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Article

Hydrogeological aquifer characterization using a multi-technique framework: Application to the Lower Casas Grandes Basin, Chihuahua, Mexico.

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Abstract: Groundwater is a strategic resource for economic development, social justice, environmental sustainability, and water governance. The Lower Casas Grandes Basin located in the state of Chihuahua, Mexico is in a semi-arid region that has increasing groundwater demands, while confronting regional challenges such as adverse climate change scenarios and depleting aquifers. Even though there is official information about the availability of groundwater, comprehensive aquifer characterization is still uncertain and needs interdisciplinary investigation using a diverse suite of tools and multiple data sources. This study presents a multi-technique framework to evaluate potential sites to drill for groundwater resources. The main components of the methodology included: wellhead leveling correction with a differential global positioning survey to define piezometric levels, principal component analysis using Landsat-8 images, application of geospatial tools, geophysics using Time Domain Electromagnetic Surveys and Vertical Electric Soundings and structural geohydrology to define aquifer characteristics. Results show that application of the framework enhances the possibility of a successful drilling for groundwater while saving time and money using "pin-point" positioning for drilling sites as compared to a traditional extensive groundwater exploration approach. Low resistivity values (35 Ohm-m) were found at depths from 50m till 85m at sites where regional static water level reached 245 m deep adding a shallow groundwater potential at sites where intersection of fracture trace was identified. This procedure can be used at other sites where limited or minimum information is available for groundwater exploration to reduce risk of drilling dry wells at complex hydrogeological environments.

Keywords: groundwater exploration; fracture trace analysis; geophysics, geomorphology, geospatial tools.

1. Introduction

Groundwater has become one of the most important sources of water around the world and transboundary aquifer characterization is important for a sustainable approach to binational groundwater governance [1]. It is the main water resource in arid and semi-arid zones and represents more than 99% of the freshwater availability in the world [2]. However, groundwater is one of the least studied and understood from the perspective of its nature, formation, movement, recharge, availability, and extension worldwide [3]. Between Mexico and the United States, the Great Chihuahua Desert is recognized as one of the largest deserts in the world which is shared between the two nations. In this arid region groundwater is used to supply water to cities, industries, and agriculture. Consequently, due to its economic importance water use for agriculture and livestock the extraction of ground-water in desert plains of the state of Chihuahua has received considerable attention [4] Groundwater in the state of Chihuahua has been compromised in recent years due to high water stress caused by drought, population growth, weather conditions, groundwater concessions, and its growing demands, presenting a marked decrease in piezometric levels of the aquifers, favoring the depletion and overexploitation of shallow aquifers (<200 m) [5]. According to CONAGUA [6], about 72% of the water concessions assigned in the México correspond to agricultural uses where groundwater inventories in the closed basins of Northern Mexico are limited. Furthermore, in recent years a drop in piezometric levels has been identified in these aquifers, varying on its depletion from 35 cm to 1.5 m per year over the past 20 years [7]. Within the geographical location of the state of Chihuahua, the areas of high population growth, water withdrawals for irrigation of crops and livestock, as well as drought and the increase in temperature makes the state a vulnerable zone for overexploitation of aquifers [8].

In the paper, we present a multi-technique framework for the characterization of the aquifer. This procedure is based on the use of traditional methods, such as the characterization of structural geology, surveys of wells and field work with GPS RTK, and the mapping of "Water by Air", through the spectral analysis of satellite images with statistical techniques as principal component analysis. The results obtained are useful for designing actions that favor a sustainable use of groundwater.

There are few studies concerning of aquifers of Chihuahua [7], and in the case of the studied area, the information is scarce, or lacks the detail required to make the extraction of groundwater more sustainable [9]. The situation is similar throughout the arid north of Mexico, where problems of overexploitation of groundwater and the absence of data are frequent. Both are crucial issues for the sustainability of water, so the characterization of the aquifer, combining remote sensing data, mathematical analysis, and traditional geophysical methods, contributes to the management of groundwater and its governance. This issue is necessary for the sustainability of water, particularly in the US-Mexico binational region and in all the northern states of Mexico.

2. Materials and Methods.

2.1 Study area.

The study area is the Ranch El Milagro in Ascensión, Chihuahua, Mexico south of Luna County, New Mexico in the U.S. Ranch El Milagro is approximately 31 km from the town of Ascensión and is south of Laguna San Juan aside of the slopes of Sierra El Capulín. It is a region characterized by agricultural and livestock activity, and the water supply is mainly withdrawn from the local aquifer named as the Ascension Aquifer (0801) [9] The study area is in a closed surface water basin which is surrounded by mountains that function as watershed divides. Surface water flows towards the low point at the Laguna de San Juan where runoff gathers during the rainy season and eventually evaporates (Figure 1).

Figure 1. Location of the Ascension Aquifer (0801) [9]

In Ascensión, Chih., the summers are warm and partly cloudy, and the winters are short, cold, dry, and mostly clear. During the year, the average monthly temperature generally ranges from 9°C in January to 28°C in June, rarely falling below -4°C or rising above 40°C. The minimum daily average temperatures are 4°C and correspond to the month of January and the maximum daily temperatures reach 40°C in June. The average annual rainfall is about 300 mm, and the average annual relative humidity is 42%.

This paper applies a multi-technique framework (Figure 2) to support well siting efforts in the Lower Casas Grandes Basin (LCGB). Agricultural and livestock production are economically important for the agrarian communities in desert plains of the state of Chihuahua [8]. The recurrent drought in the area has caused the urgent need to find new sources of water, mainly in the upper region of the Sierra El Capulin, where there is an urgent need to provide water to the existing cattle on the Ranch El Milagro. Several failed drillings attempts have jeopardized rural development of the Ranch El Milagro. The absence of water at the headwaters of the watershed made it necessary to implement a pumping system to provide water upstream from a source located in the valley situated to the southwest of the study area. The use of water is primarily for cattle, so a source that produces a large volume of water is not required. The costs involved in pumping water from the well located downstream on the valley to the upper part of the mountain front justified a geohydrological study and geophysical prospecting to identified suitable sites for a supply well for the ranch instead of water importation from downstream areas. The presented framework can be applied in other regions to increase the success of well drilling efforts at suitable sites identified through robust hydrogeological investigations.

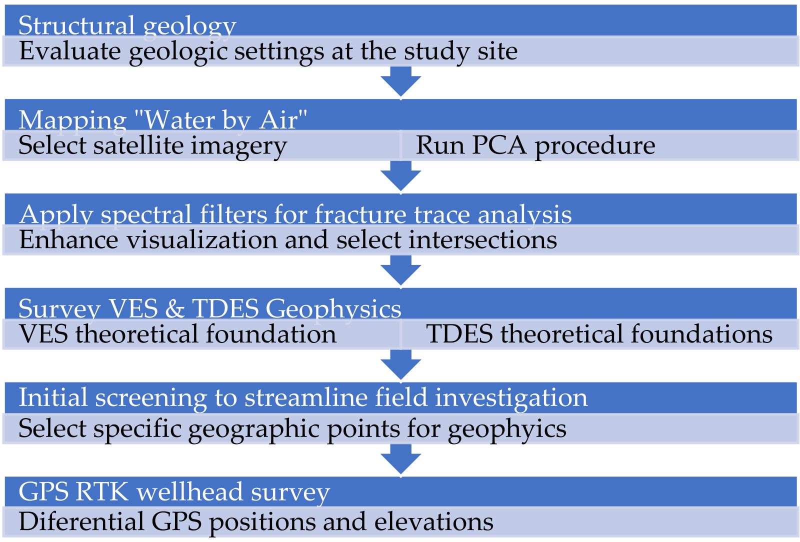

Figure 2. Roadmap for Multi-technique framework

2.2 Structural geology

The youngest rocks that outcrop in the area are alluvial deposits of the Quaternary (Qal <10 thousand years) formed by fragments of weathered rock which originate in the mountains that define the watershed divide of the basin. These deposits include sand, silt and clay in different proportions as a result of the erosion that are subsequently deposited by streams and within the paleolacustrine system of the Laguna de San Juan. Intermontane basins of the Basin and Range (B&R) province-Mexican Highland Section (MHS) have three major landscape components: piedmont slopes, basin floors, and river valleys. Piedmont slopes comprise 1) narrow erosional surfaces (rock pediments) adjacent to mountain fronts, and 2) broad fan-piedmont surfaces formed by coalescent alluvial fans, or by alluvial slopes without distinctive fan morphology [10]. From the end of the Tertiary (> 5.1 Ma [Ma= Millions of years]), conglomerates (Tcg) formed by clasts larger than the alluvium, reaching sizes as large as boulders located in the streams, together with a poorly classified matrix of silt sands and clays. The mountain ranges are composed of Tertiary rocks from an alternation of rhyolite spills with acid tuffs (Tom(R-Ta)), great thicknesses of ignimbritic tuffs (T(Ti)) and acid tuffs (T(Ta)) outcropping the mountains. Towards the East, outside the area covered by the geological plane, sedimentary rocks of Cretaceous age (> 65 Ma) appear, which form the basement of the tertiary volcanic sequence that dominates the study area. The sequence of Cretaceous sedimentary rocks was initially affected by compressive tectonic forces that caused reverse-type faulting, as well as large folds that gave rise to the anticlines and synclines present in the Sierra de Las Lilas to the east of this study area. Subsequently, the entire stratigraphic sequence has been subjected to distensive stresses that have given rise to normal-type faulting and fracturing. During the stage of intense volcanism, it also generated faulting and fracturing in the pre-existing rocks, especially due to the thrust efforts of the magmatic chambers, which might generate a secondary porosity for groundwater to flow through these fractures [11].

2.3. Mapping of “Water by Air”

“Mapping Water by Air” applies specifically to groundwater studies using satellite imagery and aerial photography. In this method, various spectral techniques are exercised using satellite images as the main input. The procedures used in this practice were initially proposed by a group of researchers led by Gold and Parizek [12], where what is defined as an analysis of lineaments and fractures are identified by means of spectral manipulation. Before going out in the field, the first step in the investigation consisted in carrying out a geostatistical calculation for the principal component analysis (PCA). This procedure made it possible to visually identify, enhance and highlight the geological anomalies of the place on satellite imagery. This procedure is carried out by generating a geostatistical analysis defined as principal component analysis (PCA) with the aim of reducing data redundancy in multispectral images, also reducing the variance in digital data from satellite images. This method allows one to locate the points of intersection of faults and lineaments that could be related to areas of greater potential for detailed exploration for groundwater, serving as a basis for the successful drilling of a groundwater well [12].

For the development of this study, satellite images from LANDSAT 8 platform obtained from the United States Geological Survey (USGS) online server were used. The images were selected based on the oldest date and clearest skies possible, to rule out any visual alteration in the terrain, as well as to create a better-quality representation of the study area in terms of its geomorphology and the possibility of detecting faults and geological lineaments. Once the satellite image was selected, the PCA was applied using ArcMap GIS software, to eliminate fuzzy digital data within the satellite image from matrix projections. The digital procedure was performed on the pixels of the image (~30m x 30m spatial resolution) which were selected in a "kernel" matrix where the criterion was to select the eight closest neighboring pixels to the point of interest (“input”) and the spectral values of each of the immediate neighboring pixels were averaged to assign a new value to the selected one (“output”). From this, the amount of information found within the original data of the satellite image was reduced, highlighting the main component with the most significant amount of information.

Once the PCA was carried out on the imagery, subsequent filters were applied to the main component with the largest amount of data to highlight the characteristic pixels or those belonging to the same data group. For this, a low-pass filter was applied, smoothing the data by reducing local variations and removing noise from the image. A high-pass filter was used to accentuate the comparative difference between surrounding pixels. In this way, fuzzy data was removed from the image and linear patterns within the terrain were highlighted for future observation. Once the application of subsequent filters to the main component was carried out, an unsupervised classification of the image was carried out from eight spectral classes taken from cluster pixels with defined values. This procedure is used for the characterization and grouping of characteristic pixels within the image, classifying them within the assigned classes. The classes were assigned based on the spectral values and integrated into this "cluster" of spectral values ("input") which were defined within the eight selected classes. This allowed the attenuation of the lineaments observed within the study area by considering topographic descents, which usually represent aligned valleys, runoff alignments, vegetation alignments, and soil tones [13] [14]. Subsequently, an information sweep was carried out, comparing the geological faults documented within the mining geological chart H13-4 of the Mexican Geological Service and INEGI [15] and the images obtained with the spectral procedure carried out in this investigation, identifying the lineaments and fractures within the study area based on the "Water by Air" methodology.

2.4 Apply Spectral Filters for Fracture Trace Analysis

Fracture trace analysis is the technique of using satellite images to locate lineaments and fractures and other geological features [12]. Such geological abnormalities can be identified on processed satellite imagery by looking for linear features such as abnormal linear vegetation growth, minor topographic linear discontinuities, linear arroyos, linear ground depressions such as “potholes”, and aligned soil tones with darker spectral reflections, and all of them and many others can be enhanced by digital computer processing. This technique may be used to estimate an indirectly map groundwater flow [12] and has been useful for the identification of potential well drilling sites in areas with a large concentration of geological fractures and lineaments and its interpretation [13]. Additionally, it was identified that the fields of pumping wells near fractures or their intersections present a greater presence of groundwater [14]. Furthermore, it has been studied that data acquired through satellite images and remote sensors can provide information about changes in characteristics that influence geohydrological revisions, among these is the analysis of water recharge while using thermal images, multispectral and radar data [14]. It is also known that such geological abnormalities can be identified on processed satellite imagery by identifying enhanced linear features such as abnormal linear vegetation growth, minor topographic linear discontinuities, linear arroyos, linear ground depressions such as "potholes", and aligned soil tones with darker spectral reflections, and all of them and many others can be enhanced by digital computer processing. Aiming at these geomorphic linear features can reduce risk of drilling a dry groundwater well. Furthermore, it has been documented that such groundwater infrastructure sitting at a fracture zone has higher yields and specific capacities due to its extended elongation that could captured recharge from far away locations within a watershed [16].

In Mexico, fracture trace analysis for groundwater assessments have been carried out in different locations. For example, in Nayarit a study was carried out based on the processing and interpretation of structural lineaments from LANDSAT images using computer programs for the application of band compositions and Principal Component Analysis (PCA) with the objective to highlight the lineaments and fractures of the study area [16]. In the same way, in Baja California, Mexico, the analysis of LANDSAT satellite images was applied using a digital elevation model for the formulation of a cartography of the geomorphology and geology of the area, in addition to obtaining structural features (lineaments and fractures), to identify recharge and discharge areas in the San José del Cabo Hydrological Basin [16]. Furthermore, investigations of lineaments and fractures have been carried out based on a PCA analysis in the Lower Casas Grandes River Basin, specifically in the community of Guadalupe Victoria, using the processing of satellite images for the identification of linear feature structures [5] [17] [13].

2.5. Survey VES & TDES Geophysics

2.5.1. VES theoretical foundations

In the application of electrical resistivity methods, Vertical Electrical Soundings (VES) are used for groundwater studies [17] [18]. It is generally performed by applying a direct current or low-frequency alternating current to the subsurface in order to differentiate the various resistivities to flow of electric current. Moreover, it is indirectly interpreted as different types of geological materials located in the subsoil according to their resistivity. The electrical potential is measured between two electrodes through which the electric current with a specific voltage is injected for the corresponding calculations. Variations in the electric current with respect to depth cause variations in potential difference measurements, which provides information on subsurface structure and materials. In general, the geoelectric methods used for aquifer and hydrostratigraphic characterization, a system of four electrodes embedded in the ground distributed symmetrically is used. On the outside, two electrodes (A and B) are used to introduce the electrical current into the subsoil. Also, two central electrodes (M and N) are used to measure the potential generated by the passage of the electric current in the subsoil at different depths depending on the electrode arrangement of the terminals AB and MN. The electrical method used in this investigation was the vertical electrical sounding (VES) modality, using the electrode array device known as Schlumberger [19]. The mathematical expression for the calculation of the apparent resistivity in this Schlumberger electrode arrangement is given by:

$$\varrho a = \Delta V / I \,.\, K; \text{ where } K = (2\pi / (1/AM - 1/BM - 1/AN + 1/BN)) \quad \text{(Eq. 1)}$$

Where $\varrho\alpha$ is the apparent resistivity measured in Ωm; K is the geometric factor that depends only on the electrode openings of the geometric arrangement of the electric current injection pins; ΔV is the potential difference; I is the current intensity in mA; A and B is the distance between the current electrodes; L is the spacing between the current electrodes A and B; M and N is the separation between the potential electrodes.

2.5.2. TDES theoretical foundations

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Geophysical methods for groundwater prospecting using Time Domain Electromagnetic Surveys (TDES), measure the decay of a transient secondary magnetic field by cutting off power to the transmission loop [20]. The secondary field generated by the flow of the induced current in the ground is measured by a receiving coil after the cutoff of the transmitted current. The stress of the secondary or transient field in the first-step window gives information about the conductivity of the shallow subsurface whereas the transient stress in the last-step window is influenced by the conductivity of the subsurface at depth. The waveform of the secondary magnetic field (induced currents) generated by the interruption in the flow of electricity in the loop or transmitter frame where the active period (time on), the off time (ramp time) and the measurement period after cutting off the current flow (time off) are the measurement times to obtain a sounding record. The decay curve measurement windows were 25 decay curve windows for the readings taken with a frequency of 16 Hz and 28 for 32 Hz. The time domains in the current transmitted and the primary magnetic field where between the on time and the off time, there is a ramp time to later manifest the current of the magnetic field resulting from the induced currents and the measurement windows along the path of a time end measurement. This allows the resistivity of materials to be identified at different depths in the lithological section in the measurement zone.

2.6. Initial screening to streamline field investigation

The geostatistical interpretation applied was to calculate a matrix of statistical values identified as eigenvalues highlighting the main component (image that clearly highlighted the lineaments or geological faults). A process of applying subsequent spectral filters to the satellite image was used to better visualize the linear features of the terrain, facilitating the interpretation of lineaments and fractures within the study area. An unsupervised classification from eight spectral classes selected from the databases obtained from the digital filters was then applied. Similarly, the unsupervised classification allowed for characteristic pixels to be highlighted for later interpretation, assigning similar pixels to each of the specific designed classes. Once the geostatistical processing of the satellite image was completed, "Water by Air" methodology was carried out where the analysis of lineaments and fractures were visually compared with the geological faults identified by the official Mexican geological cartography reported by SGM [15].

Specific geographic points for the geophysics were selected from the lines representing fault crossings and lineaments identified in the PCA spectral mapping procedure of "Water by Air". Next, we proceeded to work in the field with these geographic coordinates for the sounding points for the geophysics procedure gathering the resistivity data on the geologic materials underground at the survey sites. A graphical display of these values on a double logarithmic paper with which sections of curves of resistivity values and their subsequent geological interpretation were obtained. This information required a pre-interpretation process, which consisted of a displacement and/or adjustment of a "slight smoothing" calibration process of the gathered field resistivity curve and in which new values of apparent resistivity were obtained. Finally, the calibrated resistivity values obtained were processed in IX1D software for final interpretation [21]. Additionally, a Digital Elevation Model (DEM) of the study area was used to understand the dimensions of the basin under consideration and to identify the main drainage network in the basin, as well as the exact location of groundwater wells in the study area. In addition, the DEM was used to locate the exact location of the piezometric level survey and equipotential lines of groundwater that allowed delineating the static water level in the basin.

Two VES and two TDES were carried out in the study area. The maximum opening (AB/2) was 320 meters for VES-1 sounding and 400 meters for VES-2. The surveys were carried out in the Schlumberger modality and the geographical location data in the field of the 2 VES and the 2 TDES are presented in Table # 1.

Table 1. Locations and elevations of Vertical Electrical Soundings (VES) and Time Domain Electromagnetic Surveys (TDES) in Universal Transverse Mercator (UTM) projection.

ID	UTM East	UTM North	Elevation (masl)
VES-1	231,615	3,427,155	1530
VES-2	238,083	3,423,970	1621
TDES-1	231,131	3,427,380	1516
TDES-2	231,615	3,427,155	1530

TDES-1 was carried out in a well (*Pozo El Menón*) previously drilled with negative results and TDES-2 was carried out at the same point where VES-1 was surveyed and which showed groundwater possibilities based on the "Mapping Water by Air" procedure and so that the TDES could verify the geo-electric units defined by the VES. The hydrostratigraphic units at both sites was further investigated with a downhole video camara recording in the previously drilled well (*Pozo El Menón*) till a depth of 150 m. A current of 10 A was applied in a 100 x 100-meter box for a dipole moment of 100,000 A-m2 for both TDES soundings.

2.6. GPS RTK wellhead survey

Differential GPS positioning and elevations were determined at well locations to further resolve current piezometric levels of the area. A 220-channel Rover STONEX S9, UHF radio modem and dual-frequency GPRS equipment was used to perform an RTK survey. The survey mode was fast static (Static Vertical Accuracy: 10mm +/- 2ppm which requires post-processing against a CORS, RGNA Base or Reference Station). The base station was left at the point defined as CAST and was in operation during the field survey. Subsequently, the survey was carried out with base and mobile GPS RTK Trimble Unit. Throughout the survey, the base station was collecting data to process the records acquired with the mobile GPS receiver (rover) for at least 20 minutes. The precise location (~2 cm in X-Y; ~2-5 cm in Z) of the surveyed groundwater wells where then use to determine the elevation at the well location. During the rover data collection, the static groundwater level in the surveyed wells were measured with a Solinst Water Level Meter Model 101 by calculating the precise depth of the static groundwater level in each of the wells (Figure 3).

Figure 3. GPS RTK survey and evaluation of groundwater level

3. Results

3.1. Interpretation of Principal Component Analysis (PCA)

The PCA procedure generated eigenvalues with statistically highlighted main component, corresponds to the greatest amount of spectral information present in the satellite image related to possible lineaments. Within this statistical analysis, the main component 1 (PCA1) stood out with 87.36% of the total spectral data contained on the satellite imagery was used to evaluate the possible points to explore in the field with a procedure of geophysics (Table 2).

Table 2. Correlation of eigenvalues for principal component analysis (PCA) of LANDSAT images

PCA Layer	eigenvalue	Percent of eigenvalues	Accum. of eigenvalues
1	13360881	87.36	87.36
2	1016952	6.65	94.01
3	667394	4.36	98.37
4	164175	1.07	99.45
5	69657	0.45	99.90
6	12985	0.08	99.99
7	1462	0.01	100

Once the PCA was obtained, subsequent spectral filters were generated to eliminate noise and attenuate the main component achieved by highlighting the satellite image in relation to enhancement of faults and lineaments. The application of these spectral filters allowed a better visualization of linear characteristics facilitating the interpretation of lineaments and fractures within the study area. Once this step was finished, an unsupervised classification was carried out defining eight spectral classes to explore. This spectral classification allowed the highlighting of characteristic pixels for later interpretation. After the processing of satellite image was completed, the analysis of lineaments and fractures was carried out with respect to the "Water by Air" methodology, verifying its correlation with geological faults reported by official information published by INEGI [15] (Figure 4 and 5).

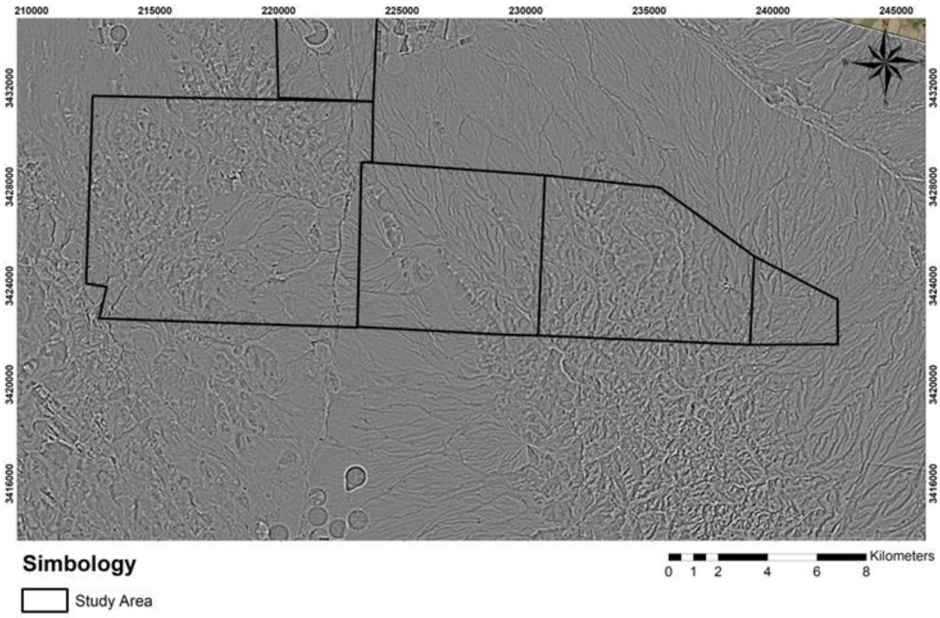

Figure 4. Image of study area after the application of spectral filters highlighting linear terrain features.

The PCA analysis yielded a total of 26 lineaments within the study area, with a total of 7 overlapping points of interest for geophysical field exploration and/or as sites for groundwater recharge potential (Figure 5 and Table 2). These points of interest corresponded to intersections between the lineaments and identified faults that could indicate groundwater conduits. The trends displayed within the area of study show the main direction of the lineaments and faults with a NW-SE orientation and a NE-SW trend (Figure 5; Table 2).

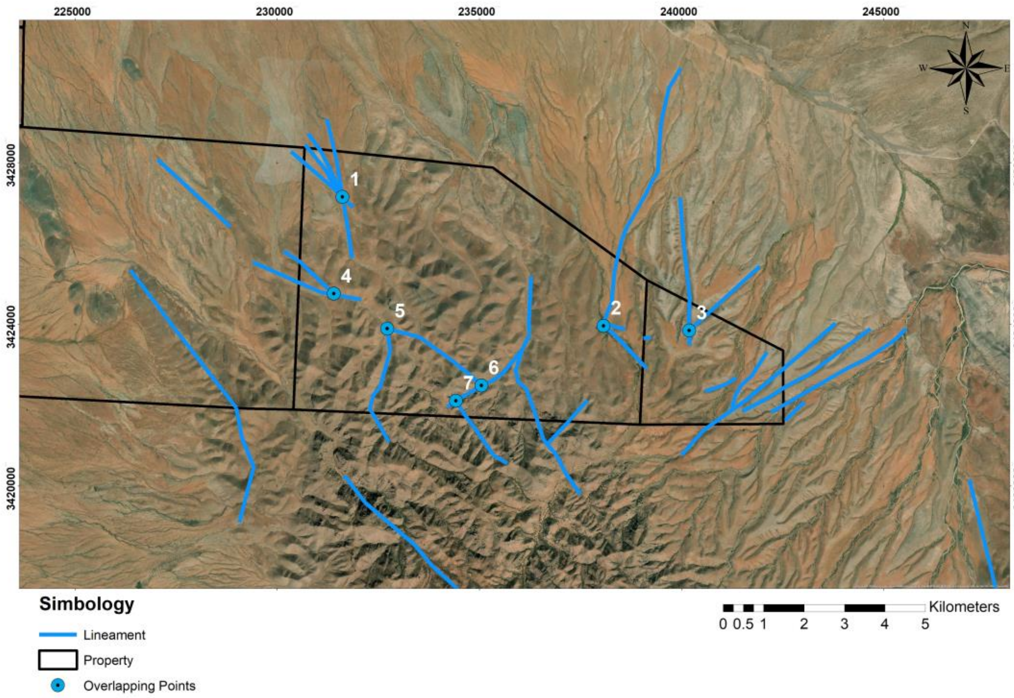

Figure 5. Map of study area showing the results of an analysis of lineaments and fractures and seven points of interest that are potential geophysical exploration sites.

Table 2. Locations (and elevations) of the points of interest for geophysical exploration developed by the fracture trace analysis using the "Water by Air" methodology [12]. Locations in Universal Transverse Mercator (UTM) projection (elevations in meters above mean sea level)

Point ID	North (UTM)	East (UTM)	Elevation (masl)
1	3,427,155	231,617	1526
2	3,423,970	238,084	1619
3	3,423,851	240,192	1623
4	3,424,764	231,394	1638
5	3,423,891	232,720	1694
6	3,422,487	235,050	1682
7	3,422,105	234,424	1720

3.2. Interpretation of VES and TDES

The interpretation of VES and TDES was accomplished by first identifying of the number of lithological units and their approximate resistivity values. In this way, a layered lithological model was established, and the direct solution could be automatically adjusted within the applied interpretation software IX1D [21] to fit the observed data. The second interpretation consisted of using the inverter of the interpretation software to fit the smoothed field curve with the best fit of the hydrostratigraphic model. Both methods reduced the possibility for error on its interpretation. The TDES were interpreted using the TemMerge module of the WinGLink software to average the data with the same frequency and filter the points or windows with high errors to finally generate the input file for the inversion [20] .

Interpretation of field data generated by the VES´s are represented by a curve of best fit and the layered model. The VES field data and curve of best fit at site 2 is presented in figure 6.

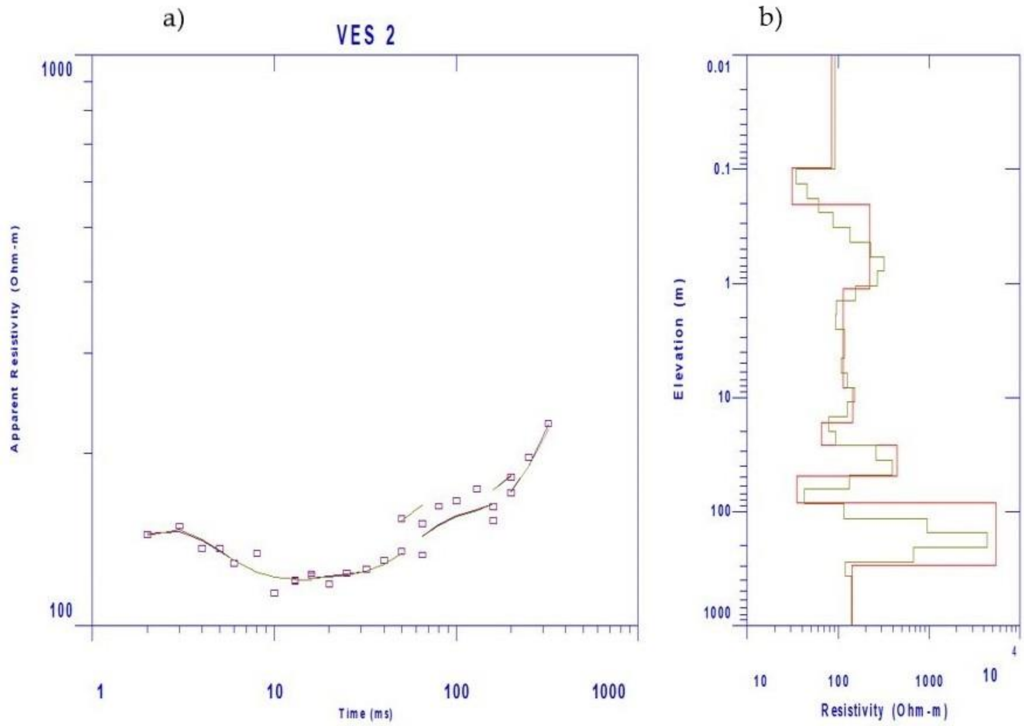

Figure 6. The best fit curve and layered models for Vertical Electrical Sounding (VES) at site 2.

The values obtained from field work are represented by lithology segments showing the subsoil model with approximate thickness (m) of the layered materials on the y-axis and the apparent resistivity values (Ohm-m) of these materials are represented on the x-axis (b on figure 6). The thickness and apparent resistivity values are presented for two vertical electrical surveys carried out in the area. The continuous magenta line represents the curve of best fit in which a smoothed model on the left side of figure displaying the modeled parameters showing resistivity values and thickness of the surveyed strata (a on figure 6). VES results in figure 6 shows resistivities as low as 35 Ohm-m starting at about 50 m to over 85 m depth, indicating the potential for shallow subsurface groundwater flow that could provide water for livestock. Furthermore, there is a second layer of low resistivity values deeper than about 200 m and separated from the shallow layer by one of higher values. Associating this intercalation with two layers of deposits that could be conglomerate-type materials separated by pyroclastic material from an intrusive volcanic eruption. The resistivity layer between depth of 85 and 200 m is above 5000 Ohm-m which corresponds to healthy rock with little or no permeability. It is important to highlight that groundwater flows might be present in the area and 85 m drilling depth at this point would be enough to capture water from that fractured area at the specific geographic point defined in this site.

The VES at site 1 indicates a thin stratum with relatively low resistivity values is present within the first 8 m but increasing to above 1700 Ohm-m up to 95 m deep. From this point in depth values of resistivity are reduced reaching 193 Ohm-m at a depth of 192 m and further lowers the resistivity to 34 Ohm-m to a depth of 240 m (b on figure 7).

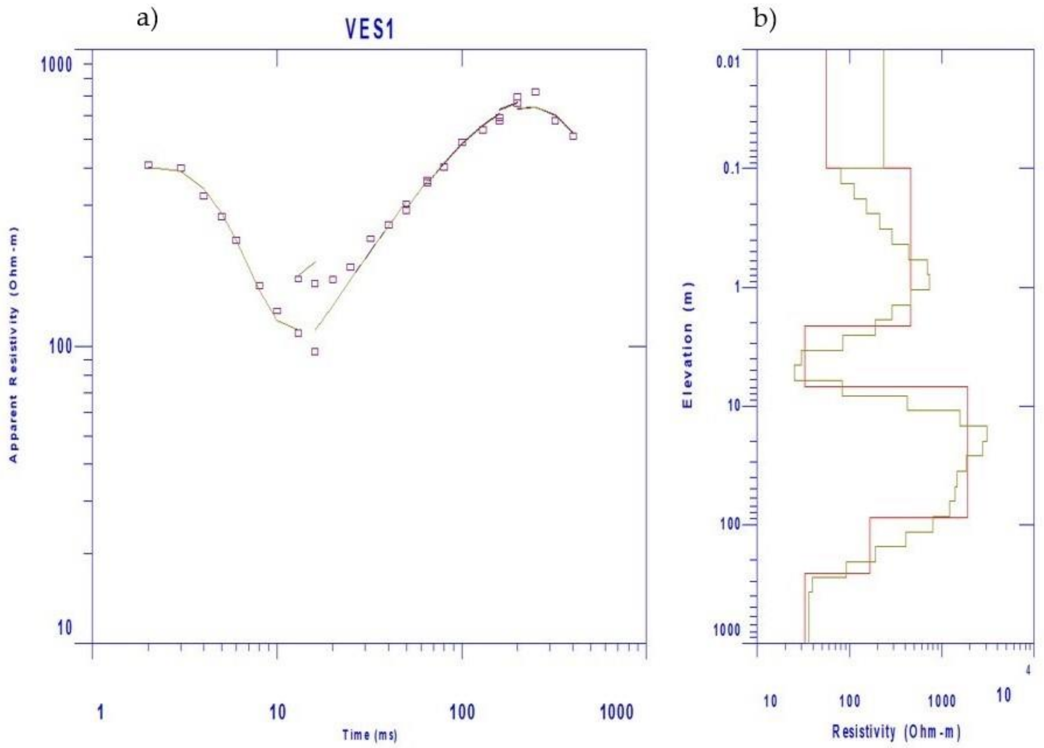

Figure 7. Vertical Electrical Sounding (VES) at site 1 best fit curve and layer models.

It is possible that some lithological sections at this site (b on figure 7) corresponds to volcanic rock with different degrees of fracturing and the deepest stratum may be the sedimentary rock basement or the fractured rock which was defined as one of the points to explore for a groundwater well at this site. However, non-functioning well (*Pozo El Menón*) which was previously drilled to a depth of approx. 244 m showed no groundwater potential and the same geologic unit continued up to 278 m and from that depth the resistivity increases significantly (2062 Ohm-m), which is interpreted as the presence of massive material, so further drilling at this site was not recommended. Red lines represent the AB electrode separation, and the 18.8 m distance represents the displacement alignment between VES at site 2 and the previously non-functioning well *Pozo El Menón* were TDES at site 1 was accomplished (Figure 8).

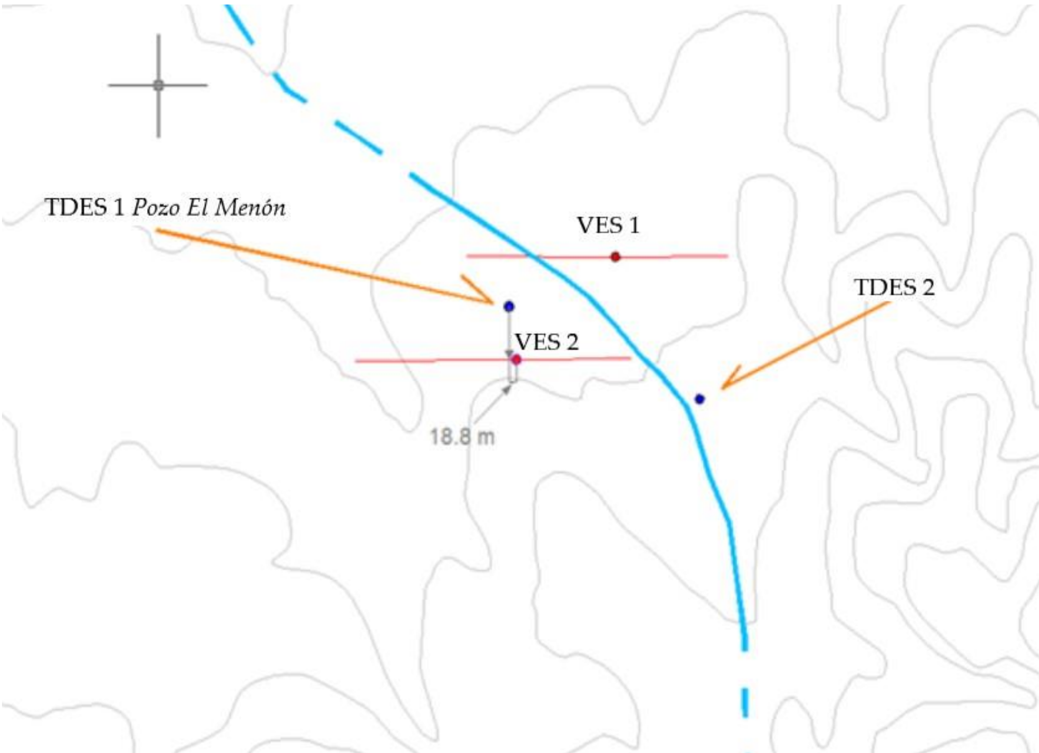

Figure 8. Location of surveyed Vertical Electrical Sounding (VES 1 and 2) and Time Domain Electromagnetic Survey (TDES 1 and 2). Blue line represents one of the lineaments surveyed with the “Water by Air” procedure [12].

For the site where the second TDES (Figure 8) was carried out, the characteristics for the occurrence of groundwater improves significantly. At this site there is a low resistivity lithological section that has its base at 290 m deep and continues with low resistivity values of 75 Ohm-m for a total thickness of 134 m. The resistivity values of this unit indicates that it is likely to store and be capable of release groundwater through the siting of a groundwater well at this site (Figure 9).

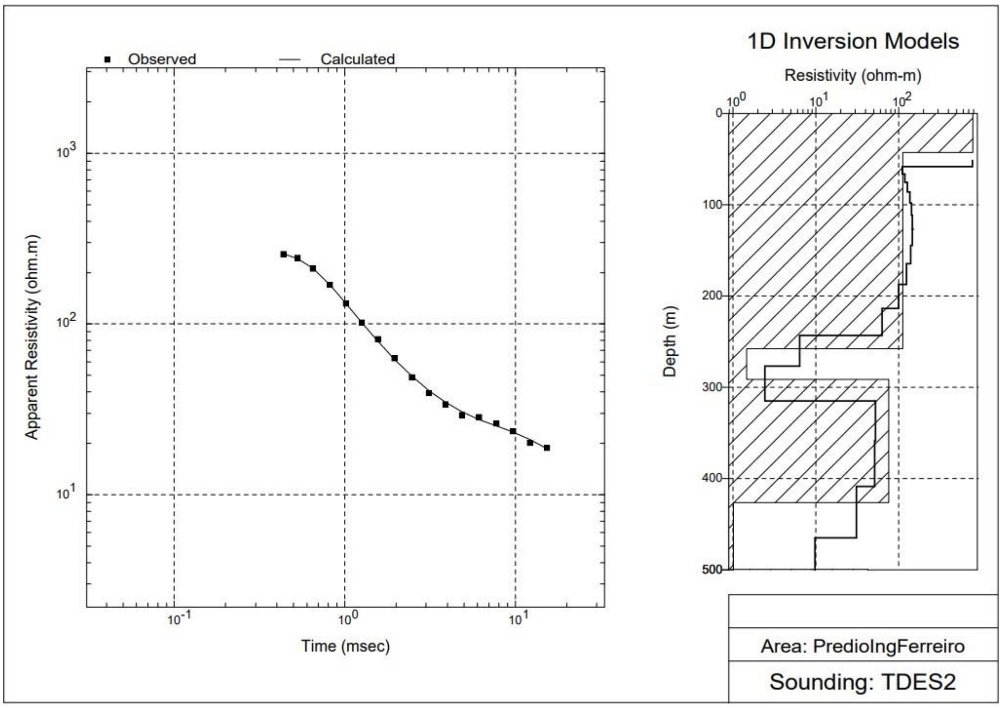

Figure 9. Time Domain Electromagnetic Surveys (TDES) at site 2 showing low resistivity values with potential for groundwater

A resistivity cross-section was constructed with the surveyed TDES (TEM1 and TEM2 on figure 10) and a discontinuity of resistivity values between both sites can be observed. The site where TDES 2 was surveyed shows stratified lower resistivity values which can be associated with deposits such as conglomerates or alluvial deposits or rock with intense fracturing with good possibilities of groundwater production in between high resistivity values. This discontinuity may be due to the fault that was identified as a lineament in the fracture trace analysis.

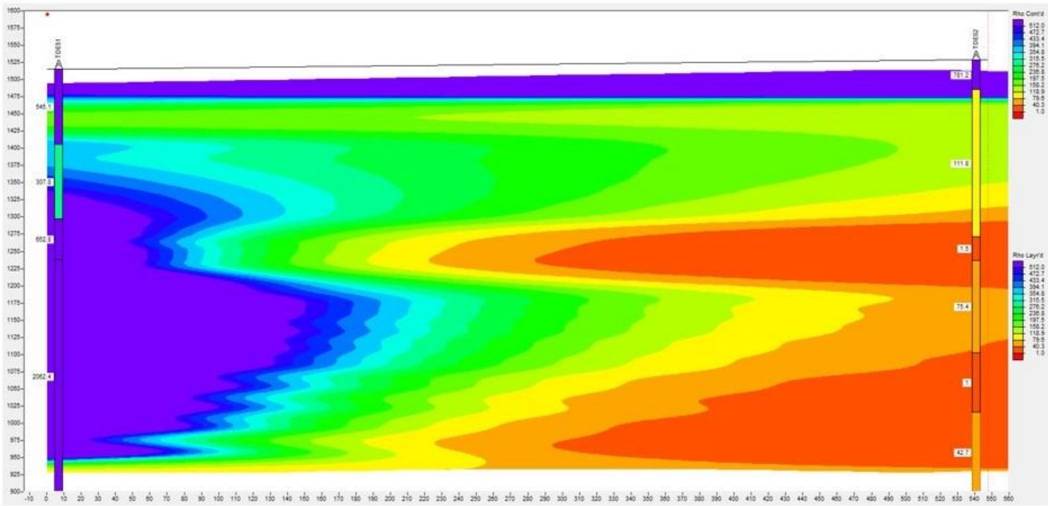

Figure 10. Resistivity cross-section based on surveyed Time Domain Electromagnetic Surveys.

3.3. Piezometric surface construction

The application of a geohydrological analysis to define groundwater potentials is basic to understand groundwater flow and is complemented by the geophysical determination of the hydrostratigraphic units (HSU) in a watershed. This allows us to locate sites that could show the best possibilities for a saturated strata or geological formation in the explored site, which can be used to establish an economically feasible groundwater well. To determine the groundwater potential of the various HSU at the study site, a geohydrological analysis was carried out and a schematic diagram was created by surveying these geological formations and evaluating the possibility of receiving water from some source, either by recharge of pluvial origin or from groundwater flows from regional aquifers (Figure 11). To achieve this objective, it was necessary to carry out a topographic survey to generate static water levels (SWL) to model equipotential lines of groundwater flow for a battery of wells in the region. With this procedure, it was possible to define SWL at the points where the piezometric data was taken and to map the networks of these equipotential lines of the subsurface flow and groundwater level for the regional aquifer.

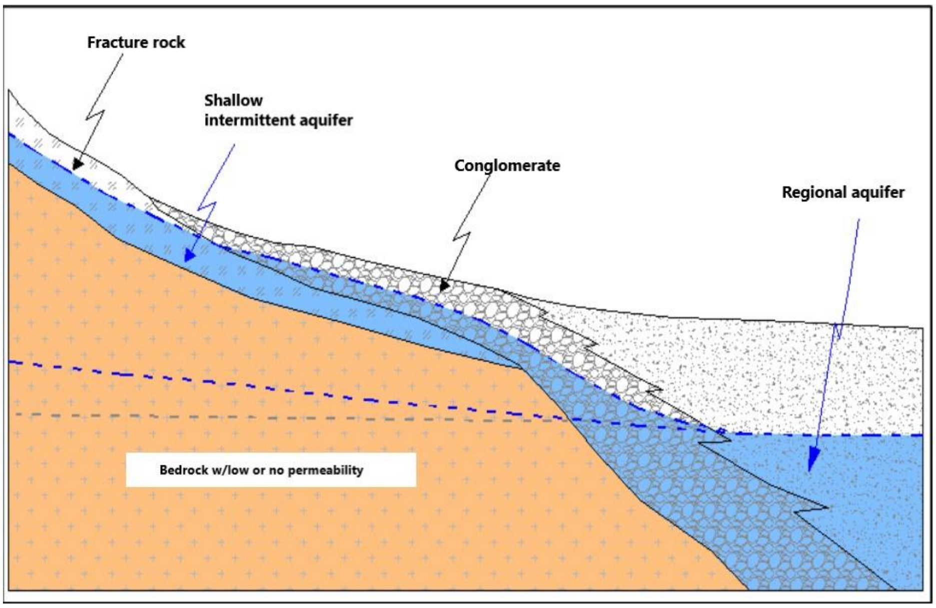

Figure 11. Schematic of the shallow and regional aquifers on the study area.

The approximate direction in which groundwater movement could be occurring in the study area is presented in figure 12 [9]. This aquifer is in alluvial deposits and fractured conglomerates in the upper parts of the basin and flows downslope until it intercepts the regional aquifer. The upper shallow aquifer of alluvial deposits functions as intermittent recharge for the below regional aquifer and is manly located in watercourses at the headwaters of the basin and in fractured conglomerates that were altered by tectonic forces of the regional natural geological formation. These recharge lineaments formed by the arroyos can feed water recharge to rock formations that underlie it if these have some degree of fracturing or secondary porosity. Identification of these lineaments was undertaken by the "Water by Air" method described above.

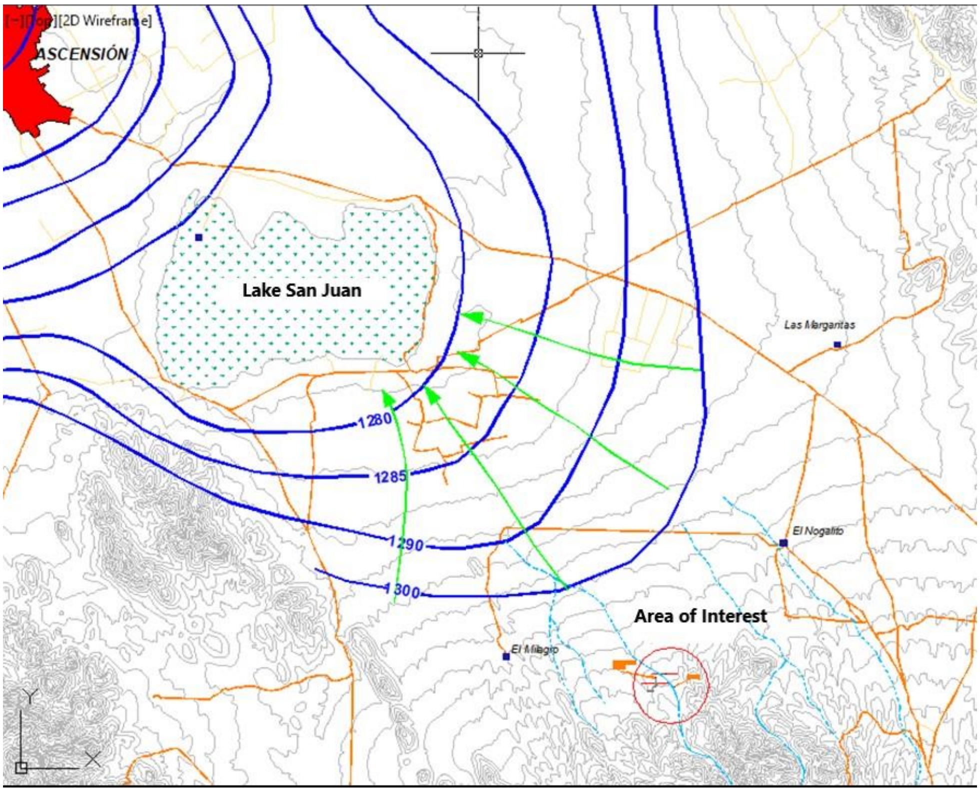

Figure 12. The reported 1998 Equipotential lines (in meters above NAD27) and groundwater flow direction [9]

Average annual groundwater availability in 1998 for the Ascension aquifer (0801) was published by official sources [9]. Equipotentials in this report for 1998 define a groundwater flow system moving from the Sierra El Capulín (area of interest) towards Lago San Juan (Figure 12). According to this flow system, the direction groundwater moves in the study area is represented by the green arrows clearly shows the direction of the flow, while the equipotential lines represent the groundwater elevation measured in meters above sea level. The higher elevation contours indicate that an important recharge source comes from the Sierra El Capulín. Equipotential elevation closest to the area of interest according to this database had an elevation of 1,300 masl in 1998, while the groundwater elevation at the area of interest (red circle in figure 12) was measured to be approximately at a surface topographic high of approximately 1530 masl. Since the information on elevation of SWL or piezometric measurements were officially obtained since 1998, it was necessary to update the values of this parameter by carrying out a survey of recent equipotentials and updating of piezometric levels in the area.

3.4. Update of equipotentials and piezometry

The real-time kinematic (RTK) survey of wells was completed using the IMIP base station in Ciudad Juárez, Chih., and the INEGI stations installed in the City of Chihuahua and in the City of Hermosillo. A constellation of 12 to 18 satellites was used to acquire a position at the points of interest and at each site the mobile GPS and was left taking readings for 20 minutes to link it to the base station sited on the Castañeda location. In total, position coordinates of 5 wells were obtained where the depth to SWL was also obtained (Table 3).

Table 3. Real-time kinematic survey of wellheads and piezometry. Locations in Universal Transverse Mercator (UTM) and elevations in meters above sea level.

ID	UTM East	UTM North	Elevation	Wellhead	Depth to SWL (m)	SWL (masl)
Base	222,601	3,434,253	1304.96	-	-	-
Castañeda	225,570	3,434,241	1305.92	1305.92	30.65	1275.27
Tellez	226,882	3,435,078	1307.39	1397.39	31.05	1276.34
Ramirez 1	225,222	3,433,380	1314.38	1314.38	38.15	1276.26
Ramirez 2	224,656	3,433,338	1313.46	1313.46	34.4	1279.06
Huerfano	227,154	3,431,206	1361.65	1361.65	86.5	1275.15

Table 3 shows the UTM coordinates resulting from the baseline georeferenced process for the control station located on the Castañeda site with resulting georeferenced coordinates of points that were positioned with the mobile GPS. The georeferenced coordinates were mapped using the WGS-84 Datum with the GGM-10 reference geoid and in a geographic format which were later converted to flat UTM coordinates. Figure 13 shows equipotentials of updated SWL for 2022 showing the depletion that had occurred in the aquifer during the period from 1998 to 2022 which is around 7 m (approx. 30 cm of SWL depletion per year).

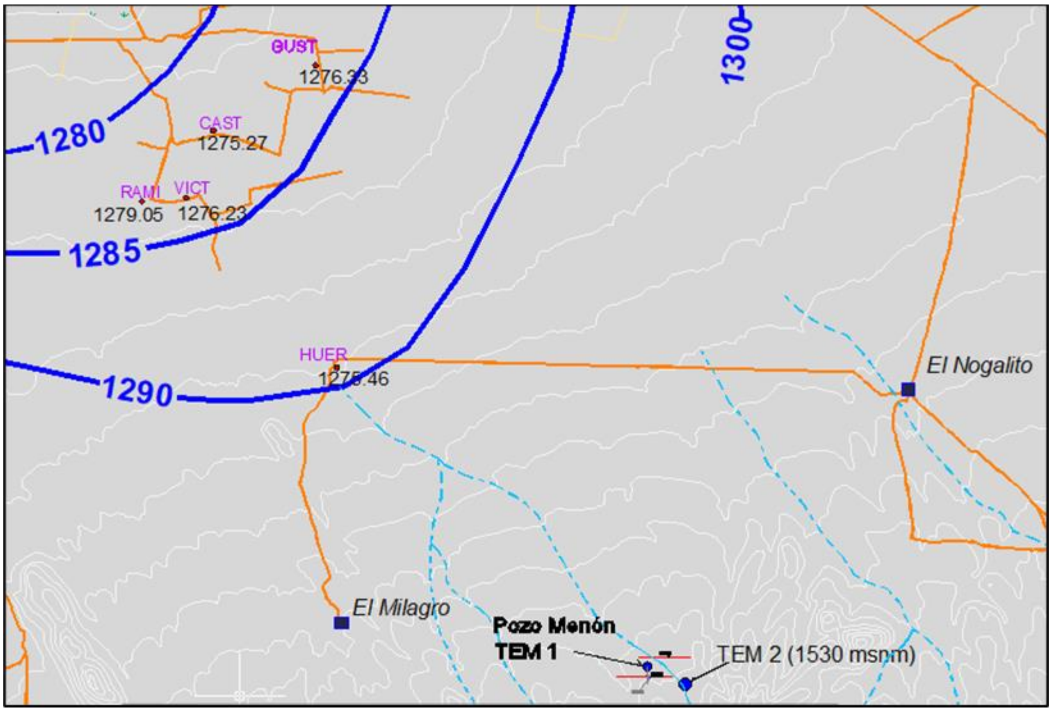

Figure 13. Updated SWL for 2022 for the regional Ascension aquifer (0801)

Considering the topographic elevation of the validated site for the location of a new well by the exploration methods explained in previous sections of this paper, an equipotential line was defined at 1530 masl in the area if interest. Hence, the depletion in the aquifer at this site was estimated to be of 7 m compared to the 1998 hydrocensus. A probable drilling depth can be recommended at this site to reach the level of the regional aquifer at the point of interest and additionally take advantage of the recharge that probably is provided by the mapped crossing fault systems and mapped lineaments. In such a way, if it is considered that the last equipotential projected in 1998 towards the area of interest was 1290 masl, depth of drilling must have a depth greater than 247 m to be able to enter at the SWL of the regional aquifer in the area. Similarly, it is possible that during the drilling of this new well, shallower groundwater from rainwater recharge may be present from the remained saturated zone of fractured rock identified by the exploration stage with the "Water by Air" and geophysical methods.

4. Conclusions

The present study consisted of a geohydrological evaluation using a multi-task approximation to locate potential drilling sites for a groundwater well in a basin with semi-arid climatic conditions, complex geological settings, and continuous depletion of groundwater levels. The focus was to locate a well site in order to provide water to livestock. Given the site´s complex hydrogeological conditions, it was a complicated task to find the location of a potential drilling point that could supply a minimum volume for the development of the mentioned activity. A spectral analysis of geologic and geomorphic lineaments and fractures was carried out based on a geostatistical analysis identified as the main components, together with the processing of satellite images to eliminate fuzzy data within the sets of LANDSAT TM8 satellite images used on the process. The spectral processing and digital manipulation of these satellite images allowed the enhancement and visualization of linear features within the terrain under analysis, which allowed the highlighting and classifying pixels with similar characteristics through the procedure previously mentioned. Results obtained from the "Water by Air" methodology identified a total of 26 lineaments and fracture traces within the study area out of which seven sites were selected as potential points with intersected crossings of faults for further geophysical field exploration. Furthermore, it is considered that these intersections of lineaments and faults are the points of greatest potential for groundwater exploration by geophysical methods, reducing the time of fieldwork and exploration and increasing the chances for a successful drilling.

A survey of the structural geology and the geophysics at the sites of interest identified that complex geology indicating the presence of a predominantly acidic volcanic layer, formed by tuffs, ignimbrites and rhyolites, which have unaltered healthy state presented without permeability; that is, these units do not store or transmit water. However, within the telluric processes, the compressive and distensive events of tectonic origin that have occurred in the area have caused faulting and fracturing at some regions in the existing rocks that have produced secondary porosity in them, which functions as potential recharge areas that could generate potential flow of groundwater on upper sections of the predominant strata at the fractured system. Furthermore, the difference in the resistivity profile between TDES1 and TDES2 indicates a discontinuity that can be interpreted as a fracture zone towards TDES2. This fracturing zone can be justified because it is in a fracturing or faulting zone as it was identified in the previous exploration studies explained in the mapping groundwater by the "Water by Air" section. According to the exploration methods used including field methods to activate electromagnetic soundings, it is identified that the place with the best probability of finding groundwater was the point where the TDES2 sounding was carried out.

Additionally, a hydrocensus was carried out georeferencing wellheads of such local infrastructure to update groundwater evolution for the regional aquifer and extended upstream into the headwaters of the watershed aiming at the area of interest. This procedure included SWL measurements at selected wells and redefining the equipotentials for the regional aquifer at the time when this study was accomplished. Towards the area of interest in the study, the regional aquifer has dropped by around 7 m from 1998 to date declining at a rate of 30 cm per year on average. In correspondence with the geohydrological analysis and complemented with the geophysical study surveyed in the area of interest, SWL on the regional aquifer can be located approximately at 247 m deep at the point indicated by the UTM coordinates suggested in the "Water for Air" method for exploratory drilling at this site. On the other hand, there is the possibility for groundwater that could be added by subsurface flows present in the upper fracturing zone (from 50 m depth till 85 m), for which there is the possibility that during drilling water may be found that is shallower than at a depth of 247 m indicated as the regional aquifer.

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