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Evaluation of the Groundwater System And Integration of Data Using GIS in the Western Slope of Pampean Mountains, Córdoba Argentina

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***Abstract**: The objective of the research was to carry out the hydrogeological characterization of the regional groundwater system in a basin of the western slope of the Pampean Mountains (Córdoba Province, Argentina) and to integrate the information into a Geographic Information System (GIS). Satellite images, Digital Elevation Model, topographic maps and climate data were used. The water table depth was measured in 30 wells and 30 groundwater samples from the unconfined aquifer were obtained and analyzed. The data was stored in a GIS. According to the geological and geomorphological characteristics, two aquifer environments were distinguished, which have different K, sediment thickness and extraction flows (Q). 1) Villa Dolores Aquifers Systems (thickness aprox. 30 m and Q= in the order of 8 m^3/h) and 2) Los Cerrillos Aquifers Systems (thickness= 100-120 m and Q= 90-455 m^3/h). The groundwater flow is in the East-West direction and two zones clearly differentiable according to the hydraulic gradients were observed. In general, the groundwater is fresh (less than 2,000 mg/L). The high gradients, no so long paths traveled by water and the dominance of very permeable sediments favored the low saline contents. The design of the hydrological database in a GIS is useful for environmental management.*

***Keywords:** Geographic Information System, Hydrodynamic, Unconfined aquifer, Pampean Range, Córdoba*

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I. Introduction

The water resources, and the range of services they provide, support economic growth, poverty reduction and environmental sustainability. From food and energy security to human and the environment health, water contributes to the livelihood of billions of people and improves social well-being [1]. In this framework, the scarcity or lack of data and their suitability to the management needs of water resources is still one of the fundamental challenges of researchers and managers ([2], [3], [4]). In the province of Córdoba (Argentina), numerous activities (human use, irrigation, livestock, etc.) are supplied by groundwater, mainly located in sedimentary aquifers, 70% of which is used to irrigate cultivated areas [5]. One of the main problems related to groundwater is the lack of studies in numerous regions and the need to know the hydraulic, chemical and lithological characteristics of the different aquifer layers, since many of them are used without hydrological and environmental criteria of sustainability.

In addition to the evident need of new information that may allow better water management, the data itself should be considered as a strategic resource, ensuring its temporal continuity, to guarantee its existence and usefulness beyond the objectives of the project that generates them. In this sense, Geographic Information Systems (GIS) constitute one of the most dynamic and novel fields of application of informatics to the environment in the last four decades, with an undoubted effect on society ([6], [7]). The main advantage of these systems is that, in addition to allowing the representation of the real world from digital databases, they store and give integrity to the data, allowing to analyze and to compare different spatially related topics. These characteristics make it possible to define the variation of system components over time and their possible interaction. In all applications, GIS are used as a key element in the integration and spatial analysis of multiparameter data. Furthermore, they are used to generate thematic maps with very diverse criteria ([8], [9]).

II. Location Of The Study Area, Hypothesis And Objective

Taking into account the big interest of studying areas where little geological and hydrological information from the subterranean environment is available, an area of vital importance for the province was selected for the present study. It is an important basin of the western slope of the Pampean Mountains (Fig. 1), in which the Villa Dolores city is located (36,700 inhabitants). The present study was carried out founded on the basic hypothesis that the variety of regional reliefs and lithologies have a strong influence on hydrological, hydraulic and geochemical aquifer characteristics and that the planning and management of an area with such complexity will be improved if there is a system that allows the integration and better use of information. Then, the objective of the research was to carry out the hydrogeological characterization of the regional groundwater system and to integrate the information into a GIS system.

Figure 1. Location of the study area.

III. Materials And Methods

The compilation, analysis and integration of preceding information of the area was made ([10], [11]). The investigation was carried out at a scale 1:50,000, on the basis of the analysis of satellite images (Google Earth, LANDSAT ETM +), Digital Elevation Model (Shuttle Radar Topography Mission) with a spatial resolution of 30 x 30 m (data available from the U.S. Geological Survey) and topographic maps made by the National Geographic Institute. The climatic characterization of the area was carried out through the processing and interpretation of local data, from a station (Villa Dolores city) located in the lowland plain area. The emphasis was put on the precipitation (P) behavior (1961-2014 series, data from the National Weather Service), taking into consideration that it is the variable that constitutes the main input function to the hydrological system. Regarding the land uses, a field survey was carried out, registering aspects related to agriculture, agrochemicals, livestock activity, water uses, and so on.

The geological-geomorphological study was carried out through the description of the relief and the outcropping and deep lithological profiles. Regarding the hydrogeological study, a field survey was made. Then, 46 wells that involve the sedimentary aquifer, the most important and widespread in the area were surveyed. The obtained information was mainly related to lithologies, water wells design (depth, screens, etc.) and different hydraulic aspects. To characterize the aquifer layers behavior by means of the classic hydraulic parameters (transmissivity (T), hydraulic conductivity (K) and storage coefficient (S)), previous pump test data [10] obtained with the Theis method, were available. To verify this information, a pump test was performed in a non-permanent regime and at a constant flow rate ($Q = 180\ m^3/h$) by means of the Jacob method. In addition, textural descriptions from the drilling records were obtained, which were used to typify Hydraulic Conductivities (K) values from bibliography [12]. For the hydrodynamic analysis, the equipotential map and the water table depth map were elaborated and interpreted. The water table depth was measured in 30 wells using a water level sensor probe (Solinst). For the groundwater extraction, enough water renewal in each well was guaranteed. Finally, 30 groundwater samples from the unconfined aquifer were obtained and field parameters were measured in situ: pH (Electrode Orion 9104), electrical conductivity EC (Hanna Instrument, HI 9033) and temperature T (YSI Model 95 Handheld Temperature System). Although water samples were collected and later analyzed, in this paper only water salinity (as a function of EC) is shown.

The collected data was stored in a relational database designed specifically for the study area. Initially, a conceptual model of a Geographical Data Base (GDB) or GEODATABASE was developed, with a point topology, corresponding to each surveyed well, using different information fields. After that, a physical model was developed, which was definitively migrated to a database engine. In this case, Microsoft Access was selected due to its compatibility with the ArcGis software, which was used to elaborate the general and groundwater related maps.

IV. Results And Discussion

IV.1. Land uses and climate

Concerning land use, the region is characterized especially by intensive and extensive agricultural activities, extensive cattle rising, soil mining for bricks, and small urbanized areas (Fig. 2). For several decades, the area has been characterized by potato cultivation, but in recent years there has been an explosion of irrigated agriculture (whose main input is groundwater) heavily subsidized by agrochemical products. Industrial development (linked to olive production, brink making), waste disposal and sewage discharges, among others, are potentially polluting activities that cause the population concern. The climate is semiarid and mesothermal [13], with an average annual rainfall of 628 mm. Almost 77% of the rainfall is concentrated both in spring and summer. There is a gentle precipitation gradient from the highest mountain elevations (800 mm isohyet) to the piedmont plains (700 mm isohyet; [14]).

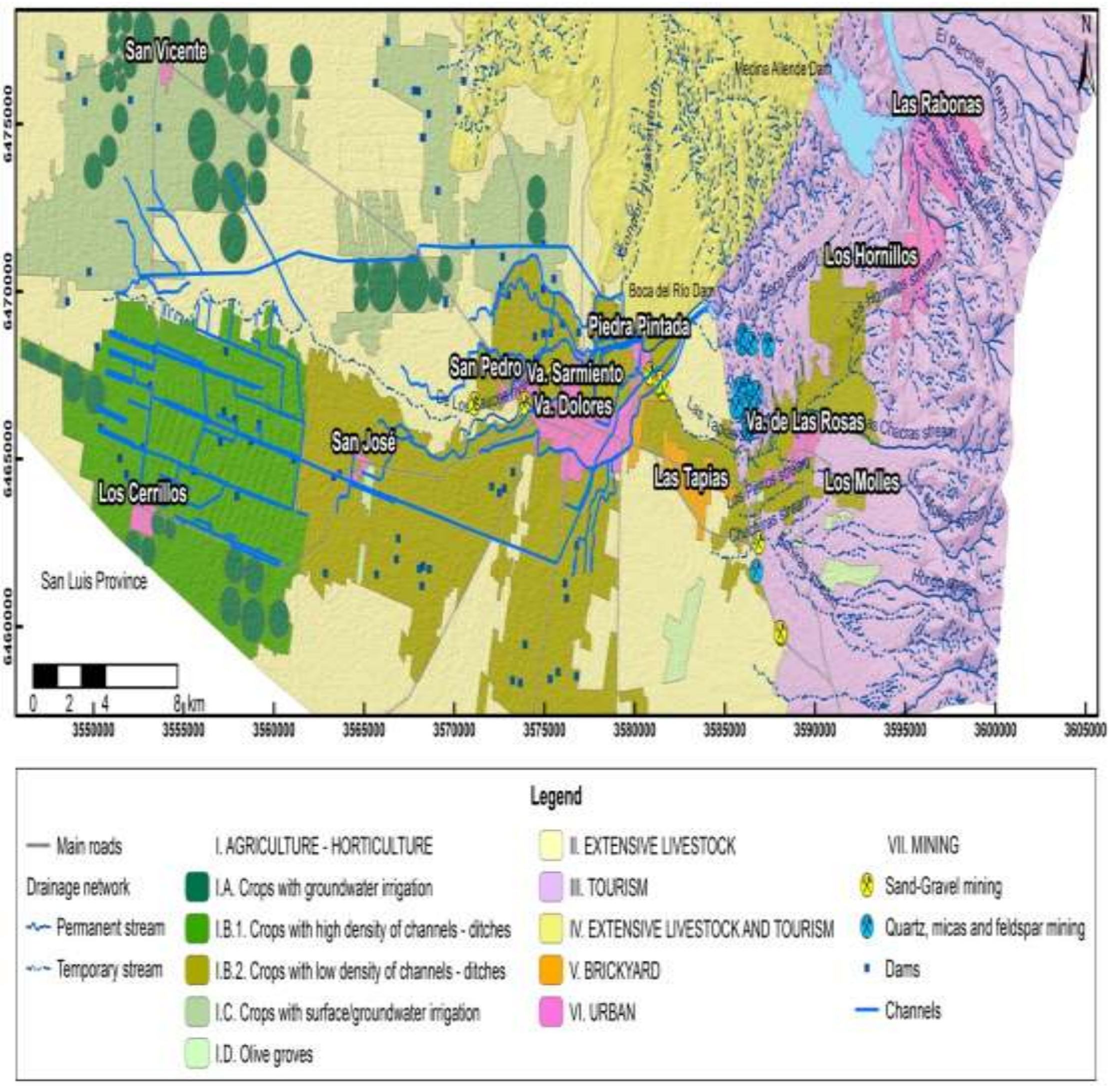

Figure 2. Land uses map.

IV.2. General geological and geomorphological aspects

From the geological point of view and under the influence of the Pampean Mountains geological setting, the area shows the classical tectonic block arrangement defined by regional faults (Niña Paula, Los Molinos and Nono faults, among others). Toward the East, the Sierras Grandes are formed by metamorphic and granitic rocks (Precambrian–Paleozoic), which show the highest altitudes and rough slopes in the region. In the piedmont area, two levels of Cenozoic alluvial fans are recognized (Fig. 3) with a strongly undulated relief and evidence of neotectonic activity [11].

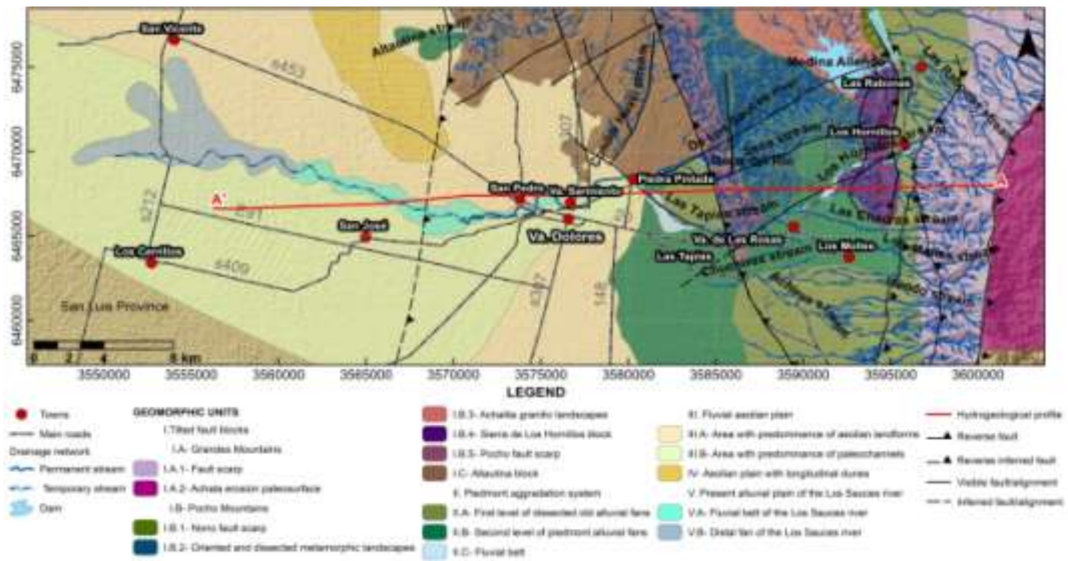

Figure3. Geological – geomorphological map.

To the west, an extensive flat plain with a gently undulating relief is developed, with low slopes, in the order 0.3%. It constitutes the eastern edge of a great intermountain depression (Quines-Ulapes-Chancaní) that extends towards the western Argentinian region. It consists mainly of psamitic/psefit alluvial Cenozoic sequences of the Los Sauces river alluvial megafan and, secondarily, of loessical mantiform and sandy dune aeolian deposits. Los Sauces river, the most important in the region, drains a large basin (approximately 1,200 km^2), developed mainly in granitic rocks located in the Sierras Grandes mountains. This river has a high capacity for sediment supply and transport. These characteristics, added to the regional structural context, favored the formation of a large alluvial fan during the Cenozoic, associated with climatic changes and neotectonic activity. At present it is inactive and is incised (up to 6 m) in its proximal and middle part by the Los Sauces river, which is regulated since the 40´ (Medina Allende dam).

4.3. Hydrogeology

A previous regional study conducted by [10] that covered a much larger area, served as the basis for this research and even for temporal comparisons. From a hydrological perspective, that is, taking into account the capacity of geological materials to receive, store and transmit water, two large hydrogeological environments were defined. For this purpose, several geological-hydrogeological profiles were carried out, showing in this work the AA' profile, very illustrative of the studied area. This profile was carried out along the E-W transect indicated on the map of Fig. 4.

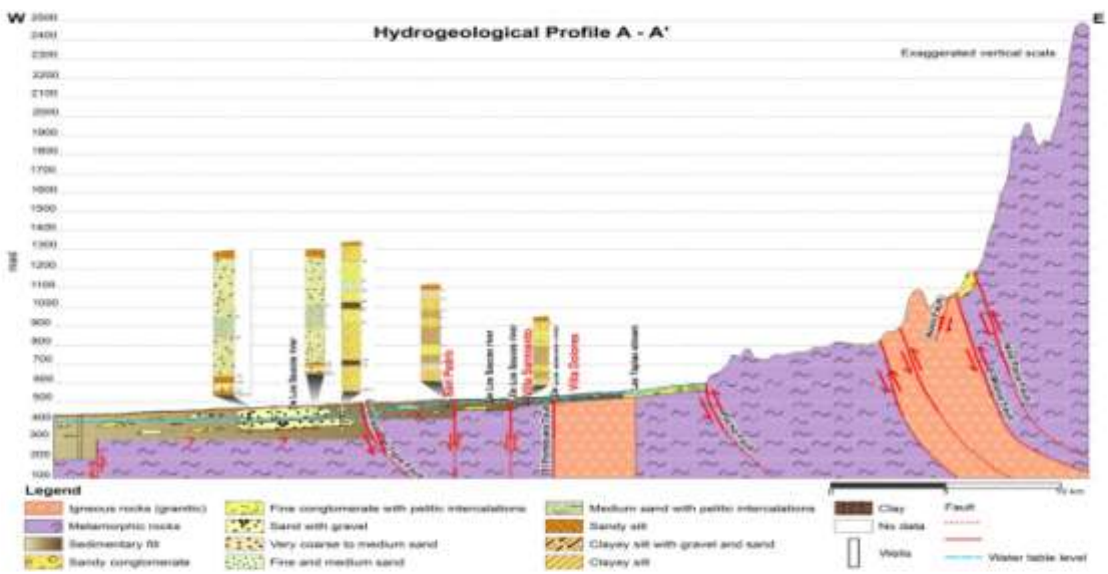

Figure 4. Hydrogeological profile

A. Fissured aquifer system: constituted by all the identified metamorphic and igneous rocks. The outcrops located in Sierras Grandes and Sierra de Altautina mountains highlight. Due to the important fracturing and diaclasing, these materials have a secondary K that allows the water circulation, constituting an unconfined fissured aquifer. Although less important amounts of water than in porous media may be obtained, they are enough to sustain springs and streams in the mountain environment, which later infiltrate in the piedmont recharging the sedimentary aquifer system. In depth, the bedrock acts as the base of the sedimentary aquifer system. It descends towards the West, due to the strong structural control, until approximately 240 m deep, Fig. 4. The current technological advance has allowed drilling in the rock outcrops, as it happens in many sites of the Pampean Mountains of Córdoba where, although small flows are abstracted (1,500 L/h), the water has high suitability for different uses [5].

B. Sedimentary aquifer system: it is formed by the Neogene-Quaternary sediments that fill the intermountain valleys and those sediments that constitute thick sequences in the piedmont and the undulated plain environment. In the latter, two aquifer environments can be distinguished, according to the different K of sediments and the sediment sequence thickness.

B.1. Villa Dolores Aquifer system: This is located in piedmont area, with a thickness in the order of 30 m. The sediments show textural variability from fine to coarse. Thus, sandy silts predominate in relation to coarse sands and gravels. These materials constitute a moderately good aquifer, with K = 0.5 to 2.0 m/d. In those sedimentary sequences where much coarse sediments appear (such as gravels and coarse sands) the K values have a variable range between 20 to 200 m/d. In this whole area, the aquifer is unconfined with S values in the order of 0.05 or higher.

B.2. Los Cerrillos Aquifer system: It is located in the western area. It shows a thickness in the order of 100-120 m. In general, coarse grains domain (coarse sands and gravels) being subordinated sands with clay intercalations, mainly deposited by fluvial activity. At 100-110 m depth, aquitard/aquiclude type materials such as silts and clays appear (these have a thickness of 30 m in the southwestern zone) interlayered with coarse and medium-sized sand layers (Fig. 4). This is a very good to an excellent aquifer with K = 14-407 m/d, high T values (in the order of 2,000 m^2/d) due to the important observed thicknesses. In this sector, the clay layers act as aquiclude formations, conferring a certain confinement degree to the deeper aquifer layers. This is evidenced by the storage coefficients S = 1-2.4 x 10^{-4}, typical of semiconfined aquifers.

In both aquifers (Villa Dolores and Los Cerrillos systems) and according to the involved layer thickness, the textural features and the well design, different extraction flow (Q) and specific flow (q) rates were observed. In the Villa Dolores aquifer the maximum well depths reaches 60 m. Q and q are in the order of 8 m^3/h and 3-6 m^3/h/m, respectively. In general, the water is used for human consumption in domestic scenarios. The flows extracted from Los Cerrillos aquifer system are much larger, with wells that reach 140 m in depth. Q and q are in the order of 90-455 m^3/h and 23-90 m^3/h/m, respectively. The water is used for irrigation (pivot systems or flooding strategies) of large extensions of potatoes, wheat, corn, cotton and soya crops.

In the equipotential map for the sedimentary aquifer (Fig. 5), it is observed that the general groundwater flow is in the East-West direction. It should be noted that, at least for the used map scale, no water divides can be seen. The discharge of groundwater flow is outside the study area in the Quines-Ulapes-Chancaní depression, in another western province of Argentina. The studied sector is in general a transit groundwater area, recharged by precipitations. A preferential recharge area is located in the piedmont sector, mainly due to the influence of the infiltration of streams. There are two zones clearly differentiable according to the hydraulic gradients. In the piedmont zone, especially in the valleys, a divergence of groundwater flow is observed, with high hydraulic gradients (between 0.8 to 3.0%). In the western plain, the hydraulic gradients decrease markedly (0.2 to 0.3%). Both can be explained by the control of the topographic gradients. Towards the west-middle sector of the map, north of San Jose town, the changes observed in the equipotential lines are associated with the high water flows that some wells used for irrigation extract. For the hydraulic gradients and K obtained, groundwater velocity varies between 0.2 m/d and 3 m/d for coarser sediments (gravel and very coarse sands) and 0.05 m/d for silts.

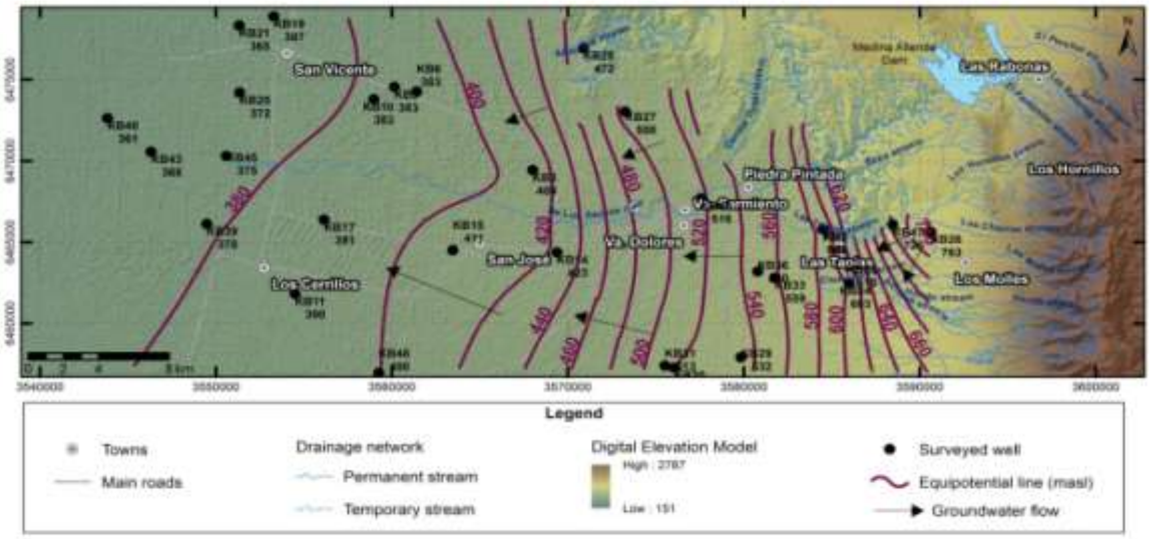

Figure 5. Equipotential map of the unconfined aquifer.

The water table level depth (Fig. 6) is fundamentally linked to the strong structural control of the study area. In the East sector, the water table level ranges from 20 to 30 m, increasing to almost 80 m in the central zone. In general, in Los Cerrillos aquifer area, values that vary gradually from 60 m to 16 m are common. It is noted that the greatest depth at which the water level was measured was 77.4 m at point KB3 (Fig. 6), corresponding to a well that extracts a flow rate of 200 m^3/h for irrigation. Depending on season of the year, these wells are used most of the day, being their use restricted in a certain time interval due to the consumption of electrical energy. For these reasons, the recovery of the water level may not have been reached its original value, measuring a deeper value than it would correspond without such intensive exploitation. Towards the west, the thickness of the unsaturated zone decreases again, with the water level being found at a depth of 20 m in the most western sector.

Taking into account that some wells measured for the present work coincided with those sampled by the [10], it was observed that, despite the significant spending of water in irrigation activities, the water levels have risen, in a range that varies between approximately 1 and 12 m. According to [15] this situation is strongly linked to the change in average P, since in the period 1961-1975 was 546 mm, whereas in recent years it increased markedly (2004-2014, P = 628 mm). This information coincides with the general increase in water excesses in soil water balances over the last 40 years throughout the province of Córdoba [5], which caused more recharge to the aquifers and the increase in surface runoff.

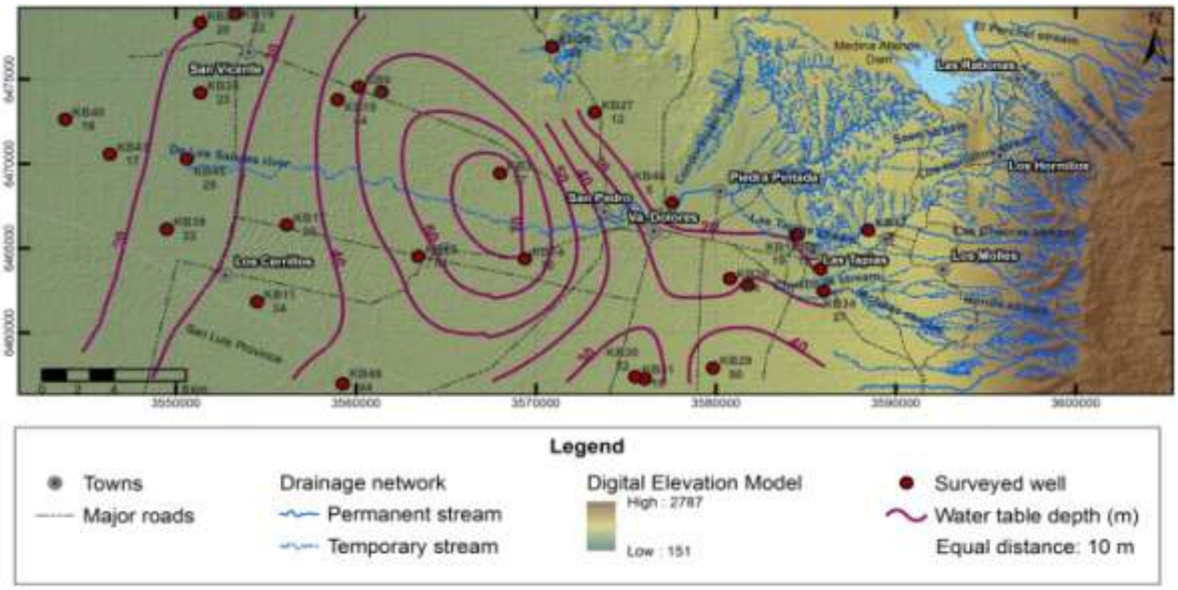

Figure 6. Map of the water table depth

The groundwater salinity varies from the piedmont to the western plain in a sense that could be qualified as opposing to the “normal water evolution” in the flow direction (Fig. 7). Thus, it is observed that, in general, the groundwater is fresh (less than 2,000 mg/L). Those samples with higher salt values are located within the Villa Dolores aquifer, especially at the south of the Villa Dolores town (for example KB32). The salinity spatial configuration is due to the fact than in Villa Dolores area, the wells are shallower and they involve more fine sediments (fine sand/loess), where the typical processes that supply ionsto the solution (dissolution, cation exchange, etc.) prevail. On the other hand, in the more closely zone to the mountains environments, where very coarse grains predominate (alluvial fans), the fresh water infiltrates quickly, with almost vertical gradients, reaching the aquifer. Then, groundwater rapidly circulates in very permeable and more deep strata to remote areas where also coarse sediments predominate, existing few possibilities of salinization. This justifies the fresh waters of the eastern plain of the study area.

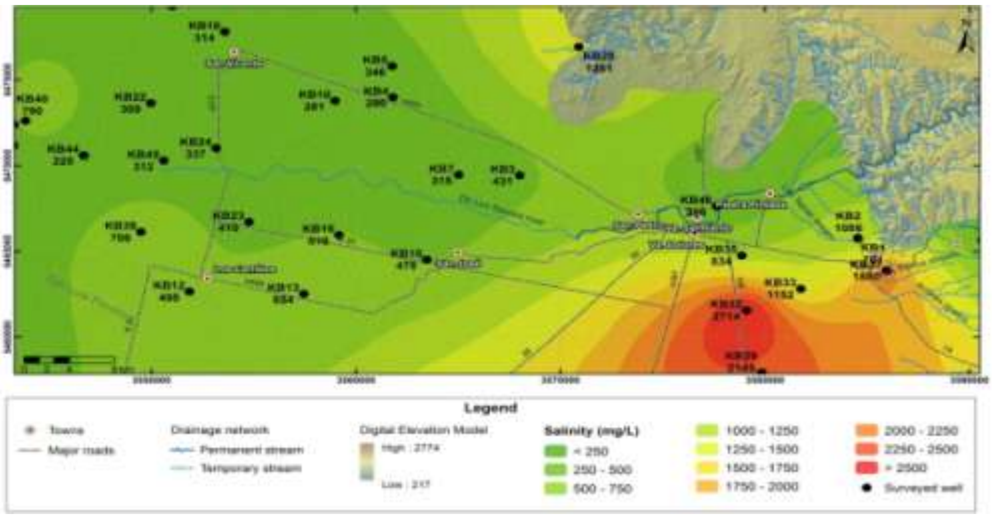

Figure 7. Groundwater salinity map

In Fig. 8 a synthesis of the explained hydrogeological system is shown, with a simplified block diagram containing the sediments/rocks and the water behavior.

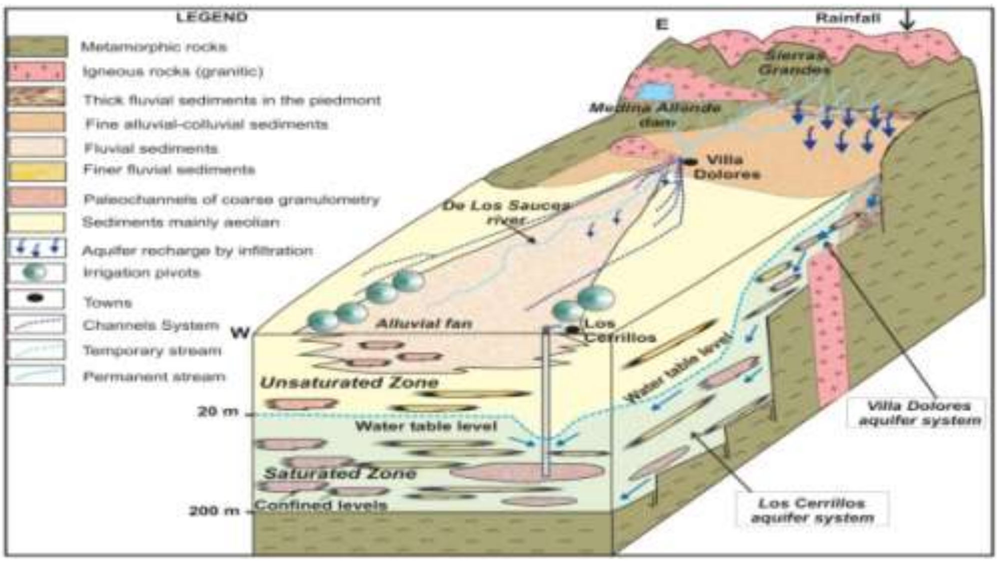

Figure 8. Hydrogeological scheme of the Villa Dolores-Los Cerrillos area

V. Conclusions

The structural framework of the area formed by blocks of crystalline bedrock that descend gradually from the mountain sector towards the western depression, favors the development of sedimentary basins of varied thickness. The sedimentary fill is mainly associated with the Neogene-Quaternary fluvial activity of the Los Sauces River, due to its high availability of sand–gravel sediments and its high transport capacity. Moreover, important layers of aeolian sediments, especially of loessical type, can be emphasized. The described geological framework allowed defining two large aquifer systems, Villa Dolores and Los Cerrillos systems. They differ in thickness, sedimentological features and hydraulic parameters and, therefore, in the water quality, flow rates, water reserves and quantity of groundwater that can be extracted. Both systems are heterogeneous given the significant changes in the hydraulic conductivity values. Although the saturated upper part acts as an unconfined aquifer (the upper 50 m) in the Los Cerrillos aquifer system, the deeper layers begin to show some confinement. However, in no case artesian wells were detected and the piezometric levels are, in general, practically coincident with the water table level. This situation indicates the hydraulic connection between layers and the small grade of confinement of the deeper aquifer layers that now are being used. The aforementioned geological-geomorphological and hydrodynamic characteristics of the area (high gradients, no so long paths traveled by water, dominance of very permeable sediments), added to the climatic aspects, condition the chemical composition of the groundwater. Thus, the chemical weathering processes that supply solutes to the solution are not favored, a situation that results in the observed low ionic contents. The design of the hydrological database in a GIS and the use of its tools allowed the elaboration of the cartography for the Villa Dolores area and the assessment of the groundwater resource as a basis for environmental management.

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