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ORIGINAL PAPER

Relational spatial database and multi-criteria decision methods for selecting optimum locations for photovoltaic power plants in the province of Seville (southern Spain)

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Abstract
This work aims to develop a methodology for selecting optimum locations for the construction of photovoltaic power plants. In order to achieve this, a data model is defined and a multi-criteria decision methodology, based on an analytical hierarchy process, is applied. In contrast to the previous studies, in which the spatial analysis was undertaken by a GIS managing different layers of information (grids, shapefiles, etc.), in this work the spatial analysis is carried out by means of an open-code spatial database management system: PostgreSQL-PostGIS. This system uses Structure Query Language to manage different tables in the context of relational spatial databases. The case study is the province of Seville (southern Spain), where this sort of facility already exists. The empirical analysis concludes that a large percentage of the province of Seville has an excellent potential for the installation of photovoltaic plants. The methodology allows the dynamic updating of criteria and parameters, as well as the reproducibility, scalability and automating of analyses carried out in other fields.

Keywords Solar PV · PostgreSQL-PostGIS · Data model · Analytical hierarchy process · Seville

Introduction

The European Commission encourages member states to adopt a joint energy policy to combat climate change. These policies are divided into three major strands: to promote energy saving and efficiency; to increase proportional consumption of renewable energy; and to reduce emissions of greenhouse gases (European Commission, EC 2007a, b).

In Spain, the promotion of renewable energy is particularly important, given the country's dependence on external supplies—Spain only produces 22% of the energy it consumes (Agencia Andaluza de la Energía, AAE 2016)—but also its optimum conditions for the production of renewable energy. This has led to the recent proliferation of renewable energy plants in Andalusia, which has caused some concerns and even some public opposition towards these plants (Frolova and Pérez 2008; Frolova et al. 2014). Various authors have suggested that the application of criteria for the localisation of these plants would go a long way in overcoming this reluctance (Rodman and Meentemeyer 2006; Janke 2010; Sánchez-Lozano et al. 2014; Watson and Hudson 2015), and several studies already exist (Voivontas et al. 1998; Yue and Wang 2006; Domínguez and Amador 2007; Ramírez-Rosado et al. 2008; Aydin et al. 2010; Angelis-Dimakis et al. 2011; Resch et al. 2014, etc.) concerning the location of energy. For solar plants, some of their findings are illustrated in Table 1. The following conclusions may be drawn from the analysis of these findings:

- Most studies propose similar basic steps. First of all, unsuitability criteria are determined and the areas considered unsuitable for solar plants are demarcated. Second, suitability factors are determined and the best locations for the installation of solar plants are identified. These criteria and factors are represented in different GIS layers. Finally, different weights are assigned to each factor and aggregated, resulting in a potential index.

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Table 1 Overview of PV solar farm site-selection studies

Author/study area	Approach (1 criteria; 2 factors; 3 method)
Arán Carrión et al. (2008)/Granada (South-east Spain)	1. Exclusion criteria (protected natural areas; sites of public interest; livestock trails (public domain + affected zone); road networks (access zone + patrolled area); rivers; coastline 2. Evaluation Factors: Environmental (land use, visual impact); orographic (slope, orientation); localisation (highway access, distance to substations, distance to urban areas); and climatic (global radiation diffuse radiation, average daily sun hours, average temperature) 3. GIS (ArcView), AHP and sensitivity analysis
Sánchez-Lozano et al. (2013)/Cartagena-Murcia (South-east Spain)	1. Exclusion criteria: Types of location; lines of communication and infrastructure; topography; hidrology; protected heritage sites; sites of public interest; plots under 1000 m^2 in size 2. Evaluation Factors: Environmental (agro-ecological potential); orographic (slope, orientation, plot size); localisation (distance to main roads, distance to power lines and substations, distance to towns or villages); and climatic (solar radiation, average temperature) 3. GIS (gvSIG), TOPSIS and AHP. No sensitivity analysis is performed on the AHP
Uyan (2013)/Karapinar region, Konya (Turkey)	1. Exclusion criteria: Buffer of 500 m to residential areas; 100 m to roads; 500 m to protection areas (archaeological sites, military areas, forested areas, wildlife protection areas, biologically significant areas and environmental protection areas); rivers, lakes, wetlands, and dams 2. Evaluation Factors: Environmental (distance from residential areas, land use), economic factors (distance from roads, slope and distance from power lines) Solar potential was not evaluated as a factor, because it is between 1650 and 1700 kWh/m^2/year throughout the study area 3. GIS (ArcGIS), AHP but with no sensitivity analysis
Sánchez-Lozano et al. (2014)/Torre Pacheco-Murcia (South-east Spain)	1. Exclusion criteria: Urban areas; protected and undeveloped areas; high landscape value areas; hydraulic infrastructures; military zones and livestock trails; watercourses and streams; archaeological sites; paleontological sites; cultural heritage sites; roads and railroad network; areas of public interest 2. Evaluation Factors: environmental (agro-ecological potential); orographic (slope, orientation and plot size); location (distance to main roads, distance to power lines and substations, distance to towns or villages); climatic (global radiation and average temperature) 3. GIS (gvSIG), ELECTRE-TRI
Tahri et al. (2015)/Southern Morocco	1. Constraint layers, such as agricultural land, urban and protected areas, lakes, and infrastructure sites, were not taken into account in the evaluation of potential locations 2. Evaluation factors: Land use (areas without vegetation); orography (slope and orientation); location (distance to urban areas and roads); Climatic (potential solar radiation in kW h/m^2/year) 3. GIS (ERDAS), AHP but no sensitivity analysis
Watson and Hudson (2015)/South-central England	1. Exclusion criteria: Grades 3a, 3b, 4, 5, agricultural land categories; < 1000 m from areas of historical significance; < 1000 m landscape designated areas; < 500 m residential areas; < 1000 m wildlife designated areas; SE–SW facing; slope > 10° 2. Evaluation Factors: Technical (solar radiation); visual (distance from historically significant areas, residential areas), ecological (distance to wildlife designated areas) and economic factor (distance from transport links and network connections) 3. GIS (ArcView), AHP and sensitivity analysis

Table 1 (continued)

Author/study area	Approach (1 criteria; 2 factors; 3 method)
Al Garni and Awasthi (2017)/Saudi Arabia	1. Exclusion criteria: Urban and protected areas; road network; slope > 5º 2. Evaluation Factors: Technical (solar radiation; temperature) and economic (slope; land aspects; proximity to urban areas; proximity to roads; proximity to power lines) 3. GIS (ArcGIS) and AHP but no sensitivity analysis
Uyan (2017)/Karaman (Turkey)	1. Exclusion criteria: Buffer of 500 m to residential areas; 100 m to roads; 500 m to protection areas (see Uyan 2013); 500 m to rivers and lakes 2. Evaluation Factors: Environmental (distance from residential areas, land use), economic factors (distance from roads, slope and distance from power lines) Solar potential was not evaluated as a factor, because it is between 1650 and 1700 kWh/m^2/year throughout study area 3. GIS (ArcGIS) and AHP but not sensitivity analysis

- No study of these characteristics has been carried out in the province of Seville, but some have been undertaken in nearby provinces. Arán Carrión et al. (2008) used GIS and multi-criteria decision methods (MCDM) to identify the most suitable areas for the installation of solar plants in Granada (south-eastern Spain), and Sánchez-Lozano et al. (2013) and Sánchez-Lozano et al. (2014) did the same in the province of Murcia (south-eastern Spain).
- To date, all these studies have used GIS, both to apply MCDM and for spatial analysis, especially ArcGIS (ESRI) or its previous version ArcView, as well as open-source software gvSIG and ERDAS. The authors are not aware of previous use of a relational spatial database management system (Oracle Spatial, PostgreSQL-PostGIS) in this sort of analysis.
- Concerning multi-criteria evaluation techniques, various methods have been used, e.g. Elimination and Choice Translating Reality (ELECTRE), analytical hierarchy process (AHP), Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS), among others. However, most previous works use Saaty's analytical hierarchy process, one of the most popular MCDM techniques. This is because this method, put forward by Saaty (1980), allows for the evaluation of qualitative, and not only quantitative factors, which are typically left out of the analysis due to the difficulties involved in measuring them. In addition, AHP provides a powerful and simple way to weight decision criteria; the method does not involve complex maths. The method also reduces bias in decision-making by giving a measure of consistency; this consistency index is essential for evaluating the impact of the assigned weights on the final results. For all of this, the method is universally regarded and is widely used in optimum location studies in general, and in the location of renewable energy plants in particular. For instance, Bennui et al. (2007), Tegou et al. (2010), Al-Yahyai et al. (2012), Effat (2014), Szurek et al. (2014), Sunak et al. (2015), Al-Shabeeb et al. (2016) and Díaz-Cuevas et al. (2018) use AHP for the location of optimum locations for wind farms, and Choudhary and Shankar (2012) use it to evaluate the best location for a thermal power plant location; Table 1 illustrates the use of the method in the location of photovoltaic plants.

This work proposes a methodology to identify optimum locations for solar plants in the province of Seville by using the spatial database management system PostgreSQL-PostGIS with MCDMs. The model will determine areas with greater potential for the installation of solar plants, as well as those in which the construction of these facilities is inadvisable.

This paper contributes to the existing literature mainly in two ways:

1. The province has not been subject to this sort of study before. As such, this paper will be a reference for future studies.
2. In most previous studies, spatial analysis was undertaken by desktop GIS. In contrast, the spatial study presented in this paper has been carried out with the open-access spatial database management system PostgreSQL-PostGIS, through the construction of spatial Structured Query Language (SQL) sentences. Desktop GIS (QGIS) has been used only for the semiotic representation and the spatial visualisation of results. PostgreSQL-PostGIS facilitates reproducibility, scalability and automating of the analysis.

The present paper is divided into several sections: "Legal framework and study area" section presents the area under consideration; "Data and methods" section deals with sources and methodology; "Results and discussion" section presents the main results and discussion; and "Conclusions" section presents the conclusions.

Legal framework and study area

The study area is the province of Seville (Fig. 1), which is situated in the region of Andalusia (southern Spain). Andalusia is particularly suitable for generating solar energy, because of the high levels of potential solar radiation and a long tradition in applying technological development to solar energy.

The province of Seville is 14,011.39 km^2 in size, with a population of 1,940,000 in 2016. The province is divided into 105 municipalities grouped into six territorial units, according to the Territorial Organisation Plan (Consejería de Obras Públicas y Transportes 2006).

- *Vega y Bajo Guadalquivir* characterised by fertile agricultural land and an irrigation agricultural landscape.
- *Campiña de Sevilla y Sierra Sur* dominated by cereal and olive tree agricultural land, as well as by developed agro-towns characterised by slightly positive demographic dynamics.
- *Aljarafe-Condado* the area presents a slightly more diversified landscape, but largely based on the alternation of dryland agriculture and olive tree groves, with some vineyards and irrigation agriculture areas.
- *Sierra Norte de Sevilla* dominated by large tracts of protected natural landscape and homogeneous agroforestry, sparse and dispersed population, and lacking in medium-sized urban nuclei.
- *Centro Regional de Sevilla* characterised by the urban structures typical of regional centres. This territorial unit includes the city of Seville, capital of the province.
- *Aljarafe-Marismas* formed by the combination of various ecosystems. To the north, low marly farmlands at the foot of Sierra Morena and silty and sandy terraces that progressively descend towards the south, merging into the Guadalquivir marshland. This territorial unit is part of one of Europe's most important natural areas: the Parque Natural y Nacional de Doñana.

Currently, Seville is the Andalusian province with the highest photovoltaic output; 217.33 MW are pumped into the electric network and 1.28 MW are generated in isolated systems, which amounts to 24% of the Andalusia's total output (AAE 2016). This significant development is largely due to a decided political bid for renewable energy. In 2007, the regional government published a regional plan for energy sustainability for the period 2007–2013 (AAE 2007), one of

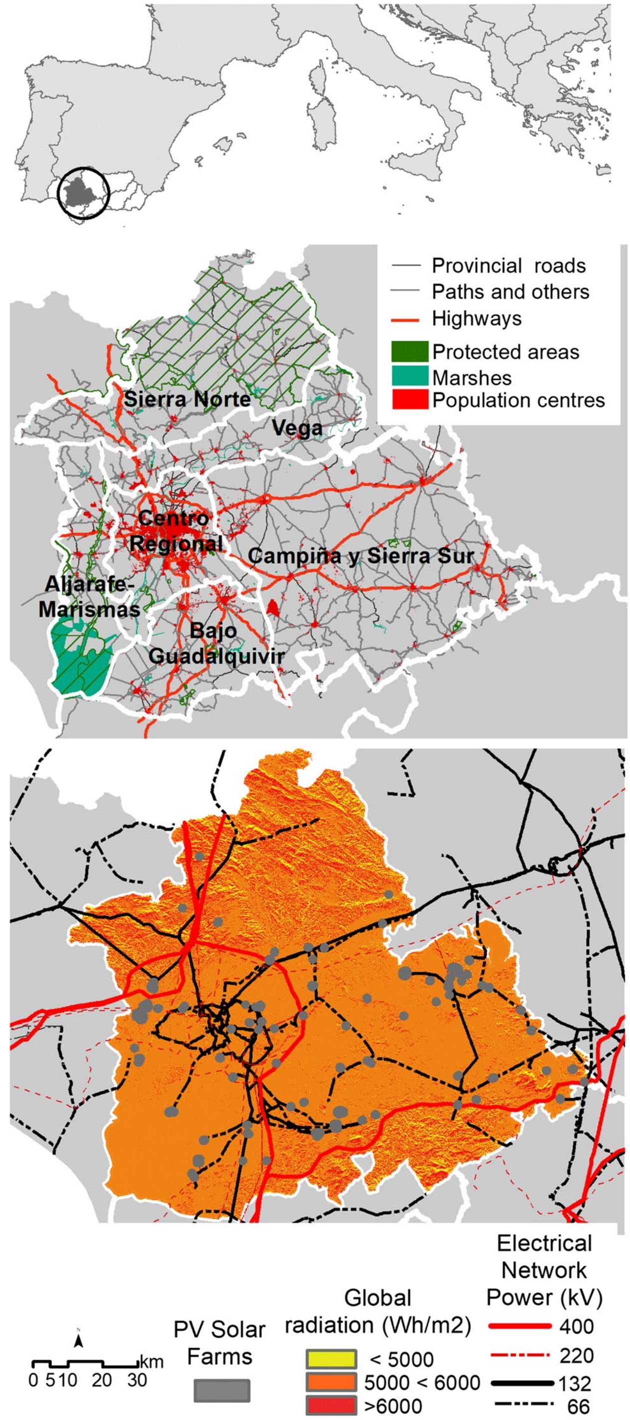

Fig. 1 Land use, population centres, global solar radiation, PV solar farms and electrical network in the study area

the key targets of which was to prioritise renewable energy sources as a way to reduce the region's energy dependence (94% in 2007).

The enactment of the Energy Act in 2007 (Ley 2/2007, de 27 de marzo, de fomento de las energías renovables y del ahorro y eficiencia energética de Andalucía) was a decisive step in this regard. In addition, one of the targets of the ongoing Energy Strategy of Andalusia 2015–2020 (AAE 2016) is to increase the contribution of renewables to gross energy consumption to 25% by 2020, which is beyond even the targets set out in Directive 2009/28/EC on the promotion of the use of energy from renewable sources (which sets the target at 20%). Therefore, it is of great interest to establish what areas can be further developed and contribute to meeting these broad objectives.

Data and methods

Data

For the site selection for PV solar farms in the province of Seville, different spatial data need to be collected (Table 2).

Spatial data are available at the Instituto de Estadística y Cartografía de Andalucía and the Dirección and the Catálogo de Información Ambiental, both dependent on the regional government. In addition, the 2013 aerial orthophotograph data (the most recent available at the time the study was carried out), collected by the Infraestructura de Datos Espaciales de Andalucía, has been used to digitalise the location of solar plants.

Property distribution in the study area has been consulted with data from the Dirección General del Catastro, which is a key source in territorial studies, owing to its high recording standards: the information is detailed and up to date. Data were collected concerning property distribution in the 105 municipalities of Seville in 2017. (The total number of properties considered was 751,485.)

Solar radiation, average temperature and soil quality maps are available at the Catálogo de Información Ambiental. The rest of the data was collected from the Instituto de Estadística y Cartografía de Andalucía.

Methodos

The methodology adopted to determine the most suitable areas for the installation of solar farms in Seville is divided into five steps (Fig. 2).

1. Identification of data requirements (Fig. 2; stage 1): this includes defining exclusion criteria with which to reject unsuitable areas, as well as factors with which to evaluate the potential of suitable areas.

A series of criteria are used to evaluate different areas in the province. Table 3 describes the territories that are considered unsuitable for the construction of solar farms, according to the legal framework and the existing literature (Sánchez-Lozano et al. 2013, 2014; Tahri et al. 2015; Watson and Hudson 2015; Al Garni and Awasthi 2017; Villacreses et al. 2017; Uyan 2013, 2017).

The selection of suitability factors follows Arán Carrión et al. (2008) and Sánchez-Lozano et al. (2013, 2014), who

Table 2 Data used

Data	Supplier
Cities, villages and rural buildings	Instituto de Estadística y Cartografía de Andalucía
Motorways, paths and railways	
Airports, aerodromes	
Items of cultural interest	
Landscape roads, cattle trails and green ways	
Electrical network	
Orientation (MDE 100 m × 100 m)	
Slope (calculated from MDE 100 m × 100 m)	
Nature reserves and national parks; other protected areas; natural areas (LIC and ZECs): Ramsar and Biosphere Reserve Areas	Catálogo de Información Ambiental
Birds and bats	
Coastline	
Forest areas	
Global solar radiation	
Agro-ecological soil quality	
Annual average temperature	
Plots and subplots	Oficina del Catastro
Solar farms	Digitised from aerial orthophotographs collected by Infraestructura de Datos Espaciales de Andalucía

have worked in southern Spain (Murcia and Granada, among others), which present a similar political and institutional framework to that which applies in the study area. The areas with the highest potential for the installation of solar farms are those which have a:

- Low soil quality: highly fertile soils are to be avoided owing to their agro-ecological value;
- Gentle slopes: pronounced slopes can lead to extra infrastructural investment;
- High annual average temperature and global solar radiation: in order to locate the solar power plants in more productive areas;
- Areas facing south, south-east and south-west: these areas in the northern hemisphere, they are exposed to radiation all year round, especially during the middle hours of the day, when the radiation is most intense;
- Areas closest to the existing electrical network, due to the need to distribute the energy generated;
- Areas closest to settlements, in order to facilitate distributed generation (DG);
- Areas closest to the road network, as this will facilitate installation and reduce future impacts, such as those caused by the building of new roads;

2. Design of the database conceptual model (Fig. 2; Stage 2): as the database will include spatial geographical information, the design of the relational spatial database must be both versatile and reliable. Data were modelled with the aid of an Entity Relationship Diagram (ERD), which allows the representation of the relevant entities in an information system as well as their properties and mutual relationships, which must be identified during this step. Primary and foreign keys were also identified, and the entity relationship diagram was defined.

The spider-shaped E-R diagram is composed of a central geometrical entity (GRID), which represents the 100-m^2 cells into which the province of Seville was divided. Each

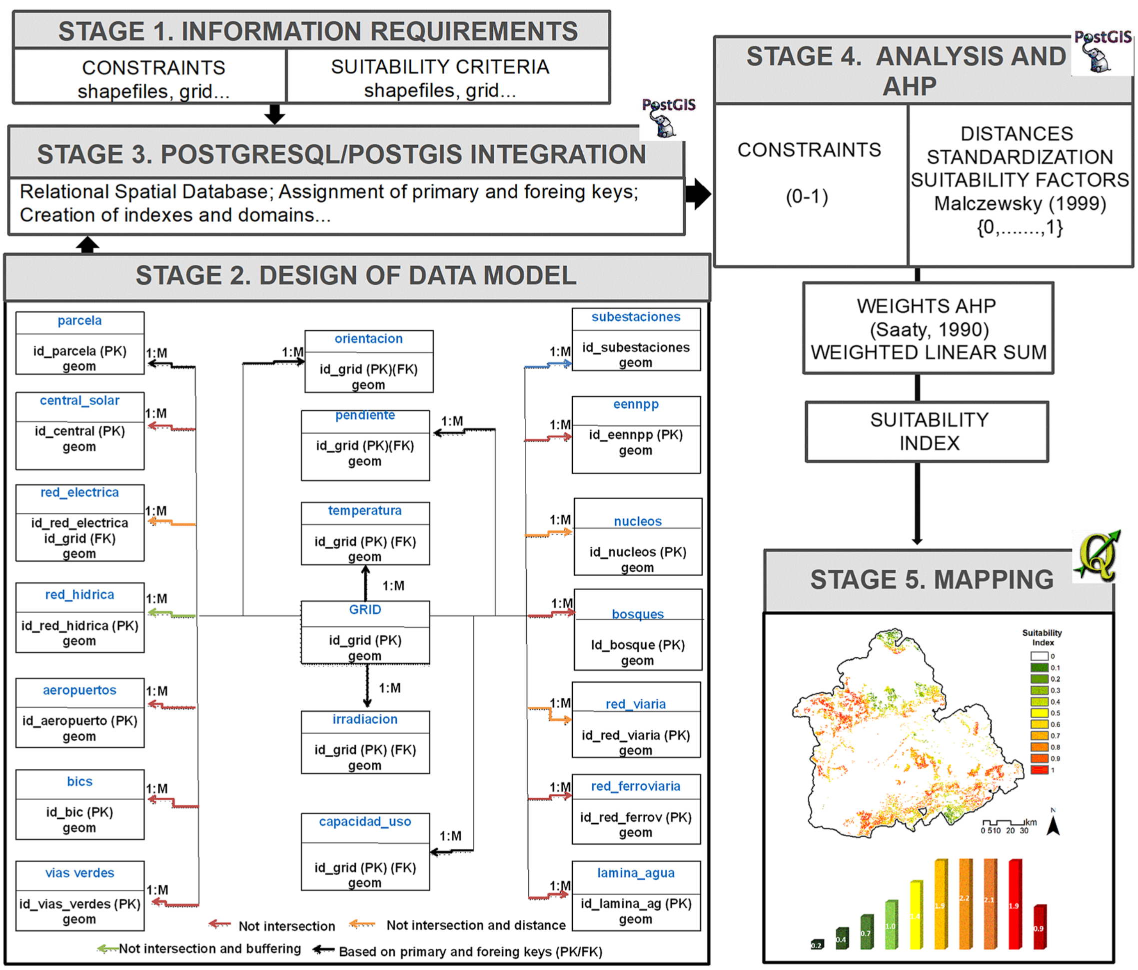

Fig. 2 Work flow

Table 3 Exclusion criteria for defining unsuitable areas and assessing the potential of suitable areas

Exclusion criteria	
Populated areas, airports and aerodromes, cultural heritage items, lakes and water reserves, marshlands, etc.	Sánchez-Lozano et al. (2013, 2014), Uyan (2013, 2017), Watson and Hudson (2015)
Areas within 140 m of motorways and highways, within 110 m of any other road and railway and within 100 m of footpaths	Ley 8/2001, de 12 de julio, de carreteras and Ley 9/2006, de 26 de diciembre, de servicios ferroviarios de Andalucía, which aim to establish clear boundaries for, and a security perimeter around, areas under the public domain
Territories located within 175 m cattle tracks, within 135 m of restricted byways, within 20 m of lanes and within 100 m of other green paths	Ley 3/1995, de 23 de marzo, de vías pecuarias and Decreto 155/1998, de 21 de julio, por el que se aprueba el Reglamento de Vías Pecuarias en la Comunidad Autónoma de Andalucía
Rivers and areas of hydraulic public domain	Real Decreto 9/2008, de 11 de enero, por el que se modifica el Reglamento del Dominio Público Hidráulico, aprobado por el Real Decreto 849/1986, de 11 de abril
Fluvial inundation areas for a period of 100 years	Villacreses et al. (2017)
Properties under 1000 m^2 in size, which is considered the profitability threshold	Sánchez-Lozano et al. (2013, 2014)
Protected natural areas	Natural parks: depending on the parks own planning requirements
	Other protection categories: the entire surface of the protected areas, according to the function of these spaces, as established by Ley 2/1989 and 4/1989
Areas with the highest slopes – for economic and logistic reasons	Sánchez-Lozano et al. (2013, 2014); Watson and Hudson (2015); Al Garni and Awasthi (2017)
Forested and high-potential agricultural areas	Sánchez-Lozano et al. (2013, 2014); Uyan (2013, 2017)
Areas already occupied by solar farms	
Suitability factors	
Proximity to the electrical grid and substations	Arán Carrión et al. (2008), Sánchez-Lozano et al. (2013, 2014)
Proximity to urban areas	
Flatter areas	
High-potential irradiation and average temperature areas	
Low soil quality areas	
High radiation areas	
High-temperature areas	
Proximity to the road network	

cell has a unique code id_grid. The total number of entries is 1,475,042.

This geometrical entity is related to a cardinality 1:M with a series of entities/tables that characterise it. These cardinalities are based either on primary or foreign keys or on spatial relationships, especially intersection and distance. The description of each table is as follows:

- Tables: aeropuertos, central_solar, bic, lamina_agua and bosques; polygonal collected variables representing airports, solar plants, cultural heritage sites, water surfaces and forests. Cells that intersect these spaces will be considered unsuitable.
- Table parcela: polygonal collected variables representing plot property structure in the 105 municipalities that form the province of Seville. Only plots of land of over 1000 m^2 in size will be considered suitable.
- Table eennpp: polygonal collected variable representing protected natural areas, based on the relevant planning documents. Cells that intersect these spaces will be considered unsuitable.
- Tables: vias_verdes, red_ferroviaria, red_viaria: lineal geometry variables representing green paths, railroad network and road network. Cells that intersect these spaces or with the adjacent areas affected by public domain will be considered unsuitable.
- Table pendiente: grid that represents slope gradient values in each cell. Cells in which the slope is over 15° will be considered unsuitable and therefore excluded from the analysis. Conversely, cells with the lowest slope values will be regarded as most suitable for the construction of solar plants.
- Table orientacion: represents the orientation of each cell. South-facing cells will be regarded as most suitable for the construction of solar plants.
- Table capacidad_uso: represents the agro-ecological potential of the soil in each cell. Cells with a low soil

quality will be regarded as most suitable for the construction of solar plants.

- Tables temperatura and radiacion: represent temperature and radiation values in each cell. Cells with the highest temperature and radiation values will be regarded as most suitable for the construction of solar plants.
- Tables red_electrica and substaciones: represent electric grid and substations in the study area. Cells located in the vicinity of these will be regarded as most suitable for the construction of solar plant.
- Table nucleos: represents the polygonal geometry of urban centres, rural settlements and rural buildings in the province of Seville. Cells intersecting these polygons will be considered unsuitable. On the other hand, cells located in the vicinity of these will be regarded as most suitable for the construction of solar plants.

3. Physical implementation of the data model in a spatial data management system (Fig. 2; stage 3), which in this case is PostgreSQL which, in combination of PostGIS, allows the management, indexation and application of spatial functions. As such, the data were entered into this data management system (PostgreSQL 10.2/PostGIS 2.3) and prepared for further processing by assigning primary and foreign keys from the different tables and by creating spatial and thematic indexes which make using the data a much more agile process. The graphical tool used was PgAdmin3, and the text editor selected to write the code was Notepad++ v.7.5.

Following the legal framework (Real Decreto 1071/2007), the coordinate system used was the European Terrestrial Reference System 1989 (ETRS89), UTM zone 30 N.

4. Analysis and exploitation of the data (Fig. 2; stage 4): after the implementation of the data management system, different spatial SQL enquiries were formulated, which are the basis of the main results.

First, it was determined which cells occupied areas in which solar farming was unsuitable or highly inadvisable. Afterwards, the potential of remaining areas was calculated based on the previously defined suitability factors (Table 3).

The distance ranges of distance-dependent factors were calculated by measuring the distance between the cells and urban nuclei, road network, and electricity grid and substations. This was followed by the calculation of the orientation and slope variables, based on a digital elevation model with a resolution of 100 m. Finally, agro-ecological factor, soil quality, annual average temperature and global radiation were already available at the Catálogo de Información Ambiental (see Table 2).

Once these values were available, they were normalised to a 0–1 scale, using Malczewsky's (1999) Eq. 1, which is common in this sort of study (Arán Carrión et al. 2008; Sánchez-Lozano et al. 2014; Watson and Hudson 2015 among others), where x equals the value of a variable in the original data set:

$$Xz = \frac{(x - \min(x))}{\max(x) - \min(x)} \tag{1}$$

The remaining factors were assigned a value between 0 and 1 by a panel of experts comprising three PhD holders, two engineers and a geographer specialised in energy planning (Table 4). Figure 3 provides the normalised area maps for each factor.

Once criteria were standardised, they were weighted to generate the suitability index. Weights were established using the analytic hierarchy process (AHP). This method, proposed by Saaty (1980), is widely used in this sort of study (Sánchez-Lozano et al. 2014; Watson and Hudson 2015, etc.). The method is based on linguistic decision-maker's preferences, incorporated by a pairwise comparison process that compares the importance of each criterion over others using the values of the Saaty scale (1989), as illustrated in Table 5.

In the present study, weights have been assigned by the aforementioned panel of experts. The experts compared pairs of criteria by answering the following questions: 'Which of the two criteria is more important?' and 'By how much?' This assessment is expressed on the Saaty semantic scale (Table 5), which determines to what extent a given criterion is relatively more important than another.

For instance, if the relative importance of attribute C_1 over attribute C_2 is judged to be 3 'moderate importance in Saaty scale', the relative importance of attribute C_2 with regard to C_1 has the reciprocal value, that is 1/3. Values 2, 4, 6 and 8 on the scale correspond to intermediate situations. This process generates an auxiliary matrix (2).

$$X = \begin{bmatrix} 1 & a & b \\ 1/a & 1 & c \\ 1/b & 1/c & 1 \end{bmatrix} \tag{2}$$

The pairwise comparison of criteria yields value W_1, which represents the order of priority of factors, calculated by aggregating the values obtained on the previous scale and determining the weight to be assigned to each

Table 4 Standardisation of qualitative factors

Variable	Type	Standard value
Soil quality	Moderate to marginal quality soils	1
	Medium-quality soils	0.5
Orientation	SE/S/SW	1
	Other	0.5

Fig. 3 Normalised area maps for each factor. **F1** Agro-ecological potential; **F2** slope; **F3** annual average temperature; **F4** global radiation; **F5** road network; **F6** electricity grid and substations; **F7** orientation; **F8** urban nuclei

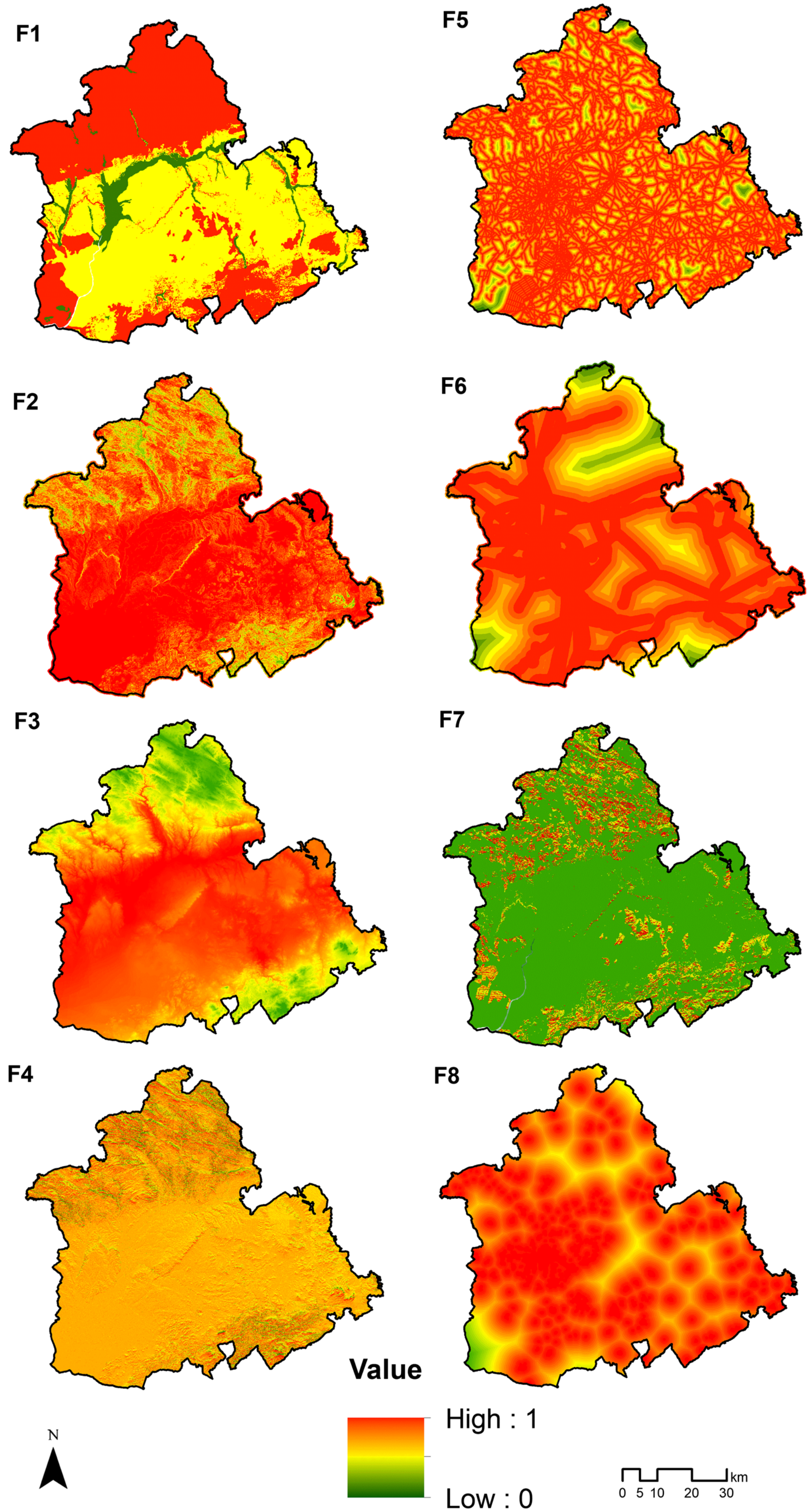

Table 5 Saaty scale

	1	3	5	7	9
Definition	Equal importance	Moderate importance	Strong importance	Very strong importance	Extreme importance

Table 6 Value of random index

Order matrix	1	2	3	4	5	6	7	8	9	10
Definition	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 7 Factors and weights for level of suitability

Factor	*F*1	*F*2	*F*3	*F*4	*F*5	*F*6	*F*7	*F*8	W_1	*W*
*F*1	1	1/7	3	2	1/4	1/6	1/2	1/3	7	0.058
*F*2	7	1	6	5	4	1/2	5	4	33	0.254
*F*3	1/3	1/6	1	1/2	1/3	1/5	1/2	1/4	3	0.026
*F*4	1/2	1/5	2	1	1/2	1/5	1/2	1/4	5	0.040
*F*5	4	1/4	3	2	1	1/3	3	2	19	0.145
*F*6	6	2	5	5	3	1	6	8	36	0.281
*F*7	2	1/5	2	2	1/3	1/6	1	1/4	8	0.062
*F*8	3	1/4	4	4	1/2	1/8	4	1	17	0.132

$\lambda = 8.7$; $C_\mathrm{i} = 0.1$; $C_\mathrm{r} = 0.07$

F1, Agro-ecological potential; F2, Slope; F3, Annual average temperature; F4, Global radiation; F5, Road network; F6, Electricity grid and substations; F7, Orientation; F8, Urban nuclei

criterion. Finally, the table also includes the main normalised eigenvector *W*, which indicates the value of the weights, in this case normalised to 1. Once the weights have been calculated, the next step is to determine the internal coherence of the decision-maker's judgements by calculating the consistency ratio (C_r) Eq. (3). This is calculated using the consistency index (C_i) Eq. (4) and the random index (R_i) by applying the following formula:

$$C_\mathrm{r} = \frac{C_\mathrm{i}}{R_\mathrm{i}} \tag{3}$$

$$C_\mathrm{i} = \frac{(\lambda - n)}{(n - 1)} \tag{4}$$

where n is the number of variables in the comparison matrix, and λ is the value of the main normalised eigenvector '*W*' multiplied by the pairwise comparison matrix.

The random index (R_i) is the C_i of a randomly generated pairwise comparison matrix of order 1–10 (Saaty 1980). Table 6 shows value R_i sorted by the order of matrix.

If $C_\mathrm{r} < 0.10$, the ratio indicates a reasonable level of consistency in the pairwise comparisons; if, however, $C_\mathrm{r} > 0.10$, then the values of the ratio are indicative of inconsistency, and therefore, it requires the weighting of variables to be revised.

Table 7 presents the pairwise comparison matrices and weights. The pairwise judgements were tested for their consistency ratio. Since most of the province presents values between 6000 and 9000 Wh/m^2/year, the experts decided not to prioritise solar potential as an evaluation criterion. Proximity to the electricity grid was the key weighting factor.

Once weights have been assigned and their consistency estimated, the suitability index using the linear weighted sum can be calculated (Eq. 5).

$$\mathrm{SI}p = \sum_{i=1}^{n} w_i x_{ip} \tag{5}$$

where SI is Suitability Partial Index for the cell p; w_i the relative weight of the factor i; and X_{ip} normalised value of the cell p for the factor i.

5. Semiotic representation of views by QGIS (Fig. 2; stage 5): the spatial views generated have been represented with open-access software QGIS, which is capable of visualising data in PostgreSQL-PostGIS formats, and is a serious alternative to proprietary software, being both faster and more stable. In addition, it is compatible with the Open Geospatial Consortium (OGC) standards, which allows for the exchange of geographical information and permits access to several users at the same time.

Results and discussion

Figure 4 illustrates excluded areas for the construction of PV solar plants, comprising an aggregate of 12,206 km^2, i.e. 87% of the total area of the province.

The territorial units Sierra Norte de Sevilla, Aljarafe-Marismas and Centro Regional de Sevilla have the highest percentage of their territory characterised as unsuitable for solar farming. Sierra Norte de Sevilla is largely forested and covered by protected natural areas, and the construction of solar plants is not considered in the relevant planning documents. Aljarafe-Marismas is chiefly composed of protected marshlands. Finally, Centro Regional de Sevilla embraces the most urban areas, where the road and rail networks are particularly dense. As such, it is the territorial unit with the fewest suitable areas for solar farming.

The presence of great expanses of highly fertile land in La Vega and Campiña Sevillana-Sierra Sur rules out much of their territory as unsuitable, although they are the areas with the highest percentage of land suitable for solar farming. This is because these territories are mostly flat and forested areas are few. Unlike in Sierra Norte, where agroforestry remains a significant economic sector, in Campiña and Sierra Sur de Sevilla the economy is based on dry-farming and marginal crops.

Concerning the areas with the highest potential, Fig. 5 presents the potentiality index values, normalised to a scale from 0.1 to 1. A value of 1 expresses the maximum potential.

As the results indicate, 1008 km^2 present a high potential (with values between 0.7 and 1), that is 7.1% of the territory of the province, of which 128 km^2 present the maximum potential (0.9% of the territory under study).

The highest value areas are mostly found in Sierra Norte, in the northern sector of Aljarafe-Marismas and in Sierra Sur. In general, these are flat areas with poor agricultural soil. Sierra Norte and Campiña-Sierra Sur score the highest in terms of solar radiation, especially in south-facing, unforested flat areas. High values are also attested in La Vega and Bajo Guadalquivir, also corresponding to highly exposed flat areas. This unit, however, hosts some of the main agro-towns of the province, and the road network and electricity grid are fairly well developed.

La Vega and Bajo Guadalquivir get top scores in 5 of the 8 evaluation factors (comprising 90% of the weight), and it is, therefore, unsurprising that most existing photovoltaic plants were built in these areas.

Considering that in order to be profitable a photovoltaic plant must be at least 10,000 m^2 in size, suitable areas decrease quite substantially (Sánchez-Lozano et al. 2014). Figure 5 illustrates the top-scoring areas (value 1), which can host plants of this size have an aggregate area of 60.8 km^2.

Although this may seem rather small, if we consider that the surface of the existing solar plants is approximately 10 km^2 (calculation based on the photointerpretation and digitalisation of the aerial photographs taken in 2013) and that their output is 212 MW, we may conclude that province

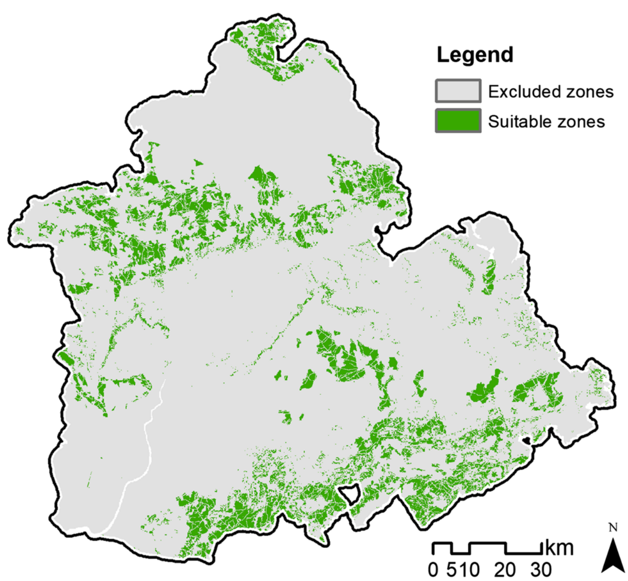

Fig. 4 Excluded and suitable zones

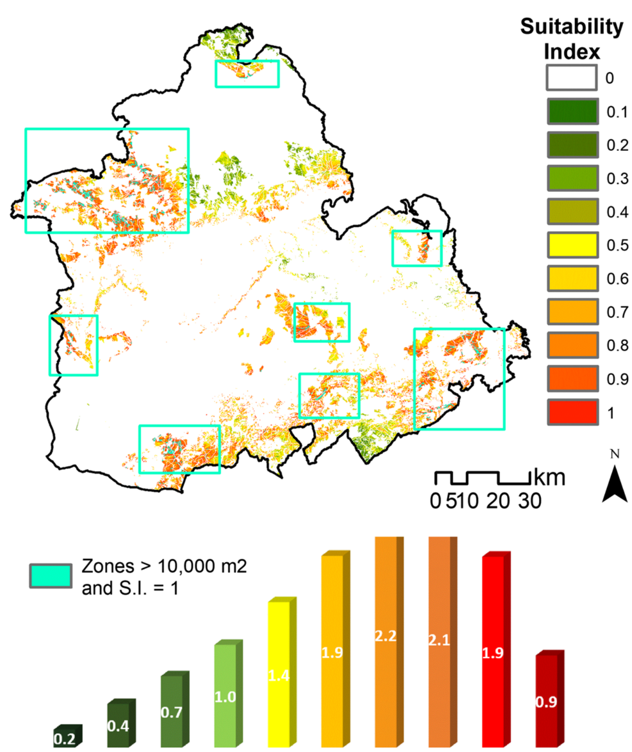

Fig. 5 Suitability Index

of Seville still has great untapped potential in terms of solar power.

It is worth commenting upon the weight assigned to the criterion 'global solar radiation'. In contrast to other works, in which this criterion was assigned the most weight (for an exception, see Uyan 2013, 2017); in this work, this variable is only fourth in importance, with a value of 0.11. This is owing to the fact that almost the whole of the area under study scores very high in this variable, and for this reason invited experts have decided that the variable is of little relative importance for the analysis.

Finally, a sensitivity analysis, which aimed to assess the impact of weights on the potentiality index, was undertaken. We designed a scenario 2 (Fig. 6a), in which potentiality index is calculated assuming that all factors carry the same weight (Tegou et al. 2010; Watson and Hudson 2015). The parameters were modified in the primary code.

The number of most suitable sites (suitability index = 0.9–1) for PV solar plants is relatively low in both cases (0.9% original scenario; 0.7% scenario 2). In addition, the proportion of the area under study which scores higher values (0.7–1) increases (0.7%) in the scenario 2 with respect to the original scenario, reaching 7.8% of the territory of the province.

According to the spatial distribution of the changes, the results show that a total of 525 km^2 (30% of the compatible territory) maintain the same potential value in both scenarios. In the other areas, 341 km^2 (19% of the compatible territory) decreases its potential value in scenario b and 939 km^2 (approximately 52% of the compatible territory) increases its potential value, by 0.1–0.2–0.3, respectively (Fig. 6b).

Conclusions

The present work aimed to determine the most suitable areas for the installation of photovoltaic plants in the province of Seville. We proposed a new methodology based on the combined use of a relational spatial data base managed by PostgreSQL-PostGIS and AHP; AHP is a common methodological choice for this kind of study. We began by defining a series of incompatibility criteria, based on the existing literature and planning documents. Then, we selected potentially

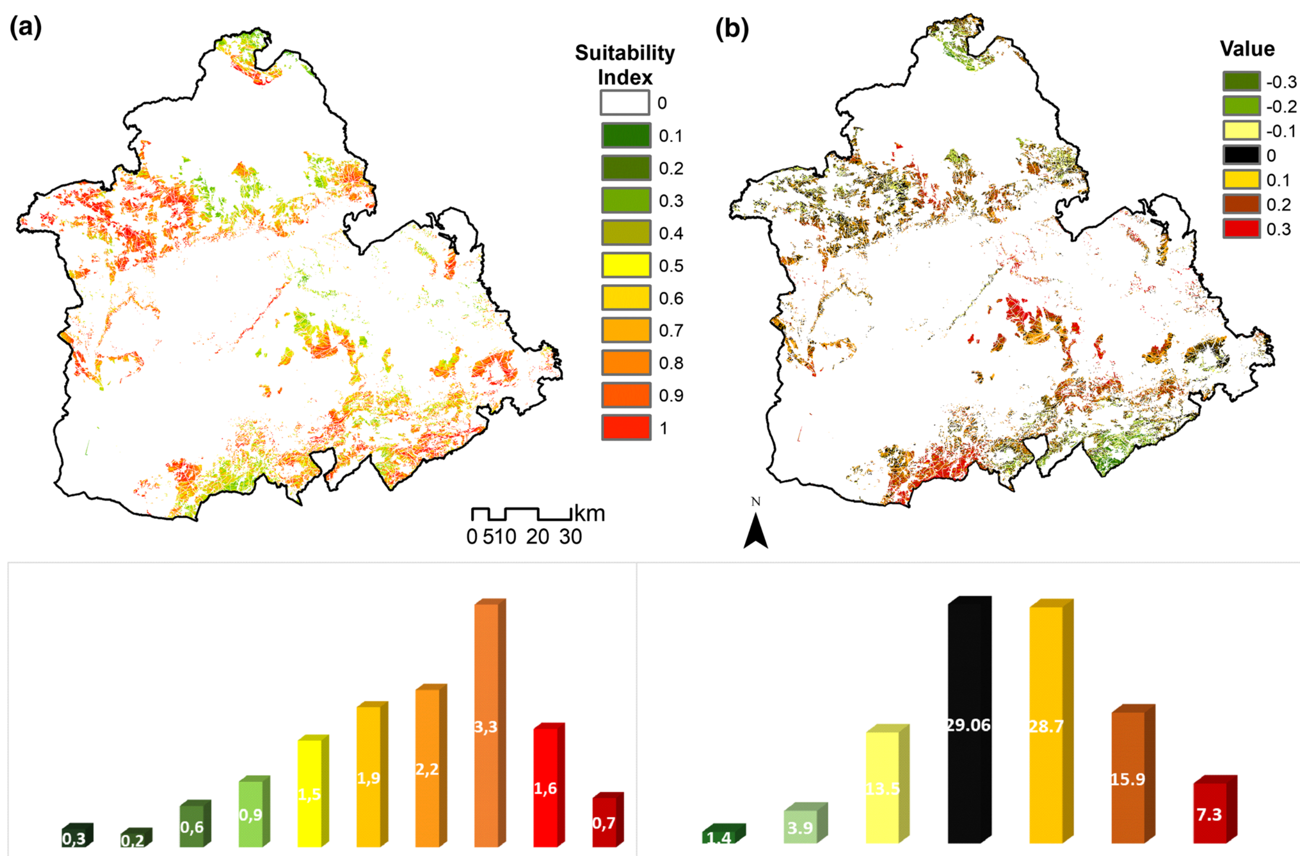

Fig. 6 Suitability Index in scenario 2 (**a**) and changes in the potentiality of the territory (**b**)

factors based on previous similar works and asked an expert panel to assign weights to these factors.

In contrast to other methodologies, which use multi-criteria analysis with geographical information systems, in this work the analysis has been carried out with a conceptual data model implemented by a spatial database managed by PostgreSQL-PostGIS. The great potential of this database manager has been facilitated by the generation of a SQL enquiry code with which to manage the data and undertake the necessary calculations.

Since the methodology leads to the generation of SQL views, once the codes have been created, the method can be applied to other geographical settings, and even to change some of the parameters to undertake a different analysis. This is crucial, because should the conditions change (construction of new solar plants, changes in the electrical grid and substations, new roads, etc.) or should we want to analyse a different region or area, the code does not need updating, and only the input tables in the database manager need to be changed. This is one of the greatest advantages of using PostgreSQL-PostGIS instead of GIS in the exploitation and analysis Stage, which makes this methodology a valid and useful tool for planners and investors.

All the operations undertaken in this work use open-access software: the spatial database manager PostgreSQL-PostGIS and desktop GIS QGIS. The latter has only been used for the spatial visualisation of the results.

The empirical analysis concluded that although in a substantial percentage of the province of Seville, around 12,206 km^2 (87%) are considered unsuitable for the generation of photovoltaic energy. Although the remaining percentage may seem small, it represents great untapped potential in terms of solar power.

We think that this work will be useful for planners and investors, and as a work of reference for future studies concerning the province of Seville.

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