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A GIS-Based Information System for Moderate- to Low-Temperature Mexican Geothermal Resources

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ABSTRACT

Mexico's geothermal resources are abundant and widely distributed. Most of them are of moderate- to low-temperature (T<200°C), appropriate mainly for direct applications. However, only a small fraction of these resources have been exploited so far, and its utilization has been almost exclusively restricted to balneology, disregarding many other technically possible and potentially profitable applications. One important reason for the prevalence of this unwanted situation is lack of knowledge about these resources. To promote knowledge and exploitation of these valuable indigenous resources our group has been involved the last few years in a project to assess the Mexican medium- to low-temperature resources and its possible applications. In this context we are developing a Geographical Information System (GIS) to integrate, organize and visualize in numerous useful ways, information on these resources.

Our system is built on the ArcView 8.2 geographic data visualization, query and mapping GIS platform. It integrates a previously developed relational database, built on the MS Access database management system, which includes location, general characteristics and chemical data on 2,332 hot springs, water wells and other Mexican geothermal localities with temperatures ≥ 27°C. The integration process required exporting the original tables to the personal geodatabase format defined in ArcView 8.2. With this conversion ArcView software is able to display all the data stored in MS Access based on its location data. The system also includes a set of thematic layers with information on topography, hydrography (rivers, lakes, etc.), political sub-divisions, infrastructure (roads and railroads), cities and towns, and shaded relief images, and will eventually incorporate geological and economic data. So far our system uses 1:1,000,000 and 1:250,000 scales, for different applications. These scales are appropriate for the size and location of Mexico and for the applications we envision.

One important application of our GIS is to automatically estimate the areas and mean coordinates of numerous geothermal systems. This was achieved by defining groups of geothermal localities by superposition of their "areas of influence". We estimated areas of influence by circles of fixed radii. In this way we were able to estimate minimum, maximum and probable areas for the geothermal systems. We used these results as an important input for estimating the heat reserves of these geothermal systems. Another application is to correlate the locations of geothermal localities with regional structures evident in the shaded relief images. This facilitates the interpretation of the data necessary to define geothermal systems.

In this paper we describe the current state of development of the system. Our aim is to develop a tool that will facilitate visualization and analysis of the complex datasets necessary to interpret our geothermal data and their relationships with geographic, geological, political and economic information pertaining to our country, to apply these results to estimate its geothermal reserves. We are also aiming to use this tool to recommend particular applications for these reserves, based on technical and socioeconomic local parameters. The system could also be used to help Mexican authorities to legislate and establish proper rules for the exploitation of geothermal resources, and to promote its use in direct applications.

1. INTRODUCTION

Mexico's geothermal resources are abundant and widely distributed: there are more than 2,300 known geothermal localities, spread over 27 of the 32 Mexican States. Most of them are moderate- to low-temperature (T<200°C) resources. However, so far only a small fraction of them have been exploited, and its utilization has been almost exclusively restricted to balneology, disregarding many other technically possible and potentially profitable applications. One important reason for the prevalence of this unwanted situation is lack of knowledge about these resources.

To promote their knowledge and exploitation, our group has been involved the last few years in a project to assess the Mexican medium- to low-temperature resources and its possible applications. For this project we carried out a systematic work which included updating the inventory of Mexican hot springs, water wells and other thermal manifestations with surface temperatures ≥ 27°C; developing a relational database about these resources; subsequently implementing it into a Geographical Information System (GIS); estimating Mexico's medium- to low-temperature geothermal reserves; and recommending suitable applications of these resources. Details about the development of the relational database are described in Torres *et al.* (2005; these Proceedings). Some of our results on reserve assessment are described in Iglesias and Torres (2003) and in Iglesias *et. al* (2005, these Proceedings). Examples of recommended applications are presented in Iglesias *et al.* (2002). The present paper describes the current state of development of our GIS system, its applications and some results. This development is an ongoing task, and therefore the present paper may be considered a progress report.

In the following sections we discuss the main characteristics of our system and its data structure, describe its applications and results, portray future work and state our conclusions.

2. THE SYSTEM

In the context of our main project, summarized in the previous section, and consistently with its main goals, we conceived this system mainly as a practical tool to:

- facilitate visualization and analysis of the complex datasets necessary to interpret our geothermal data and their relationships with Mexican geographic, geological, political and economic information;
- help infer the existence, size and location of individual medium- to low-temperature geothermal systems;
- assist the assessment of geothermal reserves;
- correlate the characteristics of these resources with the socioeconomic parameters of the collocated populations, to recommend particular applications of the corresponding geothermal reserves;
- help Mexican authorities to legislate and establish proper rules for the exploitation of geothermal resources, and to promote its use in direct applications.

2.1 Main system specifications

The main system specifications considered for our GIS were:

(1) because of the widespread geographical distribution of Mexican geothermal resources, the system must include information on the whole Mexican territory;

(2) it must use coordinate systems and scales compatible with the available base cartography and with standards used in Mexico;

(3) the software package implementing the GIS platform must run on Windows, the dominant computing platform in our institution;

(4) this package should be able to set a dynamical link between the GIS and the MS Access geothermal database previously developed;

(5) the GIS should have the capability to eventually be implemented on a local network, to serve a workgroup.

(6) this software should provide tools to easily visualize correlations between our geothermal data and geographic, geological, political and economic information.

2.2 The GIS platform

To implement the first stage of our system we chose the ArcView 8.2 software package from Environmental Systems Research Institute (ESRI). This is the entry-level module of ArcGIS, a powerful scalable system that can be deployed to implement a GIS of any size, from a single-user system to workgroups, departments and large enterprises (ESRI, 2002). We started with a single-user system, will evolve to a workgroup system, and plan to eventually deploy data and applications on the Internet, in the course of our project. We deemed ArcView a good starting point, because eventually we will be able to upgrade to other capabilities of ArcGIS.

ArcView 8.2 is a powerful, user-friendly GIS platform that runs on Windows NT, 2000 and XP. Its ability to run on Windows is important to us because this happens to be the dominant computing platform in our institution.

This software package provides comprehensive mapping, reporting and map-based analysis tools. In following sections we exemplify the usefulness of these characteristics for our goals.

Also, ArcView 8.2 has specialized capabilities that make it compatible with most commercial database managing systems (DBMS). This is important to us because before this system we had developed an extensive database on the Microsoft Access DBMS (see Torres *et al.*, 2005; these Proceedings). Thus it was relatively easy to combine both software packages, a task that saved untold man-hours. An important bonus is that by associating the original MS Access relational database with ArcView we obtained an object-relational DBMS, with the ability to store geographic information in standard relational database management system tables. In addition to vector features, all other spatial data types can be managed and stored in the relational tables.

In this first stage of development, our GIS is installed as a single-user system on a personal computer running Windows 2000, connected to a local area network.

2.3 The data

As mentioned, we had previously developed an MS Access database where all the available geothermal data were integrated. These data comprise information on location, general characteristics, surface temperature and chemical and isotopic parameters (when available) on 2,332 hot springs, water wells and other geothermal manifestations (Torres *et al.*, 2005). This database constituted the core of our GIS.

Digital geographic information about Mexico was available basically from the Instituto Nacional de Estadística, Geografía e Informática (INEGI, the National Institute of Statistics, Geography and Informatics) at diverse scales and formats. Vector and raster data corresponding to digital topographic charts at 1:1,000, 000 (INEGI, 2001a) and 1:250,000 (INEGI, 2000) scales constituted the major source of data for the conformation of the geographic base for our system.

Digital information on Mexican political subdivisions and geostatistics (INEGI, 2001b) is another important component of the information system. It includes the state and municipality boundaries and areas.

We chose the North American Datum of 1927 (NAD27) as the reference system used by our GIS. Because of Mexico's mean latitude and E-W geographic extension we decided to use the Lambert Conical Conformal (LCC) and the Universal Transversal Mercator (UTM) projections, for the 1:1,000,000 and 1:250,000 scales, respectively. This coordinates systems are compatible with standards used in Mexico and with the cartography edited by INEGI. They are also convenient for our applications.

Information on major geological features (units, faults, fractures, volcanoes) is available from relatively few sources, and only in hard copy. We plan to convert this information to digital format and eventually incorporate it to the system.

3. STRUCTURE OF DATA

Our system is presented as a set of layers (maps) in different formats, which include information on the geothermal resources, and a geographic base constituted by topographic, hydrologic, political and infrastructure maps. Table 1 describes in detail the themes, layers, forms and formats adopted for our GIS.

Geographic base maps provide a reference to correlate the location of the geothermal resources with surrounding landscape, cultural and geo-political elements, and the relation of its distribution with major geologic-tectonic features.

3.1 Geothermal information

One level of information in our GIS is a point location database of geothermal localities in Mexico. As mentioned, our group had previously developed an MS Access database with information on 2,332 geothermal localities with temperatures ≥ 27°C. A significant fraction of these localities' geographical coordinates are given with a resolution of 1 minute, the rest with better resolution. Of these records, 2,023 were properly georeferenced using LCC (Lambert Conformal Conical projection) and UTM (Universal Transversal Mercator projection) coordinates. The remaining 309 records did not include information on its coordinates, and could not be georeferenced.

On the basis of our preexisting MS Access database on the geothermal localities, we generated a geothermal localities point data set in a so-called "personal geodatabase" format. The new dataset was computer generated using specialized tools included in ArcView 8.2. A personal geodatabase is an object-relational database, a convenient proprietary format that can be used by ArcView.

This format has two main advantages for our GIS. First, personal geodatabases may be stored in MS Access, with the advantages provided by relational databases mentioned in the previous section. And this allowed us to set up an interactive link between ArcView and MS Access. In this way, we are able to display and query all geothermal data contained in the new Access relational database tables, from the ArcView interface (ArcMap).

The second advantage is that it allows automatically delineating and calculating the area of polygon features representing different geothermal systems. Details about this functionality are discussed later in the text.

3.2 Geographical information

The other level of information is the geographic base. This is a set of different layers with information on topography, hydrography (rivers and lakes), political subdivisions (state, municipality), infrastructure (roads, railroads) and population centers (cities and towns). This set of layers is used as a reference to correlate the location of the geothermal resources with the surrounding landscape, topography and cultural and geo-political elements. These correlations are related to the assessment of its possibilities of development and/or regulatory compliance.

The different layers were obtained basically from digital topographic vector maps at 1:1,000,000 scale edited by INEGI (2001a; 2001b). Almost all the layers required additional processing in order to enable its integration into the GIS database. This processing involved mainly converting data between formats, redefining parameters of coordinate systems and correcting flaws in vector data.

Digital topographic charts and shaded relief images obtained from digital elevation models (DEM) at 1:250,000 scale (INEGI, 2000) were also integrated to the GIS database. Shaded relief images were joined in mosaics of 6° longitude x 4° latitude and later integrated into a single shaded relief image of the Mexican Republic. This image is used to visualize the distribution of geothermal localities and its relation with regional geological structures and to delineate probable geothermal systems based on that relation. Topographic chart images were useful as background information to correct flaws and update vector data e.g. rivers, lakes, roads, etc.

4. RESULTS AND APPLICATIONS

By means of our GIS we have generated a digital map of the Mexican moderate- to low-temperature geothermal resources. Its base scale is 1:1,000,000, and it incorporates information from the 1:250,000 scale charts from INEGI.

The map may be displayed in different scales in the computer screen and in prints, by zooming with the ArcView standard tools. At any zoom setting one can move over the map at will, or increase/decrease the scale, to find other areas of interest, consider their relationships, etc. These features greatly facilitate analysis of regions with a wide range of sizes.

At any scale, the map may include the information deemed convenient for the task at hand, by activating or deactivating information layers (for layers see Table 1). One may retrieve information regarding individual geothermal manifestations, geothermal systems, population centers, infrastructure and hydrology stored in the database, just by clicking on their corresponding representations. One can also implement from simple to complex queries of the full (geothermal and geographical) database, by means of user-friendly SQL-type tools provided by the software. In what follows we offer several examples of applications and results.

Figure 1 presents the areal distribution of the 2,023 georeferenced geothermal manifestations in the database; the locations of the 5 high-temperature, currently drilled, Mexican geothermal fields (yellow triangles); the general topography; and the state limits. At this scale it is easy to visualize the widespread distribution of the Mexican geothermal resources, which are found in 27 of the 32 states of the country. One can also grasp general correlations between the main topographic features and the distribution of the geothermal resources. Note however that, in order to keep the picture from being crowded, we have not included in this view any information about hydrography, infrastructure (except geothermal fields) or population centers (see Table 1).

To gain insights relating to these features one can zoom in and include the corresponding layers. For example, in Figure 2 we have zoomed in on a west-central region of the country, between Guadalajara city and the Pacific ocean. We have also activated the Hydrography and Population Centers layers. In the left window of the screen in the figure the ticked layers are the ones that are activated. As can be seen, at this scale and with the layers activated the map shows considerable detail. Detailed correlations between the distribution of geothermal resources with topographic trends and with population centers are easily perceived.

This figure also illustrates a very powerful characteristic of the system already mentioned. Note the turquoise dot labeled Jal-412 west of the La Primavera geothermal field.

It represents a geothermal manifestation in the database. Clicking on it with the **"i"** tool highlighted in the top menu deployed the information window above it. This window presents all the available information corresponding to the geothermal manifestation Jal-412. Its left panel shows there are chemical and isotopic analysis and geothermometric data associated with Jal-412. Clicking on the different levels of the left panel shows the information about Jal-412, in the right panel. For example, the text highlighted in blue corresponds to the information shown in the right panel: fluid sample number 1 was collected from Jal-412 on August 6, 1985, and the values computed for several geothermometers from the chemical analysis of that sample. Similarly, clicking on "JAL412" would show the state, municipality, number, name, coordinates, sample temperature, geothermal system to which it belongs, etc., corresponding to this geothermal anomaly. The available chemical analysis results can be obtained the same way.

Figure 3 illustrates the SQL-type query capability mentioned at the beginning of this section. In this case we have selected, by means of the auxiliary window "Select by Attributes" combined with a spatial-type query all the geothermal anomalies from the state of Queretaro that have sample temperatures greater than 33°C. They appear highlighted in the map, as shown. In our project we use this tool to select, among other things, geothermal systems that are within certain distance, say 5km, from population centers that could profit from developing them.

Preparing maps in advance for sampling surveys in our main project is one application of the GIS we find extremely useful. For this task we use, in addition to the mapping tools of our GIS, its query capabilities to find geothermal localities within predefined distances from some road or population center. The inferred distances are used in the planning stage of the surveys.

One important application of our GIS is to automatically delineate and estimate the areas and mean coordinates of geothermal systems. Whenever there is evidence indicating that more than one geothermal anomaly pertains to a geothermal system, we estimate the system area and its limits as a superposition of "areas of influence" from the anomalies. As a first approximation we assume each geothermal anomaly has a circular "area of influence" with a 925 m - radius. International experience indicates this is a reasonable assumption (e.g., Brook et al., 1978). And in Mexico 925 m ≈ 0.5 minute, while the spatial resolution of a significant fraction of our current data is one minute. The system automatically computes the area and the perimeter of the polygon defined by the superposed areas of influence, and its mean coordinates. Figure 4 illustrates this useful feature. The auxiliary window shows the number of the geothermal system, its area, perimeter and coordinates, and the numbers of the geothermal anomalies within. We use the areas estimated in this way for reserve assessment, in our group's main project.

Reserve assessment is an ongoing task and we need to obtain much more data before we can claim with a high degree of certainty to have individualized all the intermediate- to low-temperature Mexican geothermal systems. However, assuming all the geothermal anomalies lying within 925 m from each other pertain to the same geothermal system, we were able to estimate the number of intermediate- to low-temperature geothermal systems in Mexico, their locations, area and perimeter. To do that we overlaid the 2,023 georeferenced geothermal locality points, each with a 925 m-radius buffer representing probable areas of influence, with 1:250,000 topographic maps and shaded relief images, to find the likely geothermal systems. We found the number of likely intermediate- to low-temperature Mexican geothermal systems to be 1,133. Of course, this result neglects the existence of the 309 known geothermal manifestations for which we have no coordinates yet. In this way we generated a geothermal systems dataset, which we stored as a new table in the preexisting MS Access personal geodatabase. This dataset corresponds to the Geothermal System layer (see Table 1) in our GIS. It stores the areas, perimeters and locations of the identified geothermal systems.

Our geodatabase includes tables with the input parameters of our reserve assessment calculations as well as its results. Therefore, we can query our GIS to show these parameters and results. Figure 5 exemplifies this feature. It shows, highlighted, the geothermal system LGTO-142, in the state of Guanajuato. The auxiliary window presents the results of the Monte Carlo simulations we performed to estimate its heat reserves. In a similar way one may depict the input parameters for the reserve assessment computations.

5. FUTURE WORK

As mentioned, the development of our GIS is an ongoing task. We envision adding important new capabilities to it, to enhance its usefulness.

In the context of our main project we will continue gathering chemical, isotopic, location and geological data of Mexican geothermal anomalies. The objective is to improve the quality of the current information and to get data on anomalies for which there is currently only partial information or no information. Ideally we would like to upgrade the location data to GPS-standards. We will also endeavor to double-check the quality of the available chemical and isotopic data for a number of anomalies, for which we have processed results (e.g., geothermometers) but not the underlying chemical and isotopic data.

On the geological front we plan to include the available information on Mexican structural geology, the Mexican geological provinces, and the Mexican geothermal provinces. These additions will allow us to more precisely delineate and interpret the characteristics of geothermal systems, and to improve the results of our reserve assessments.

We will also collect and include socio-economic data corresponding to areas collocated with geothermal systems of interest. This will help us propose adequate applications of the corresponding heat reserves, particularly in direct uses. Our recommendations will thus consider the relevant socioeconomic parameters of the neighboring communities.

6. SUMMARY AND CONCLUSIONS

We have developed the first stage of a GIS-based information system for the Mexican geothermal resources of intermediate- to low-temperature. The system includes geothermal and geographic (topographic, hydrographic, infrastructure, political, and population centers) information. It is a practical tool to visualize, delineate and help assess the country's geothermal resources, correlate the characteristics of these resources with socioeconomic parameters of collocated populations, assist in developing recommendations for particular applications of these resources, and help the Mexican authorities legislate and promote the use of these indigenous resources.

On the basis of this system we developed a digital map of the moderate- to low-temperature Mexican geothermal resources that may be used in a wide variety of scales. Its users may activate or deactivate the information layers according to their needs. They may also query the available information in several user-friendly ways, to a high degree of detail.

We have used this tool, among other things, to delineate geothermal systems and compute their approximate areas and perimeters, estimate the likely number of moderate- to low-temperature geothermal systems in Mexico and find their locations, prepare maps for sampling surveys of our main project, find population centers collocated with geothermal resources, etc.

Further system development will involve inclusion of information on structural geology, geologic provinces, geothermal provinces, and socio-economic data corresponding to areas collocated with geothermal systems of interest. We will also endeavor to improve the quality of the current data and to add more information on geothermal localities and systems.

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Theme	Layer	Form	Format
Geothermal	Geothermal locality Geothermal system	Point Polygon	Geodatabase
Political subdivisions	State Municipality Urban area Island	polygon polygon polygon polygon	Shapefile
Population centers	Capital city City Town	point point point	Shapefile
Infrastructure	Geothermal field Road Railroad	point line line	Shapefile
Hydrography	River Lake	line polygon	Shapefile
Topography	Digital Elevation Model (shaded relief)	raster	Raster

Table 1. Datasets included in the GIS

Figure 1. Whole country view of the Mexican geothermal resources digital map

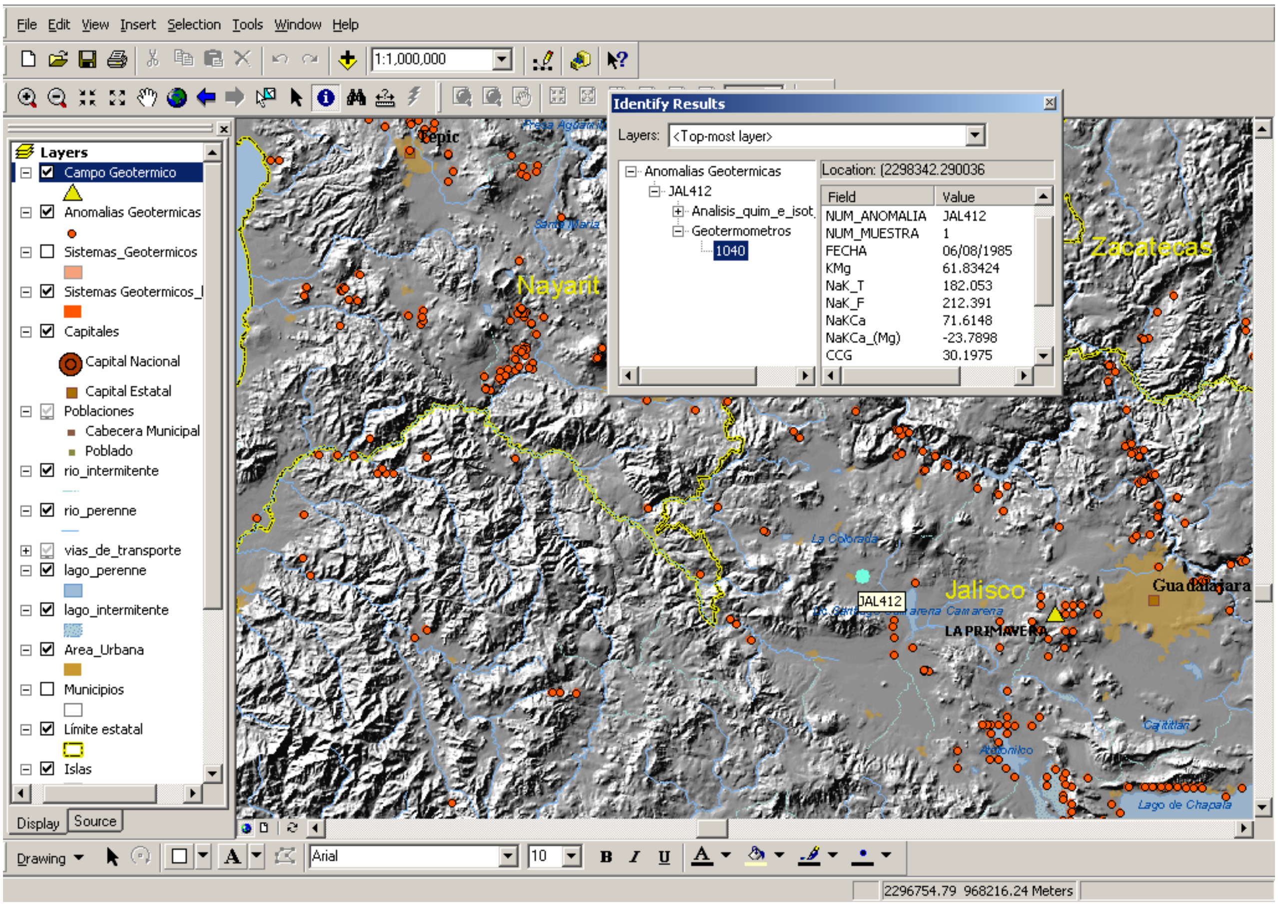

Figure 2: Example of information retrieval: data associated with geothermal manifestations, in this case JAL412, can be shown by clicking on the point representing it with the "i" (identify results) tool, highlighted in the top menu.

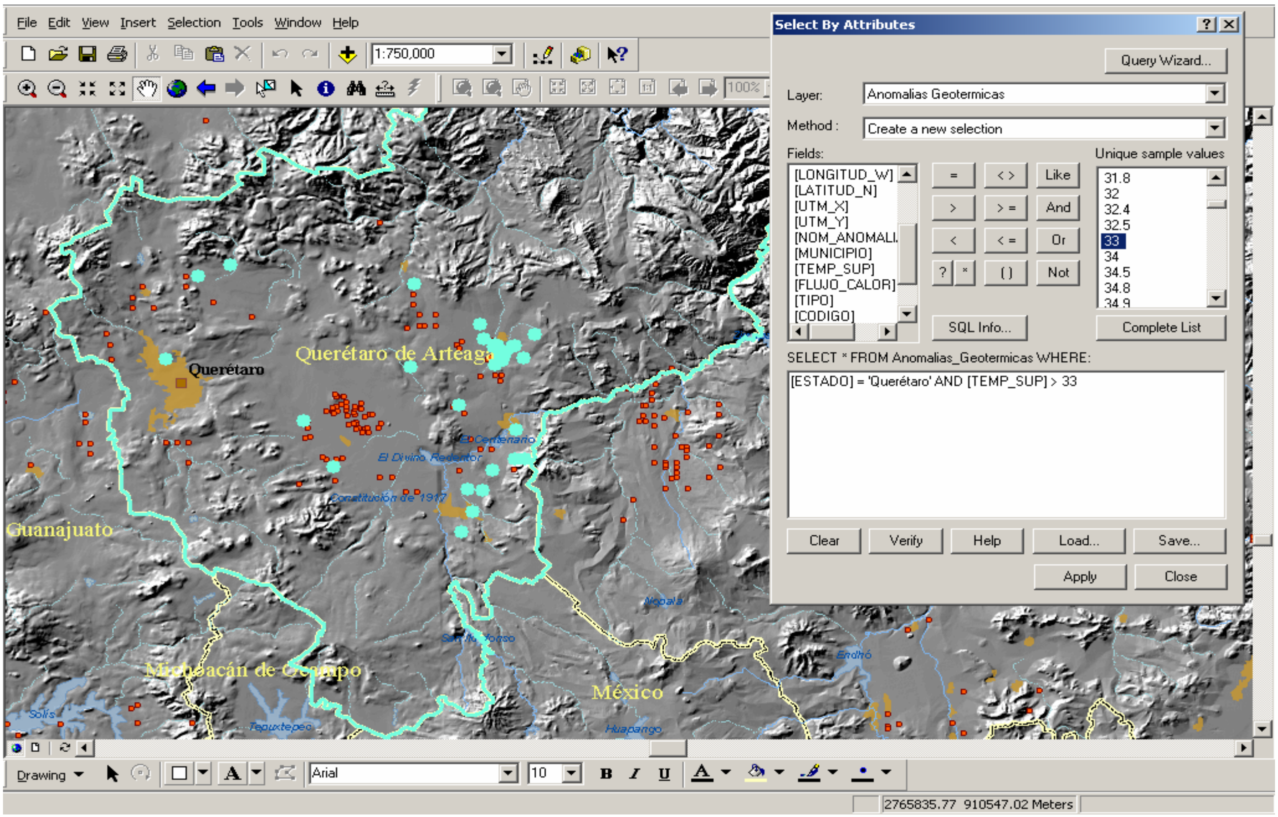

Figure 3: Example of SQL-type query.

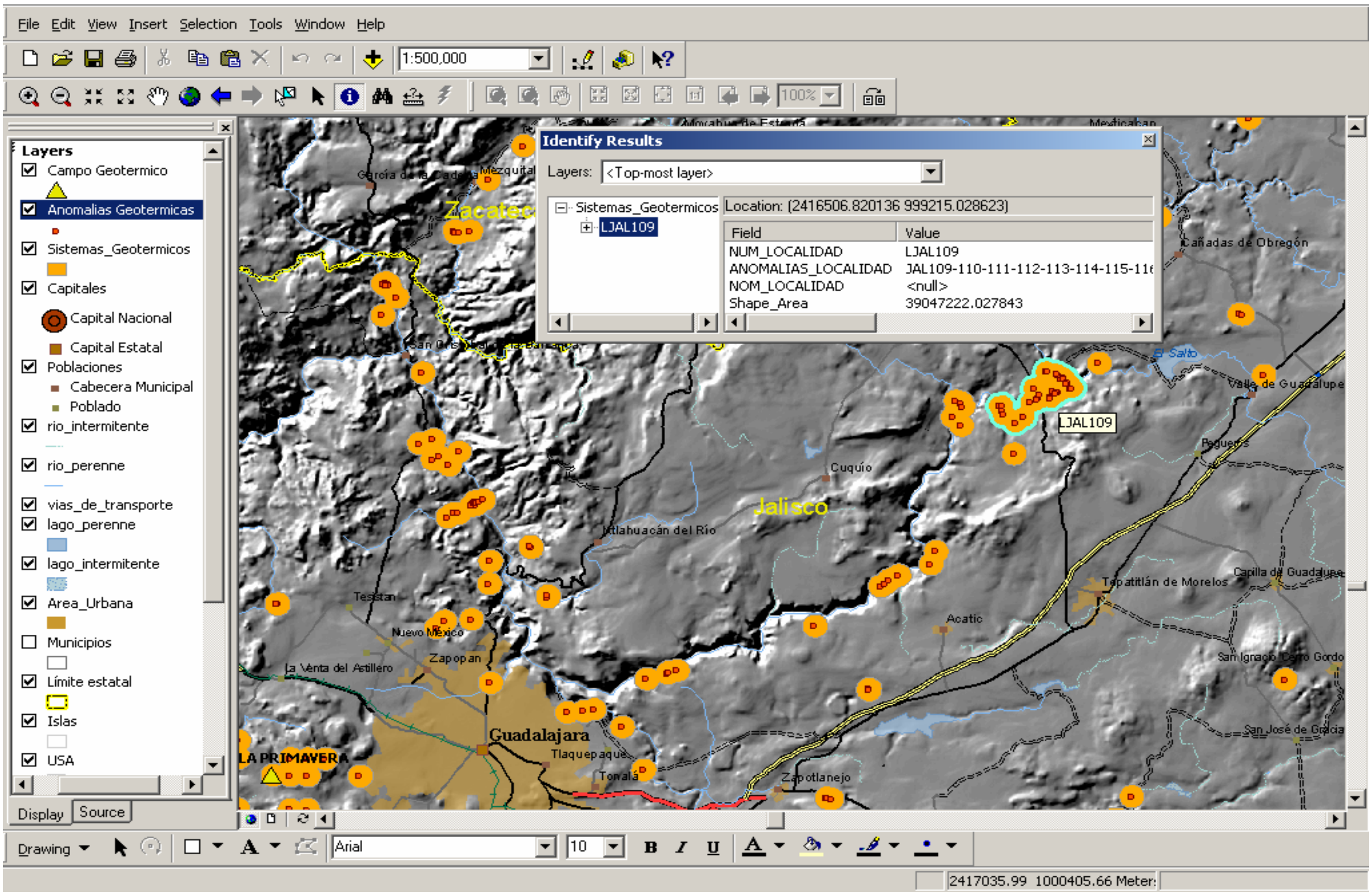

Figure 4: Example of geothermal system areas automatically estimated by superposition of circular buffers of fixed radii.

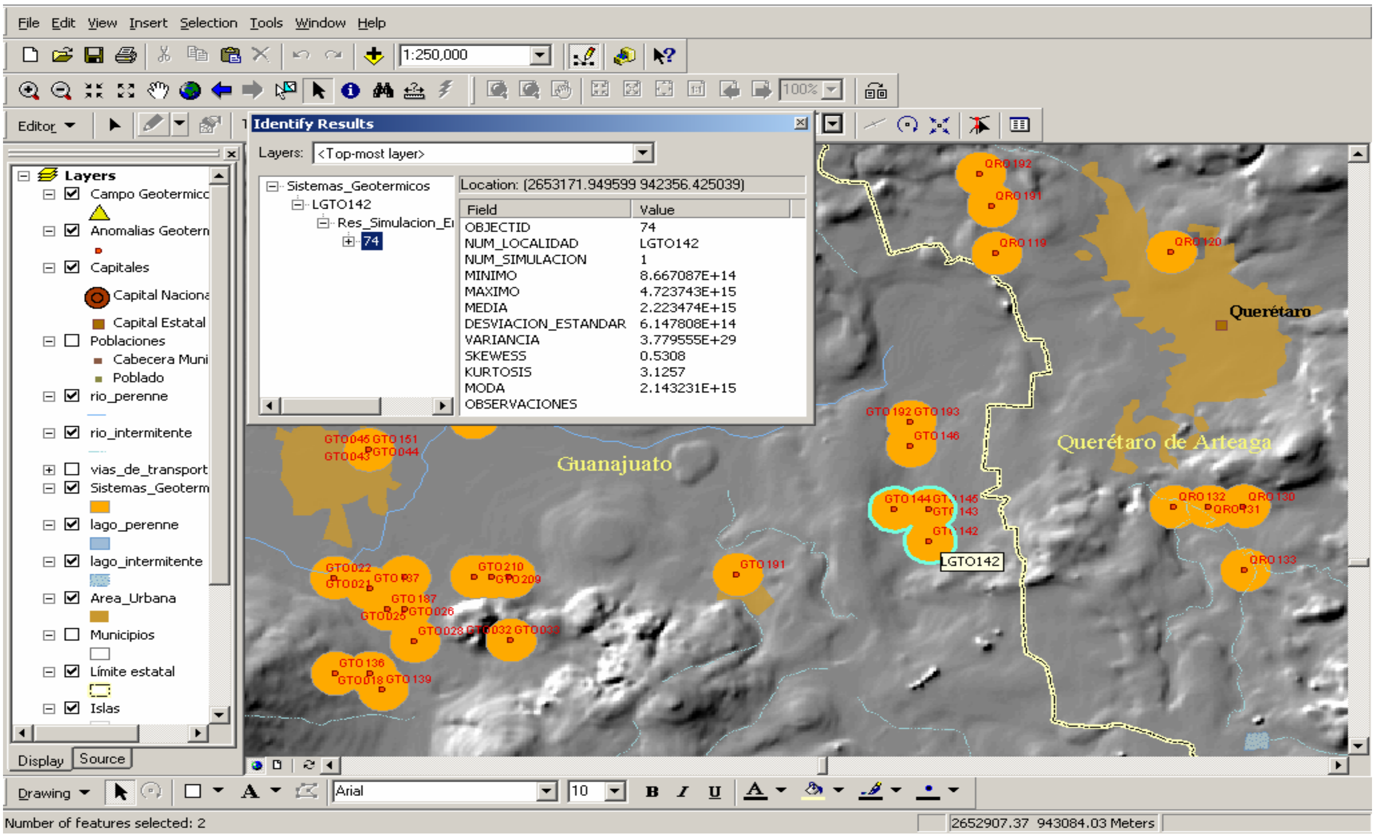

Figure 5: Estimates of a geothermal system (LGTO142) reserves estimate and of their uncertainty displayed with the "Identify Results" tool.