

Geographic Information System for Optimization and Integration of Photovoltaic Solar Energy in Agricultural Areas with Energy Deficiency and Water Scarcity

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Abstract The high cost of fossil fuels and the energy dependence of agriculture, primarily for use in irrigation groundwater, has been a serious challenge to agriculture in Spain. Other factors, such as the shortage of rainfall in the Mediterranean climate, increase the problem of water scarcity for farming in these areas. In response to this scenario, a sustainable development in rural areas is necessary, seeking to optimize the water and energy resources. As a useful tool to optimize and analyze natural resources, Geographic Information Systems (GIS) are proposed. GIS allow to provide crucial information, both physical and meteorological, of the study area and help in optimizing water resources and reducing energy consumption. Furthermore, the integration of renewable energy with GIS tools offer great potential in reducing greenhouse gas emissions (mainly CO₂). This can be seen in the paper with an example of optimization in the integration of photovoltaic solar facilities in the rural and agricultural sector through the use of GIS.

Keywords Renewable energy source (RES) · Resource optimization · Energy efficiency (EE) · Sustainable rural development · Geographic information systems (GIS)

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1 Introduction

Behind this energy crisis and as a result of a global energy model, underlie other crises associated with the rising prices of the fuels, such as the problematics of energy in agriculture. This problem is more complex than a priori expected and is much harsher in arid zones, where an evident problem of water scarcity and the need to pump groundwater exist. Concretely for this article, it is a question of an area on the Acuífero 23 that has been declared overexploited. The irrigated agriculture practiced here is at risk because of years of unsustainable extractions, inefficient irrigation methods and permissiveness regarding crops of high water needs, which have been undermining the capacity of that agricultural zone. This need for water pumping with diesel generators is a major economic burden for the farmer, providing him with an increasingly limited profit margin.

To explain this problem, it becomes necessary to address, in the first place, the world energy demand, which grew at a pace of 5% in 2010 and predictably will do so by up to one third more until 2035 according to the IEA (International Energy Agency).

This is due to the fact that new developing and densely populated countries, such as China or India try to accede to electricity. This then accelerates the demand for crude oil and its depletion and, therefore, its cost rises (Lara Coira 2007). Thus, for the year 2035 the IEA expects that the use of fossil fuels will slightly decrease, although they will continue having an important role in its global participation. The IEA also outlined several scenarios for the prospects of the behavior of the Brent barrel, as shown in Fig. 1. These increases will in turn generate cost increases in other areas, such as in electricity, in transport, in food or in industry.

Although today it seems that oil has given a respite with lower prices, economic analysts say that a combination of factors has led to this situation, as A. Gary Shilling of Bloomberg View says in the article “Get Ready for \$10 Oil”. Among these factors is the economic crisis that has reduced the demand, geopolitical offensive strategies of producing countries and an increase in supplies, in part, at expenses of future oil reserves. Others go further, prophesying a sudden rebound of the price effect; the downward trend may end in the second half of 2015, according to the IEA.

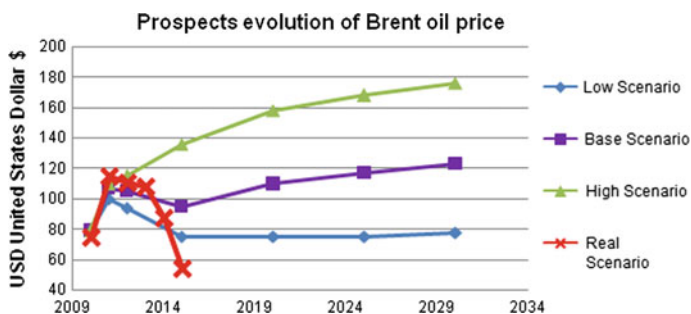


Fig. 1 Prospects evolution of Brent oil price (Boston Consulting Group, “Developments in technology and prospective costs for renewable energy technologies in 2020–2030”). *Note* Real price curve of Brent barrel until March 2015

But another protagonist appears in this current situation, the silicon. The price of the solar silicon and therefore that of the solar modules is progressively decreasing principally due to the fact that the industry has grown because of the high demand of modules, as well as the competitiveness between manufacturers (IDAE 2010). Moreover, the industrial processes in obtaining silicon and the efficiency of its production have improved substantially. This reveals the competitiveness of solar power, auguring a need to bet on it, being able to compete in price and safety of supply with the diesel equipment (Bengoetxea et al. 2006).

In this way, it becomes necessary to study the potential of the irrigation system with fossil sources to be converted to systems supported by solar power, assessing the viability of its operation. This would achieve sustainable development that respects natural resources, making it necessary to develop new sustainable energy models for change capable of generating an environmental and socio-economic benefit, either locally or at other higher levels.

The principal aim of this article is the study of the specific agricultural zone of La Mancha, with emphasis on its agricultural activity, on its aquifers, on the degree of their overexploitation, and on the socioeconomic situation of the agriculture in the above-mentioned zone. A software of Geographical Information Systems (SIG) is used to carry this out.

2 Water and Energy Problems in the Agriculture of La Mancha

The study region, La Mancha, is an extensive plain over an aquifer. There is a sedimentary basin formed by the Alpine orogeny and refilled with detrital sediments at the base, covered by alluvial mantles and “continental stuffed of Miocene and Pliocene” (García Rodríguez et al. 1996), in which the limestone karst system responsible predominates.

The area of La Mancha is, according to the Köppen-Geiger climate classification, declared as Bsk or Semiarid cold, and is determined by a continental Mediterranean climate associated with hot, dry summers reaching 43 °C, with high insolation. It has an average annual temperature “range between 14.1 and 15.3 °C” (Pérez González and Sanz Donaire 1998), where winters are cold, often below 0 °C, and a period of frost. The seasons of spring and autumn are mild and wet. Its low rainfall (300–500 mm) and very high evaporation are evidence of the arid climate, by the Martone Index, with values between 10 and 20, confirming a semiarid status.

The Mediterranean agriculture (olive tree, cereal and grapevine) has played the role of sustenance of autochthonous cultures there, as evidenced by some constructions like irrigation ditches, dams, mills, etc. It is now necessary to face up to a series of problems for the future. On the one hand, climate change predicts less rainfall, an increase in the temperature and more droughts. On the other hand, the loss of a more sustainable traditional agriculture has brought with it the abandoning of the small plots and the depopulation of large rural zones.

In Spain in general, as in this zone, there has been a marked decrease of the active agrarian population, but whereas at national level the participation of agriculture in the GDP (Gross domestic product) is very low compared to other sectors, in the study zone the agricultural sector has a very high influence in the local economy and, to a great extent, is their sustenance. The 486,296 inhabitants who live on the Acuífero 23 depend on this, including important cities such as Ciudad Real, Tomelloso, Villarrobledo, Alcázar de San Juan, Valdepeñas or Manzanares. The depopulation begins to be a problem, with a clear decline between 2013 and 2014.

2.1 Case Study

In the study area (Acuífero 23 with 5500 km²) irrigation is an essential improvement for the agricultural production (Instituto Tecnológico Geominero de España 1989). La Mancha offers the best example of the vast dry plains that have been put in irrigation over the last century either by building dams, canals or through the banks and draining wetlands, water or the exploitation of aquifers (Bernao 2002). The water of the Acuífero 23 began to be used due to a major investment in pumping technology (Naredo 1980). During the past 40 years, the modernization of the countryside and the high production, that the large irrigation zones of well-water were contributing to, made it impossible for the traditional small farms to continue competing (economically and productively) with large plots recently put into irrigation, which were thus increasingly causing a great water strain on Acuífero 23 (Cruces de Abia et al. 1997, 1998).

Because of years and years of excessive crops (with high water demand and inefficient and incoherent irrigation technologies compared with the hydrological characteristics of the zone), unsustainable extraction coupled with poor environmental training of farmers and lack of control of the agent in charge to avoid overexploitation, caused the water table to drop dramatically (Confederación Hidrográfica del Guadiana CHG 2008). “From 1988 to 1995, which covers a period of drought and the maximum values of exploitation, with extractions of around 600 hm³/year, the declines are accentuated reaching a mean value of 2.3 m/year” (IGME 2004). Today, there are still struggles over access to water, creating problems to reconcile agriculture with the environment (Fig. 2) (López Sanz 1993).

Today in La Mancha, they have become aware that natural resources (and the groundwater) are not inexhaustible and, also, that there is a need to regulate and take action on water management, modernizing drip and sprinkler irrigation methods, as demand and water use efficiency inevitably affect the life of the farmer (Confederación Hidrográfica del Guadiana CHG 2013; Mejías Moreno 2012).

The drop in the groundwater level is a problem difficult to support for the farmer, since it forces to take a significant share of the profits from production, to pay for the fuel to pump the necessary water to avoid spoiling the land and harvest. This causes a reduction in the profit margin for farmers, that can only increase the price of products at risk of losing out against competition with cheaper products from developing

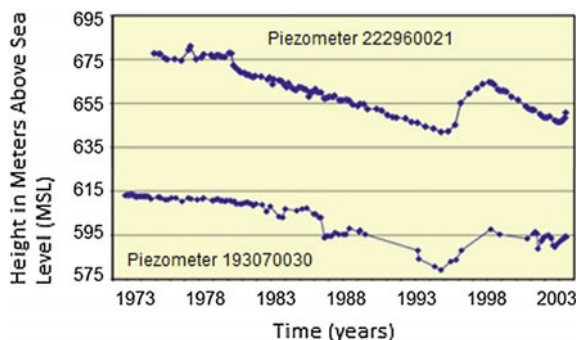


Fig. 2 Example of the descent in the water table in Acuífero 23 in two piezometers (*Instituto Geológico y Minero de España IGME*). Note A rapid recovery was observed between 1997 and 2000, caused principally by a humid period and some restrictions imposed in the extractions derived from overexploitation

countries, which in fact is what happens on many occasions (Lamo de Espinosa 2009). Others leave the crop or the agricultural plot, which although perfectly suitable for dry farming generates so little profit that they cannot survive on it. Thus, the small plots of 2–6 ha with a well are disappearing as it is not profitable to maintain the well, in benefit of big particular groups of 20 or more hectares.

This forces the Spanish Government to subsidize the agricultural use of fuel, necessary in order to at least support agriculture and with it the life of the farmer. According to Article 52, of the Law 38/1992 of Special Taxes, it recognizes the right to the partial return of the quotas of the Tax on Hydrocarbons to farmers and ranchers.

A rise in energy prices in the future puts those sectors that depend on oil into very serious difficulties, and this includes agriculture. This can generate a massive land abandonment in which it is not economically viable to pump irrigation water. Therefore, this shows clear evidence of how the energy problem finally emerges, conditioning the economic viability of many crops and agricultural areas, and the need to find a short term solution.

In this way, and considering the gradual integration of renewable and local resources in every zone, it becomes necessary to analyze solar power as a good tool to improve this situation and to study the potential conversion of fossil fuel irrigation systems to systems fed on solar power, valuing its viability.

3 Methodology

The GIS (which first appeared in the last 20 years) are made up graphic and alphanumeric data bases with functions of digital mapping tools. That is to say, operating with two types of information, spatial location and thematic, and they should be capable of integrating, storing, editing, analyzing and sharing data, and present the results. Therefore, GIS are tools for query, analysis, visualization and

geographic edition. Their aim is to provide solutions to problems and challenges raised in the territory, allowing to create models of evaluation, to carry out processes of simulation, to plan and to analyze the spatial reality with the intention of managing the models proposed for optimal performance on the territory, and assess the consequences of an action minimizing risks. In short, they allow “a continuous updating of information, making a dynamic GIS system” (Basildo et al. 1998). With the GIS, what is sought in this case is to determine the agricultural plots and their applicability to the solar pumping of the study zone (Sánchez-Lozano et al. 2012).

3.1 Process of Application of the GIS to the Case Study Determination of the Agricultural Plots and the Applicability of Solar Pumping

A methodology has been followed which sought to isolate the plots of agricultural use over the Acuífero 23 exclusively, as can be seen in Fig. 3. Thus, several blocks of maps of the zone of study are taken. A few maps or layers with descriptive

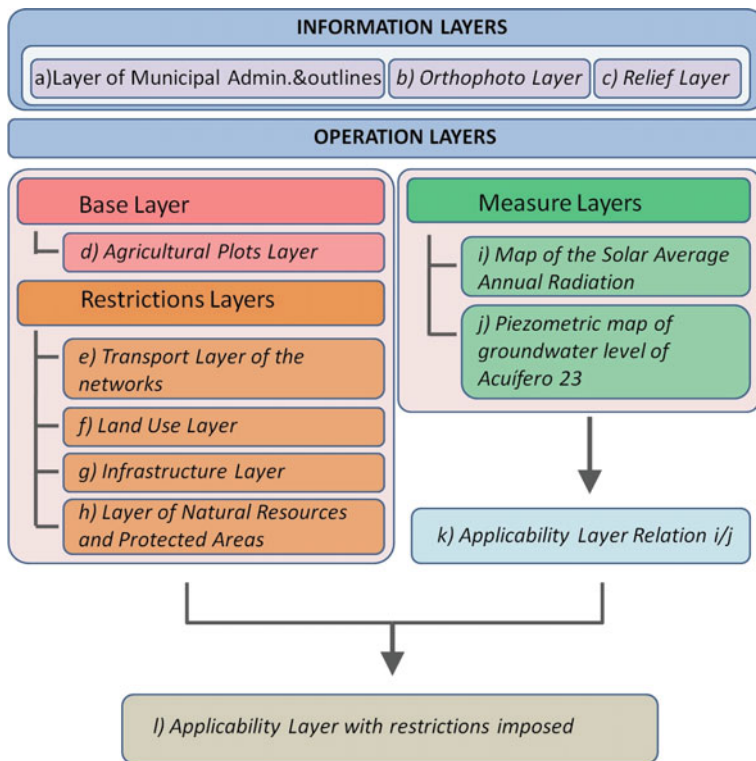


Fig. 3 Application of GIS process to case study (compiled by author)

information to frame and to locate the zone of study are: (a) Layer of Municipal Administrations and outlines, (b) Orthophoto Layer, and (c) Relief Layer.

Furthermore, the layers of operation are divided into:

- Subblock of base-layer of rustic plots over which it is working.
- Subblock of restrictions, with which elements of the base-layer are extracted that do not have an agricultural use.
- Subblock of layers of measure, among which are the map of solar radiation and the map of depth of aquifers.

Taking (d) *Agricultural Plots Layer* over the Acuífero 23 as the base a file is opened using SIG. An intense precision work was carried out on this map, eliminating the information that appears in the following layers to obtain the plots in which there is not another activity other than strictly the production of food and agricultural products of the zone (Olive grove, vineyard, cereal, vegetables, etc.).

- Stage 1. The layer of restrictions was loaded and the plots, with a codification relating to some of the restrictions, were extracted by the tool “differs” or from the table of attributes. If it is a line that was to be extracted, before that it was necessary to generate a polygon with the “buffer” tool.
- Stage 2. A difference has been made between (e) *Transport Layer of the networks* and (d) *Agricultural Plots Layer*.
- Stage 3. After that, the difference has been established between (f) *Land Use Layer* and the Layer Resulting in the previous stage.
- Stage 4. Later, the difference between the (g) *Infrastructure Layer* and the Layer Resulting in stage 3.
- Stage 5. Subsequently, the difference between the (h) *Layer of Natural Resources and Protected Areas* and the resulting layer of stage 4, thus obtaining a layer with agricultural plots where there is only agricultural activity.
- Stage 6. The information from the meteorological stations is applied on (i) *Map of the Solar Average Annual Radiation*, to produce a map of solar radiation of the zone.
- Stage 7. The same was done with the piezometric data that was introduced into (j) *piezometric map of groundwater level of Acuífero 23* to result in a depth map.
- Stage 8. The (k) *Map of the Average Annual Solar Radiation/piezometric map of groundwater level of Acuífero 23* is elaborated, thus obtaining the layer applicability in all of the Acuífero 23 (earlier restrictions have not yet been imposed to this layer).
- Stage 9. Finally, the applicability layer is applied to the layer of agricultural plots, to those plots on which later restrictions will be imposed, thus obtaining the (l) *Applicability Layer with restrictions* imposed. This is a layer with rustic parcels located on the aquifer, likely to be irrigated with groundwater and hence of having an agricultural production with the restrictions imposed by the study and with the degree of applicability for solar pumping.

3.2 Layers Used

This step has sought to define the study area to the area of the Acuífero 23 in Castilla La Mancha. The 65 municipalities have part of their municipality on the Acuífero 23 and are located at the confluence of the provinces of Toledo, Cuenca, Albacete and Ciudad Real, with much of the latter province.

As soon as the study zone is known, the study and description of the area in all its characteristics that are useful for this research is performed. To do this, the layers that indicate some restrictions or provide information or guidance are listed.

- (a) *Layer of Municipal Administrations and outlines.* It is a national and regional information layer. The study area and the administrations responsible for the conservation of the agriculture in the above mentioned zone can be easily located. Figure 6 in Appendix.
- (b) *Orthophoto Layer.* This layer is necessary for a major description of the environment and understanding of what happens at ground level, although it does not contribute specific binding information with the final result. Figure 7 in Appendix.
- (c) *Relief Layer.* With this, it seeks to provide the information relating to the orography and the altitude of the study area by using the curves of level, allowing to clearly seeing the flat terrain of this area surrounded by small elevations. Figure 8 in Appendix.
- (d) *Agricultural Plots Layer.* To go deeper it was necessary to discharge through “Sede Electrónica del Catastro” some detailed maps of agricultural plots and every one of the municipalities sitting on the Acuífero 23 that irrigate their fields with groundwater. Figure 9 in Appendix.
- (e) *Layer of Transport networks.* In this layer, the principal arteries destined for transport are shown—the highways appear, along with national and regional roads and different roads of minor importance such as the tracks between towns. Additionally, landing strips and means of transportation such as the train are included. For example, the high speed AVE (Alta Velocidad Española) Madrid-Seville line is included passing through Ciudad Real, as well as the conventional train. Figure 10 in Appendix.
- (f) *Land Use Layer.* In this part, all the polygons are collected that refer to constructions and developments, which can be: urban, spread constructions, such as chalets or agricultural constructions. Also, in this layer it is possible to find the zones of industrial use. Other type of plots are in this layer, such as quarries or open pit mines. Figure 11 in Appendix.
- (g) *Infrastructure Layer.* In this layer, the infrastructures of electrical type are indicated, such as power lines and power generation facilities that are included within the study zone, in this case, solar plants or wind farms. The distribution of fuels and gas pipelines are also indicated. Figure 12 in Appendix.
- (h) *Layer of Natural Resources and Protected Areas.* In this layer, the rivers of the River Guadiana basin (Guadiana-Alto Guadiana) and its tributaries (Záncara, Córcoles, Cigüela, Azuer) are shown, as well as the channeling artificially

made (Channel of the Great Prior) and areas irrigated with surface water and the newly renovated irrigation area of “Estrecho de Peñarroya”. On the other hand, it also shows the lagoons and wetlands among which the protected area Las Tablas de Daimiel must be mentioned. To these, other wetlands formed between Pedro Muñoz and Alcazar de San Juan that are the product of the outcrop of water springs, must be added, also indicating these areas of special interest and protection. Figure 13 in Appendix.

- (i) *Map of the Average Annual Solar Radiation.* Through the data of 9 stations in the study area, property of the Siar of Castilla La Mancha, an agricultural organization that uses this data to assess and advise farmers in irrigation and has specialized pyranometers SKYE SP1110 (CAMPBELL), an analysis of incident solar resource in the area of the aquifer has been conducted. A detailed map of solar radiation with a GIS, distribution of radiation on the study area has been produced with annual data for each of the stations. Figure 14 in Appendix.
- (j) *Piezometric map of groundwater level of Acuífero 23.* A GIS layer profile of the aquifer has been performed. The area also has information about the depth at which the aquifer is located in different parts of the study area, through information gathered from 26 piezometric stations in the Guadiana River Basin, used to keep track of that body of water and in collaboration with the Community of Irrigators of Acuífero 23. This map does not take the reference height in meters above sea level (MSL) of the groundwater level of the Acuífero 23, but its depth from the surface. Figure 15 in Appendix.

It is necessary to indicate the difficulty of drawing the outline of the Acuífero 23, since it is a dynamic water mass influenced principally by two factors: the height of the groundwater level and the geological materials that use as continent, which can be impermeable (as in the case of the Mounts of Toledo) or on the contrary be permeable (and have a very diffuse line of delimiting). Likewise, several maps delimiting the Acuífero 23 have been taken to establish its actual dimensions and to determine which of them is more adjusted to the area.

4 Results

On the one hand, the results provide the Applicability Layer, which shows an index of applicability associated with the relation between solar incidental radiation and the level of the groundwater (Fig. 4). On the other hand, the Applicability Layer with restrictions, shows the applicability of the solar power to the above-mentioned zone in the plots that remain available for a strictly agricultural use (Fig. 5).

It is evident that the results provide a wide green zone that serves to show the potential that solar power has in the above-mentioned zone. It is important to indicate that this final layer shows the degree of applicability, or differently said, the easiness with which the water would be obtained by solar pumping. As has already

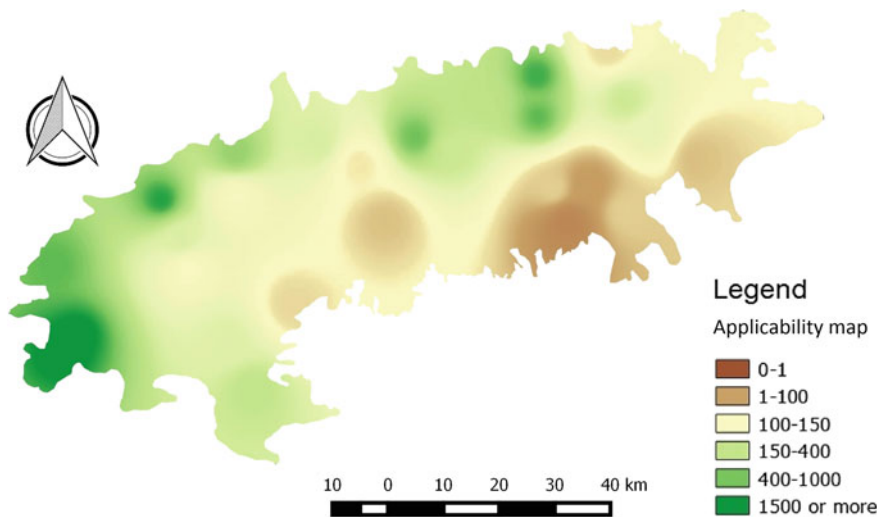


Fig. 4 Applicability layer (compiled by the author). *Note* Graduation of colors observed between the zones with higher values of the relation “Radiation/water depth” in *green* and the zones with lower values in *brown*

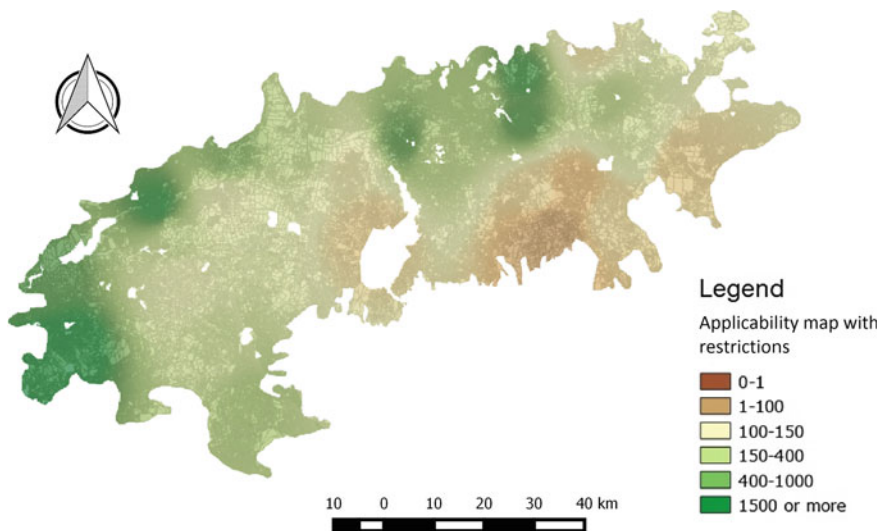


Fig. 5 Applicability layer with restrictions (compiled by the author) *Note* It is clearer with aspects already erased: cities and towns, protected zones and irrigation with superficial waters zones

been stated, this last layer indicates in what places, for the same use (irrigation of an equivalent number of hectares), the investment could be major or minor. Bearing in mind that both zones can be profitable or economically feasible, in the green tone areas as well as in the brown tone ones, it will only be necessary, hereinafter, to compare it with the current expenses of the farmers pumping with diesel.

5 Conclusions

With the present article it is possible to see how the solar power has a great future in agricultural applications. For those zones that have difficulties due to the high price of fossil fuels that needs be dedicated to groundwater pumping, and more concretely in the study area of the Acuífero 23 in Castilla La Mancha, this study has demonstrated that another way of obtaining water for agriculture is possible. It is also a milestone in modernization, with GIS programs, of the agriculture of La Mancha that satisfies its water needs from Acuífero 23.

In agreement with the aims of the article, the analysis is focused on the substitution of energy sources and the agricultural reorganization to make a more efficient use of solar power. Moreover, it is possible to generate other associated benefits in topics as important as employment, safety in agricultural facilities or water efficiency.

It is proposed as future work, the assessment of the degree of group of plots in order to create irrigation installations with ponds where the farmers could irrigate automatically, with an efficient use of water and energy. In addition, the economic, social and environmental sustainability can be studied to achieve, the above-mentioned agricultural reorganization.

Thus, it appears that the application of renewable sources for agricultural use is a field that, although it takes years to develop, still needs a lot of work to research and to apply, principally in the modernization and automation of agricultural processes and in the agricultural cooperativism in search of the common benefit.

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Appendix

Layers used in the process of characterizing the applicability of solar pumping to the study area (Figs. [6](#), [7](#), [8](#), [9](#), [10](#), [11](#), [12](#), [13](#), [14](#) and [15](#)).

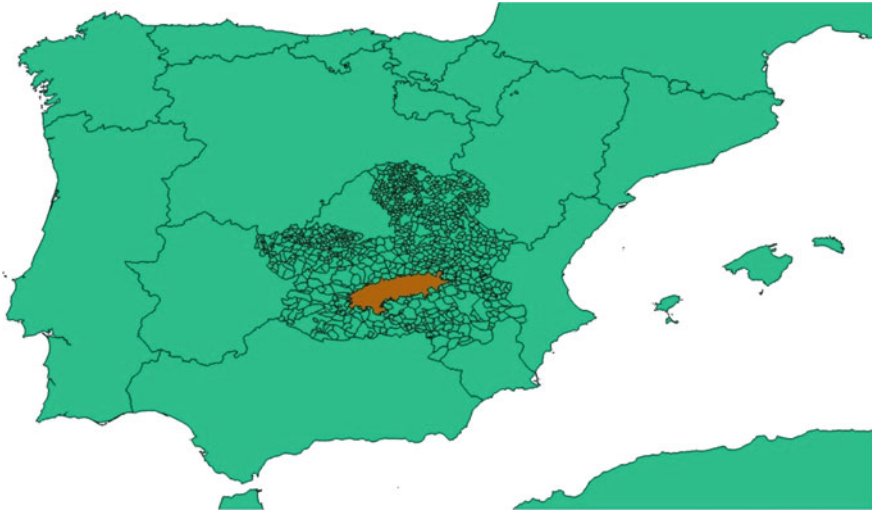


Fig. 6 Layer of municipal administrations and outlines. *Source:* National Geographic Institute (IGN)

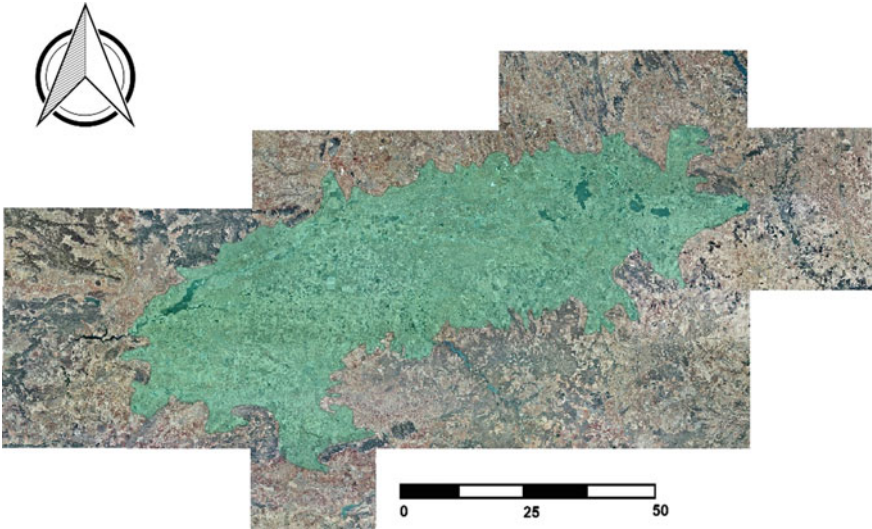


Fig. 7 Orthophoto layer. *Source:* National Geographic Institute (IGN)

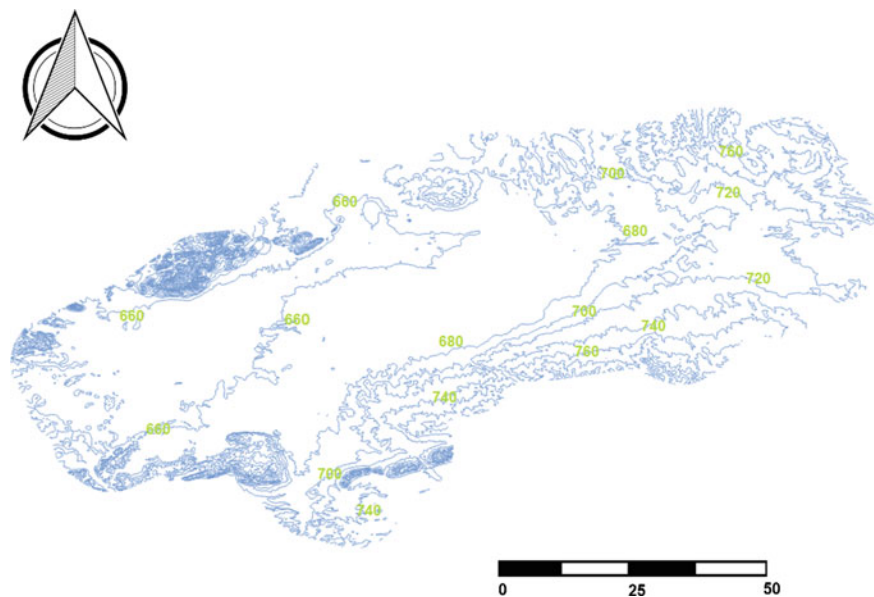


Fig. 8 Relief layer. *Source:* National Geographic Institute (IGN)

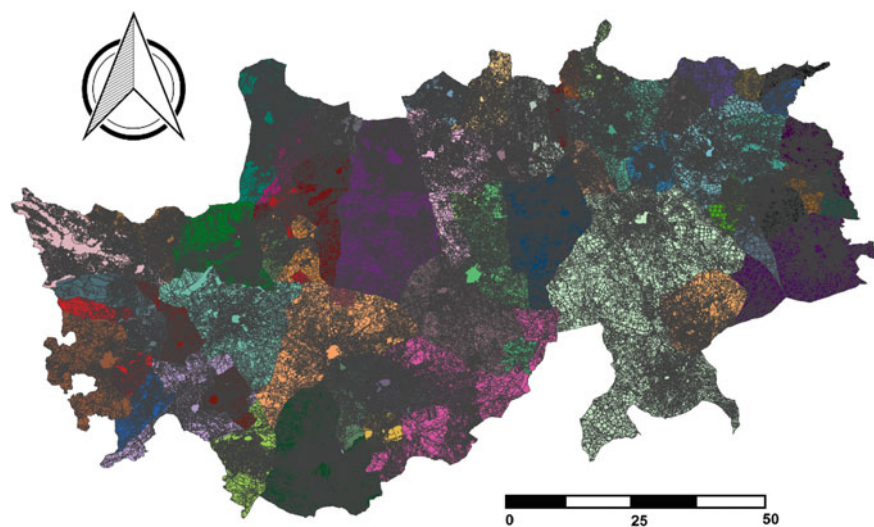


Fig. 9 Agricultural plots layer. *Source:* National Geographic Institute (IGN)

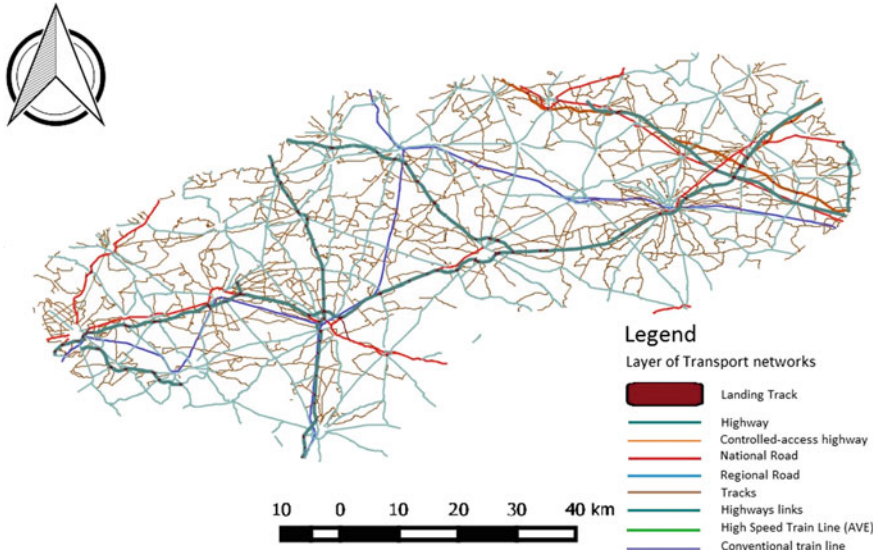


Fig. 10 Layer of transport networks. Source: National Geographic Institute (IGN)

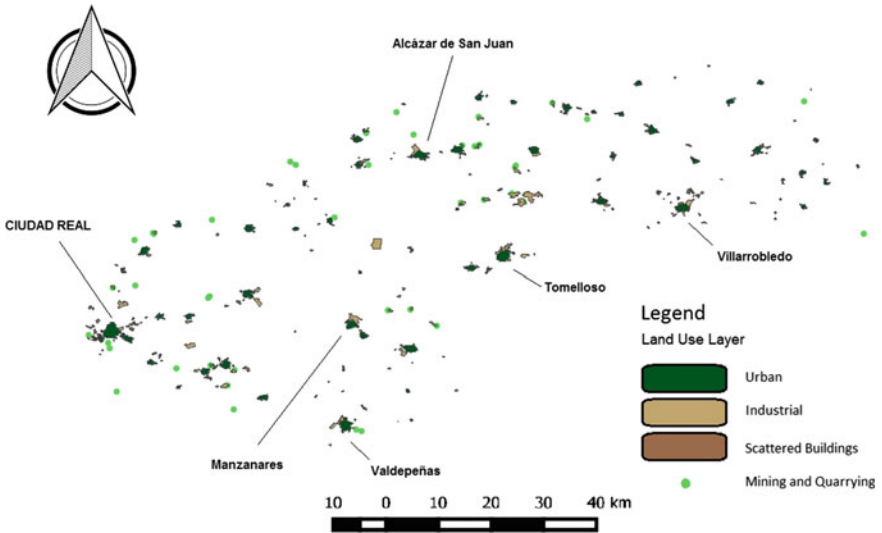


Fig. 11 Land use layer. Source: National Geographic Institute (IGN)

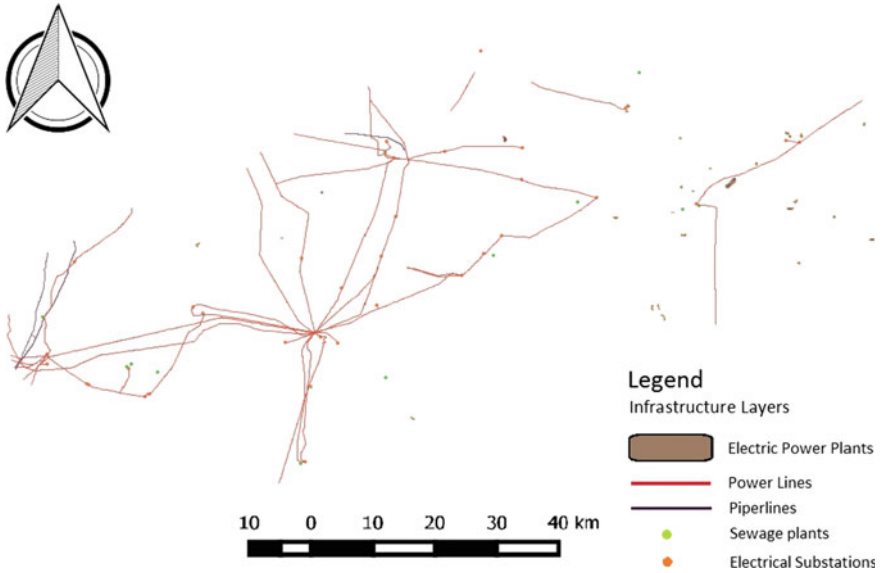


Fig. 12 Infrastructure Layer. *Source:* National Geographic Institute (IGN)

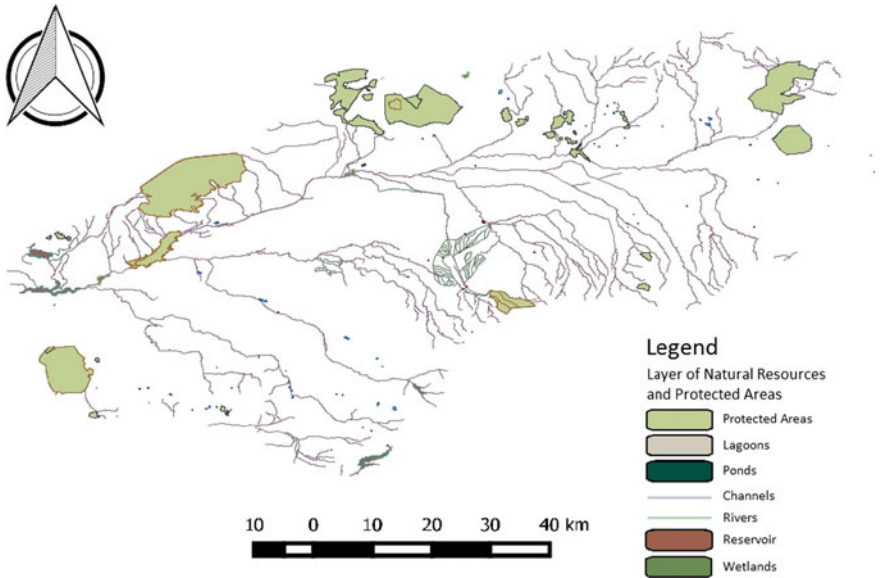


Fig. 13 Layer of natural resources and protected areas. *Source:* National Geographic Institute (IGN)

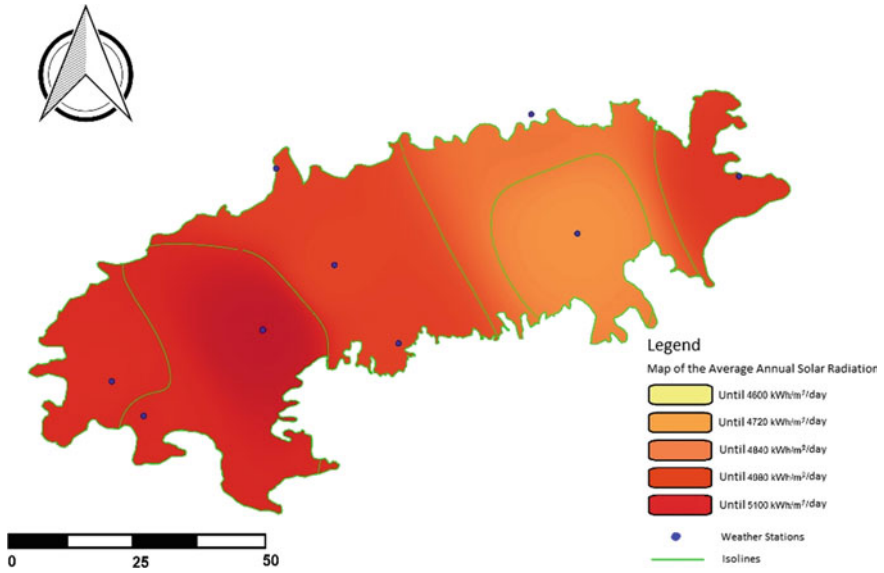


Fig. 14 Map of the average annual solar radiation. *Source:* Author's own Research

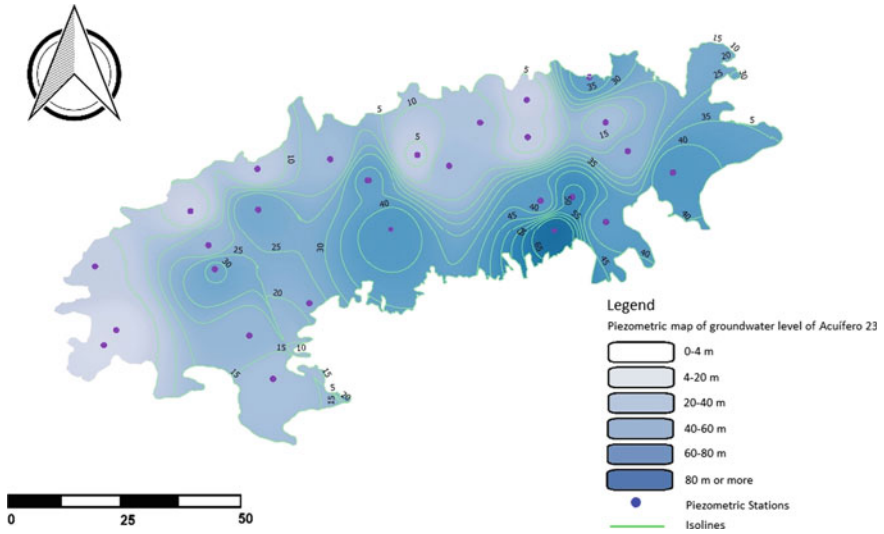


Fig. 15 Piezometric map of groundwater level of Acuífero 23. *Source:* Author's own Research

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