deviates from the anti-ideal scenario.
6. Disagreement and agreement index estimation: For each alternative, the agreement and disagreement indices are computed based on its relative distances to the ideal and anti-ideal solutions, respectively. The agreement index quantifies the proximity of an alternative to the ideal solution in comparison to other alternatives, while the disagreement index evaluates the distance of an alternative from the anti-ideal solution relative to other alternatives.
7. Ranking index estimation: For each alternative, a ranking index is derived by consolidating the agreement and disagreement indices into a unified metric. This index serves as a composite measure, integrating both the proximity to the ideal solution and the distance from the anti-ideal solution, thereby facilitating the ranking of alternatives.
8. Sorting of alternatives: Finally, the alternatives are ordered according to their ranking indices, with those exhibiting lower indices — indicative of superior performance — positioned at the top of the hierarchy.

3. Results

This section presents the spatial analysis developed to identify optimal locations for ZLD-desalination plants. The results are structured according to the spatial distribution of alternatives, the application of exclusion layers, and the evaluation of criteria weights and rankings.

3.1. Alternatives

Hydrological data and maps derived from Shuttle Elevation Derivatives at Multiple Scales (HydroSHEDS) [49] constitute a global hydrographic dataset that provides consistent and comprehensive hydrological information suitable for both regional and global-scale applications. This dataset includes a variety of geo-referenced data in both raster and vector formats, encompassing stream networks, watershed boundaries, drainage directions, and additional layers such as flow accumulation, distances, and river topology. HydroSHEDS structures watershed data into a hierarchical system across multiple levels, with each level representing a subdivision of watersheds into progressively smaller units, from Level 1 (the largest watersheds) to Level 8 (the smallest units). For the purposes of this study, Level 7 data are selected, giving high-resolution information and being ideal for detailed analyses at the scale of individual watersheds within a specific country. This level of resolution is comparable to, or even surpasses, many national-scale datasets, thereby making HydroSHEDS an indispensable resource for in-depth hydrological and environmental research.

3.2. Layers of restrictions. Selecting suitable areas

The selection of suitable areas is based on three criteria: (1) land cover, (2) water stress, and (3) sea proximity. The land cover layer serves as the main database for this analysis.

The European Commission launched the Coordination of Information on the Environment (CORINE) [50] program to create a standardized, harmonized dataset on European land cover and land use. This inventory includes 44 thematic classes, ranging from pastures to pit bogs. The analysis differentiates between urban and agricultural areas. From the different classes, Table 1 lists the suitable ones for desalination plants, while the rest are excluded from the study area. The water stress areas are identified using data from Copernicus. These areas are projected to face additional stress under a 3 °C temperature increase [51]. The data range from values <−0.01 to >0.11. Areas between 0.03 and 0.25 were selected as the most stressed areas. Sea proximity is considered by selecting alternatives located up to 50 km inland. In terms of the interior part, high-water stress areas determined the selection.

Fig. 4 shows the selected interior and seaside areas, as well as the dismissed regions. Of the 8854 possible alternatives, 3309 were selected: 286 from the interior and 3023 near the coast. Most interior options are in the Iberian Peninsula and, particularly Spain, where water stress regions cover almost 300,000 km^2, accounting for 59% of the total surface. The seaside options cover 3023 areas, with a total surface of almost 2 million km^2, representing 10% of the European Union member states total area. These regions are evaluated using the MCDM method, based on criteria such as land suitability, climatic factors, environmental impact, and economic viability.

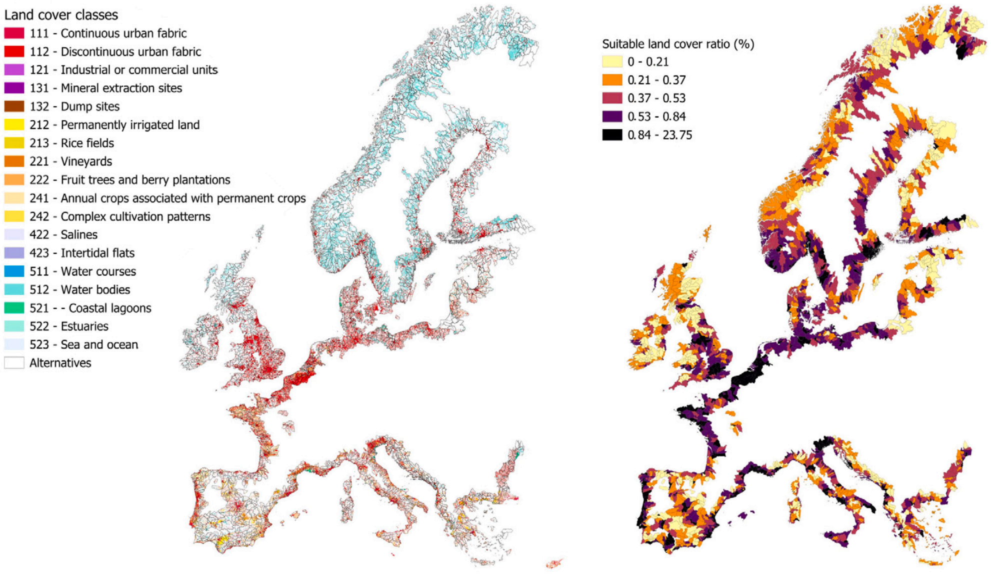
3.3. Criteria

To identify optimal locations for ZLD-desalination plants, a set of seven criteria were evaluated, grouped into four thematic categories: land suitability, climatic conditions, environmental impact, and economic viability. These factors were chosen based on their relevance to the technical, environmental, and operational performance of the proposed system.

3.3.1. Land suitability

The various land cover classes for the selected areas are illustrated in Fig. 5(a). The most prevalent class is 512 (water bodies), which accounts for nearly 22% of the total alternatives, followed by 242 (complex cultivation pattern) at 16%, and 112 (discontinuous urban fabric) in third place. In contrast, the least frequent classes are 132, 422, and 131 (dump sites, salines, and mineral extraction sites, respectively). Regarding spatial distribution, water bodies are predominantly found in northern countries, such as Norway, Sweden, and northern Britain. Central European countries are characterized by a high presence of discontinuous urban fabric, while southern countries exhibit a mixture of discontinuous urban fabric and permanently irrigated land. The suitability of the selected land cover areas is evaluated based on the ratio between the area of suitable land cover and the total area of the alternatives. Alternatives with the highest percentage of suitable land cover are considered the most optimal. The spatial assessment indicates that the percentage of land cover ranges from 0 to 24% of the total area of the alternatives, with an average of 1.65% and a standard deviation of 8.3. The areas with the highest values correspond to the most densely populated regions within the study area, specifically along the Mediterranean and Atlantic coasts, as well as in Belgium, the Netherlands, and the Greater London area—see Fig. 5(b), dark color highlighted areas.

Distance to the water source for potential use in ZLD-desalination results are depicted in Fig. 6. They show that the inland areas those that has by far a higher surface with available water compared to the coastal areas. Areas with high accessibility are primarily concentrated in southern Europe, especially in Spain and parts of the Mediterranean. Small islands also account for higher coverage surface as they usually have both water resources everywhere. Apart from this, Coastal areas around the study case have a similar percentage. But they are affected by their shape and how they are located, for instance, those with long shapes along the coast are considered more optimal as the majority of the surface possesses accessible water. Of the total alternatives, half of them do not have accessibility to water (light gray color alternatives in the map from Fig. 6). This approach allowed for the exclusion of 65% of the study area that did not meet the proximity criteria, while the remaining 35% was classified as optimal. Proximity to the coastline is critical for accessing saltwater, which is necessary for desalination processes, making this analysis essential for selecting viable seaside alternatives. While proximity to groundwater was a key factor, this



(a) (b)

Fig. 5. Land-related results: (a) Land cover and (b) Suitable land cover ratio of the selected areas.

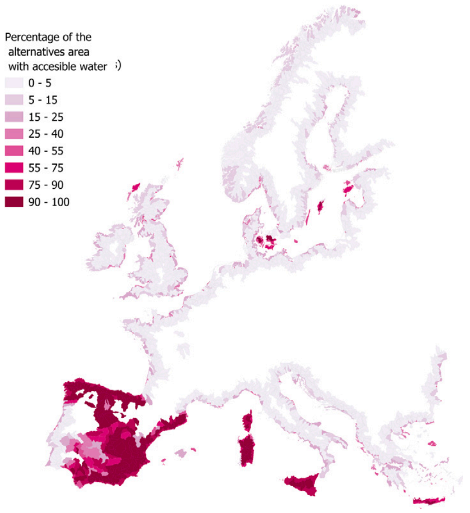


Fig. 6. Percentage of the surface of the alternatives with accessible water resource.

analysis did not take into account crucial hydro-geological characteristics, such as aquifer depth, which could affect water accessibility. Despite this limitation, reliance on groundwater was considered more important than proximity to surface water sources, such as lakes or reservoirs. Future research should address these additional factors to provide a more accurate assessment of groundwater-based desalination plant alternatives.

3.3.2. Climatic factors

The RH data were sourced from the dataset titled ‘Decadal time series of spatially enhanced relative humidity for Europe’ [52]. This dataset provides daily time series of RH, derived from the ERA5-Land reanalysis. The RH is calculated using air temperature (measured 2 m above the ground) and dew point temperature, employing Wright’s formula for saturated vapor pressure. The data are presented as daily averages, with values scaled by a factor of 10 to represent percentages. For example, a value of 750 corresponds to 75% RH. The dataset covers Europe with a daily temporal resolution, and each file is labeled by year, month, and day. For this assessment, annual average data, which can be easily extracted from the dataset, was utilized. The observed RH values (Fig. 7a) range from approximately 524 to 910, reflecting regional climatic patterns across Europe. As expected, areas with lower precipitation exhibit lower humidity values, while regions with higher rainfall show elevated humidity. Notably, northern Spain, as well as Mediterranean regions such as Sardinia and Sicily, demonstrate relatively high humidity levels.

The wind speed data was obtained from the open-access catalog of the Joint Research Centre (JRC) of the European Commission, specifically from the monthly wind speed (MAPPE – Multimedia Assessment of Pollutant Pathways in the Environment) dataset [53]. This dataset comprises 12 raster maps representing monthly mean wind speed at a height of 10 m above the surface. These data were overlayed within a GIS environment to integrate into the analysis. The data presented in Fig. 7b illustrates average annual wind speed values ranging from 0 to 8 m/s. A clear spatial pattern emerges, with higher wind velocities (from 5 to 8 m/s) observed in the northern regions, particularly influenced by Atlantic winds, and lower wind speeds (from 0 to 3 m/s) concentrated in the Mediterranean region, mostly in the Adriatic part.

The ground surface temperature (GST) data were sourced from [54], where GST was derived using air surface temperature data from WorldClim Version 2, see Fig. 7c. GST is altitude-dependent. At elevations up to 1500 m above sea level, it was assumed to match the air surface temperature. For altitudes higher than 1500 m, a correction factor ranging from 1 to 2 K was applied. The analysis integrates spatial data with a resolution of 2.5 arc minutes (approximately 3.6 km^2) and digital elevation models (DEM) to account for altitude effects. Within a GIS framework, the average GST is computed for each alternative, enabling precise estimation of GST at varying locations by incorporating both temperature and elevation factors across the study area.

3.3.3. Environmental impact

This study assessed the eutrophication status using the HEAT+ tool, which classifies European seas based on a range of indicators related to nutrient concentrations and their ecological impacts. The analysis utilized datasets including Eutrophication in Europe’s Seas [55], which provides eutrophication classifications for various coastal regions, and the eutrophication status of groundwater aquifers derived from DATISTA [56]. It is based on documentation from Spain’s third-cycle water management plans (2022–2027) developed by the corresponding Watershed Authorities.

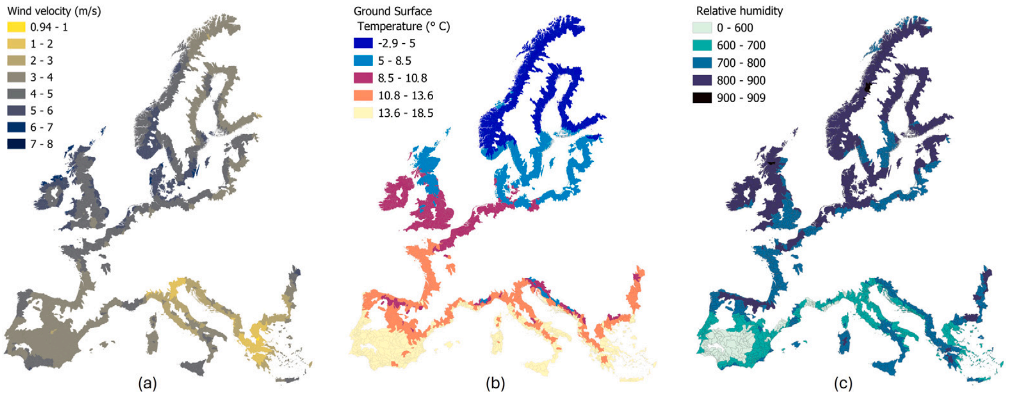


Fig. 7. Criteria related with the climatic factors: (a) Relative humidity. The values are scaled to represent percentages (multiplied by 10). (b) Annual average wind velocity at 10 m height. (c) Average annual ground surface temperature.

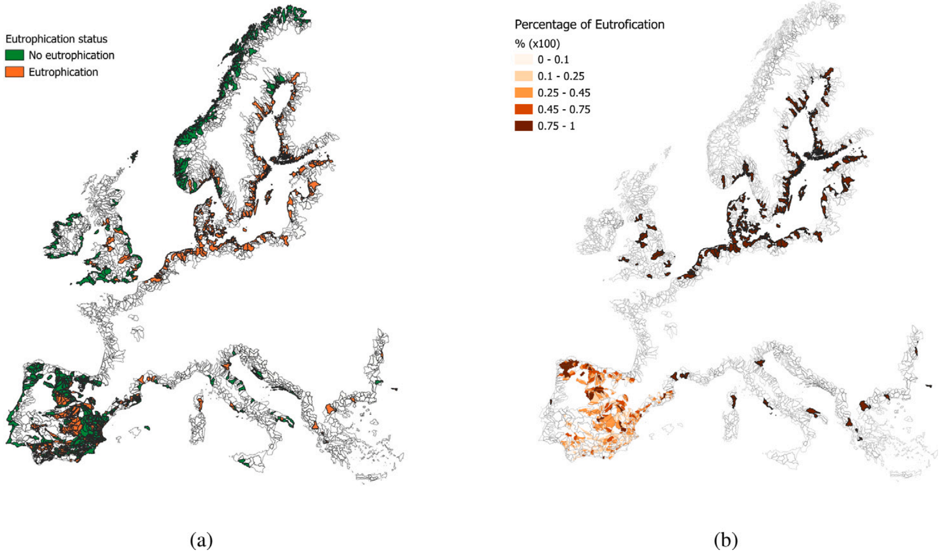


Fig. 8. Europhicated results: (a) Spatial distribution of eutrophicated and non-eutrophicated areas (b) Percentage of the areas affected by eutrophication with respect to their total surface.

In the first dataset, eutrophication status is classified into two primary groups: “Non-problem areas” and “Problem areas”. The “Non-problem areas” group is further subdivided into “High” and “Good” categories, while the “Problem areas” group includes the classifications “Moderate”, “Poor”, and “Bad”. These qualitative indicators were reclassified into three new categories for this analysis: “No data” for areas with no available data; “Eutrophicated areas” for areas classified as “Moderate”, “Poor”, or “Bad”; and “No eutrophicated areas” for areas classified as “High” or “Good”, as well as areas with no data. The second dataset, which pertains to the status of water bodies, categorizes them into two groups based on nutrient presence: “Good state” and “Bad state”. These classifications were directly translated into “No eutrophicated areas” and “Eutrophicated areas”, respectively. Spain has been the only country where underground water conditions were considered as approximately 20.1% of groundwater is in poor condition, placing it among the countries with the highest contamination rates in Europe. The results are presented in Fig. 8(a).

To evaluate the impact of eutrophication on each alternative, the proportion of eutrophicated areas relative to the total surface area of each alternative was calculated, see Fig. 8(b). The analysis concluded that 75% of the assessed areas were classified as non-problematic, and 25% categorized as eutrophic. Coastal eutrophic zones with the highest risk levels are predominantly concentrated in northern regions, including The Netherlands, Denmark, and areas of the Baltic Sea. Inland groundwater areas affected by eutrophication are located exclusively in Spain, where nutrient inputs from anthropogenic activities, such as agriculture and urban runoff, are most pronounced.

3.3.4. Economic viability

Non-household consumer gas price data is subsequently analyzed; representing the most relevant option in the case study in the different territories to determine the thermal energy cost required by the ZLD desalination plant. Data were sourced from Eurostat [57] for European Union member states and Statista [58] for non-EU countries. Fig. 9 shows the collected data. Note that territories within the same country share identical gas prices. In particular, Norway has exceptionally low prices, close to 0 €/kWh, due to its status as a gas and oil producing nation; in stark contrast to Montenegro, where prices reach 0.77 €/kWh.

The use of renewable thermal energy would be ideal for this type of installations and thus the use of thermal energy from biomass. However, for this, it would be necessary to study the availability of biomass in the vicinity of the installation’s location, which would require a customized study for each potential installation.

3.4. Alternatives ranking: multi-criteria decision making application

The weights obtained for each criterion using the entropy method (see Section 2) are presented in descending order of importance. In this

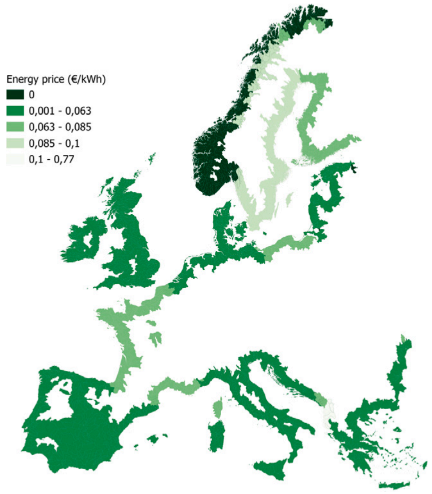


Fig. 9. Non-household gas price.

method, criteria with greater variability across the set of alternatives are assigned higher weights, as they are considered to provide more information for the decision-making process. Among the seven criteria considered, the most influential was the distance to eutrophicated areas (19.07%), followed closely by energy price (19.05%). These were followed by the ratio of suitable area to total area (13.45%), percentage of water accessibility (13.12%), and ground surface temperature (11.83%). Wind speed (11.76%) and humidity (11.72%) showed slightly lower but comparable influence. These weights were subsequently integrated into the VIKOR method to rank the 3064 alternatives according to their overall performance.

The alternatives were ranked using the VIKOR method, evaluating and categorizing each based on its suitability for the implementation of ZLD-desalination plants. Rankings range from highly optimal (dark green) to less optimal (red), as depicted in Fig. 10. This ranking serves as a critical tool for identifying potential deployment zones for ZLD-desalination facilities. The results indicate that zones ranked between 1 and 100 are predominantly located in southern Europe, specifically in southern Spain, parts of Portugal, and sections of the Mediterranean coast. These areas are highlighted in green on the map, reflecting their high suitability for the installation of ZLD-desalination plant. This favorable ranking is attributed to factors such as elevated eutrophication levels, low energy costs, abundant land availability, and proximity to water sources. Conversely, zones with the lowest rankings (2900 to 3058) are primarily situated in Northern Europe, particularly in Scandinavia (Norway and Sweden), parts of northern Italy, and regions of Eastern Europe. These areas appear in red on the map, indicating low suitability for ZLD-desalination projects. The Baltic Sea region, despite colder temperatures, benefits from advantageous factors such as land availability, significant eutrophication in specific areas, and favorable renewable energy conditions, enhancing its potential for ZLD applications. In contrast, southern Italy and the Adriatic region face constraints such as limited space, higher energy costs, and challenges with eutrophication, which diminish their suitability despite a Mediterranean climate. These geographically specific findings emphasize the need for a tailored and region-sensitive approach in the planning and development of ZLD desalination projects across Europe.

4. Discussion

Regarding the proposed methods, the site selection process for ZLD desalination plants integrates technical, environmental, and economic factors to effectively address the challenges of water scarcity. By incorporating ZLD, the technology ensures the complete elimination of brine discharge, being an improvement over conventional systems that often exacerbate aquatic ecosystem pollution and eutrophication. ZLD systems also allow the recovery of valuable resources from the brine, such as salts and minerals, turning waste into economic opportunities. Water stress in Europe's coastal regions and the inland areas of the Iberian Peninsula was described and evaluated as a case study. It is aligned with the principles of the circular economy and supports the sustainability goals of the European Union as the Zero Pollution Action Plan [59]. This study identified 3309 suitable areas, of which 3023 are near the coast and 286 inland, covering a total surface area of approximately 10% of the EU member states' area. These regions offer high land suitability and proximity to water resources, making them ideal candidates for sustainable ZLD-desalination facilities. The inclusion of inland sites demonstrates the adaptability of ZLD, which can utilize groundwater resources sustainably, unlike conventional systems that primarily depend on seawater.

The replicability of this analysis is based on two main pillars: the use of public data sources and the detailed description of the presented methods. Furthermore, a detailed model [27] is developed and validated based on the experimental results obtained from a real ZLD system. This ZLD model can simulate the ZLD system's response based on the meteorological data at different locations [60]. This fact ensures that other researchers can independently reproduce the results by using the presented type of data and methods. However, the reproducibility of the ZLD system in different contexts can be more complex. The methods and models used, while generalizable, are influenced by location-specific factors and certain variables as described in Section 3. Therefore, a location-specific contextualization is previously necessary to carry out the adaption and/or calibration of the proposed ZLD system. The authors encouraged future research to apply the proposed methods to other geographic contexts, and validate the consistency and robustness of the results. Nevertheless, the results of this study are replicable provided the same types of data and procedures are followed, and reproducible considering the adjustments to be incorporated for the specific variables of each particular region.

The decision matrix highlights the percentage of eutrophication (19.07%) and the price of energy (19.05%) as the most influential factors for the selection of the site, beyond the proximity to water resources. Areas with eutrophication levels between 0.03 and 0.25 were prioritized, underscoring the suitability of regions like southern Europe, particularly Spain and parts of the Mediterranean coast. These areas experience high eutrophication levels and relatively low energy costs, enhancing the feasibility of ZLD-desalination plant implementation. The adoption of ZLD technology addresses these challenges by eliminating brine discharge, which can exacerbate nutrient overloading and algal blooms, common issues in agricultural zones. This aligns with the Farm to Fork Strategy [61], which seeks to reduce nitrogen pollution caused by agricultural activities. The zero-discharge approach of ZLD mitigates the release of nitrogen-rich brines into water bodies, thereby preventing further eutrophication and supporting the EU's goals of sustainable food production and environmental preservation. Energy costs are equally significant in shaping the economic viability of desalination plants. Southern Europe offers substantial potential for integrating renewable energy sources, such as solar and wind, into ZLD systems. This integration not only reduces operational costs but also supports a transition to sustainable energy use in desalination operations, ensuring both environmental and economic sustainability in water-scarce regions. While proximity to the sea remains a vital criterion for accessing saltwater, this study also highlighted the strategic importance of inland groundwater sources. Groundwater availability in Spain offers a sustainable alternative for ZLD-desalination systems, addressing seasonal water shortages and reducing dependency on overexploited surface water. The dual inclusion of coastal and inland locations reflects the flexibility of the ZLD-desalination approach. Climatic factors such as RH, wind velocity, and GST were also evaluated for their influence on

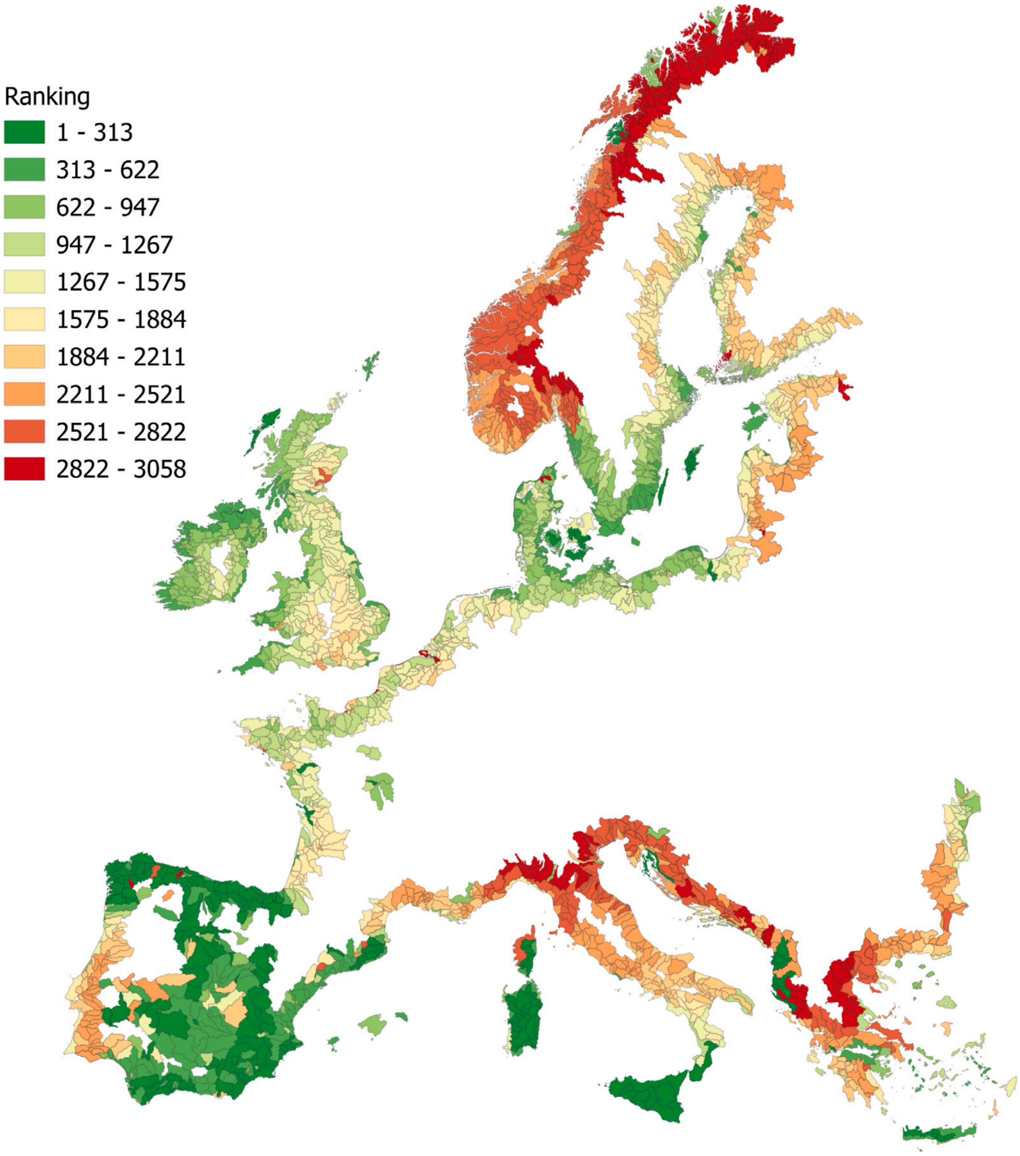


Fig. 10. Alternative ranking results: multi-criteria decision making application.

evaporation efficiency. The results show that optimizing these parameters enhances system performance, particularly in southern European regions with higher wind speeds and high temperatures. Lower temperatures and higher energy costs make these regions less viable for ZLD systems compared to southern Europe. This underscores the need for tailored, region-specific approaches that align with the European Green Deal's emphasis on renewable energy and sustainability [62]. In sensitive coastal zones, ZLD technology is essential for mitigating eutrophication risks and controlling nutrient pollution, as emphasized by the Nitrates Directive (91/676/EEC) [63]. Through its adaptability and environmental benefits, ZLD represents an environmentally responsible and economically viable solution for addressing water scarcity in a changing climate. Despite its strengths, the study faces limitations. Data gaps, such as the lack of high-resolution water quality rasters, groundwater depth distance, and comprehensive biodiversity assessments, may impact the precision of site suitability analysis. Future research could address these gaps by incorporating additional exclusion criteria.

5. Conclusions

By addressing the limitations of traditional desalination technologies, this paper emphasizes the environmental and economic benefits of ZLD systems for optimal location of desalination processes. The approach ensures sustainable water management while minimizing the ecological footprint of desalination, making it a viable solution for addressing water scarcity in a changing climate. The use of GIS-based modeling and MCDM ensures a comprehensive analysis of seven criteria, integrating land availability, climatic factors, environmental risks, and energy costs into the decision-making process. Europe's coastal regions and the inland areas of the Iberian Peninsula were selected and evaluated as a case study. The results revealed 3309 optimal sites, covering 10% of the EU's surface area, with 59% of Spain experiencing water stress. These regions benefit from favorable climatic conditions, including high temperatures and wind speeds, which improve evaporation efficiency and reduce operational costs. The flexibility of ZLD-systems to operate in both coastal and inland areas, supported by sustainable groundwater resources, extends their applicability to diverse regions facing seasonal water shortages. Integrated ZLD-desalination into regional water strategies aligns with EU policies and SDGs, offering a sustainable solution to water stress in areas identified as suitable in our analysis.

CRediT authorship contribution statement

Adela Ramos-Escudero: Writing – original draft, Validation, Methodology, Formal analysis. **Francisco Vera-García:** Writing – review & editing, Validation, Supervision, Formal analysis. **Angel Molina-García:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Amanda Prado de Nicolás:** Writing – original draft, Software, Formal analysis, Data curation.

Declaration of competing interest

The authors 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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Data availability

Data will be made available on request.

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