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Wind farms suitability location using geographical information system (GIS), based on multi-criteria decision making (MCDM) methods: The case of continental Ecuador

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ABSTRACT

The aim of this research was to implement a geographical information system with multi-criteria decision making methods, to select the most feasible location for installing wind power plants in continental Ecuador. In addition, a standardization process was performed, which consists of establishing an overall performance index to evaluate the results. Finally, the Pearson correlation coefficient is used to analyze mutual correspondence between multi-criteria decision making methods.

In this research, different selection criteria which include meteorological parameters (wind speed, air density), relief (slope), location (distances to substations, road network, urban areas, transmission lines, charging ports) and environmental parameters (vegetation coverage), have been considered.

The results of this research revealed that the site with the highest overall performance index is the Andean region of Ecuador, with an area of more than 617.5 km^2. The outcome of the overall performance index indicates that the four selected multi-criteria decision making methods provided similar results, where the value was equal to or greater than 75% of the maximum punctuation of an ideal location. In this context, the methods analyzed converge to similar solutions and indicate that the multi-criteria decision making method is a powerful tool for selecting ideal locations for wind farms.

1. Introduction

Energy consumption is one of the clearest measures of progress and social welfare. In this way, the function of the current economic model that depends on continuous expansion requires an equal growth in the demand of energy to be sustainable. However, an important concept related to this issue is the “energy crisis”, which occurs when the price in the supply of energy resources rises within an economy. The energy crisis is currently of concern, due to the world’s demands on the limited natural resources that are used to power industrial societies. These resources are diminishing as the overall demand rises. These natural resources are available in limited supply as either they are finite, dependent on climatic conditions or dependent on finite resources. Consequently fossil fuels are a finite resource, which reveals the fact of the energy crisis in the world’s economy. Additionally, the excessive use of oil, gas and coal (or so called fossil fuels), produces more carbon dioxide (CO_2) than the planet can maintain, which leads to global warming and ecological unsustainability. In this regard, many countries worldwide introduce renewable energy systems in their energy supply sources, to produce reliable and environmentally friendly energy.

A key feature of the expansion of renewable energies, on 2014 around the world was the investment of $131.3 BUS$ in developing countries [1,2]. In the case of Ecuador, the development of the energy sector has entered into a new phase since 2011 [3]. Ecuador is rich in renewable energy resources such as wind, solar, geothermal and biomass. These energy resources have not been explored in the past due to a solid fossil fuel energy supply. Nowadays, Ecuador is transforming the energy mix in order to fulfill the country’s energy demand with renewable energy resources and environmentally sustainable standards. The main changes in the energy mix are an increase in an optimal and sustainable manner of access to primary

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energy resources, while changing residential and commercial consumption patterns, as well as transportation possibilities, to more efficient ones. For this reason, 5227 MW of renewable energy power will be installed by 2022, which represents an investment of 9.128 BUS$, and will cover 83.61% of the country's energy demand [3]. In the case of wind energy, Ecuador has explored the land's resources in the Andean, Coastal and Island regions according to the Wind Atlas published by the Ministry of Electricity and Renewable Energy of Ecuador (MEER) [4].

Wind power is considered the energy implantation source with the fastest growth in the world [4,5], according to five important factors listed below:

- The need linked to the progressive depletion of fossil fuels and the search for sustainable energy development without compromising future generations.
- Potential for sufficient wind resources on various parts of the earth.
- Technological capability to develop increasingly efficient wind turbines.
- The vision of the pioneers in this field, who in the second half of the last century led the technological development bringing us to the current situation.
- The policies to facilitate the implementation of wind energy, both in terms of administrative procedures and compensation for producers.

One of the inherent difficulties of wind power and renewable energy is the fitful nature of production. A conventional energy source power plant can be located anywhere and does not depend on where and how the fuel supply stands. Instead, wind farms must be located where the wind is most available. In addition, the wind farm location is subjected to the wind resources assessment, where the wind turbines on average work above 3 (m/s) wind speed [4], [6]. Therefore, it is vital to choose the best location for wind farm settlement with rigorous considerations, such as electrical and communication infrastructures and environmental and economic feasibility.

This shortcoming can be dealt with by adopting a multi-criteria decision making (MCDM) method. MCDM methods are important tools for the selection of wind farm locations, because of their ability to provide adequate solutions. The evaluation of MCDM methods compares different elements according to their characteristic properties in order to select the best wind farm localization alternative (distance to urban areas, distance to distribution substations and transmission lines, land uses, distance to ports, airports or terminals transport, slope, wind speed, air density, etc.) [7–12].

The application of MCDM methods has been conducted in many disciplines. For instance, Pohekar and Ramachandran [8] and Ho [10] performed an applications review, which integrated the Analytic Hierarchy Process (AHP). In addition, there are many examples of the application of MCDM methods in renewable energy sources research, such as: Gwo-Hsiung et al. [13], who studied the use of MCDM for new energy system development in Taiwan by AHP and the Preference Ranking Organization Method for Enrichment Of Evaluations (PROMETHEE). The decision makers (DSS) and PROMETHEE II for new renewable energy exploitations have been applied by Georgopoulou et al., [14]. Pohekar and Ramachandran [8] published a review for a sustainable energy-planning project, which included MCDM methods such as PROMETHEE, AHP, Elimination and Choice Expressing Reality (ELECTRE), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Fuzzy, etc. More recently, Amy et al. [15], developed a model based on AHP associated with benefits, opportunities, costs and risks (BOCR), to perform a strategic selection of wind farms in China. The VIKOR method to investigate the selection of a renewable energy project in Spain has been applied by San Cristobal [16].

The MCDM methods in this research were processed with geographical information systems (GIS). The use of GIS allows the organization, storage, manipulation, analysis and modeling of large amounts of data from the real world that are linked to a spatial reference shaped grid. GIS facilitates the incorporation of social, cultural, economic and environmental criteria that leads to a more effective decision making. Furthermore, when GIS is joined to MCDM methods, it provides a good tool for selecting the optimum site for wind farms. On the basis of these conditions, the MCDM methods provide a range of techniques and procedures for structuring the advantages, disadvantages and risks associated with the decision making problem, evaluating the alternatives under specific considerations.

Several studies relating GIS-MCDM have been conducted about new energy resources such as: Sanchez-Lozano et al. [17], who evaluated solar farm locations in south-eastern Spain based on GIS and MCDM methods, as well as AHP and TOPSIS. GIS with an AHP-Ordered Weighted Averaging (OWA) aggregation function to derive a wind farm land suitability index, to spot wind farm locations in Oman has been developed by Al-Yahyai et al., [18]. Aydin et al. [19], applied GIS-based on the OWA method for wind farm locations in the west of Turkey.

This research aimed to analyze the most feasible location for installing wind turbines based on GIS-MCDM. The area of study was continental Ecuador, where no previous research has been conducted. The MCDM methods applied to this research were the AHP method that was implemented for calculating the weights, the (OWA) Occupational Repetitive Actions (OCRA), VIKOR and TOPSIS. An Overall Performance Index (OPI) has been applied to evaluate the results. Finally, the mutual correspondence between MCDM methods has been evaluated by a Pearson correlation coefficient.

The current research is structured as following: The Materials and methods for the study is described in Section 2. The results are presented in Section 3. The discussion of the results is described in Section 4. The conclusions of the research are exposed in Section 5.

2. Material and methods

2.1. Geographic information systems

GIS has been used as a tool of research and application since the 1970s. It involves a number of academic fields including wind technology. GIS are designed to store, retrieve, manipulate, analyze and map geographical data [20]. Raster and vector are the two types of coverage representation with which GIS operates. The raster is represented by a rectangular grid called pixels that contains specific information according to a specific geographic location. Vectors maintain a geometric figure (points, lines and polygons), which define limits that are associated with a reference system [17]. The storage of this information is presented in a geodatabase which provides order, structure and standardization of the data. All the geographic information was processed as a raster in this research, due to the continuous analysis of the spatial variables such as: wind speed, terrain elevation, air density and vegetation cover among others. GIS is a powerful tool in gathering and organizing spatial data, as many successful examples to identify potential locations for generating renewable energy emerge [20,21].

The raster processes are faster in the evaluation of problems, including mathematical combinations such as the MCDM methods. The MCDM in a GIS environment is based on criteria represented by a layer of georeferenced cartographic information; therefore, every point of the territory received a value regarding the object activity of the decision [21]. The ArcGIS software was used to rasterize and standardize the data layers under linear and logistic functions in this research. With this starting point and the inputs generated, the multi-criteria analysis and the comparison of results were conducted using R, which is a programming language specializing in calculus and statistics.

2.2. Multi criteria decision making (MCDM) methods

Wind farm sitting is a MCDM problem. The selection is made by a number of alternative locations in accordance with a set of criteria and possibilities. MCDM methods are analytical tools employed to judge the best alternative of a set of possibilities and easy to adapt to different requirements. The MCDM methods can be broadly divided into two categories; (i) multi-objective decision making (MODM), and (ii) multi-attribute decision making (MADM). There are also several methods in each of the above mentioned categories. Priority based, outranking, preferential ranking, distance based and mixed methods, are some of the popular MCDM methods commonly used to select a location for renewable energies [8,10].

The AHP method has been widely applied in solving a variety of problems, including applications related to planning renewable energy installations [13,15,18]. In this article the AHP process has been used to calculate the weight of the criteria to install wind farms in different locations. The OWA, OCRA, VIKOR and TOPSIS methods were used to evaluate the problem. These methods were chosen because each alternative can be evaluated with the GIS assessment criteria database. Finally, the Pearson correlation coefficient is used to perform the statistical comparison between the different MCDM methods.

2.2.1. The analytic hierarchy process (AHP) method

The AHP is a structured technique to help people to deal with complex decisions. It was developed by Thomas L. Saaty [9] in the 1970s and has been considerably improved since then. The AHP identifies the important criteria for the decision making process. It creates a hierarchical structure consisting of successive levels, starting from the overall objective, sorting criteria and sub-criteria, and ending with the proposed alternatives.

The method employs a pair-wise comparison measurement mode to quantify the importance of each criterion or sub-criterion, using a nine point internal scale.

A great amount of information about the AHP method is found in literature [8,9,22,23]. The AHP method steps used in this research can be observed in Fig. 1.

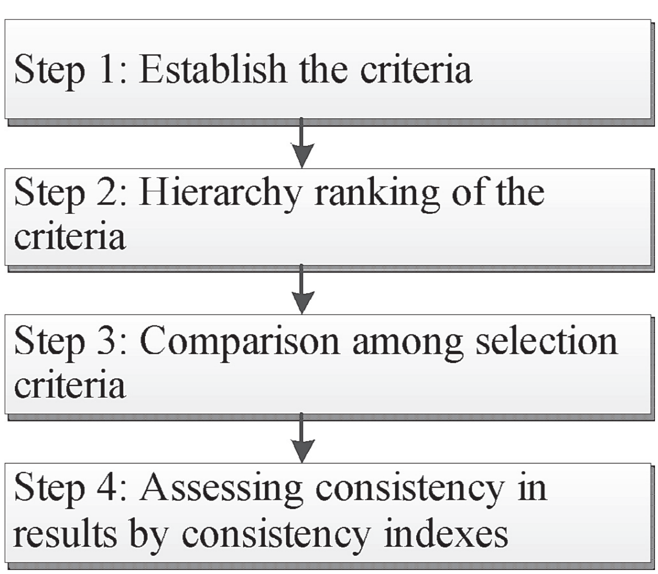

Fig. 1. AHP method algorithm.

2.2.2. The Ordered Weighted Averaging (OWA) method

The OWA method provides a parameterized family of aggregation operators, which have been used in many applications [24]. An OWA operator of dimension n is a mapping OWA: $R^n \rightarrow R$ that has an associated weighting vector W of dimension n having the properties $w_j \in [0, 1]$, $\sum_{j=1}^{n} w_j = 1$ defined in equation (1).

$$OWA(a_1,\ a_2,\ \ldots a_n) = \sum_{j=1}^{n} w_j \cdot b_j \tag{1}$$

where b_j is the jth largest of the a_i.

2.2.3. The Occupational Repetitive Actions (OCRA) method

The OCRA method uses an intuitive technique to incorporate the

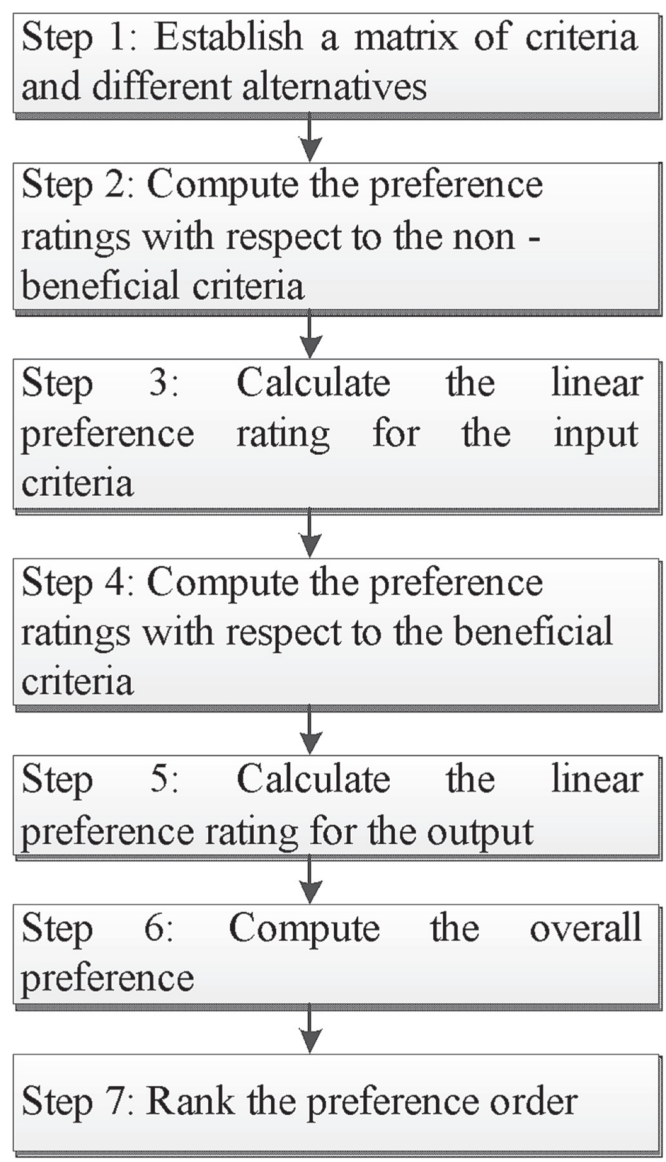

Fig. 2. OCRA method algorithm.

preferences of the decision maker on a relative importance of the criteria [11]. The OCRA method diagram can be observed in Fig. 2.

2.2.4. The VIKOR method

The VIKOR method was developed by Serafim Opricovic to solve decision problems with different criteria [12]. VIKOR ranks alternatives and determines the solution, denominating it as a "compromise", obtaining the ideal solution. More information about the VIKOR method is found in literature [12,16]. The VIKOR method algorithm is presented in Fig. 3.

2.2.5. The Technique for Order of Preference by similarity to ideal solution (TOPSIS) method

The TOPSIS method is a multiple criteria method to identify solutions from a finite set of alternatives, developed by Hwang and Yoon [6]. The basic principle of the TOPSIS method is to choose the alternative of the shortest and longest distance from the positive and negative ideal solutions, respectively. An ideal solution is defined as a collection of scores or values with the shortest geometric distance for all criterions considered. The TOPSIS method diagram is presented in Fig. 4.

2.2.6. Correlation between MCDM methods

Several techniques allow us to compare qualitatively and quantitatively raster maps, recognizing visual or numerical similarities on the analyzed datasets at the current time [25]. Numerical comparisons use procedures based on statistical and mathematical modeling to find relationships between large datasets [25].

As in other studies that are based on GIS techniques, in this research a pairwise comparison of maps using the Pearson correlation is analyzed [26,27]. The comparison has been performed using the raster map values for processing each pixel at each method described in MCDM methods.

In this research, the raster map solution of the MCDM methods was compared with the Pearson correlation expressed in equation (2). In this context, each alternative was compared twice, for all pixel values of each alternative and on the pixels which have a value greater than 70. In the second case of comparison, six different masks were elaborated to compare each method.

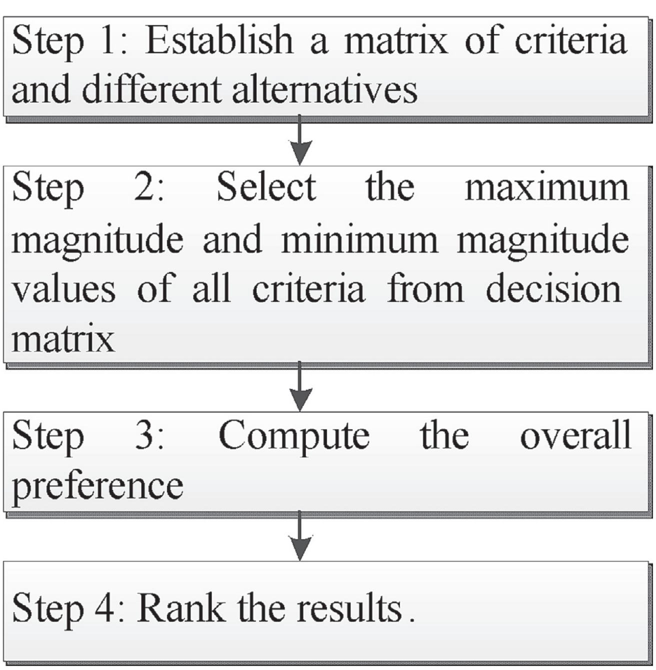

Fig. 3. VIKOR method algorithm.

$$\rho_{xy} = \frac{n\sum x_i \cdot y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - \left(\sum x_i\right)^2} \cdot \sqrt{n\sum y_i^2 - \left(\sum y_i\right)^2}} \quad (2)$$

where, x_i and y_i are the values of the raster maps to be compared, ρ_{xy} is the Pearson Correlation Coefficient and n is the number of values analyzed.

2.3. GIS–MCDM methodology to prioritize locations for wind farms suitability

Combining GIS with MCDM allows us to evaluate the criteria with its factors through the use of attributes within a certain range of decision rules and assessment [17]. The most common use of GIS-MCDM corresponds to the selection of suitable sites for locating human activity.

For this assignment, a methodology based on the spatial analysis for the multi-criteria evaluation was used. The research was performed in two stages; the first one was the definition of factors and restrictions in the investigated area. Consequently, the information was prepared by a rasterization and a standardization process. The second stage consisted in an evaluation of the most suitable site through MCDM methods (Fig. 5). The AHP method was used to

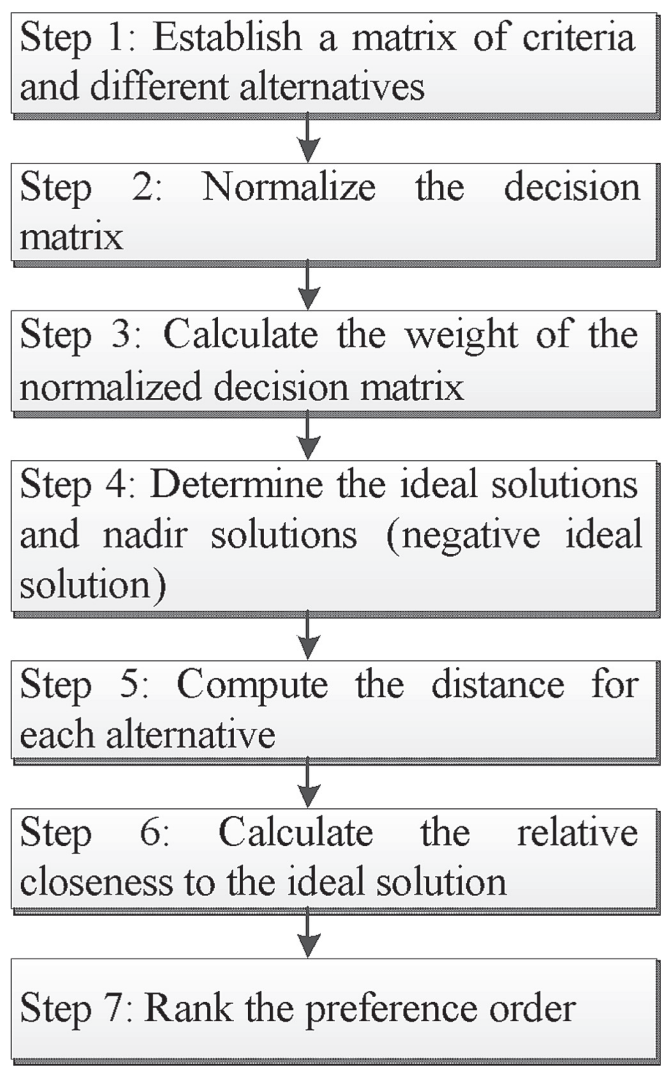

Fig. 4. TOPSIS method algorithm.

quantify the importance of the different factors used during the process. Hence, OWA, OCRA, VIKOR and TOPSIS were used to evaluate the different alternatives.

2.3.1. *Definition of restrictions and factors*

2.3.1.1. Definition of the analyzed geographic extension. The continental area of Ecuador has been selected for the implementation of wind farms in this research (Fig. 6). The area covers 249 000 km^2, which includes all the continental provinces of Ecuador.

MEER published the Wind Atlas of Ecuador in 2013 [4]. The wind resource modeling is operated with a spatial resolution of 200 m $\times$ 200 m and the integration of a digital map that uses geoprocessing resources, which calculate the performance and electrical energy production. All the information considered in this research was presented in the raster format, with the same resolution and extension as the Wind Atlas of Ecuador [4].

2.3.1.2. Compilation of cartographic information and identification of factors and restrictions. The raster and vector cartographic information was determined with help from Ecuadorian government's public institutions as it is presented in Table 1. The information includes different criteria such as physical, socio-economic, technical and environmental issues. In order to perform the evaluation of land suitability, the following criteria were considered: wind speed, digital elevation model, distance of substations, air density, distance to roads, distance to transmission lines, vegetation coverage and land use, charging ports distance, urban areas, etc. Criteria were considered as factors or restrictions within the MCDM methods.

The restrictions reduce the positive wind farm suitability over the studied area, based on policy or social-environmental issues. In most cases, legal restrictions were taken into account to establish the suitable areas to locate wind farms. While in other cases, the physical impossibility or simply the inadequacy of the land was a sufficient restrictive criterion to eliminate certain areas. However, most of the restrictions are due to legislation, so an inventory of the legal framework had to be established with the current laws [28,29].

Environmental impacts associated with wind farm energy generation are commonly accepted and considered by scientists. These impacts are generally listed as effects on animal habitats such as bird collisions, noise generation, visual impact, safety issues, electromagnetic interference, and distance to airports and to population centers. Moreover, flood area, seismicity and volcanic hazards are considered as a restriction because these natural phenomena can cause structural damage to wind farms or even electric shock [15,18,19,30,31].

The identified criteria of restrictions based on literature reviews is presented in Table 2, and the map of suitable and restricted areas for wind farm site location is illustrated in Fig. 7. The layer of the Ecuadorian territory with all the land register includes 6 225 000 pixels, each of which is a record in the database that has the following assigned information: A filter was performed on the layer with the restricted areas. The raster included 3 832 583 pixels located in suitable areas.

Factors are based on the weighting and compensation variables that will influence positively (aptitude) or negatively (impact) on the activity of the object of decision, so they should be inventoried and classified previously [22]. Table 1 presents the summary of layers with information selected as factors for this study, which have been selected by its positive and negative importance and influence the analysis in this manner. The coverage criteria considered in the analysis of the study was wind speed, ground slope, distance to the electrical substations and to the road, transmission lines, distribution lines and seaports, which are described in more detail below:

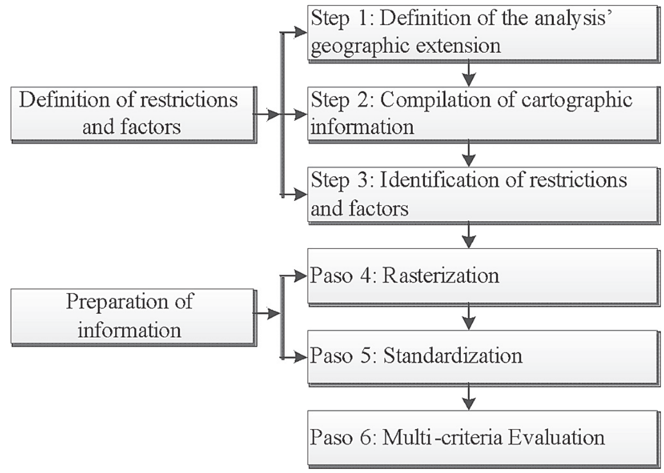

Fig. 5. Steps to develop the MCDM methods.

- The wind speed model selected was the 80 m height, according to the wind turbines mean hub height for 2 MW of nominal power at 3 m/s. The wind speed was integrated in the Ecuadorian surface. In this case, the annual average wind speed was equal to or higher than 5 m/s [4].
- For the elevation digital model, the average ground slope criteria established as not exceeding 15%. For this reason, the most suitable areas were those that had zero slopes, and the least suitable sites were those with average ground slopes of maximum 15% [4].
- The construction of wind farms close to existing electric substations, road network, to the transmission and distribution lines, is preferable [17,18,22]. The construction of this

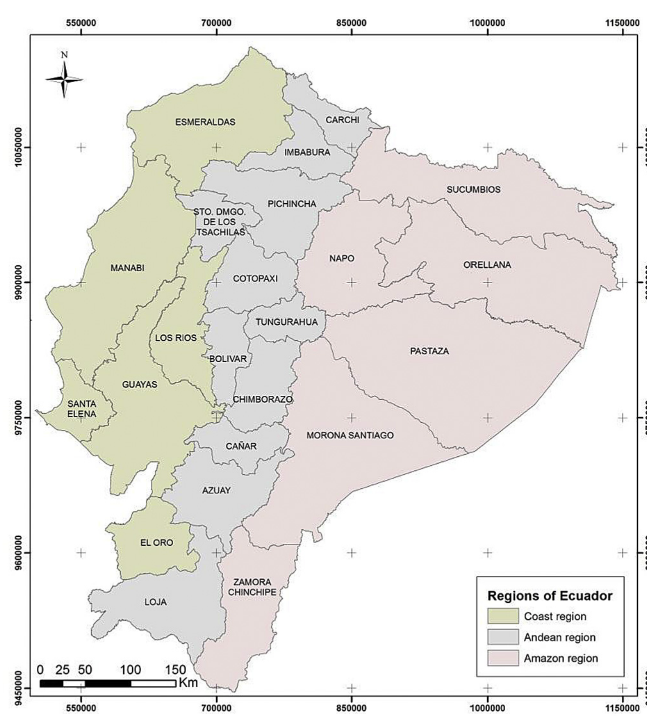

Fig. 6. Continental Ecuador separated by regions and provinces.

Table 1
Cartographic information and identification of factors and restrictions.

Criterion	Institution	Year	Identification of factors and restrictions
Wind speed over 80 m	Ministry of electricity and renewable energy	2013	Factor
Digital elevation model	Ministry of electricity and renewable energy	2013	Factor
Substations distance	Agency of regulation and control of electricity	2015	Factor
Air density	National institute for energy efficiency and renewable energy	2015	Factor
Road network	Ministry of transport and public works	2015	Factor
Transmission lines	Agency of regulation and control of electricity	2015	Factor
Vegetation coverage and land use	Ministry of agriculture, aquaculture and fishing	2002	Factor
Charging ports	Ministry of transport and public works	2012	Factor
Urban area	Military geographical institute	2013	Factor /Restriction
Flood area	National institute of meteorology and Hydrology - ministry of agriculture, aquaculture and fishing	2002	Restriction
Volcanic hazard	Risk management secretariat	2009	Restriction
Airports	Ministry of transport and public works	2012	Restriction
National system of protected areas	Ministry of environment	2015	Restriction
Mangroves	Ministry of environment	2015	Restriction
Archeology	National institute for cultural heritage	2015	Restriction

Table 2
Criteria of restrictions.

Criteria	Restriction
Urban area	Considered 3000 m of security area [32]
Flood area	Completely restricted area
Volcanic hazard	Completely restricted area
Airports	Completely restricted area or 2500 m away from airports [32]
National system of protected areas	Completely restricted area or 250 m from ecologically sensitive areas [33]
Mangroves	Completely restricted area or 4000 m from water bodies [34]
Archeology	Completely restricted area

infrastructure causes deforestation, disruption of habitats and wildlife crossing, urban sprawl and an increased cost and transport of construction materials over long distances, which also increases the emitted pollutants [22]. Distances to the electric substations, to the road network, to the transmission and to the distribution lines can be minimized by different methods such as Euclidean distance, Euclidean Allocation, Euclidean direction, cost distance, etc. In this research the Euclidean distance to the suggested wind farms site has been used. These conditions could reduce costs in the implementation phase and amortize the investment in a short time period. In this manner, costs for machinery and equipment transportation; as well as increasing the electrical grid would be less expensive. Several examples can be consulted in the literature for how to employ this tool to reduce distances [18,19,22].

- The seaports are the most important transport terminals, where different equipment and machinery for the wind farm project enters the country. The different charging ports selected influence in the costs of the project, according to the distances to the ports. Therefore, the costs will be lower if the charging ports located in the coastline are closer to the wind farms. Due to the aforementioned reasons, the Euclidean distance has been taken into account to minimize the distance to seaports.
- According to the bibliography [4], the turbine power density depends on the air density. In the case of high altitudes as in the Andean region, there is low air density and high wind speed, which comprehends areas of great interest for further investigation [4].
- The optimal areas considered for the construction of a wind farm are those that present no vegetation coverage and a high degree of alteration by human intervention. It is not possible to build wind farms in urban areas because they affect the residents' wellbeing. Therefore, a 3 km security zone from urban areas was considered as a forbidden location to generate wind power [19].

2.3.2. Preparation of information

Preparing information is related to the organization and layout of geographic information for its analysis with different MCDM solution methods. During this period, original data was transformed in different procedures to secure its appropriate use during the MCDM evaluation.

2.3.2.1. Rasterization. The analyzed data employed in this study was available as vector structures (point, lines or polygons), or as a matrix structure, called raster. To convert vector coverage to a raster format requires an acquainted extension grid. The precision of the extension grid is defined by the cells size. In this case, the pixel size was 200 m $\times$ 200 m, and the extension grid covered the continental territory of Ecuador. The MCDM requires a raster where each pixel contains a numerical attribute according to the represented variable. Therefore, rasterization is considered a previous assignment in order to continue with the MCDM methods.

In the rasterization process, each type of variable to be transformed is considered. A raster model derived from original information is considered as a factor model. Moreover, vector structures are simply transformed to raster like structures when dealing with a restriction. Rasterization processes of applied values in different coverages are summarized in Table 3.

The air density map was estimated from the ideal gas relation based on ISO 2533-1975, which depends on atmospheric pressure and temperature. The temperature map was calculated with weather values/data from the National Institute of Meteorology and Hydrology of Ecuador (INAMHI), that were interpolated using

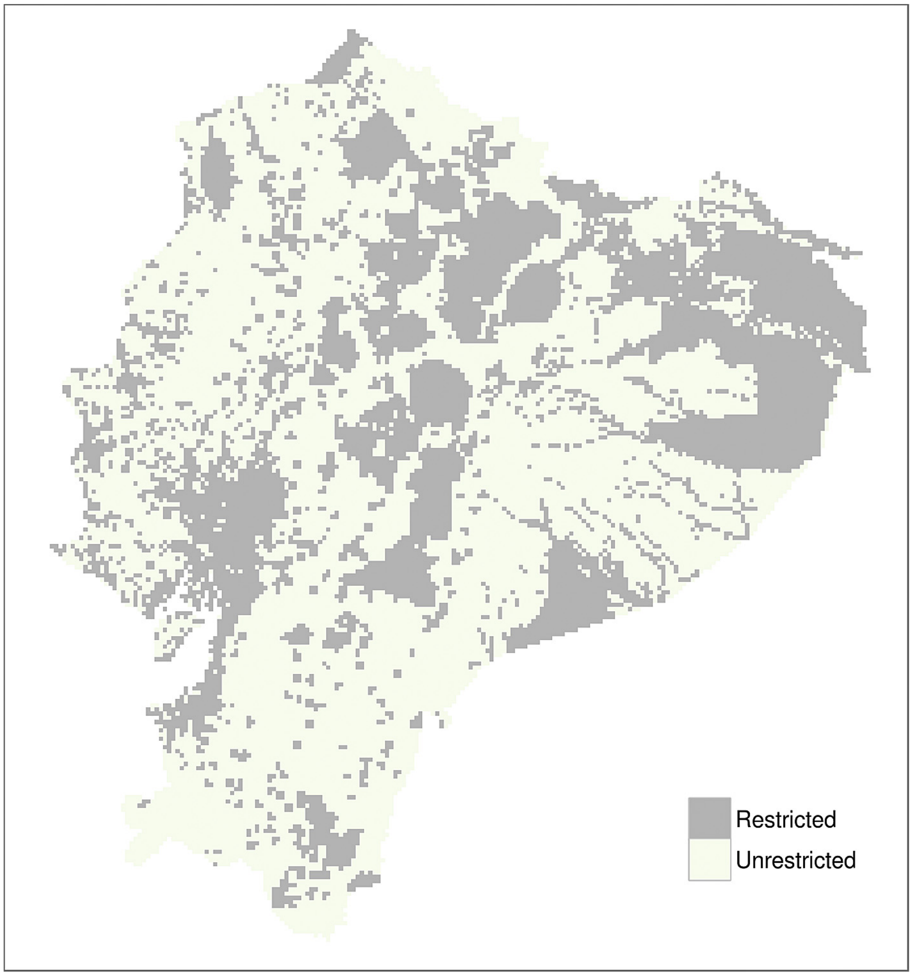

Fig. 7. Map of suitable and restricted areas for wind farm site selection.

Table 3
Rasterization processes applied to each criteria of information.

Criteria	Rasterization
Wind speed over 80 m	No transformation
Digital elevation model	Calculating slopes
Substations	Euclidean distance calculation
Air density	Air density map is estimated from ISO 2533-1975.
Road network	Euclidean distance calculation
Transmission lines	Euclidean distance calculation
Vegetation coverage and land use	Value assignment and rasterization
Charging ports	Euclidean distance calculation
Urban area	Euclidean distance calculation
Urban area	Transformation binary raster
Flood area	Transformation binary raster
Volcanic hazard	Transformation binary raster
Airports	Transformation binary raster
National system of protected areas	Transformation binary raster
Mangroves	Transformation binary raster
Archeology	Transformation binary raster

regionalization methodologies of meteorological variables of Fries et al. and the National Institute of Energy Efficiency and Renewable Energy of Ecuador (INER) [35,36]. The raster map is based on data with normal climate from 1981 to 2010 and maintains the previous analyzed resolution.

The atmospheric pressure map was estimated through the barometric relation between altitude and pressure, which was obtained from the hydrostatic equation [37,38]. This relation is expressed in equation (3).

$$p(h,T) = P_0 e^{-\frac{mgh}{kT}} \tag{3}$$

where, $p(h,T)$ is the atmospheric pressure at a height above sea level, P_0 is the atmospheric pressure at sea level, which is

Table 4
Functions applied for factor standardization.

Id	Factor	Standardize function
a	Wind speed	Logistic growth
b	Slope	Decreasing function
c	Distance to electrical substations	Logistic growth
d	Air density	Logistic growth
e	Distance to road network	Logistic growth
f	Distance to an urban area	Logistic growth
g	Distance to transmission lines	Logistic growth
h	Vegetation coverage and land use	Value Assignment
i	Distance to charging ports	Linear function and cost distance

approximated 1010 mb, g is gravity, and k is the Boltzmann constant. Last, h and T correspond to the elevation and temperature map. The constant m is estimated from the molar mass M_A of air and the Avogadro number, N_A where $m = M_A \cdot N_A$.

Air density is estimated from the relation of ideal gases, as the standard ISO 2533:1975 [39] recommends. Air density is expressed in equation (4).

$$\rho_a(T,\ p(h,\ T)) = \frac{M_a p(h, T)}{RT} \tag{4}$$

where, ρ_a is the air density, M_a is the air molar mass equal to

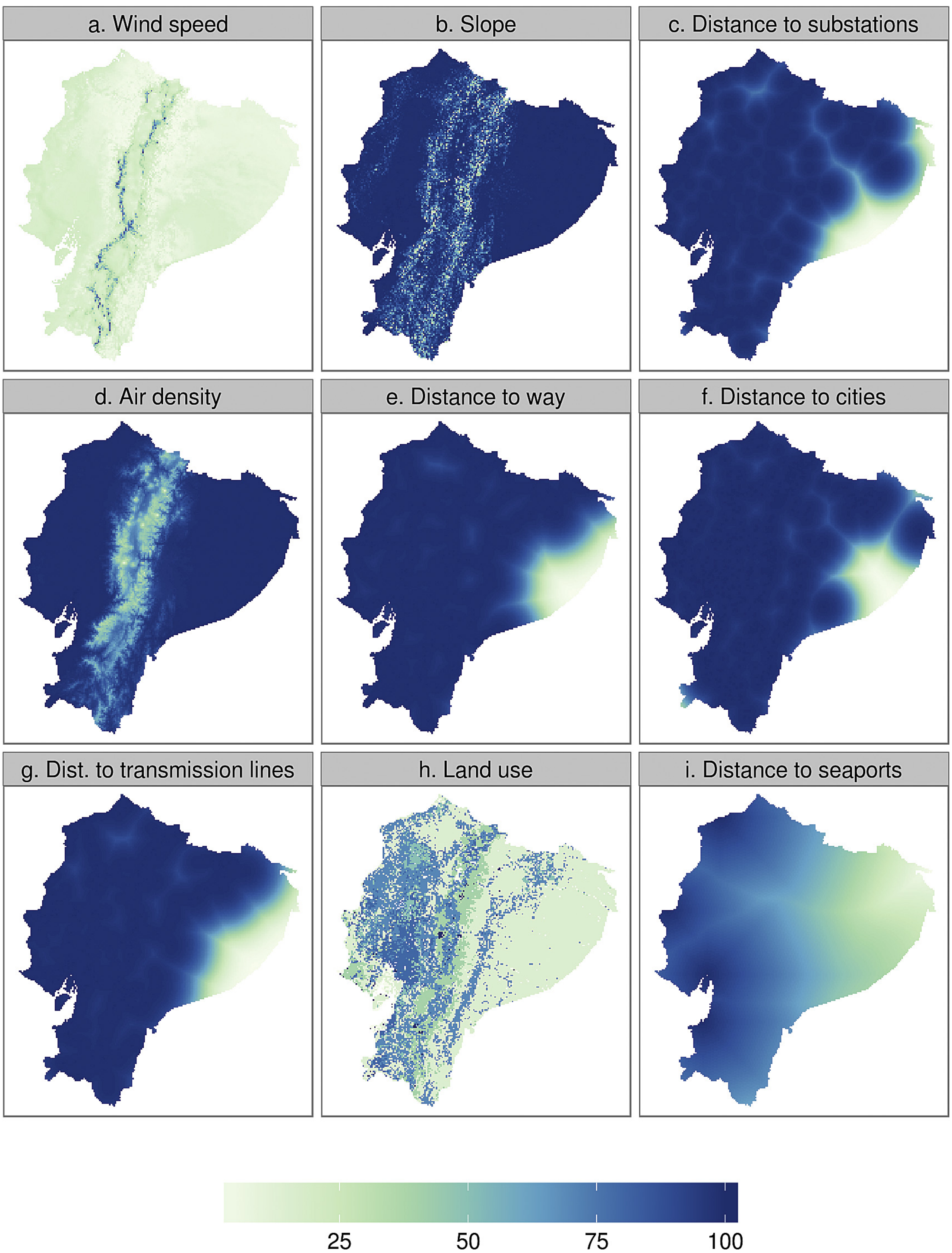

Fig. 8. Layers of the factor standardization.

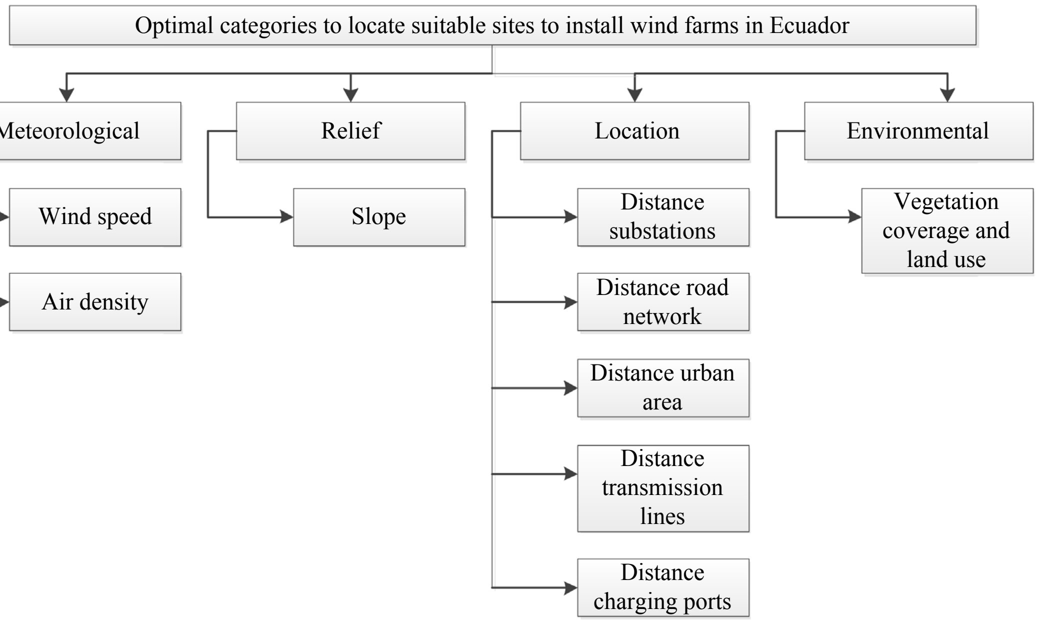

Fig. 9. Hierarchy of criteria and factors.

Table 5
Component weights and its factors.

Category	Weight	Factor	Weight
Meteorological	0.5309	Wind speed	0.3982
		Air density	0.1327
Relief	0.2151	Slope	0.2151
Location	0.2150	Distance to electrical substations	0.1009
		Distance to road network	0.0432
		Distance to urban area	0.0432
		Distance to transmission lines	0.0185
		Distance to charging ports	0.0092
Environmental	0.0390	Vegetation coverage and land use	0.0390

0.02896 kg/mol, R is the universal gas constant equal to 8.314 Pa*m^3/mol*K. Replacing equation (3) in equation (4) the air density regarding altitude and temperature is obtained in equation (5).

$$\rho_a(T,\ p(h,T)) = \frac{M_a P_0 e^{-\frac{mgh}{kT}}}{RT} \tag{5}$$

2.3.2.2. Factors standardization. For the selection of wind power plants it is necessary to consider factors such as wind speed, distance to electrical substations, air density etc., which do not have linear behavior in the standardization process for the site selection. The optimal values of these factors must be prioritized in each case, so most of the time a linear function should not be used.

The standardization process consists of a rescale of raster values that starts using a mathematical function (line or curve), specified according to predefined standardization criteria.

In a suitability model, the decreasing logistic function is ideal when the minor incoming values are less preferred. When the incoming values increase, the preference decreases rapidly to a stage where the minimal preferences are established for higher incoming values. While the preferences in transformation logistic functions increase instead of decreasing [40]. Meanwhile, the transformation of the linear function is ideal when the preferences for the values increase or decrease linearly [40].

The resulting scale is a range of continuous whole values between 1 and 100, where the minor value is the less important and the highest value is the most representative. In this assignment logistic or linear functions were used according to the variable, as illustrated in Table 4.

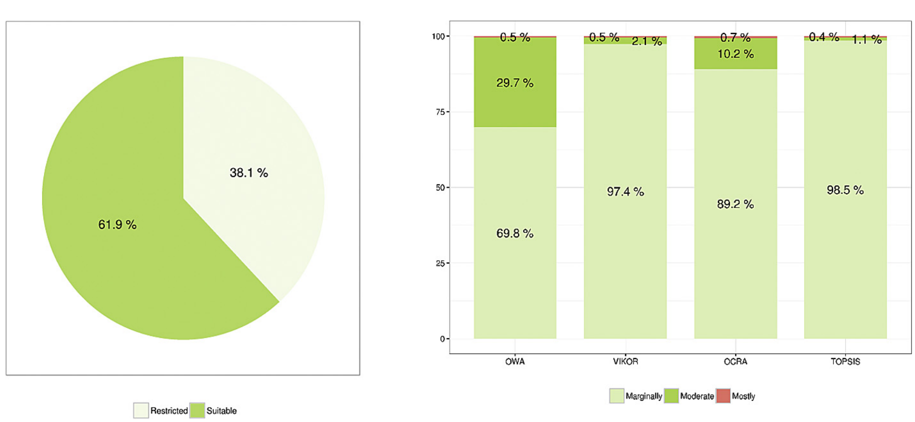

Fig. 10. Suitability surface distribution (left) and MCDM methods classification for suitable land surface (right).

The resulting layers of the factor standardization process mentioned in Table 4 are illustrated in Fig. 8. All layers that were considered as factors present values between 1 and 100 for this calculation. However, layers considered as restrictions were added in just one binary layer map that represents values of 0 (Restricted) and 1 (Unrestricted), as illustrated in Fig. 7.

2.3.3. MCDM evaluation

Once the factors have been standardized it is necessary to calculate the weight of the specific criteria, to put the problem under analysis.

Wind power plants can be considered desirable. However, they produce adverse effects on society or on the environment. Although a wind farm may cover a large area of land, other land uses like agriculture are compatible with it. The location of new wind farms can upgrade the electrical grid and infrastructure needed for its operation.

Four elements were determined by their importance for this research: meteorological, relief, location and environmental. The factors were classified according to its correspondence and importance within the different categories. Fig. 9 presents the hierarchy of criteria subject to serve as a starting point for the application of the AHP.

The criteria weights that influenced the decision problem were obtained from literature [15,17–19], in order to choose the most suitable site for installing wind farms. The obtained results of the application of the AHP method are presented in Table 5. Therefore, the most important element was the meteorological (53.1%), the second one was the relief (21.5%), the third one the location (21.5%), and the least important was the environmental (3.9%).

3. Results

Nine factors employed in this study were the inputs to the OWA, OCRA, VIKOR and TOPSIS methods, to find the most suitable location for installing wind farms in Ecuador. The results have been obtained based on the relative weights calculated with the AHP method, which are illustrated in Table 5. In addition, an OPI to evaluate the results from 1 to 100 was accomplished. The evaluation of the score from 1 to 100 clarifies that the score is proportional to the degree of suitability of the land. A high score indicates that the analyzed area is a suitable site for a wind farm. This assignation allows for choosing category ranges with more flexibility and precision, in a way that the best results are obtained with the least possible risks. The above mentioned OPI is divided into three intervals, so that each interval indicates a different capacity that contains suitable pixels; the marginally (1–49), the moderate (50–74) and the most (75–100).

The distribution of the most suitable land and the restricted areas is presented in Fig. 10. Hence, the suitable land for the installation of wind farms was 61.9%. Therefore the usable area was about 154380 km^2. With the prior determined factors and application of MCDM, an assessment classification was obtained that demonstrated that the most suitable locations to install wind farms were below 0.4%, which represents up to 617.5 km^2. Meanwhile the moderately suitable area was between 1.1% and 29.7%, and lastly, the marginally suitable surface was between 69.8% and 98.5%.

The ranking of the land suitability index map in the study area for OWA, OCRA, VIKOR and TOPSIS methods is illustrated in Fig. 11. The case study results show the most appropriate locations in red. These sites were settled in the Andean region, specifically in the provinces of Pichincha, Cotopaxi, Bolívar, Chimborazo, Azuay and Loja (Fig. 6). The sites with scores below the threshold of 70 have been found on the western area of the country (Fig. 11), which correspond to the Pacific Ocean coastline. This region presented

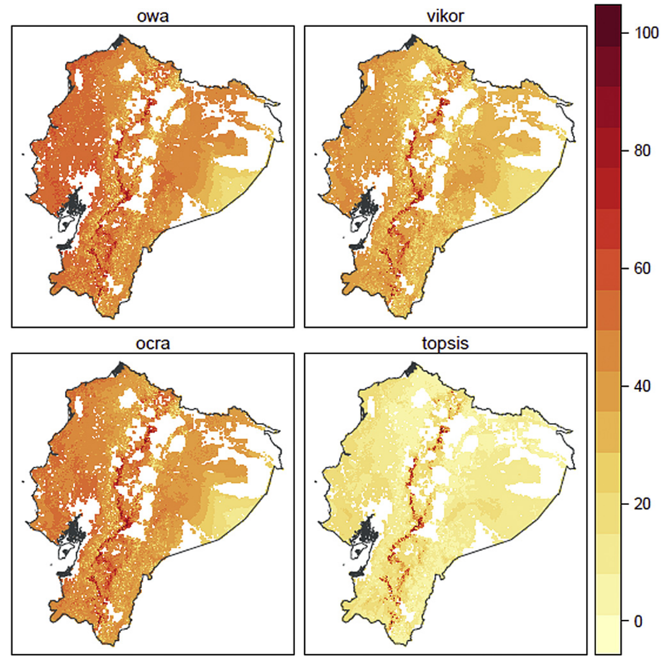

Fig. 11. Ranking of the land suitability index map in the study area for OWA, OCRA, VIKOR and TOPSIS methods.

good results at OWA, VIKOR and OCRA methods, but, generally revealed a score below 45 for the TOPSIS method. Finally, the region with the lowest obtained scores after the MCDM analysis corresponded to the eastern part of Ecuador, the Amazon region.

4. Discussion

The increasing population and improving living standards produce an increment on the energy demand. At this point, the future of the world's oil supply is uncertain. Over the last few years, a

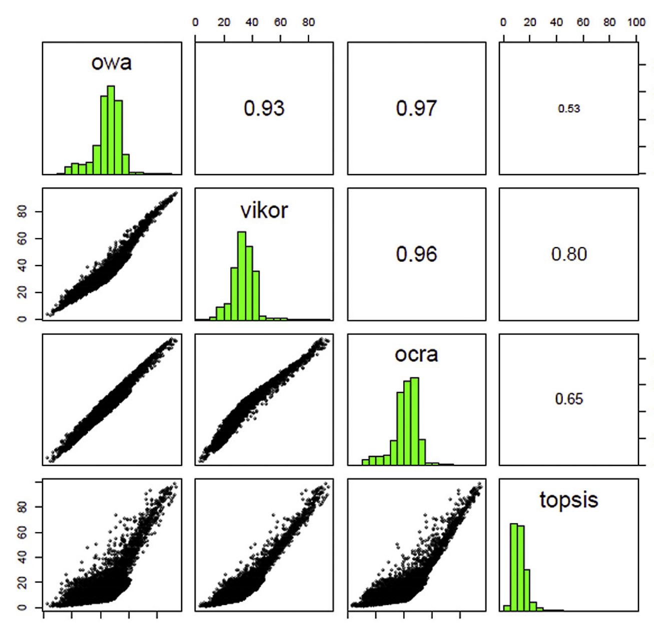

Fig. 12. Results of the Pearson coefficient correlation between MCDM methods for all values.

major concern has arisen regarding the decrease of the global oil reserves, through the increment of fuel demand in emerging economies and the associated instability of the crude oil price, driven by a strong international demand and by political instabilities within the oil producing regions. In addition, fossil fuels consumption has a negative impact on the environment. To solve this issue, the production of reliable and sustainable energy from renewable sources is proposed. In this context, wind power plants could solve the problem of energy demand in some places.

This research developed and applied GIS with four MCDM methods and the Pearson correlation coefficient to assess the suitability of building wind farms in the continental area of Ecuador. The study contributes with new added credibility of the use of expert validation the existing literature about GIS-based renewable energy suitability studies. This is the first Ecuadorian research to specifically evaluate the most suitable wind farms using GIS-MCDM. The results support future decision making to the government of Ecuador, when building more renewable energy infrastructures based on wind power plants in relation with the energy mix change.

To contrast the results with the different MCDM methods, an analysis of the results by a Pearson correlation coefficient has been performed. The results of the Pearson correlation coefficient for each MCDM method are presented in Fig. 12. It can be noticed that for the OWA, VIKOR and OCRA method, the correlation of the results is above 93%. While in the case of the TOPSIS method, the correlation of the results is about 53%. This is due to the value difference in the western of Ecuador between TOPSIS and the other methods.

The results of the Pearson correlation coefficient for each MCDM method taking a data threshold value above 70 are illustrated in Fig. 13. Besides this, with OWA, VIKOR and OCRA methods, the correlation of the results is maintained above 93%, while in the case of the correlation method TOPSIS, a value equal or greater than 75% was achieved. These results indicate that the four MCDM present similar outcomes in a value equal to or greater than 75% for the best places to install a wind farm.

The overriding consensus in bibliography is a minimal environmental impact caused by wind farms compared with other forms of power generation [19,41]. This opinion was supported by the different selection criteria considered by the experts as Al-Yahyai et al. [18], including economical (distance to road, terrain slope), social (urban area), environmental (historical locations, wildlife and natural reserves) and technical (wind power density, energy demand matching, percentage of sustainable wind, turbulence intensity, sand dunes) factors. In case of Van Haren and Fthenakis [42], the considered criteria were economic (wind resources, electric line cost, electric integration cost, land cost, access road cost), planning (visual impact, safety distances urban areas, electromagnetic interference, parks, military, airports, prisons, etc.) and physical (slope, altitude, karst ecological bird habitats/routes, forest proximity, lakes and rivers). Similar criteria and restrictions were also taken by Aydin in Ref. [19] and also Watson and Hutson [43]. In this case, the selection criteria included meteorological (wind speed, air density), relief (slope), location (distances to substations, road network, urban area, transmission lines, charging ports) and environmental (vegetation coverages) parameters, which are in relation with the literature mentioned before.

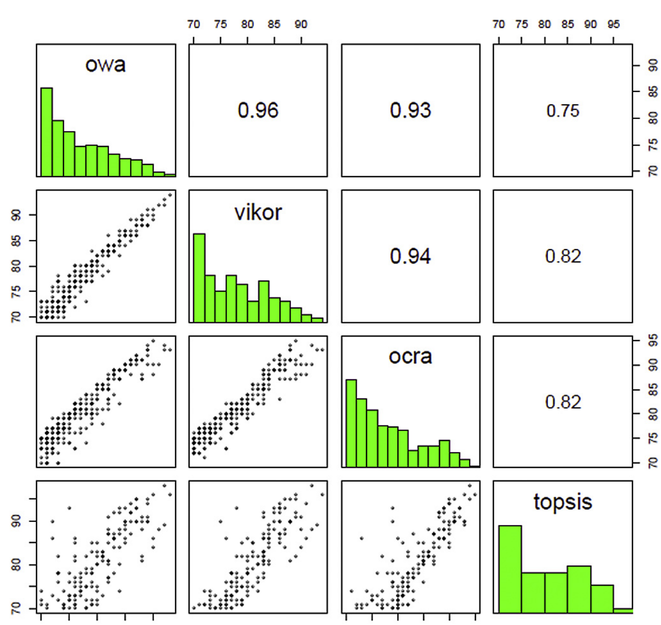

Fig. 13. Results of Pearson correlation coefficient for each MCDM. It has been taken a data threshold value above 70.

The MCDM used to evaluate the capacity to fit different locations to install wind farms in the research of Al-Yahyai et al. [18] were AHP-OWA aggregation. Aydin [19] used the OWA method. Meanwhile, Watson and Hutson [43] used the AHP and pairwise comparison. In this study, the AHP method has been used for calculating the weights and the OWA, OCRA, VIKOR and TOPSIS methods were used to rank the alternatives. Moreover, the correlation coefficient was used to analyze mutual correspondence between the MCDM methods. The use of a larger number of MCDM methods and the correlation coefficient provided greater consistency to the results.

The outcome related with the research conducted by Van Haren and Fthenakis [42], Aydin in Ref. [19] and Watson and Hutson [43], exposed areas that were suitable for installing wind farms, although the results were not representative for the entire country. Furthermore, it did not present the total percentages of suitable land for locating the wind farms. In the case of Al-Yahyai et al. [18], the case study results demonstrated that the area with the most suitable classification represented about 0.2% of the total area of Oman. However, in the case of Ecuador the suitable locations for installing wind farms are above 0.4%. The variation in the outcome between the two studies is due to the weight of the criteria. In the case study of Al-Yahyai et al. [18] wind occurrence is the most important criteria, while in the case of Ecuador there are large variations in the occurrence of wind.

5. Conclusions

In this research, the selection of places for installing wind power plants has been achieved based on GIS-MCDM methods for Ecuador. The present study found that due to the environmental characteristics of the climate, terrain, location and despite all the restrictive criteria or limitations, the valid target area has a high rate of acceptance for the implementation of wind farms.

In order to evaluate the location of wind farms in Ecuador, the VIKOR, OCRA, TOPSIS and OWA methods were applied. The results show that the most appropriate land overall is in the Andean region of Ecuador. This surface represents between 0.4% and 1.1% of the total area of Ecuador. The areas with the lowest scores are located at the east of the country.

Two statistical comparisons with the Pearson correlation coefficient have been performed using arrays of pairs between methods. In the first comparison all raster values were used, while in the second comparison the highest pixel values (>70), of each pair were selected as raster. It has been observed that there is a correlation of 75% between MCDM methods for selecting the most suitable location to install a wind farm.

To conclude, this study demonstrates that the use of GIS-MCDM tools facilitate the selection of the most feasible location in the field of renewable energy sources. These techniques will help researchers in the future to find locations from an energy development perspective.

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