THE KARST AQUIFER FEEDING THE CUATRO CIÉNEGAS POOLS (COAHUILA, MEXICO): ITS VULNERABILITY AND SAFEGUARD[5]

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Abstract
The Cuatro Ciénegas pools are worldwide renown thanks to their unique ecosystem and, in the last years, they have been investigated in detail with respect to their peculiar fauna, flora and hydrochemistry. The pools also represent a very important water resource in a region characterized by scarce rainfalls. Despite this, very little of their hydrodynamics and recharge was known until now. To fill this gap the "La Venta" association organized some research expeditions in the last 3 years, during which the pools were accurately located and studied from the hydrogeological point of view. Furthermore, the possible recharge areas were investigated in order to understand the role of local infiltration better. These studies suggested the hypothesis that meteoric waters stored in the karst aquifer of Sierra San Marcos Y Pinos represent the main source for the pools, even if the feeding into it occurs mainly through a rather deep circuit. Finally the importance of a strict safeguard is stressed for the whole recharge area due to the high vulnerability to pollution of the karst aquifer.
Key words: karts hydrogeology, thermal springs, pollution vulnerability, safeguard

Resumen: ***El acuífero Kárstico que alimenta las pozas de Cuatro Ciénagas (Coahuila, México) y los problemas de vulnerabilidad y salvaguardia.***
Las pozas de Cuatro Ciénagas son conocidas en el mundo por su único ecosistema, y son estudiadas a detalle desde el punto de vista de su

fauna, flora e hidroquímica. Estas pozas representan también un recurso de agua muy importante en una región caracterizada porque las lluvias son escasas. A pesar de esto, no se conocía prácticamente nada de su hidrodinámica ni de su cuenca de recarga. Para terminar con esta laguna, la asociación "La Venta" ha organizado en los últimos 3 años varias expediciones, durante las cuales, todas las pozas fueron cuidadamente localizadas y estudiadas desde el punto de vista hidrogeológico. Basándose en estos estudios, ha sido posible avanzar la hipótesis de que el agua meteórica del acuífero Kárstico, encontrado en la Sierra de San Marcos y Pinos, representa con diferencia la surgente más importante para la alimentación de las pozas. Alimentación que viene a través de un circuito bastante profundo. Finalmente, se destaca la importancia de una estricta salvaguardia ambiental en toda la zona de recarga, debido a una marcada vulnerabilidad a la contaminación del acuífero Kárstico.
Palabras clave: Acuífero kárstico, surgente hidrotermal, vulnerabilidad a la contaminación, Cuatro Ciénegas.

Introduction

Cuatro Ciénegas plain is a Natural Protected Area in the category of the Protection of Flora and Fauna since 1994, it is located in the state of Coahuila, Mexico, in the Sierra Madre Oriental at the eastern edge of the Chihuahuan desert. Though it receives little rain, the valley has abundant subterranean water, which creates hundreds of small pools (locally called *pozas*), marshes, rivers, lakes (large, saline lakes locally called *lagunas* or *playas*), and canals with a unique biota of great interest to the international scientific community and at risk of extinction. Namely, springs and surface water create a groundwater dependent ecosystem characterized by a unique level of endemism, with numerous species identified as specific to the area. Endemisms in the fauna are found especially in fish, amphibians, reptiles, snails, crustaceans, molluscs, insects and scorpions. A peculiar characteristic of the pools is the presence of living stromatolithes, which act as a local primary agents of the food chain. Due to the abundance of aquatic habitats, the valley supports an unusual assemblage of species, which are not entirely typical of a desert. The plant communities within the valley include basin grasslands, aquatic plants, sedge borders and marshes, gypsum dune assemblages, Chihuahuan desert scrub and chaparral.

In short, the exceptional number of endemic species testify a long and complex biological evolution as a closed system.
Despite the relevant ecological interest of the aquatic environment of Cuatro Ciénegas, no exhaustive studies about the catchment area and its hydrodynamics have been published until now. For this reason "La Venta" team undertook a study of the pools and high surrounding mountains in order to increase the knowledge on the underground water flow feeding Cuatro Ciénegas valley and to contribute to its conservation.

The study area

The region of Cuatro Ciénegas is characterised by intramontane plains and long mountains ridges that correspond to SW-facing anticlines. In the investigated area a thick succession of Cretaceous limestone, lying on continental mudstones and sandstone, prevalently outcrops (Lehmann et al., 1999). Limestone displays massive to middle thickness beddings with discontinuous levels of gypsum and marls; mudstones and sandstones of Paleogene cover it. A magmatic phase, coeval to the compressive tectogenesis, affected the whole area during Oligocene. Tectonic distension onset about 19 Myr ago (Early Miocene) and continued during Pliocene accompanied by effusion of calc-alkaline lavas.
Long rectilinear anticline ridges characterize the landscape of Cuatro Ciénegas whereas major valleys correspond to synclines. The most inclined slopes of major structures, mostly facing SW, often display vertical or overburden beds. Along them, deep transversal and longitudinal valleys form a typical trellis drainage pattern. In the pedemontane areas, several coalescent fluvial fans form a wide regular surface gently inclined (*bajadas*), where streams display e disrupted and irregular pattern. Runoff is quite absent in these areas. The plains behave as endoreic *playas* where major storms form shallow lakes and ponds, the evaporation of which, cause the formation of sulfates and halides deposits. Eolian gypsum dunes occur in these areas.
Notwithstanding the mountains consist mainly of carbonate rocks, karst landforms are quite rare, because of the intensive physical weathering. Significant karst landforms occur only in small areas, generally located along major crests; infiltration forms, such as dolines, are practically absent.

Endokarst systems are little developed and generally concentrated in restricted areas.
Solution caves are rare and often small in dimension. Along the lateral cliff of canyons, several niches and holes are detectable. Most of them are originated by "cavernous" weathering and/or mechanic enlargement of small interstratal karst conduits. Only a few caves display forms to be recognized as relict segments of a phreatic network. The most significant example is the Cueva Rosillo, in the Sierra San Marcos y Pinos, which consists of a large, 1 km long, conduit with a past water-flow towards NW. Caves with relict phreatic passages occur also in the Sierra la Purìsima, Sierra La Fragua, Sierra Madera and Sierra Menchaca. Unfortunately a more exhaustive interpretation of such caves is made difficult due to the deep degradation of conduits walls and the presence of calcite deposits or guano.
Some of the major caves in the area of Cuatro Ciénegas are hypogenic in origin, in other words, they were formed by rising thermal water. The best example is the Cueva Rancho Guadalupe, in the NE of Sierra la Fragua. This cave has a typical dendritic pattern and consists of maze conduits and spherical rooms (Bernabei et al., 2002).

Morphology, hydrology and geochemistry of the pools

In the plain of Cuatro Ciénegas, several small lakes, pools and marshes occur in a relatively restricted area: the last inventory reports more than 165 pools. Most of them are located in the northern pedemontane area around Sierra San Marcos y Pinos (Fig. 1), with the single exception of Anteojo pools, located southern of Sierra Madera. All pools are drained by the Mezquites river and other artificial channels, with an average discharge of about 3,5 $m^3 s^{-1}$.

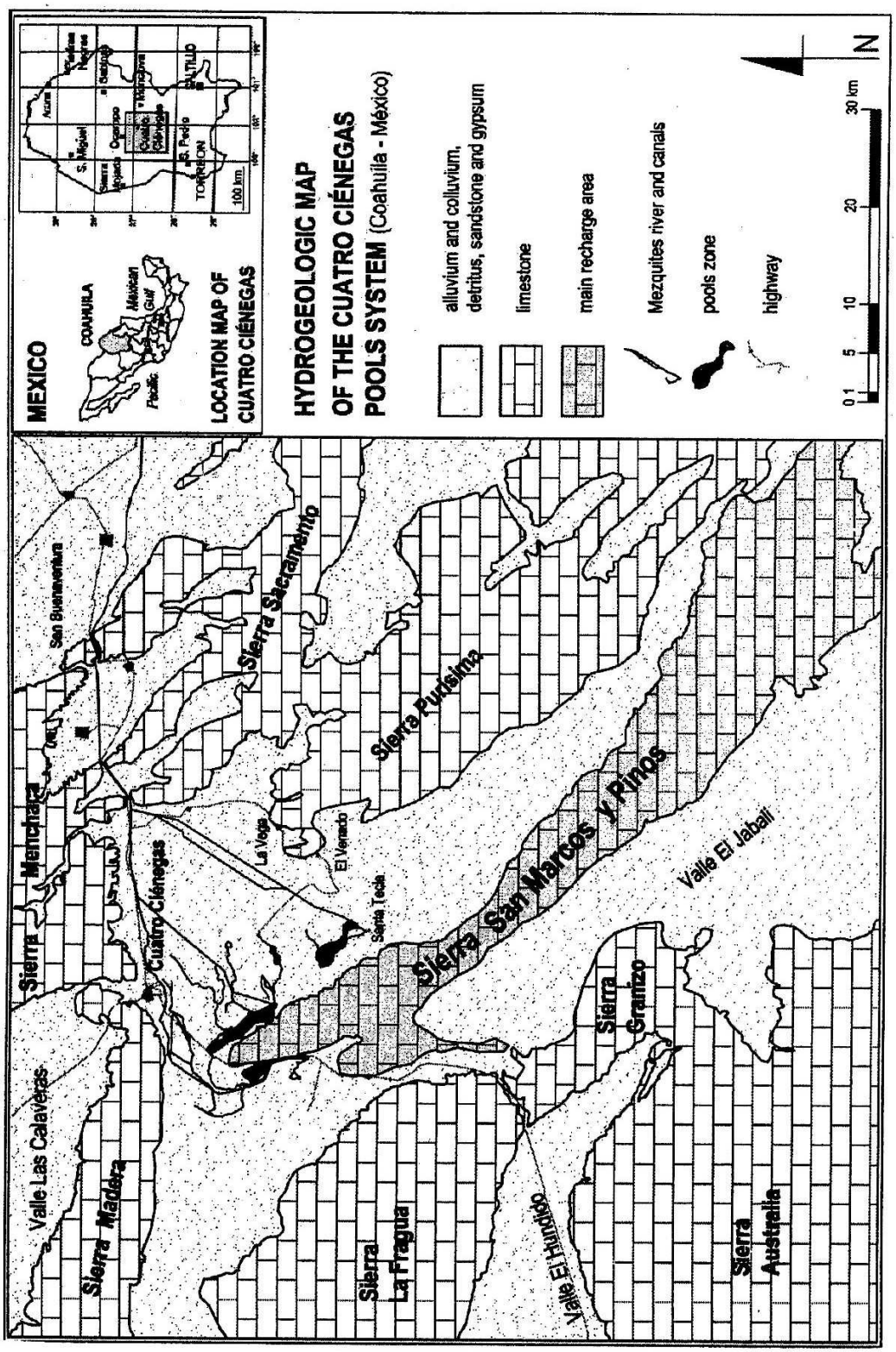

Fig. 1 – Hydrogeologic map of Cuatro Ciénegas plain and Sierra San Marcos y Pinos.

The San Marcos, Bonito, Churinche, Becerra and Garabatal pools occur westward San Marcos y Pinos at an altitude ranging from 754 m to 736 m a.s.l., (Fig. 2), while the Azul, Mojarral, Escobedo, Orozco, Rio Candido, Azules and Santa Tecla pools are located in the eastern pedemontane area, at a mean altitude of 700 m. In the central part of the plain, but only eastward of San Marcos y Pinos, there are the Los Hundidos, Ramon Manrique and La Campana pools. Most of the pools have a circular shape and a diameter ranging from 3 to 25 meters. The single Poza Becerra displays an elongated shape along the pedemontane fault westward San Marcos y Pinos. The depth of water normally ranges from a few decimeters to 5 m; maximum depths occur in the Poza Azules (-10 m) and in the Poza La Campana (-19 m). The latter is a waterfilled collapsed sinkholes in the fluvial deposit of the plain, with the water level at 688 m a.s.l. Generally, the pools have a bottom consisting of a carbonate mud, from which water bubbles up forming sand cones. In some pools, the in-flow and out-flow conduits are clearly visible and sometime accesible for a few meters.

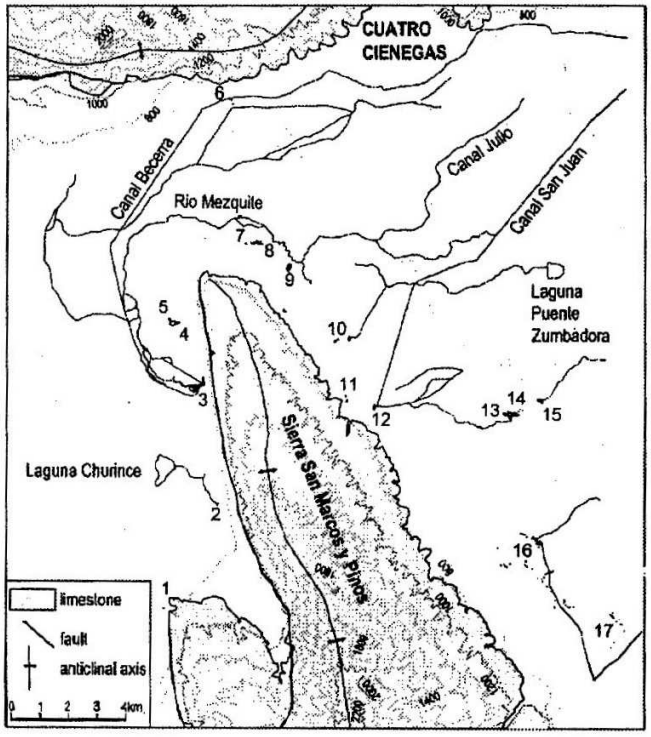

Fig. 2 – Location of the pools of Cuatro Ciénegas: 1- San Marcos; 2- Churice; 3- Becerra; 4- Garabatal; 5- Juan Santos; 6- Antejo; 7- Mojarral; 8- Poza Azul; 9- Remojos; 10- Baño Escobedo; 11- Orozco; 12 Tio Candido; 13- Los Hundidos; 14- La Campana; 15- Ramon Manrique; 16- Pozas Azules; 17- Santa Tecla.

In the Poza Becerra, the water flows directly up from a fracture in the limestone bedrock.Physical and chemical analysis of pools and springs show a high variability in temperature (19.2 to 33.6 °C), electrical conductivity (EC = 543 to 4300 µS) and salinity (0.2 to 3.8 g/L) (table 1).

Table 1 – Chemical analysis of Cuatro Ciénegas waters

pozas	pH	T (°C)	EC 25 °C (µS/cm)	Ca^{++} (meq/l)	Mg^{++} (meq/l)	Na^{+} (meq/l)	K^{+} (meq/l)	HCO_3^{-} (meq/l)	Cl^{-} (meq/l)	$SO4^{--}$ (meq/l)
Churince	7.4	27	2025	16.15	8.72	6.39	0.20	3.39	2.33	26.56
La Becerra	7.3	33.6	1778	17.40	8.97	6.65	0.19	3.75	2.54	28.13
La Becerra	7.6	32	3075	15.37	6.41			3.38	0.86	20.45
Poza Azul	7.4	32.9	1818	17.75	9.55	7.35	0.23	3.77	2.96	25.00
Escobedo sup.	7.3	26.8	2651	22.25	12.26	8.70	0.31	5.05	3.70	36.46
Escobedo	7.4	33.1	1843	17.95	9.30	6.74	0.24	3.85	2.58	28.38
Orozco	7.9	22.5	3076	22.36	11.45			4.72	4.18	45.12
Los Hundidos	7.7	19.2	4318	12.77	25.46			4.26	6.26	39.79
La Campana	7.6	20.6	4047	26.35	12.63			3.28	3.87	41.81
Los Hundidos	8.0	22		25.55	14.70			2.95	4.00	26.90
Poza Azules I	7.6	25.1	2265	17.75	9.05	6.52	0.24	4.20	3.07	28.33
Rancho Azules	7.3	27.8	1397	11.50	6.01	4.09	0.14	4.30	0.95	15.36
Santa Tecla	7.5	29.5	1092	9.55	5.19	2.83	0.15	3.80	0.71	11.72
El Venado	7.9	27.3	543	4.65	1.40	0.87	0.03	4.33	0.56	1.56
La Vega	7.4	24.5	545	5.90	1.15	0.08	0.02	4.61	0.08	1.98
Ojo Quintero	8.0			4.19	6.71			4.59	1.30	3.96

Temperature and EC clearly suggest the existence of two different waters categories: "cold" low-salinity waters and warm high-salinity waters. The former characterizes the pedemontane springs, fed by local infiltration. Most of them have very little discharge, except the La Vega spring that has a discharge of about 20 l s^{-1}.

La Vega and El Venado springs, in the north of Sierra La Purìsima, are not properly cold springs, in fact, their temperature is about 4-5 °C higher than local mean temperature; anyway their low salinity suggests a recharge from not very deep aquifers. This temperature anomaly may be explained assuming that geothermal gradient is high enough to warm the aquifers, due to the low recharge of cold infiltration water. Most of the pools have a temperature about 10°C higher than the local mean temperature of air (22°C) and thus they are real thermal springs.

Temperature monitoring of major pools was performed during October-November 2002: for the whole period the Poza Becerra resulted the warmest, followed by Poza Azul (31°C), Poza Churinche (30°C) and Poza Azules (28°C). The lowest temperatures (~22°C) have been measured in La Campana, Los Hundidos e Ramon Manrique pools. Temperature of the pool water surface is normally affected by diurnal fluctuations, in some case values higher than 36°C during the warmest days were measured.

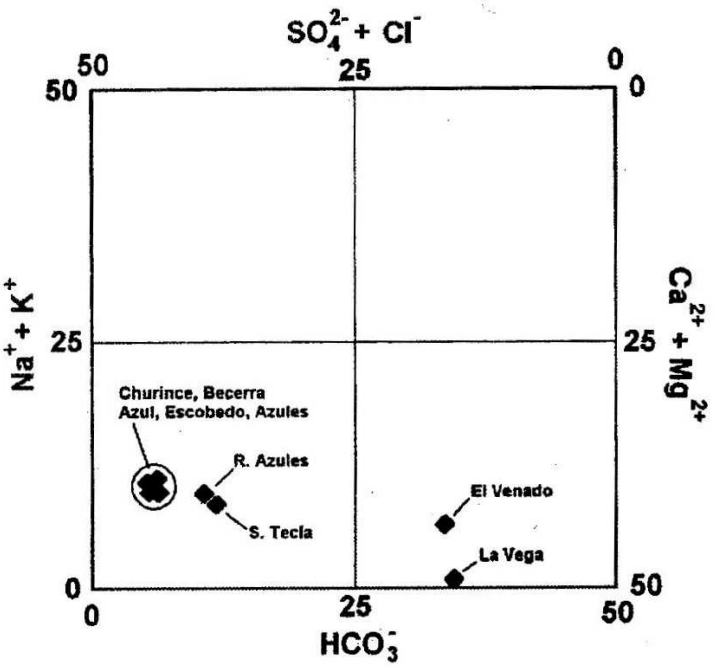

Fig. 3 – Langelier-Ludwig diagram of main waters of Cuatro Ciénegas.

The chemical analysis of major elements, plotted on a Langelier-Ludwig square diagram, evidenced two major water types (Fig. 3): sulfate-alkaline deep-flow waters (Churince, Becerra, Azul, Escobedo e Azules, R. Azules and S. Tecla pools) and bicarbonate-alkaline surface waters (El Venado e La Vega).

A third intermediate type is probably represented by the water of Ojo Quintero pools, not plotted in the diagram due to the lack of Na and K concentration: it exhibits an ionic ratio HCO_3^- toward $Cl^- + SO_4^{2-}$ which is intermediate with respect to those of the two groups.

The recharge

At present, the recharge for the Cuatro Ciénegas pools is not definitely known and, despite the social and ecological relevance of this water resource, no exhaustive studies about the hydrogeology of pools have been performed. Because all the pools are located around the northern part of San Marcos y Pinos anticline, the first hypothesis is that the main catchment area should include all the anticline structure. A water balance may give support to such an hypothesis.

In the Plain of Cuatro Ciénegas, the average rainfall is about 260 mm/yr (www.worldclimate.com), usually concentrated in the summertime. Rainfall probably is 400 mm/yr or more on the mountain ridge, but no direct measure exists to confirm it. According to the data reported in the hydrologic map edited by INEGI, the mean rainfall on San Marcos y Pinos should be about 350 mm. The map also provides an estimate of runoff rate of 5%, but we think that it could be significantly higher, despite that potential evapotraspiration is very high. In fact, almost half of the total rain is concentrated in a few storms during the summertime. During a single storm, evaporation is very low and the scarce vegetation and the almost absolute lack of soils allow water runoff on slopes converging rapidly into the streams. Infiltration probably occurs along major consequent incisions, where water flows cutting the bedding strike down. In this condition the infiltration should be even 40 % of the total rainfall, resulting an average of 140 mm/yr. Moreover the condensation processes inside slope detritus fans may supply a relevant amount of water, due to the high daily excursion of temperature. In this hypothesis the annual total infiltration on San Marcos y Pinos, whose surface is 900 km^2, results 126 x 10^6 m^3, or about 4 m^3 s^{-1}. Therefore, even taking into account some small spring in the southern part of the sierra, the estimated infiltration may justify the whole discharge of Cuatro Ciénegas pools (Fig. 4). Anyway the actual knowledge cannot exclude a recharge contribute from the surrounding ridges, such as the Sierra La Fragua, Sierra Madera and Sierra La Purìsima, through deep-seated water flow.

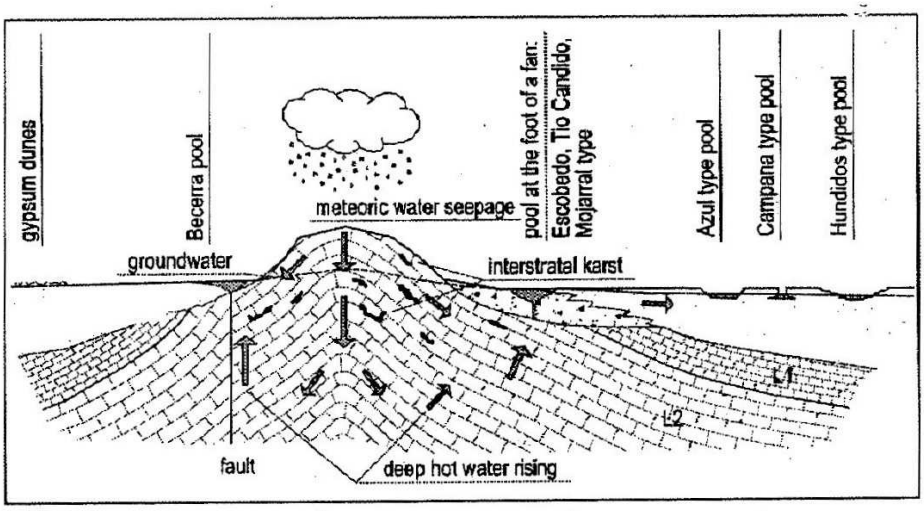

Fig. 4 – Hydrogeologic sketch for deep water circulation inside Sierra San Marcos y Pinos.

Physical and chemical characteristics of waters suggest that circulation is quite slow. Isotopic analysis of water from Becerra, Azul and Azules pools, have shown a Tritium activity that can be explained assuming an infiltration in two separate time periods: 1955-1960 and from 1980 to present. $\delta^{18}O$ suggest a mean altitude for the catchment area of 1400 m a.s.l.

According to maximum temperature measured in pools, the water circulation should reach a depth of 400-500 m below the spring altitude, if no significant mixing with local surface waters occurs. But temperatures of 26 °C (almost 4°C higher than local average temperature) were also measured in springs surely fed by surface recharge: this may be explained by supposing that the geothermic gradient is higher than normal inside the limestone aquifer. In this hypothesis a temperature of 32°C could be reached even with a shallower circuit.

In conclusion, Cuatro Ciénegas pools are surely fed by meteoric waters flowing through relatively deep-seated circuits in limestone, where waters enrich with salts and warm up by geothermal heat.

Vulnerability and preservation of the desert pools

The whole recharge area is not completely defined and most of the parameters necessary to realize a vulnerability map, by using the point count system SINTACS (Civita & De Maio, 2000), are not well known. Anyway it is still possible to make a rough average evaluation of the

vulnerability of the aquifer feeding the pools on the base of the following statements:

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- The outcrops mainly consist of fractured and karstified limestone with scarce soil cover
- The depth to groundwater is high but the transit through the percolation zone is fast
- The average infiltration is in the range of high SINTACS ratings
- The unsaturated zone may have only a scarce depuration effect by being highly fractured
- The aquifer consists of fractured and locally karstified limestone
- The aquifer hydrodynamics is relatively slow.

Therefore the intrinsic vulnerability of the aquifer should be considered from middle to high and surely any kind of pollution accidentally dispersed in the catchments area would affect the quality of the water rising in the pool in a rather short span of time.
Luckily the area is quite uninhabited and therefore anthropic pressure has been very scarce until now, moreover a national law preserves most of it as a Natural Heritage.
Anyway its vulnerability risk must not be underestimated being, in our opinion, from middle to high. This is because in the last few years water eduction was increased significantly and also tourist settlements were created close by or just over some of the pools.
The pumping directly affects the aquifer hydrodynamics and, if not strictly controlled, in a few years it may permanently deplete the recharge of the pools.
The effect of uncontrolled tourism will produce far worse results: in fact the anthropic pressure over the pools, if increased significantly and not strictly controlled, will cause a fast pollution not only of the pools but also of all the related aquifer with grave and unpredictable consequences over the whole ecosystem.
For all these reasons, for the next future it is fundamental that Scientific Community significantly improves its knowledge over the whole aquifer feeding the pools and that Local and National Authorities carefully consider any project, which may affect the pools and their fragile and precious ecosystems.

Final Remarks

The data collected in the last 3 years, during the exploration carried out in the by "La Venta" team in the Cuatro Ciénagas area, allowed to state that meteoric waters stored in the karst aquifer hosted in the Sierra San Marcos Y Pinos probably represent the main recharge source for the pools, even if feeding occurs mainly through a rather deep circuit.
Although further research are necessary in order to understand the hydrodynamic of pools system better, it would now be easier to define a safeguard policy to preserve the pools and their unique environment.

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