MCE-GIS evaluation for the potential location of RO membranes recycling plant in the Segura River Basin, Spain

Abstract

The large amount of end-of-life (EoL) reverse osmosis (RO) membrane modules needed in desalination processes represents an important opportunity of material valorization. Alternative waste management routes are being developed worldwide in order to give them a second life within the Circular Economy (CE) principles.

The aim of this study is the potential location identification for an EoL-RO direct recycling plant in the Segura River Basin, one of the most important desalination areas of Spain (with more than the 42% of the Spanish desalination capacity). Using Geographical Information System (GIS) technologies, a Multi-criteria evaluation (MCE) methodology has been used for the suitability assessment for the membranes recycling plant best location. The evaluated criteria have been divided into restricted (natural protected areas, rivers, roads, reservoirs, supply channels and flood-prone areas) and conditioning (land use, topography and distance to shoreline). The spatial analysis shows that the 0.8% and 4.7% of the river basin area is optimally and highly suitable, respectively, for the recycling plant location. On the contrary, the totally restricted areas are more than the 23% of the basin. This work will be the base for further environmental and economic studies of the reverse logistics: EoL-RO modules collection and the distribution of recycled products.

Keywords:

Reverse Osmosis; Multi-criteria evaluation; Location suitability; Analytic Hierarchy Process; GIS; Reverse Logistics

1. Introduction

Desalination and Reverse Osmosis tendencies

The increment of freshwater demand and water scarcity determine the high growth of desalination and wastewater reuse. RO is the most common and extended technology for desalination due to the low cost and operability (Virgili et al., 2016). Nevertheless, RO presents some environmental issues such as energy consumption, membrane replacement or brine emissions (Zhou et al., 2011). One of the main challenges to approach membrane technology to CE is the linear life-cycle strategy of membrane modules. Furthermore, they have a high replacement tax (15-25%) due to the short module lifespan (5-10 years). Fouling is the main reason that provokes the collapse of the membrane. Landaburu-Aguirre et al. (2016) estimated that more than 840,000 EoL RO modules were generated worldwide in 2015 (more than 14,000 tonnes of waste polymers and plastic). The main waste route is the landfill disposal and, minority, the incineration (Lawler et al., 2015).

Most remarkable researched strategies to change the life-cycle of RO modules are: i) increasing of lifespan lengthen (by improving design such as antifouling membranes and optimizing cleanings), and ii) direct reuse and recycling. Direct recycling into nanofiltration (NF) and ultrafiltration (UF) membranes have been proved and validated at pilot scale with potential environmental and economic benefits (García-Pacheco et al., 2018, 2015; Lawler et al., 2012; Senán-Salinas, 2019).

Spain is the fourth country in terms of its production capacity for desalinated water (Pulido-Bosch et al., 2019). Considering that the installed membranes have a limited lifespan, the Spanish contribution of end-of-life RO membranes to the environment is relevant. Landaburu-Aguirre et al. (2016) estimated more than 81,400 EoL RO modules (equivalent to more than 1,000 tonnes polymers and plastics) are annually dispose. CE transition and the implementation at industrial scale require the evaluation of transport environmental impact in the innovative recycling system implementation. Furthermore, alternative location studies could be conducted in order to evaluate and to select the most environmental friendly and cost effective location. This approach fits with the Triple Bottom Line term (People, Planet, Profit), which describes economic, environmental and social value of an investment (Elkington, 2004). Nonetheless, previous to the alternative selection GIS-based methodologies are required to identify plant location according to a good territorial management practice, having the Multi-Criteria Evaluation (MCE) method a series of characteristics that make it suitable for a spatial exploratory analysis for the recycling plant best location assessment.

MCE methods

The potential location assessment for the EoL-RO recycling plant (EoL-RORP) is a complex process. A proper planning of urban activities taking into account environmental criteria is necessary for an urban model that guarantees their inhabitants welfare (Criado et al., 2017). For a correct decision-making of any planning activity, both objective and subjective factors must be taken into account (Malczewski, 2004).

The optimal location analysis is defined as the combination of support decision-making methodologies MCE and GIS. This is the technique used in this study: a preliminary GIS-based MCE for the RO membranes recycling plant in the Segura River Basin. These methodologies are usually also known as multi-criteria analysis (MCA) or multi-criteria decision-making (MCDM) (Alami-Merrouni et al., 2018; Krois and Schulte, 2014; Malczewski, 2004). The integration of MCDM techniques with GIS has improved the traditional map overlay approaches to the land-use suitability analysis (Malczewski, 1999). One of the most important MCE methodologies is the Analytical Hierarchy Process (AHP), developed by Saaty (1980). The AHP method defines the study parameters' weights and criteria ranks for the location preference (Abdalla and Khidir, 2017). This methodology is accepted worldwide in several research works. It has been used in planning, best alternative position, natural resources management, etc. (Vaidya and Kumar, 2006).

2. Study Area - Segura River Basin (SRB)

The Segura River Basin is located in the southeastern territory of Spain (Fig. 1) with a surface area of 19,025 km^2 and it is included in four autonomous communities: Region of Murcia, Andalusia (provinces of Jaén, Granada and Almería), Castilla La Mancha (province of

Albacete) and Valencian Community (province of Alicante) (CHS, 2016). The SRB is the Spanish basin with the biggest problems with removable water resources (García-Galiano et al., 2015). The study area combines strong mountainous elevations and large plains, being a peculiar natural scenery in Spain (López, 1973). The hydrographic network consists of both permanent and intermittent rivers and streams of not very high flows (about 65 hm^3 total). Most of the rivers water resources are consumed in the basin, with returns almost insignificant (Pellicer-Martínez and Martínez-Paz, 2018; Pérez-Sánchez and Senent-Aparicio, 2018).

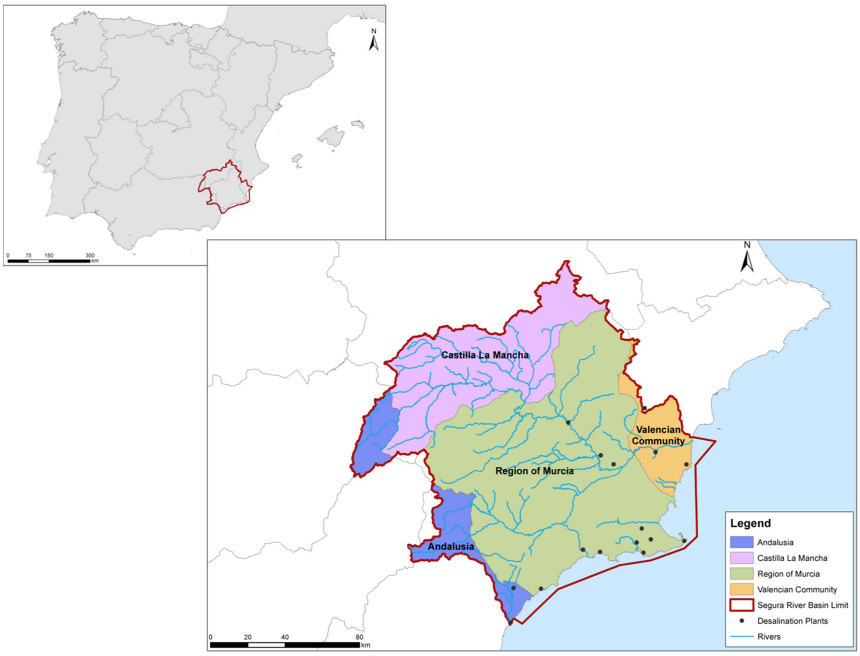


Figure 1. Segura River Basin and the most relevant desalination plants location (in terms of installed capacity).

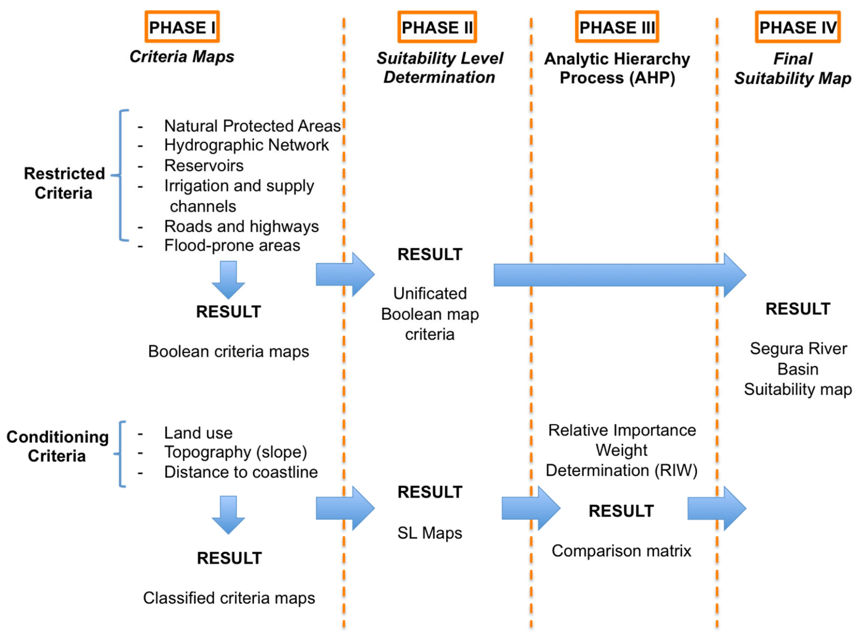
The climate is semi-arid, since temperatures are high (10-18 ºC), while average yearly rainfall is usually low (400 mm). Therefore, evapotranspiration has very high values reaching 700 mm/year (Pellicer-Martínez and Martínez-Paz, 2018). The precipitation has a very strong seasonality, being important in winter and almost non-existent in summer. The region has suffered serious problems of drought and water availability in recent decades, as surface runoff has decreased significantly (García-Galiano et al., 2015; Urrea-Mallebrera et al., 2011).

Around the 40% of the desalination installed capacity of Spain is located in the SRB (193 hm^3/year). More than the 80% of this desalinated water is consumed by agriculture, while the rest is used by urban activities (CEDEX, 2017).

Due to the large number of membranes discarded in the SRB, it has been decided to study which areas would be most suitable for a potential location of the EoL-RORP. Environmental, planning and management criteria have been considered to assess the most suitable areas for the recycling plant.

3. Methodology

The potential sites identification for the EoL-RORP was done using the MCE approach. Decisions will be necessarily based on one or more criteria – measurable attributes of the alternatives being considered, that it can be combined and evaluated in the form of a decision rule (Eastman, 1999). This approach was carried out to evaluate the Segura River Basin territory. The methodology is schematized in Figure 2.



Eliminado: . Also in reutilization is the first watershed supplying more of a 5% with this non-conventional water resource (84.7 hm^3/year). Agriculture is the major demanding sector (more than 80%) and the rest is associated to urban use

Figure 2. Multi-criteria methodology for the identification of potential sites for the EoL-RORP location.

The used method consists in four phases. The first one is the criteria maps phase, which are made by transforming the different information into spatial layers (Krois and Schulte, 2014). Each of the coverage, either vector o raster, represents a specific criterion. The selected criteria are divided into two types: on the one hand those that only allow or prevent (unique values: yes or not) the construction of the infrastructure (the EoL-RORP): restrictive criteria (Criado et al., 2017). On the other hand the conditioning criteria are those which have different values (a range of values) depending on their Suitability Level – SL. The second phase consisted on the reclassification of the criteria map in order of their suitability level using the ArcGIS reclassification tools. The next phase was based on the AHP methodology (Saaty, 1990), which has allowed to verify if the established suitability levels are correct for this study (Parry et al., 2018), calculated using a pair-wise comparison matrix. Lastly, a final map was developed according to the relative importance of each criteria over the others (Krois and Schulte, 2014). It represents the most proper places for the EoL-RORP location in the SRB.

3.1 Criteria selection and data recollection and processing

The selection of the most suitable location for the EoL-RORP was based on economic, social and environmental criteria. The criteria were divided in two categories: restrictive and conditioning criteria.

i) Restrictive criteria:

The restrictive criteria spatial information was downloaded from the Segura hydrographic confederation website (www.chsegura.es). These vector layers have been rasterized using GIS tools to be able to operate with them. In most of the criteria, an influence area of a certain length has also been added (Table 1). Only the territory that is outside the criteria areas and theirs buffers will be valid for the location of the recycling plant.

Table 1. Restrictive criteria buffer length

Eliminado: a criteria selection was made in order to transform the information data into a spatial coverage

Eliminado: These criteria were divided in restrictive (elements that impede the construction of EoL-RORP) ...

Eliminado: and conditioning criteria (those whose values are not unique because they are represented by a range of values that are expressed through their Suitability Level - SL). T...

Eliminado: step

Eliminado: development of criteria maps

Eliminado: These maps have been reclassified in accordance with the SL for each criterion. It was necessary to assign to each land unit its corresponding SL (Qu et al., 2013)....

Eliminado: the use

Eliminado: AHP

Eliminado: for the suitability assessment of the set of criteria

Código de campo cambiado

Eliminado: (Parry et al., 2018)

Eliminado: by applying

Eliminado: the

Eliminado: method

Criterion	Buffer length
Protected Natural Areas	300 m
Hydrographic network	50 m
Reservoirs	50 m
Irrigation and supply channels	50 m
Roads and highways	50 m
Flood-prone areas	-

Flood-prone is a very important economic criterion considering that water overflows have caused serious problems and monetary losses in Europe (Barredo, 2007). In the Mediterranean countries, floods have been more intensely and frequently over the last years (Jonkman, 2005; López-Martínez et al., 2017). In this study the layer with the highest probability of flooding available, which corresponds to 50 years, has been used.

In order to recognize in which areas of the basin the construction of the EoL-RORP is possible, all the restrictive criteria have been joined in a map (Criado et al., 2017). For a correct decision-making process the spatial information were joined in a GIS software (ArcGIS 10.5) for their combination with the MCE techniques (Alami-Merrouni et al., 2018; Ozturk and Batuk, 2011). The inclusion of spatial information in the MCE methodology, using GIS, has been carried out in two different ways, depending on their characteristics. On the one hand restrictive criteria have been transformed into two unique values: true / false (Boolean data type) (Eastman, 1999). With this procedure it is possible to define those areas where the intervention can be performed and where not (Criado et al., 2017). On the other hand, conditioning criteria were transformed into spatially continuous variables with different suitability values on an ordinal scale (Buzai and Principi, 2017; Eastman, 1999; Malczewski, 2004). This will be detailed in the next section.

ii) Conditioning criteria:

- **Land use:** the CORINE Land Cover (CLC) layer (from the year 2012) was downloaded from the National Center for Geographic Information of Spain (CNIG). This layer has been rasterized for its subsequent reclassification according to the suitability of each land use category for the installation of the recycling plant.

- **Topography (slope):** Digital Elevation Model (DEM) was used for get the slope map through the Spatial Analyst tools in ArcGIS (Harley and Samanta, 2018). This DEM was downloaded from the CNIG.
- **Distance to shoreline**: a shoreline vector layer was downloaded from the CNIG. The objective was to zone the SRB based on the distance to the coastline, because near the coast are the largest number of desalination plants and the most important in terms of installed capacity (Masjuan et al., 2008) (Figure 1). For this purpose, several buffer have been created from the coastline using the ArcGIS Geoprocessing tools.

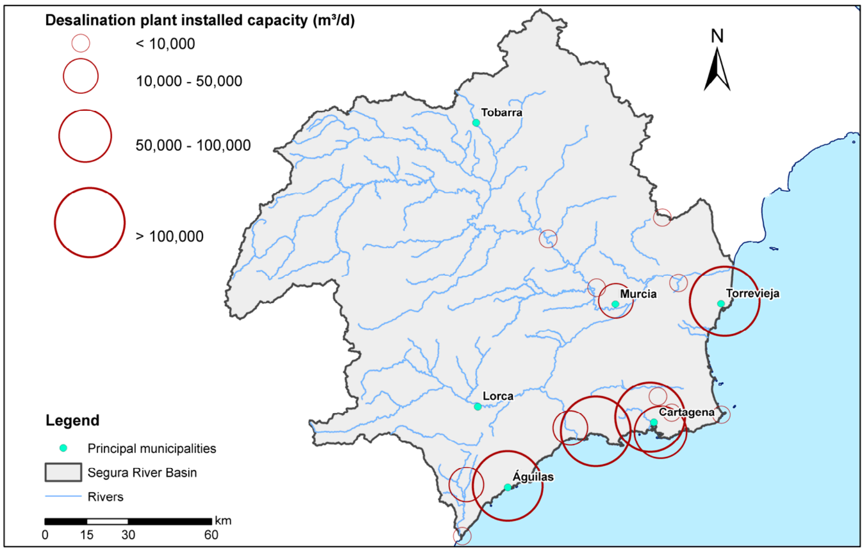


Figure 3. SRB’ desalination plants installed capacity and distance to coastline

3.2 Suitability Level determination

The decision-making was organized in a way to generate priorities in the conditioning criteria. To quantify how much more one element dominates another, the comparison has been made using a scale of absolute judgments (Parry et al., 2018). This scale designates how many times more important one element is over another regarding the compared criterion. These criteria were reclassified in a suitability values scale between 1 to 9 (Table 2), therefore they can be comparable to each other.

Table 2. Expressions of suitability rating (Burnside et al., 2002; Saaty, 1990)

Numerical expression	Suitability rating	Relative Importance
1	Not suitable	Equal importance
3	Marginally suitable	Moderate importance of one over another
5	Moderate suitable	Essential or strong importance
7	Highly suitable	Very strong importance
9	Optimally suitable	Extreme importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments	

This methodology (SL determination) has been widely used in identification of potential sites for any infrastructures or land use analysis (Bagdanavičiūtė and Valiūnas, 2012; Delivand et al., 2015; Du and Wang, 2018; Ghobadi et al., 2013; Krois and Schulte, 2014), environmental hazards assessment related with floods vulnerability or potential volcanic susceptible areas (Harley and Samanta, 2018; Ozturk and Batuk, 2011; Pozzo et al., 2006; Xiao et al., 2018), and land-use urban planning suitability studies (Criado et al., 2017; Parry et al., 2018).

All the conditioning criteria have been represented cartographically according to the level of suitability established for each of their categories. We used the ArcGIS Reclass tools. SL have been established by a specialist group with experience in the study area (Díaz-Cuevas et al., 2018), GIS spatial analysis and membrane technologies.

3.3 Decision-making process

The third phase consisted of checking the process of the MCE by the evaluation of the relative importance of each criterion using the AHP method (Mele and Poli, 2017). Saaty's method (Saaty, 1990) was chosen to weight the criteria, since it is one of the most used in related research (Abdalla and Khidir, 2017; Criado et al., 2017). A comparison matrix is used in this method (Saaty, 1987, 1990) for determine, by pairs, the significance of each criteria, defined as the Relative Importance Weight (RIW) (Krois and Schulte, 2014). This matrix, that used the Saaty's scale (Table 2), pointed out how much more important one criterion is compared to the other (Parry et al., 2018). AHP methodology allows to check the subjective decisions that the expert panel made (Mansouri et al., 2013). Therefore, it was necessary to calculate a parameter called consistency radio (CR). If the CR percentage was not exceeded Table 3), it can be concluded that there was consistency in the previously established values (the subjective judgments are correct) (Aznar and Guijarro, 2012). Once an acceptable CR was achieved, the RIW or eigenvalue of each criterion could already be calculated.

Table 3. Maximun CR percentages

Pair-wise matrix size	CR
3	5%
4	9%
5 or more	10%

3.4 Elaboration of the final suitability map

A suitability map pointing optimal locations of the recycling plant was developed using the weighted overlay tool in ArcGIS (Spatial Analyst ToolBox). This ArcGIS process is characterized by a linear summation equation of the factors multiplied by their corresponding weight. These weights are the RIW calculated in the previous step. In addition, in this analysis, the resulting map from the restrictive criteria was taken into account. These restricted areas were considered with zero suitability. Finally, the distinct SL were grouped in fewer categories for easy-friendly visualization.

4. Results

4.1 Criteria selection and data recollection and processing

The first step consisted on processing and evaluating the criteria spatial information. Figure 4 illustrates the resulting maps of the restrictive criteria Segura´s water basin. Protected natural areas layer is formed by different categories like Natural Parks, Protected Landscape or Wetlands (Figure 4-a). Hydrographic network is composed by rivers and permanent or intermittent streams (Figure 4-b), while the reservoirs layer included 36 hydroelectric, supply, irrigation and flood control reservoirs (Figure 4-c). Irrigation and supply channels are not only built aquatic infrastructure, they are also the product of a culture and social relationship with water in the Mediterranean region (Aspe, 2014). For this reason they have been excluded from the possible location of the membrane recycling plant (Figure 4-d). Roads and highways layer excludes urban streets (Figure 4-e) and, finally, flood-prone areas with a 50 years recurrence period are not going to be suitable for the recycling plant location (Figure 4-f).

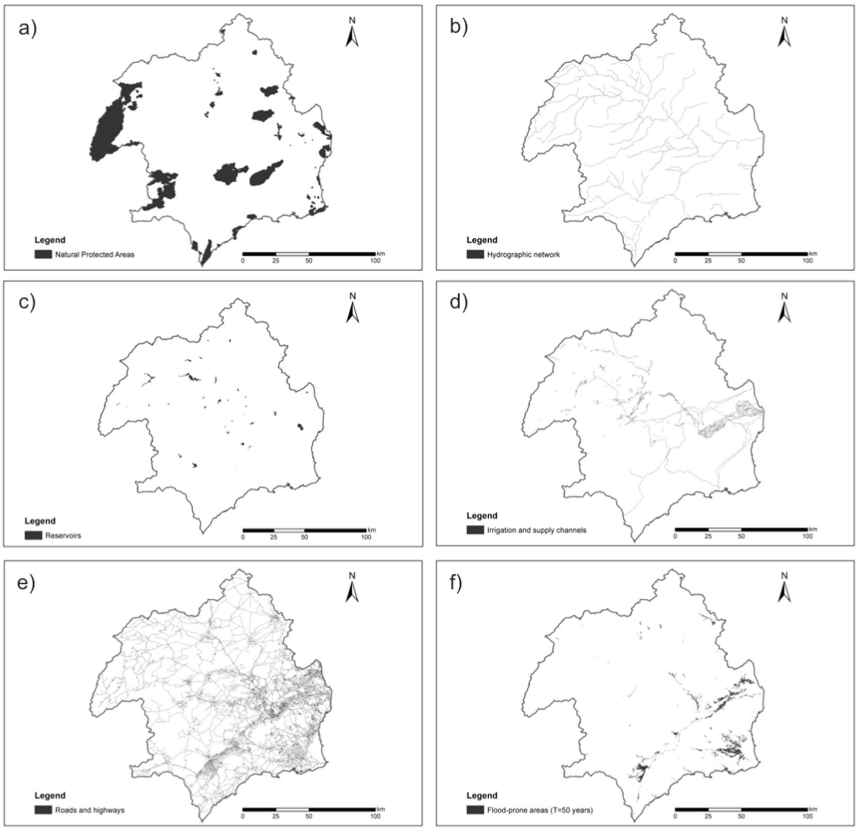


Figure 4. SRB restrictive criteria maps. a) natural protected areas; b) hydrographic network; c) reservoirs; d) irrigation and supply channels; e) roads and highways; and f) flood-prone areas.

The resulting map of the six restricted criteria of the SRB is shown in Figure 5. This map represents those areas where the RO membranes modules recycling plant is suitable (and not suitable) to be built. The basin total area where it is not be possible to build this recycling plant accounts approximately for 26% of the total.

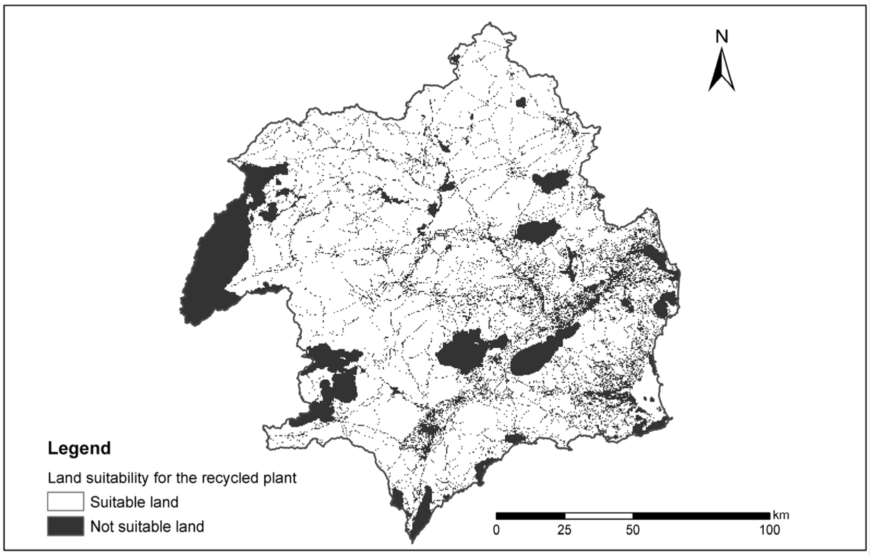


Figure 5. Suitable land for the RO membranes modules recycling plant location in the SRB

After that, the conditioned criteria maps were made (Figure 6):

- **Land use:** the different land use coverages from CLC 2012 were reclassified in 8 classes. The most abundant land use in the SRB is highly profitable agricultural land. This category covers 36.6% of the watershed area and it includes irrigated crops, vineyards, fruit trees or olive groves. Highly profitable agricultural spaces are concentrated in the east and south parts of the basin. The southeast area main territorial characteristic is aridity (Thornes and Rowntree, 2006), that has caused that the crops of high productivity have been located traditionally in the fertile river plains together with the good agronomic quality of the soil and the geologic factors (Martínez-Fernández et al., 2000). Then, forests (18.6%) and grassland (15.7%) are the second and third most common land uses. The next two most important classes are scrubland and sclerophyllous vegetation (12.3%) and low agricultural profitable agricultural land (12.1%) that consist of non-irrigated arable land and pastures. Consolidated urban areas (3.3%), water related surfaces – inland and maritime wetlands and waters – (1.2%) and beaches, dunes and sands (0.2%) completed the land use categories of the Segura watershed.

- **Topography (Slope):** the generated map shows a wide range of slope percentage within the SRB. The less abundant slopes correspond to a greater degree (9.1%) being located mainly in the Northwest of the SRB, while the others occupy a similar surface area: 0-2º (23.2%), 2-5º (23.4%). 5-10º (21.2%) and 10-15º (23.1%), with the lowest slopes concentrated in the Southeast.
- **Distance to shoreline:** the last criterion map was the distance to shoreline. In this case 3 buffer were created (less than 20, between 20 and 50 and more than 50 km from the coast line).

4.2 Suitability level selection of each criteria

In order to make comparable the different conditioning criteria Table 4 has been developed. Each criterion has been scaled between 1 and 9 according on its suitability rating. Table 4 presents the criterion suitability rating and their corresponding SL. Figure 6 shows the criteria maps in order to visualize the different SL.

Table 4. Suitability rating and levels for EoL-RORP location

Suitability rating	Not suitable	Marginally suitable	Moderately suitable	Highly suitable	Optimally suitable	Restricted
SL	1	3	5	7	9	0
Land use	Highly profitable agricultural land	Low profitable agricultural land	Forest land Scrubland and sclerophyllous vegetation	Grassland and sparce vegetation land	Consolidated urban land	Beaches, sandbanks and dunes Water related surfaces
Topography – Slope (%)	> 25	10 - 25	5 – 10	2 - 5	0 - 2	-
Distance to shoreline (km)	-	> 50	-	20 - 50	< 20	-

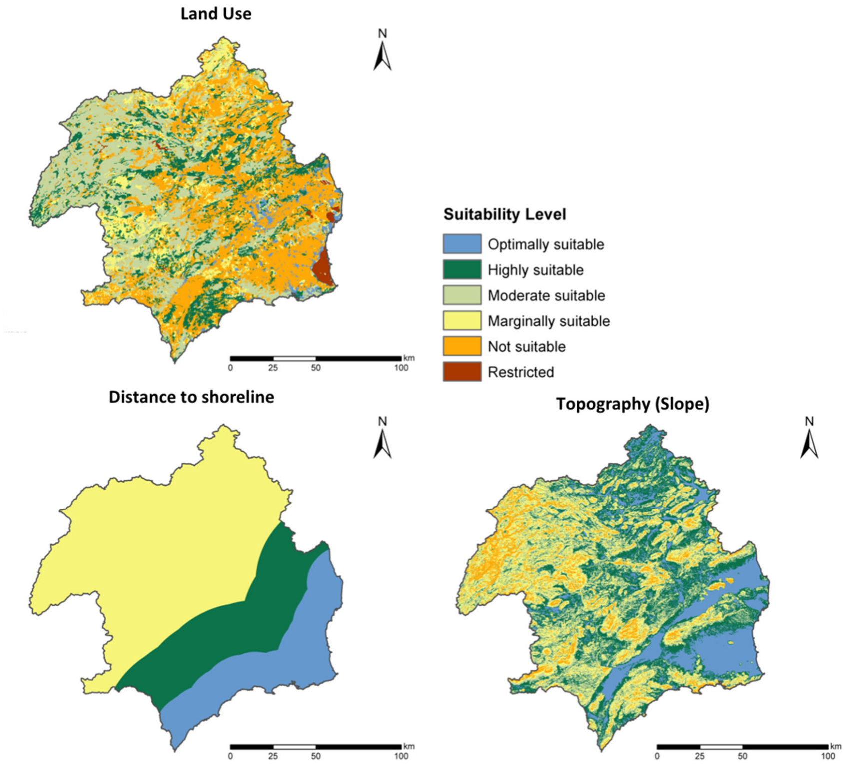


Figure 6. Conditioning criteria maps for recycling plant location in the SRB

4.3 Decision process

All the map layers were combined according to their RIW (including the zero suitability for the restrictive criteria layer). The AHP pair-wise matrix for the selected criteria is shown in Table 5. The matrix shows that the most relevant criterion is land use (RIW = 64%), followed by the topography criterion (26%) and distance to shoreline (10%). The values obtained from the matrix can be considered acceptable, because the CR does not exceed 5% (Table 5). Therefore, the subjective process' sensitivity of the relative importance of each criterion with respect to the others can be considered correct for the most suitable location evaluation process.

Table 5. Pair-wise comparison matrix for the conditioning criteria and their RIW.

	Land Use	Distance to shoreline	Topography (Slope)	RIW
Land Use	1	5	3	**0,64**
Distance to shoreline	1/5	1	3	**0,10**
Topography (slope)	1/3	1/3	1	**0,26**
Consistency Radio (CR) = 3,72%				

4.4 SRB recycling plant suitability map

Figure 7 shows the different suitability categories in the SRB for the RO membranes recycling plant location. The water basin surface has been divided into 5 suitability levels: optimally, highly, moderately, marginally and not suitable. They have been calculated combining the SL for each criteria and its RIW in a 1 to 9 scale, including the restricted extra level.

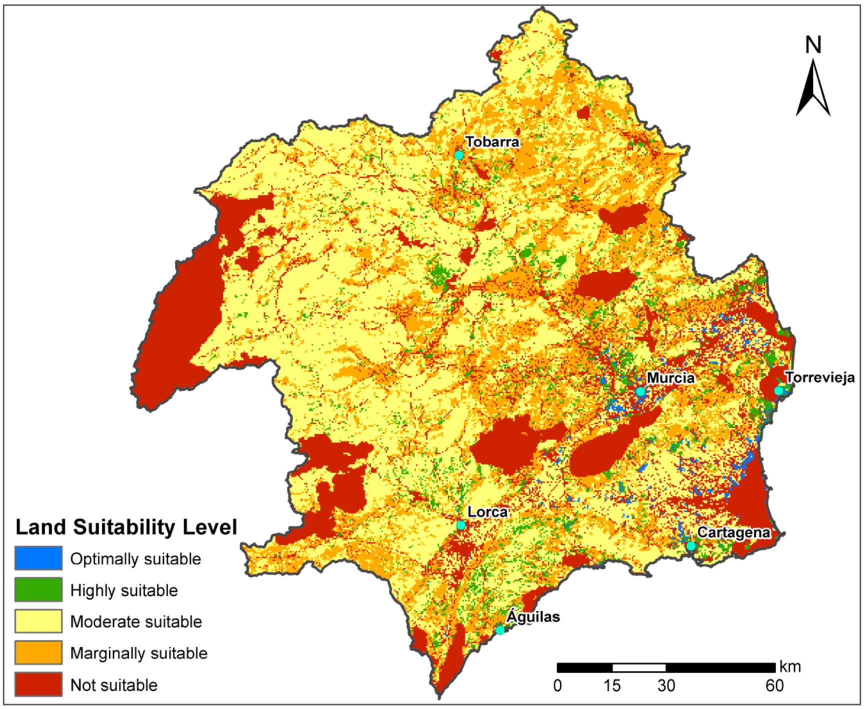


Figure 7. Suitability map of the SRB for the membranes recycling plant location

Table 6 summarizes the area and relative abundance by SL. The analysis indicates that the most abundant category in surface in the basin is the moderately suitable one with the 47.4% of the total area. The next two most abundant categories are marginally suitable and not suitable with the 23.8% and 23.2%, respectively. The highly suitable category occupies approximately the 5% of the basin (4.7%), while the best level of suitability does not represent even the 1% of the SRB.

Table 6. Suitability levels rating and area

Suitability level	Suitability Range	Area (km^2)	Percentage (%)
Not suitable	0 (restricted)	4,421.12	23.2
Marginally suitable	1 – 3	4,542.88	23.8
Moderately suitable	4 – 6	9,041.44	47.4
Highly suitable	7 – 8	901.28	4.7
Optimally suitable	9	155.52	0.8

5. Conclusions

The use of RO membrane technology is continuously growing. Despite the efficiency of the technology is reaching its limit, the management of the EOL RO membranes is still primitive. The recycling of RO membranes is an alternative solution to reduce the environmental stress of landfilling. Spain is one of the most suitable countries to lead this initiative having international recognized companies within the desalination field that could export the model around the World. For that purpose, the evaluation of the potential locations to install a membrane recycling plant have been assessed in the Segura River Basin (Spain), which contains the most installed membrane capacity in the country.

The GIS-based MCE methodology used is valid for the EoL-RORP location. The results show that in this region there are several areas with the highly value for the plant construction (around 155 km^2). There are three areas that congregate a greater number of plots of better location: the surroundings of the city of Murcia, the north of Torrevieja and a wide area between the cities of Torrevieja and Cartagena, all of them in the east-southeast part of the SRB. There are also areas with a highly suitability level, with about 900 km^2. Therefore, in the SRB there are more than 1,000 km^2 where the location of the recycling plant would be very appropriate.

The criteria that, in this specific case, are most important in the location potential assessment are, on the one hand, the land use criterion (a relative importance of 64% with respect to the other two conditioning criteria) and, on the other, the natural protected areas one. This restrictive criterion is that which occupies a larger area of the SRB, making the construction of the recycling plant impossible in 13% of the river basin.

Future works will focus on the analysis of several location alternatives taking into account, among other aspects, the transport cost of the membranes to the recycling plants and life cycle assessment. Therefore, a small number of exact locations will be chosen and economic and transport criteria will be studied in addition to the environmental or planning ones.

Acknowledgments

The authors acknowledge the financial support to the LIFE program for funding the TRANSFOMEM project (LIFE13 ENV/ES/000751), to the project INREMEM - CTM2015-65348-C2-1-R (MINECO/FEDER).

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Página 19: [1] Eliminado ALBERTO BLANCO 24/07/2019 9:01:00