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Hydrogeological simulation of the El Vigía aquifer for water supply purposes in the area between Brisas del Chama and Los Pozones. Mérida-Venezuela

Simulación hidrogeológica del acuífero de El Vigía con fines de abastecimiento de agua en la zona comprendida entre Brisas del Chama y los Pozones. Mérida-Venezuela

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Abstract

The semi-confined El Vigía aquifer, located in the Alberto Adriani municipality, Mérida state, has high potential and water quality to supply the city and nearby towns. However, the potable water supply is insufficient for the local population. This study conducted a hydrogeological simulation of the aquifer using the free Visual Bluebird software, based on an analytical elements model adapted to modern operating systems. A photogeological analysis and geological survey at a 1:50,000 scale identified Tertiary sedimentary formations, alluvium, and Quaternary terraces. A geological fault, assumed as a blind thrust, was detected, increasing hydraulic conductivity in its surroundings. Using the Thornthwaite water balance model, an annual recharge of 206.2 mm was estimated, equivalent to 11.26% of precipitation. The data obtained defined well protection perimeters and generated hydrogeological maps to propose exploiting a new well field northwest of the fault. Zones requiring special monitoring to prevent contamination were also identified to improve water resource management and preservation in the region.

Keywords: semi-confined aquifer, analytical elements, hydrogeological simulation, water management, hydraulic conductivity.

Resumen

El acuífero semiconfinado de El Vigía, ubicado en el municipio Alberto Adriani, estado Mérida, posee un alto potencial y calidad de agua para el abastecimiento de la ciudad y pueblos cercanos. Sin embargo, el suministro de agua potable es insuficiente para la población local. Este estudio realizó una simulación hidrogeológica del acuífero utilizando el software libre Visual Bluebird, basado en un modelo de elementos analíticos adaptados a sistemas operativos modernos. Se efectuó un análisis fotogeológico y un levantamiento geológico a escala 1:50.000, identificando formaciones sedimentarias Terciarias, Aluviones y Terrazas del Cuaternario. Se detectó una falla geológica, asumida como cabalgamiento ciego, que aumenta la conductividad hidráulica en su entorno. Mediante el modelo de balance hídrico Thornthwaite se estimó una recarga anual de 206,2 mm, equivalente al 11,26% de las precipitaciones. Con los datos obtenidos, se definieron perímetros de protección de pozos y se generaron mapas hidrogeológicos para proponer la explotación de un nuevo campo de pozos al noroeste de la falla. Asimismo, se identificaron zonas que requieren vigilancia especial para prevenir la contaminación, con el fin de mejorar la gestión y preservación del recurso hídrico en la región.

Palabras clave: acuífero semiconfinado, elementos analíticos, simulación hidrogeológica, gestión del agua y conductividad hidráulica.

1 Introducción

In the city of El Vigía, located in the Alberto Adriani municipality of Mérida state (Figure 1), there are aquifer units that supply both the city and nearby towns. However, despite having this source, residents do not have an optimal drinking water service, as its extraction currently requires methods that involve high costs and make access to the resource difficult.

To address this issue and reinforce previous studies (Rivas, 2000; Terán, 2003; Contreras and Suárez, 2006; Jégat and Ramírez, 2008; Velázquez and Vivas, 2008; Briceño and Tovar, 2012; Peñaloza and Rojas, 2012; Pérez and Sánchez, 2014; Mora *et al*., 2018) that address this situation using various methodologies, we propose a hydrogeological simulation of the El Vigía aquifer between Brisas del Chama and Los Pozones using analytical element methods with Visual Bluebird 2.0 software, which seeks to generate models, maps, and well protection perimeters that allow for the identification of the most suitable areas for exploitation.

The specific proposal is to develop a new field of wells, with the aim of ensuring a more efficient supply and improving the quality of life of the community.

1.1 Regional geology

The state of Mérida is crossed by a topographic-tectonic uplift known as the Cordillera de Mérida in a SW-NE direction, from the Táchira depression to the Barquisimeto depression, respectively. Within it lies the Sierra Nevada de Mérida, in the same direction, with a length of 320 km and an average width of 3 to 7 km. It is mainly formed by Upper Precambrian rocks (basement) belonging to the Sierra Nevada Association and, discordantly, Paleozoic to Mesozoic rocks (Tostós Association and formations such as Sabaneta and Palmarito) are found on top of them, with the presence of complex faults and folds (González *et al*., 1980).

The town of El Vigía is located in the Andean foothills; it sits on much younger sedimentary formations belonging to the Cenozoic era, mainly from the Miocene and Pliocene epochs, consisting of detrital material (clays, sandstones, and conglomerates) deposited in fluvial and alluvial environments (Figure 2A).

According to González *et al*., (1980), the study area is bounded to the north by the Maracaibo Lake depression and to the south by the Mérida Mountain Range, reflecting a geological evolution influenced by both tectonic provinces. Following the retreat of the Cretaceous seas and the emergence of a new continental shelf (Boesi *et al*., 1993), a compressive tectonic regime was established during the Palaeogene. This event, which predominated after the post-Palaeogene deformations, generated northward-trending thrusts and developed lateral ramp faults, shaping the current structural landscape of the Mérida mountain range. From the Neogene onwards, and particularly during the Miocene and Pliocene, successive Andean uplifts contributed to the emergence and maximum stacking of the Venezuelan Andes (Audemard and Audemard, 2002). Finally, in the Quaternary period, active and continuous tectonics favored the deposition of fluvial-alluvial sediments on the El Vigía plain, while episodes of compressional deformation continued to occur, which still influence the current dynamics of the relief and subsoil.

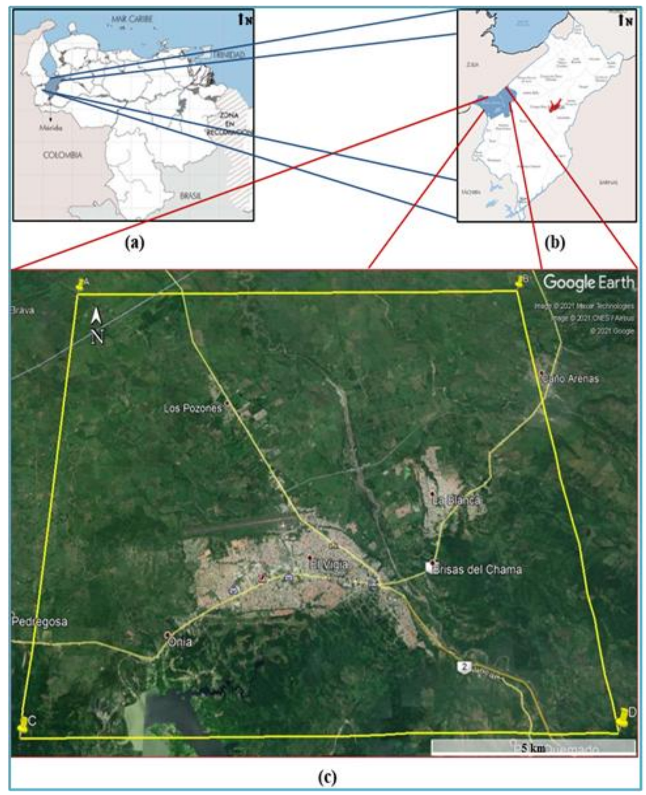

Figure 1. Relative location of the study area and, in the yellow box, its boundaries. The vertices that comprise it are defined below and expressed in UTM coordinates, DATUM WGS 84, zone 19N: A) 962100N, 200350E; B) 962100, 215120; C) 949050, 200350; and D) 949050, 200350.

1.2 Local geology

From a lithostratigraphic and structural perspective, the El Vigía area is characterised by relatively simple geology, with approximately 75% of the surface covered by Quaternary deposits associated with alluvial plains and fluvial-alluvial terraces of the Chama and Onía rivers. The remaining 25% is made up of the Isnotú and Betijoque sedimentary formations (Figure 2A and 2B).

The Miocene Isnotú Formation is dominated by clays with intercalations of sandstones, coal and conglomerates, while the Upper Miocene to Pliocene Betijoque Formation consists of massive conglomerates, siltstones, sandstones and clays. The Quaternary deposits, predominantly alluvial, are heterometric and poorly stratified, integrating rock fragments from the Precambrian to the Cretaceous, and are arranged in longitudinal and transverse systems, including terraces ranging in age from the Pleistocene to the Holocene, with thicknesses between 5 and 50 metres (Briceño and Tovar, 2012; Sutton, 1946, cited in LEV, 1997).

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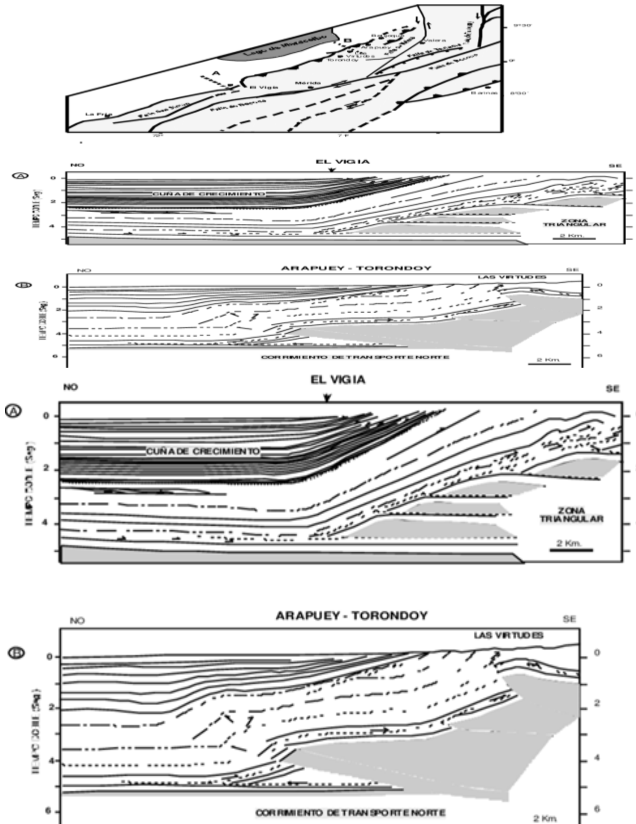

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global geodynamic perspective, north-western South America is a region of convergence and interaction between the South American, Caribbean, Nazca, Cocos and North America tectonic plates. Throughout geological time, the relative movements between these plates—including collisions, subduction, and lateral slippage—have shaped the evolution of the relief, the development of the Andes mountain range, and seismic activity in the region. In particular, the active subduction of the Nazca plate beneath the South American plate has produced episodes of orogenesis and mountain uplift from the Neogene to the present day, while interaction with the Caribbean plate introduces complex strike-slip movements and deformations in the Maracaibo Block. As a result, the area has been shaped by successive tectonic events that continue to generate deformation and seismicity processes, giving the region an active and multi-episodic structural dynamic.

B A

The Norandino flank, according to its deformation characteristics, was divided by Audemard and Audemard (2002) into two sectors: the SW segment of El Vigía and the NE segment of Valera, as shown in Figure 3.

originate in the Maracaibo basin and form a triangular zone. The Tertiary sedimentary sequence dips to the NW at high angles; the upper part of the sequence comprises the Upper Miocene and Pliocene-Pleistocene. The triangular zone is composed of four faults that have NW vergence (Figure 3A).

2 Methodology and results

The research adopted a systematic methodology divided nto three main phases, beginning with i) information gathering (bibliographic, meteorological, hydrological, cartographic data and inventory of wells) and photogeological analysis, ii) collection of surface geological data, and finally, iii) processing of the data obtained in the previous stages, where aquifer recharge is estimated, Visual Bluebird 2.0 software is implemented, well protection perimeters are established, and 2D geological and hydrogeological models are generated.

2.1. Meteorological and hydrogeological inventory

The meteorological information used in this study was obtained from the database of the former Ministry of Environment and Natural and Renewable Resources (MARNR), through the Directorate of Hydrology and Meteorology and the National Hydrological and Meteorological Information System (SINAIHME).

The data correspond to the El Vigía station (serial 3035), located at coordinates 08°36'27" N, 71°37'47" W and at an altitude of 130 m above sea level. Monthly averages of precipitation between 1945 and 2006, evaporation between 1955 and 1984, and average, maximum, and minimum temperatures between 1970 and 1984 were analyzed.

Analysis of the climate series revealed average precipitation of approximately 1830 mm/year (1945-2006) and average temperatures of 28°C (1970-1984), as well as reference evapotranspiration values of 1426 mm/year estimated using the FAO Penman-Monteith method and the evaporation tank.

For the well inventory, data from the field known as "Los Pozones" was used, originally compiled by INOS (1987) and subsequently referenced by Rivas (2019). This database includes detailed information on eight piezometers, including geographical coordinates, extraction flows, elevations, depths, diameters, and the static and dynamic levels of the wells. These data are essential for the proper hydraulic characterization of the aquifer and for the development of the analytical simulation model that allowed for the accurate assessment of the behavior and dynamics of the aquifer system.

Based on this data, it was determined that the effective porosity for this area is around 20%, while the hydraulic conductivity reaches values close to 10 m/day suggesting excellent conditions for groundwater flow and storage. The average thickness of the saturated zone of the aquifer is approximately 70 m, with a hydraulic gradient of 0.00448, an angle (θ) equal to 13° (Contreras and Suárez, 2006) and a base elevation of 7 m.

2.2. Photogeological analysis

High-resolution satellite images obtained with SAS Planet software and Digital Elevation Models (DEM) from the ALOS satellite with PALSAR radar were used to detect topographic and geological changes using microwaves. The area was divided into two parts, taking the course of the Chama River as a reference line: i) the right slope (E) and ii) the left slope (W).

On the right slope (E), the geomorphology reveals a channel of the Mucujepe River with parallel drainage patterns that evolve from intertwined to meandering, supported by poorly consolidated sediments belonging to Cretaceous, Tertiary, and Quaternary deposits.

The active tectonic regime is evidenced by abrupt changes in the direction of drainage, consistent with the concave-convex topography of the area and possibly related to a blind reverse fault defined by Sieh *et al*. (1997).

On the left slope, the river network is dominated by the Onía River and its tributaries, which have dendritic and disordered patterns depending on the varied relief, with a significant presence of Quaternary sediments and sedimentary rocks.

The predominant vegetation is grassland and trees on both slopes, influenced by the characteristics of the sediments and topography (Figure 4).

Based on these images and Digital Elevation Models, a geological map of the study area was produced, using high resolution digital elevation models (DEM) from ALOSPALSAR as the topographic base and the Geological Map of the Azulita Region, Mérida State (Ministry of Mines and Hydrocarbons, 1975) and the F-3.C surface geology map (Creole Petroleum Corporation, 1956), both at a scale of 1:50,000. In addition to all the information obtained through photogeological analysis and in the field stage with the description of outcrops and observation of geomorphological and hydrogeological features (Figure 5).

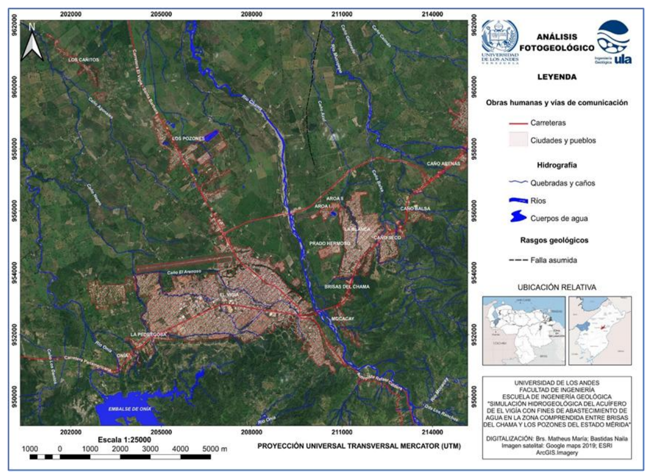


Figure 4. Photogeological analysis. Satellite image adapted from SAS Planet.

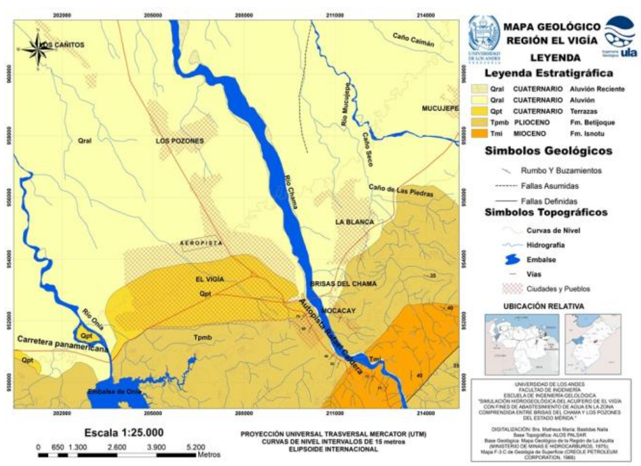
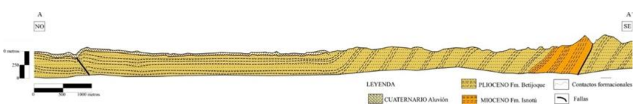


Figure 5. Geological map of the study area at 1:25000.

Geological section A-A' is located on the right bank of the Chama River, oriented NW-SE (Figure 6). To the SE are the molassic formations of the Andean foothills or northern Andean front of the Andes mountain range (Isnotú and Betijoque formations) and to the NW is the Maracaibo basin plain, where the Betijoque Formation and unconsolidated Quaternary alluvial sediments outcrop. In this section, it can be seen that these molassic units (Isnotú and Betijoque) are deformed by previous orogenic episodes and by the current relative movements between the Caribbean and South American plates, generating structures with NW-SE vergence, such as the dextral Mocacay fault with a vertical component to the SE, where the Isnotú Formation rides over the Betijoque Formation, and to the NW, on the Maracaibo Lake plain, a prograding deformation that migrates towards the foreland basin, interpreted as a blind thrust or blind fault (Figura 6).



Considering the characteristics observed in the geological section with regard to the lithology and geological structures present, it can be highlighted, in terms of hydrogeological behavior, that most of the study area consists of unconsolidated sediments (gravel, sand, silt, and clay), which have high hydraulic conductivity and porosity, favoring the accumulation of large volumes of groundwater.

With regard to the geological fault located on the right bank of the Chama River, reference can be made to Távara and Sanz (2010), who state that a geological fault acts as an impermeable barrier on one side due to its movement and jump when encountering impermeable sediments, but, on the other hand, it constitutes an escape route for water, forcing the aquifer flow to ascend through it. With regard to the behavior of hydraulic conductivity in fault zones, Mook *et al*. (2001) indicate that in unconsolidated aquifers, hydraulic conductivity and porosity generally decrease with increasing depth. It has been statistically demonstrated that hydraulic conductivity in areas near or within faults also decreases with depth, remaining high up to 1000 m. This general and continuous decrease with depth is caused by mechanical factors related to the terrain and rock. Therefore, groundwater recharge is not distributed evenly throughout the aquifer but is concentrated in layers of high hydraulic conductivity near the surface.

2.3. Balance hídrico y recarga del acuífero

A monthly water balance model was implemented using the USGS graphical interface (2010), which facilitates parameter editing and estimates key hydrological components for specific sites, although it underestimates potential evapotranspiration (ETp) in arid areas and overestimates it in humid areas. Local parameters such as latitude (8° decimals from SINAIHME) and soil retention capacity (100 mm) were calibrated using historical precipitation (1945-2006) and average temperature (1970-1984) from the El Vigía station, generating outputs such as runoff (50% of the surplus) and infiltration (50%) as summarised in Table 1.

It should be noted that part of the water that infiltrates remains in the subsurface layers of the soil or is returned to the surface, so it is estimated that only half of the in-filtrated water (25% surplus) achieves deep percolation, thus recharging the aquifer.

Reference evapotranspiration (ETo) was calculated using the ETo Calculator (Penman-Monteith FAO equation) and compared with the Class A tank method (FAO-56); for the ETo Calculator, monthly data from SINAIHME (temperatures, moderate wind U2=2 m/s, Rs=0.16, subhumid psychrometric) were used to obtain values in mm/day, while the evaporimeter tank used data from 1955-1986 with Kp=0.85 (irrigated crops, RH=74.91%), but it overestimates ETo and lacks recent measurements in Venezuela, so ETo Calculator was prioritized due to its physical robustness. Finally, crop evapotranspiration (ETc) was estimated by Kc × ETo, with Kc-NDVI from Mutiibwa and Irmak (2013) and Cuesta *et al*. (2005) using LANDSAT-8 (30 m, 6 polygons ~3000 ha via Agro Dashboard); average NDVI showed perennial vegetation, resulting in ETc=1334.47 mm/year (average stage, perennial crops), validating the approach for agricultural monitoring and droughts.

Table 1. Average inflow and outflow values from the Thornthwaite monthly water balance model for the period 1945-2006

	E	F	M	A	My	Jn	Jl	A	S	O	N	D	Anual
P prom (mm)	129,1	123,1	138	233	168,2	104,3	93,9	100,4	111,8	199,5	235,9	193	1830,2
T med prom (° C)	26,6	27,1	27,8	27,8	28,5	28,9	28,1	28,8	28,5	27,9	27,6	26,9	27,875
ETP	104	99,6	119,3	119,8	133,3	134,2	131	133,3	122,1	117,2	107,8	105,1	1426,7
Humedad del suelo	100	100	100	100	100	64,9	37,8	23,4	19,7	92,1	100	100	937,9
ETR	104	99,6	119,3	119,8	133,3	134,2	116,3	109,7	109,9	117,2	107,8	105,1	1376,2
Excedente	68,6	17,3	11,8	101,5	26,5	0	0	0	0	0	108,4	78,3	412,4
Escorrentia	34,3	8,65	5,9	50,75	13,25	0	0	0	0	0	54,2	39,15	206,2
Infiltración	34,3	8,65	5,9	50,75	13,25	0	0	0	0	0	54,2	39,15	206,2
Percolación	17,15	4,325	2,95	25,375	6,625	0	0	0	0	0	27,1	19,575	103,1

2.4. Hydrogeological modelling and 2D simulation

The two-dimensional hydrogeological modelling of the El Vigía aquifer (Figure 7) was constructed in Visual Bluebird 2.0, integrating data on porosity, hydraulic conductivity (k=10 m/day), transmissivity, existing wells (5 and 9 in Los Pozones), geological-structural analysis and recharge, with overlapping elements such as the Onía, Mucujepe and Chama (main drainage), a large recharge area and heterogeneities.

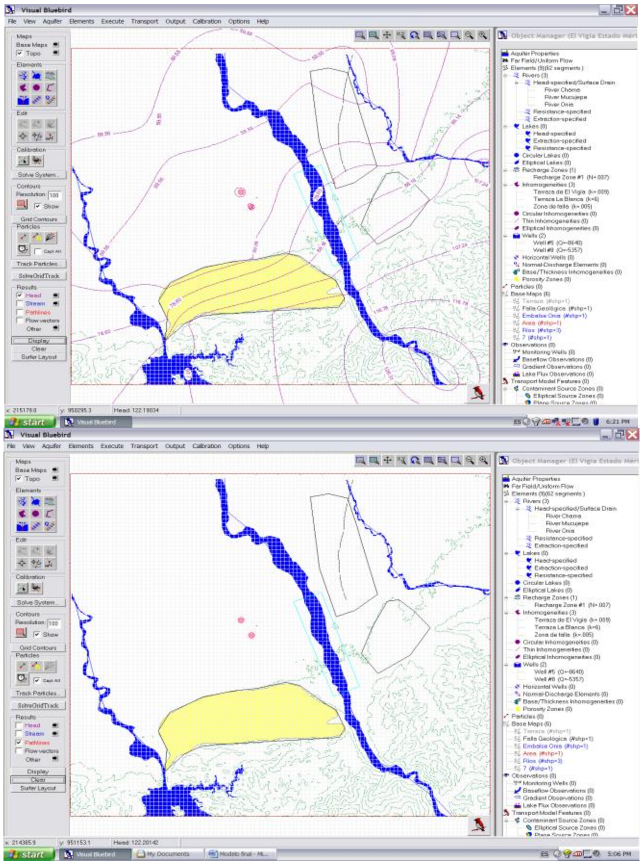


Figure 7. Two-dimensional hydrogeological model of the El Vigía aquifer. Image taken from the software.

The contour lines show low conductivities in urban terraces (El Vigía, La Blanca) and high conductivities towards the northeast due to a reverse fault (NE-SW blind thrust), which acts as an impermeable barrier and flow rise conduit (Figure 8), enhancing water tables suitable for artisanal exploitation but vulnerable to industrial depletion.

The semi-confined aquifer has a preferential SE-NW flow from the foothills (piezometric 150-300 m) towards the alluvial plain, with alluvial-fluvial fan lithology (Terán, 2003; Contreras and Suárez, 2006; Mora, 2018; Rivas, 2019) dominated by gravel, sand, silt, and heterometric clays; in fault zones, permeability decreases with depth due to mechanical compaction (Mook, 2001), concentrating surface recharge in permeable layers and delimiting zones of high/low conductivity influenced by the northwest fault.

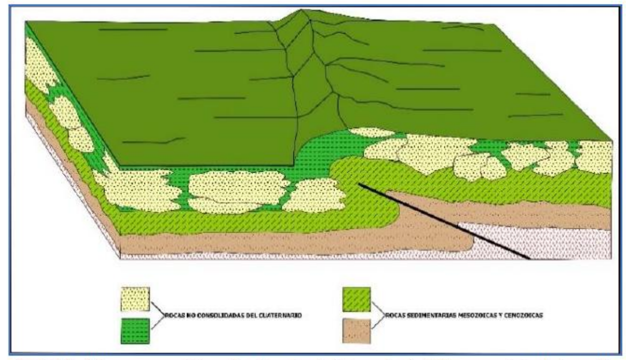


Figure 8. Idealized schematic model of the assumed fault area of the El Vigía aquifer.

2.5. Well-protected area and perimeters

One of the methods used to protect the groundwater that makes up the El Vigía aquifer consists of establishing "well protection perimeters," which have been used in various countries through the development of programmes to protect groundwater from anthropogenic contamination, including countries in the European Economic Community, the United States, Eastern Europe, the former USSR, Spain, etc. a method that was proposed to address this problem several decades ago, according to Baró *et al*. (2008).

Considering that in our country there is no regulation for well protection perimeters, we made use of the legislation established in various countries such as Spain, with the development of analytical methods to delimit this zoning.

Mora (2018) states that the literature recommends setting immediate protection perimeters of 30 days to act in the event of a nearby contaminating event, 50 days to mitigate the effects of bacterial contamination, 1-year perimeters to regulate hazardous activities, and 5 to 10 years to regulate risky activities, which is common in most legislation worldwide.

The delimitation of protection perimeters was carried out with the help of Visual Bluebird 2.0 software using particles that can be tracked for a specific period of time to delineate capture zones and estimate important areas for aquifer protection.

In fact, a simulation of 20 particles was carried out at the different recommended time intervals: 30 days, 50 days, 1 year, 5 years, 10 years, and 20 years. Figure 9 shows the set of perimeters obtained based on the aforementioned travel time criteria.

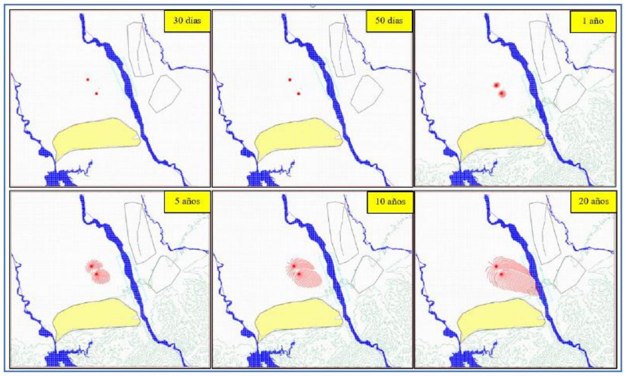


Figure 9. Simulation of 20 particles at different time intervals.

Figure 10 shows the delimitation of the protection perimeters of wells, where the Chama River recharges their catchment area, and indicates that this area should be defined to grant it special surveillance against aquifer contamination due to the presence of existing communication routes, which make this area highly vulnerable to the risk of contamination that could alter the quality of usable groundwater. Based on the above, it is necessary to implement surveillance of these sectors within the Local Urban Development Plan (PDUL) for land use planning and environmental protection.

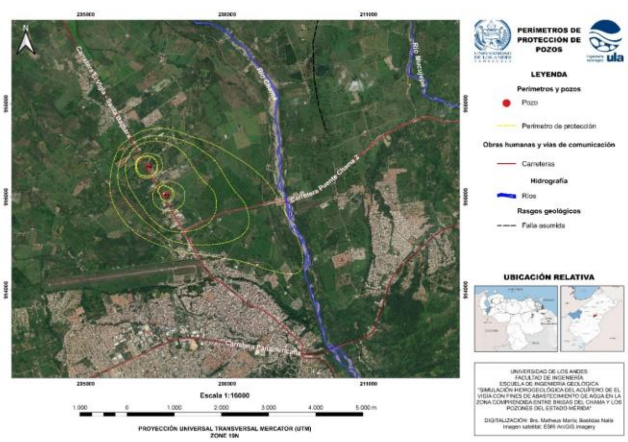


Figure 10. Delimitation of the area and protection perimeters of wells in the study area.

A new field of wells was proposed to supply water to areas far from urban settlements and main transport routes, minimising the risk of contamination from accidental spills from heavy vehicles. This area has excellent hydrogeological properties (high hydraulic conductivity, porosity, transmissivity and permeable thicknesses), according to Rivas (2000), favoring the use of the aquifer.

Surface runoff was estimated using the SCS method (number of curve), considering soil cover and antecedent moisture, where greater vegetation density improves infiltration and reduces runoff (Duque and Mora, 2020), although urbanized areas, roads and slopes limit it the selected site (Figure 11) integrates protection perimeters for 5-, 10- and 20-year horizons.

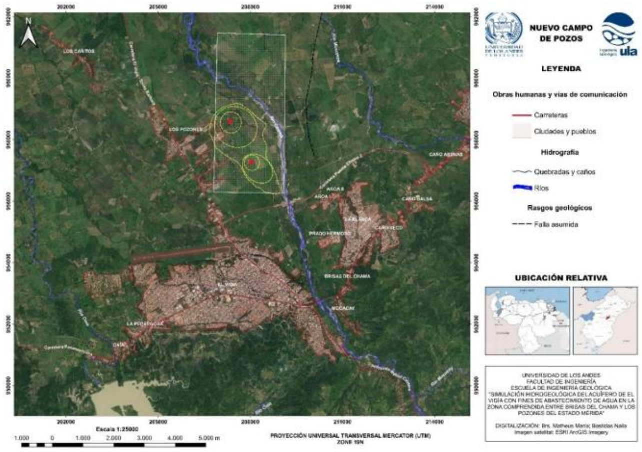


Figure 11. Delimitation of area and perimeters of protection of wells in study.

5 Conclusion

Using Visual Bluebird 2.0 software, a 2D model was created consisting of hydrogeological elements Bastidas *et al*. Science and Engineering Journal. Vol. 44, No. 1, December – March 2023 that condition the exploitation of groundwater present in the El Vigía aquifer and used them to interpret the values of the hydrogeological parameters associated with it, taking into account the calculated values of the water balance.

Likewise, this software was used to map the protection perimeters of wells, noting that the Chama River recharges the catchment area of the wells and that this area should be defined to provide special surveillance against contamination of the aquifer due to the presence of the El Vigía-Santa Bárbara del Zulia road and the new bridge over the Chama River that connects El Vigía with San Rafael de Mucujepe. Considering the threat posed by heavy goods vehicles that are accidentally exposed to spilling contaminants, this area is highly vulnerable to contamination risks that could alter the quality of the groundwater. All this is aimed at generating geological and hydrogeological models and maps as databases for the area that can be used to properly manage water resources, benefiting the population.

Based on the above data, the exploitation of a new field of wells to the northwest of the assumed geological fault is proposed, considering the conditions of the surface of the terrain and the infiltration capacity, which increases when the vegetation cover is dense. In addition to this, previous studies demonstrate the existence of very favourable values in terms of the hydrogeological properties of the soil (hydraulic conductivity, porosity, transmissivity) and excellent thicknesses of permeable rock for exploiting the potential of the aquifer in this region.

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