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GROUNDWATER GEOINDICATORS FOR THE ASSESSMENT OF ENVIRONMENTAL CHANGES – PLANNING AND POLICY IMPLICATIONS, RÍO CUARTO CITY, ARGENTINA

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Geoindicators have been developed as tools for integrated assessments of natural environments and ecosystems, and tracking and reporting on the state of the environment. This paper examines groundwater geoindicators in Río Cuarto city, Argentina, and focusses on piezometric levels and water quality indicator parameters. Since 1988, there has been a progressive rise of the water table caused by cesspool effluents and an increasing trend of rainfall excess in the water balance. In certain neighborhoods this has caused serious damage. Water quality indicators include nitrogen species, total dissolved solids (TDS) and chloride (Cl), which indicate contamination due to sanitary systems. Nitrate (NO_3) and dissolved iron were used to assess the redox state of groundwater. The neighborhoods under study present different contamination scenarios. Where oxidizing conditions prevail, NO_3 was found in all the samples, and those with the highest values showed an increase in TDS and Cl. Where reducing conditions prevail, NO_3 was not found. There was an increase in dissolved iron and in TDS and Cl in the most microbiologically contaminated samples. Taking into consideration that a great number of people are affected by these groundwater problems, the municipality has provided more than 500 families with piped running water and/or sewerage systems, and installed dewatering wells to control the high water table.

INTRODUCTION AND OBJECTIVE

We are living a period of demographical and ecological changes never before seen in the history of mankind and there is an urgent need to improve our knowledge of the changes we are causing. Environmental indicators are a valuable tool that can be used to warn about imminent thresholds that require political, institutional and human behavior modifications to mitigate risk and damage to our environment.

The objective of this paper is to apply the concept of environmental indicators to groundwater problems in Río Cuarto city and to show how these indicators have affected environmental problem solving, including planning and policy changes. Particular focus will be on changes in water table elevations and the quality of groundwater.

GENERAL CONSIDERATIONS ABOUT GEOINDICATORS

In 1992, the IUGS (International Union of Geological Sciences), through its Geological Sciences for Environmental Planning Commission (COGEOENVIRONMENT) established the concept of geoindicators as tools for integrated assessments of natural environments and ecosystems, and for tracking and reporting on the state of the environment (Berger and Iams, 1996). Geoindicators are measurements (magnitudes, frequencies, rates, and trends) of processes and geological phenomena that occur in or close to the Earth surface and are subjected to modifications that are significant in the understanding of environmental changes through periods of 100 years or less. They describe processes and environmental phenomena that are capable of changing without human interference, even though human activities may accelerate, decelerate, or deviate natural changes (Goudie, 1990). Geoindicators help to answer the following basic questions: what is happening in the environment (conditions and trends), why is this happening (causes, relations between human influences and natural processes), why is this significant (economic, ecological, and health effects), and what are we doing about it (planning and environmental policies). In this paper, the pressure-state-response concept is followed, aimed at decision makers. In this way, the indicators are used to assess 1) pressures on the environment caused by human activity, 2) resulting conditions or states in the assessed environment, and 3) policy responses to correct undesirable situations.

GROUNDWATER AND GEOINDICATORS

The changes that occur in shallow aquifer systems (0-100 m) are the most relevant to this study (Figure 1). The parameters that should be selected are those representative of key processes, susceptible to change in an appropriate time scale, and practical to measure. Monitoring is necessary since residence times, in general, increase along flow lines, and can vary from days to decades in shallow groundwater. Moreover, geological heterogeneities may result in different rates of water movement in the same part of the aquifer. The unsaturated zone acts both as the main recharge source to the aquifer and as a buffer zone for geochemical attenuation. Sampling in this type of study should take into consideration aquifer properties (heterogeneity, flow and pumping regime), distribution of existing wells, the need to measure on-site unstable parameters, and sample storage. Three types of groundwater changes are considered, which are sensitive to processes that occur in the geoindicator time scale (Edmunds, 1996), such as piezometric level changes, natural hydrochemical processes (acid attenuation and mineral dissolution, redox reactions and total dissolved solids (TDS) changes), and contamination impacts.

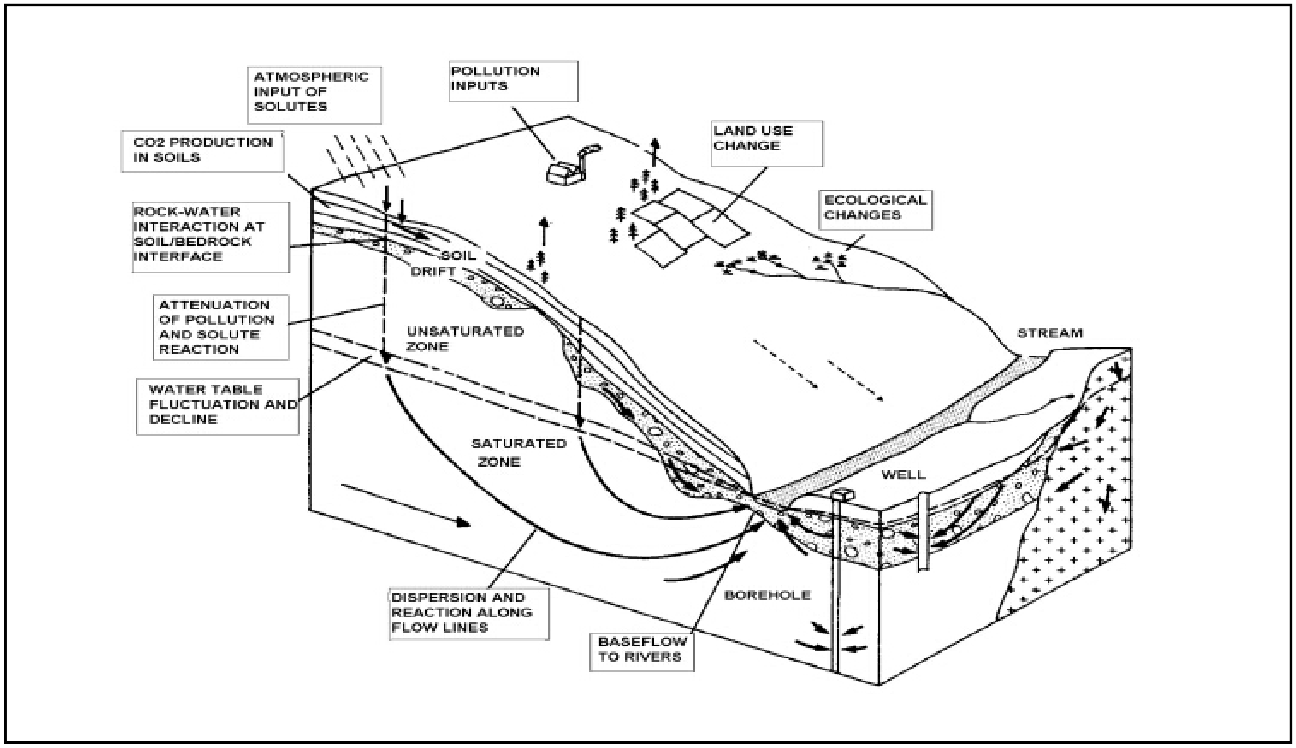

Figure 1. Components of the shallow groundwater cycle showing elements that are sensitive to environmental changes (Edmunds, 1996).

GROUNDWATER PROBLEMS WITHIN THE GEOINDICATOR FRAMEWORK

General hydrogeological characteristics of Río Cuarto city

The climate of the area is sub-humid, with an annual mean rainfall of 797 mm, most of which (82%) is concentrated in spring-summer. The annual mean evapotranspiration is 720 mm, and most excess rainfall occurrs between the months of November and March. From a geological perspective, the area is situated in the Argentine Geological Province "Chaco-Pampeana Plain" in the south part of Cordoba Province (Figure 2). The outcropping lithology is made up of sediments of aeolian (loess) and fluvial origin. The fluvial sediments are of varied grain size, and are related to the Río Cuarto river

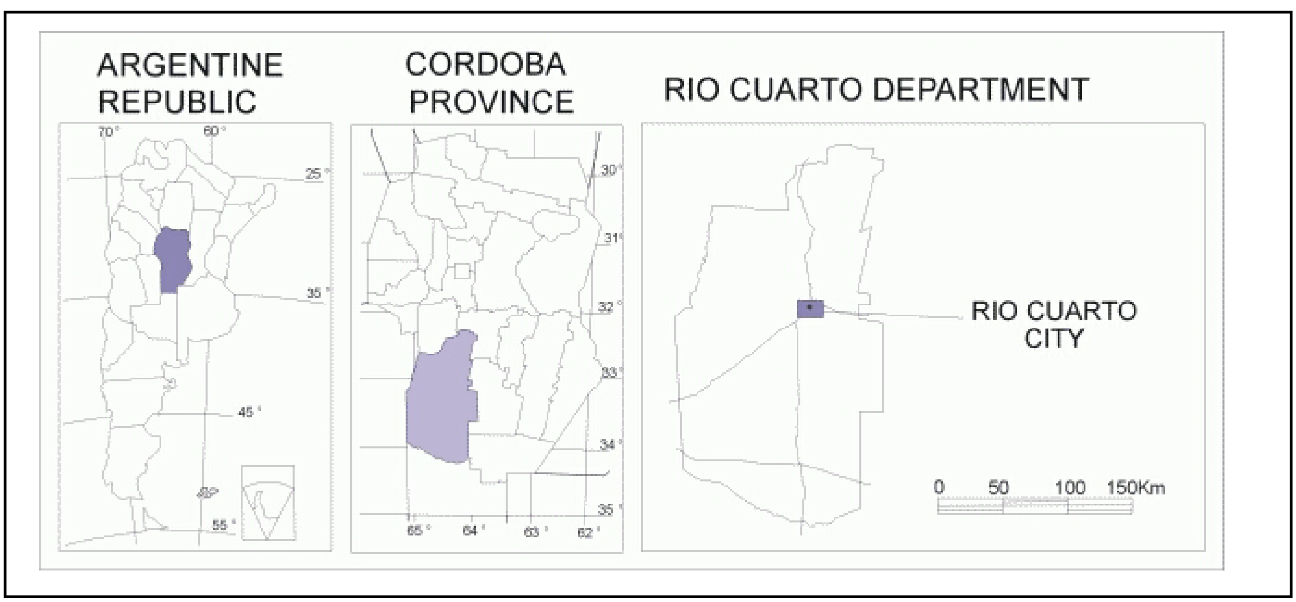

Figure 2. Location map.

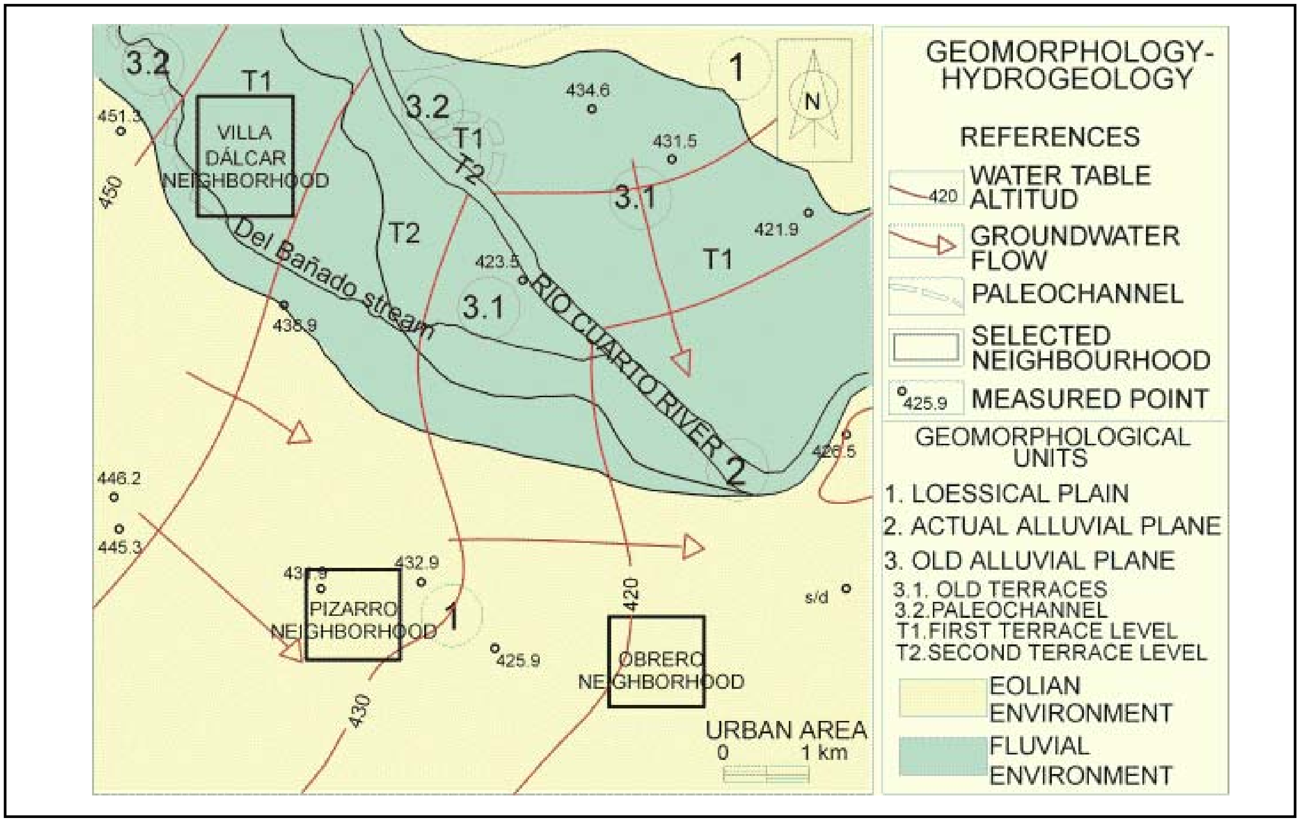

Figure 3. Geomorphology and hydrogeology map.

Holocene activity (Figure 3). The phreatic aquifer is made up of these clastic porous materials and has a thickness of 70 m. The general groundwater flow is NW-SE, and the water table depth ranges between 1 and 15 meters. The TDS of groundwater ranges from 0.2 to 1.6 g/l. In the fluvial environment, groundwater is fresh and of a calcium bicarbonate type, while in the aeolian environment, groundwater shows greater TDS and is of the sodium bicarbonate type.

Environmental problems in Río Cuarto city

Río Cuarto city has a population of 160,000 inhabitants and a surface area of 5816 ha. The major contamination problems are impacts to surface water and groundwater from untreated domestic sewage. Today coverage of piped water and sewerage is 95% and 68%, respectively. Portions of the sewerage effluents are discharged without treatment into the Río Cuarto river. The city uses groundwater for all water supplies, and the distribution of piped running water is the responsibility of "Ente Municipal of Obras Sanitarias" (EMOS). Until a few years ago, in some neighborhoods where there was no running water, groundwater was used for water supply and was obtained from domestic wells of shallow depth. The co-location of these wells with cesspools resulted in contamination of drinking water, as has been shown in several areas.

The hazard contamination map prepared for the urban area by Blarasin et al. (1993) provides a good pressure indicator. This map shows cesspool density per hectare, time of load application, type of contaminant involved, and method of disposition in subsoil. With this map and the map of aquifer vulnerability, it was possible to determine the aquifer contamination risk, and which neighborhoods had to be studied more urgently. It is also important to highlight that, when some neighborhoods were supplied with piped running water (in addition to the rainfall increase in the last five years), important changes in the water table levels occurred. Some of the most important aspects of water table level and quality problems of the aquifer in the city are described below.

GROUNDWATER LEVEL AS GEOINDICATOR

The measurement of level changes is of great importance to evaluate the problems related to subsidence due to excessive water withdrawal, water pollution caused by effluents, changes in groundwater reserves, and consequences for buildings and other structures.

An example of this problem is the significant rise in the water table level in the Pizarro neighborhood in 1999, in a topographic low sector to the south of Río Cuarto city. By 1994, the water table in the affected area ranged between 2 and 6 m depth (Figure 4). The progressive increase was caused by an increasing trend of rainfall excess in the water balance (Figures 5 and 6), especially since 1998 (Blarasin and Cabrera, 1999). Added to this trend is the contribution of effluents from cesspools (Figure 7). Due to the fact that the subsoil was completely saturated, its bearing capacity diminished causing sinking and cracks in walls, floors and roofs. Also the cesspools stopped working because of saturation, and as the residents emptied them quickly, water pressure inside the cesspool diminished causing collapse and sinking in backyards and gardens, and increasing the building problems already mentioned (Figure 8).

To solve this problem, a study commission was formed between the Municipal Department of Public Works, the EMOS (Empresa Metropolitana de Obras Sanitarias), and the Geology Department of Río Cuarto University. The detailed work consisted of drilling at crossroads, the logging of well cuttings, measurement of the water table depth and water quality parameters and hydraulic tests (Blarasin and Cabrera, 1999). The map showing water table equal depth lines was very useful (Figure 4) to show the problem to authorities. An area of 88 ha was defined, where the water table had a depth ranging from 0.5 and 1 m, with a highly compromised 12 ha area with the level at less than 0.2 m.

Aquifer pumping tests were performed in selected areas to have more information about aquifer behavior. Since the aquifer has low permeability (very fine sands and silts), the EMOS constructed an abstraction well battery made up of small wells (15 m depth, 4" diameter, 1,500 l/h yield). This

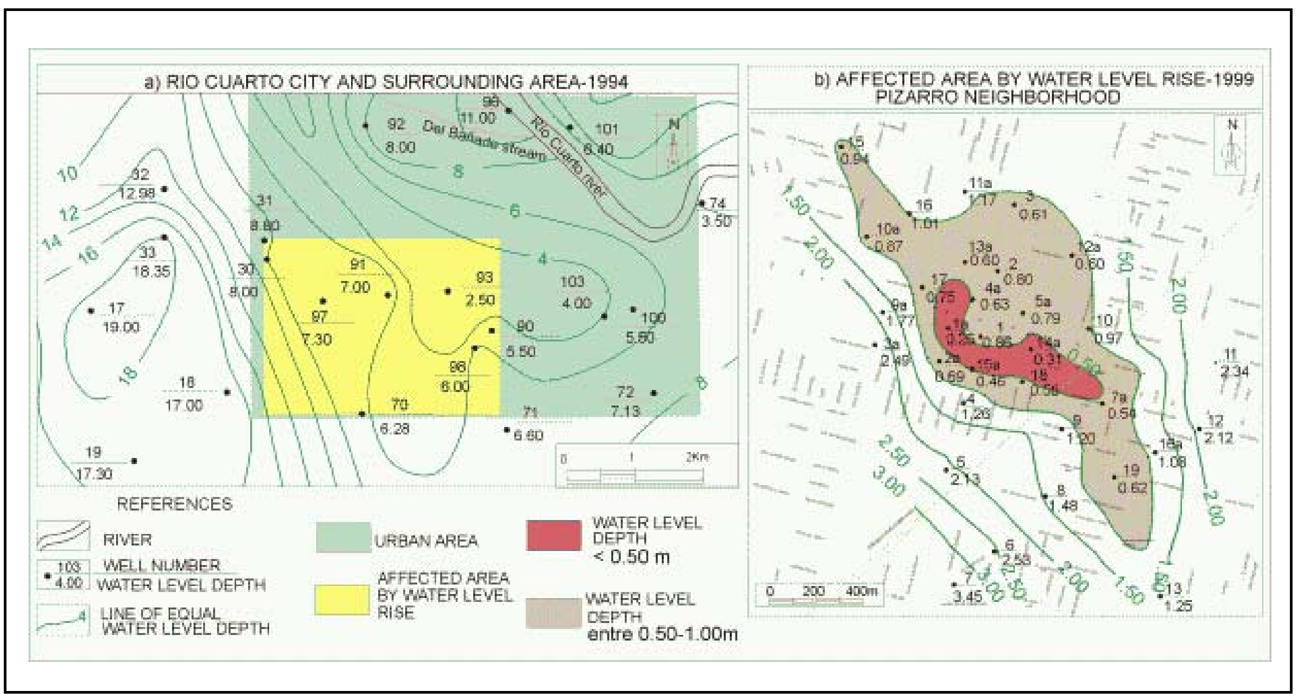

Figure 4. Lines of equal water level depth. a) Río Cuarto and surrounding area - 1994. b) Affected area by water level rise - 1999 Pizarro neighborhood.

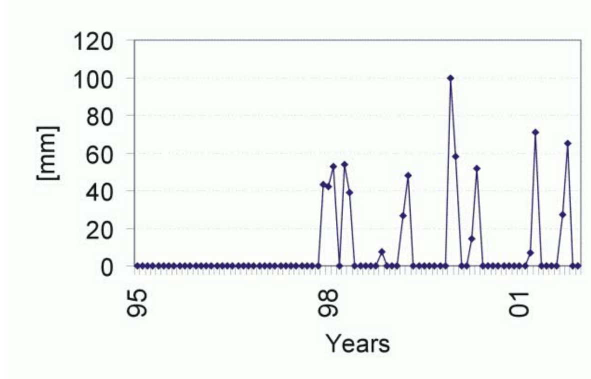

Figure 5. Rainfall excess.

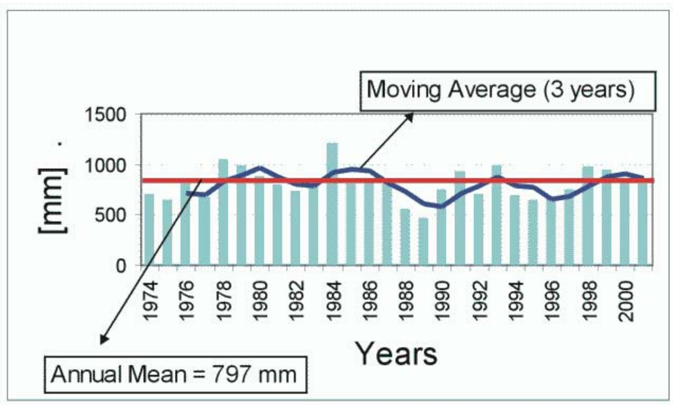

Figure 6. Rainfall distribution.

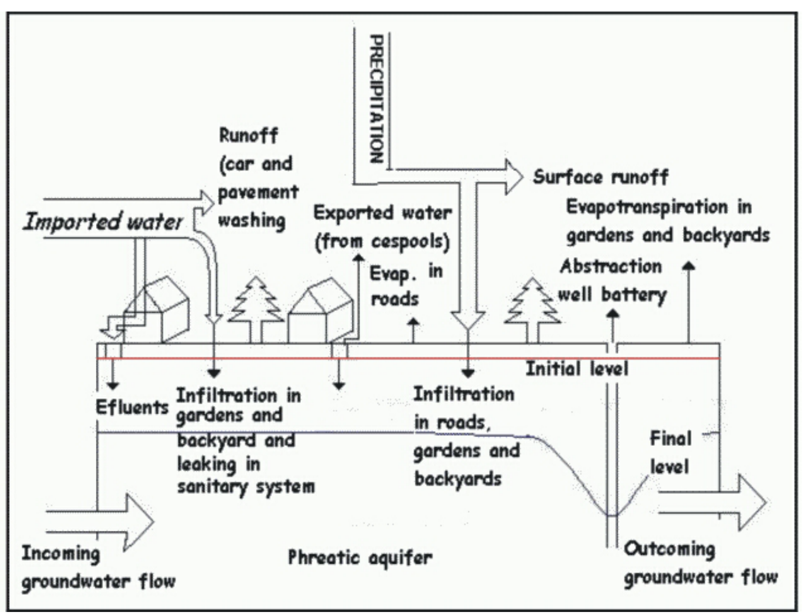

Figure 7. Conceptual model of water balance in Río Cuarto city.

battery caused a gradual decrease of water table level that did not affect the buildings, but that allowed the intersection of pumping cones of depression and the generation of an unsaturated zone of at least 4 m in thickness. Subsequently, a sewerage system was constructed in the area.

Figure 8. Cesspool collapse and sinking in a backyard in Pizarro neighborhood, Río Cuarto city as a result of the rising watertable in 1999 (Photograph from "Puntal" newspaper).

If the municipality had monitored groundwater levels regularly, it is highly probable that this situation would not have occurred. Although the problem caused severe damage, today the abstraction well battery is being permanently monitored and controlled by EMOS, and the monitoring information is an excellent indicator of levels that should not be exceeded. The Geology Department of Río Cuarto National University has installed a water table level monitoring point upgradient from the neighborhood, which provides useful information about the water table behavior in a natural state (Figure 9).

GROUNDWATER QUALITY AS GEOINDICATOR

To assess water quality, different hydrochemical studies were done in several neighborhoods of the city, especially those where there was no sanitary system (sewage and/or piped running water) and there was the highest contamination risk. In these neighborhoods, at least 30 domestic water wells were surveyed, with a density of one well per hectare. Water analyses included HCO_3, CO_3, Cl, SO_4, Na, K, Ca, Mg, pH, F, As, NO_3, NO_2, Fe, EC (electrical conductivity), TDS, alkalinity and hardness. The parameters EC, TDS, NO_3, NO_2 and Cl were considered the most significant indicators to measure periodically. The limits that are being used are those recommended by the AAC (Argentinean Alimentary Code). Microbiological analysis helped to determine total aerobic microorganisms, total and faecal coliform, *Escherichia coli* and *Pseudomonas aeruginosa*.

General aspects of contamination by nitrates, nitrites and bacteria

According to the AAC, the established limits of nitrate and nitrite in water are 45 mg/l and 0.1 mg/l respectively. Water with higher concentrations may cause methemoglobinemia in children, implications in diabetes cases, or even cancer risk (Canter, 1997). When nitrates in groundwater derive from nitrogenous organic substances, it is the result of microbial degradation to ammonia, which is biologically oxidized to become nitrites and nitrates under the influence of *Nitrosomonas* or *Nitrobacter*. These nitrifying bacteria are strictly aerobic and chemoautotrophic. The denitrifying bacteria have an aerobic metabolism but are able to survive in an anaerobic environment, obtaining oxygen from the nitrate. This can be reduced in different ways, reaching a final state of gaseous nitrogen or ammonia. Bacteria, unlike viruses, can multiply themselves outside their primary host environment if the nutrient supply is guaranteed, as in the case of an aquifer where the effluents come from on site sanitation systems. Faecal coliform bacteria are adequate indicators of faecal contamination, with *Escherichia coli* the best coliform indicator of recent faecal contamination, since it is unable to live for long outside the intestinal environment. Diseases such as cholera, hepatitis and diarrhoea,

Figure 9. Daily fluctuation of water table and rainfall. Río Cuarto 19/10/2001 - 09/09/2003.

may be transmitted microbiologically by contaminated water.

Geochemical model and indicators of contamination in a reducing environment in fluvial sediments: Villa Dálcar Neighborhood

The phreatic aquifer is made up of fine and coarse sands and gravels of fluvial origin. The water is fresh and of the calcium bicarbonate type, with TDS values ranging between 294 and 644mg/l. This neighborhood is located in a topographic low and the groundwater level is situated close to the ground surface (2-3 m). Cesspools have discharged effluents into the aquifer (Figure 10). The water wells in houses had depths ranging from 7 to 12 m. The population density of this area ranges between 8 and 80 persons/ha. In this neighborhood 54% of the groundwater was inadequate for human consumption due to bacteRiological contamination. There was a recount of microorganisms in 67% of the samples; 54% show total coliforms and 31% have faecal coliforms, with *Escherichia coli* in 20% of the samples. It is apparent that significant and widespread contamination of the aquifer by bacteria occurs as a result of the direct discharge from cesspools to groundwater.

In this neighborhood, no nitrate was detected in groundwater (Table 1, Figure 11). This is due to a lack of dissolved oxygen (anaerobiosis) in the upper part of the aquifer as a consequence of a greater availability of nutrients from the direct discharge of effluents to groundwater. This situation controls the extent of the NO_3 reduction processes. During water abstraction, the dissolved ferrous iron comes in contact with an environment with available oxygen where it oxidizes to ferric iron and precipitates in sanitary installations and pipes. The iron levels were usually low, and just in a few cases they exceed the human consumption limit. Iron is a good secondary indicator of the redox state in the aquifer (Edmunds, 1996). This condition corresponds to an anoxic, post-oxic ferrous groundwater environment (Berner, 1981). Heterotrophic microorganisms are those that release soluble iron during organic matter decomposition. The most acid conditions that result from microbial metabolism may release Fe from inorganic soluble forms. The groundwater in this neighborhood presented the lowest pH values (6.9-7.6), and the bad smell and taste of the water were characteristic of this area. The most contaminated samples showed an important increase of TDS and chlorides.

Geochemical model and indicators of contamination in an oxidizing environment in aeolian sediments: Obrero Neighborhood

The phreatic aquifer is made up of aeolian sediments (silts and very fine sands, with frequent intercalations of calcrete lenses). The water is of the sodium bicarbonate type, with TDS values ranging between 400 and 2700 mg/l. The water table is found at an average depth of 9 m and the domestic wells have a depth of between 12 and 14 meters. On site sanitation systems have an average depth of 4 m, that is to say, they have their bases in the unsaturated zone. The mean urban density of the area is of 150 inhabitants per hectare. Of the total number of samples analyzed, 87% are inadequate for human consumption, due to deterioration of chemical quality and bacteriological contamination. In this neighborhood, the plume of microbiological contaminants does not reach groundwater easily, since the decontaminating processes (mechanical filtration and biochemical transformations) typical of the unsaturated zone are active. The total recount of microorganisms exceeds the limit in 16% of the samples and total coliforms in 30% of the samples. Faecal coliforms (13.3%), *Escherichia coli* (13.3%) or *Pseudomonas aeruginosa* (10%) appear occasionally. Other important indicators of contamination (Blarasin et al., 1997) are TDS, Cl, and NO_3. Nitrates are useful indicators of the aquifer redox state (Edmunds, 1996), if dissolved oxygen (DO) and Eh

Table 1. Main Indicators of Groundwater Deterioration. Villa Dálcar and Obrero Neighborhoods

Dálcar (mg/l)						**Obrero** (mg/l)					
	TDS	**Cl**	NO_3^-	NO_2^-	Fe^{2+}		**TDS**	**Cl**	NO_3^-	NO_2^-	Fe^{2+}
Min	294.0	8.2	0	0	0	Min	482.3	45.7	25.0	0	0
Max	644.0	27.8	2.0	10.0	0.43	Max	2737.0	300.0	400.0	2.0	0
Mean	445.0	15.7	0.28	0.35	0.11	Mean	951.2	105.8	134.8	0.07	0

measures have not been carried out.

Eighty two percent of the samples exceeded the nitrate-established limit for human consumption (Figure 11), the more contaminated samples presenting contents ranging between 250 and 400 mg/l. The amines derived from the nitrogenous organic matter come from cesspools, they oxidize in the unsaturated zone, with the participation of the aerobic bacteria, producing NO_3 that reaches the aquifer (Figure 10). Due to the lack of dissolved Fe, the aquifer environment is oxic (Berner, 1981), which is confirmed by the absence of NO_2 in 90% of the samples. The highest salinity levels (TDS) are observed in the more contaminated samples (Table 1). The average salinity of the samples is 951 mg/l, the salinity of the four uncontaminated samples is 545 mg/l, while the most contaminated sample has a TDS value of 2737 mg/l. In the five most contaminated nitrate samples, the chloride averages 211 mg/l, three times more than the average (69 mg/l) of the samples that are not contaminated. As can be observed, in spite of the availability of the unsaturated zone, whose thickness and grain size indicate a good attenuation capacity, the contamination load is sufficient to produce significant degradation of groundwater, which is mainly represented by the high NO_3 values.

All the data obtained by the University were "translated" to thematic maps with "traffic light colors" (red is bad, green is good) to facilitate interpretation by non specialists, planners, and so on, and transferred to the Neighbors Associations and the Municipal Offices. After technical and economical studies, running water and/or sewerage systems were provided to the neighborhoods. The most important actions were the one carried out by the residents. The permanent complaints in mass media obliged politicians to think about solutions and to carry them out (Figure 12).

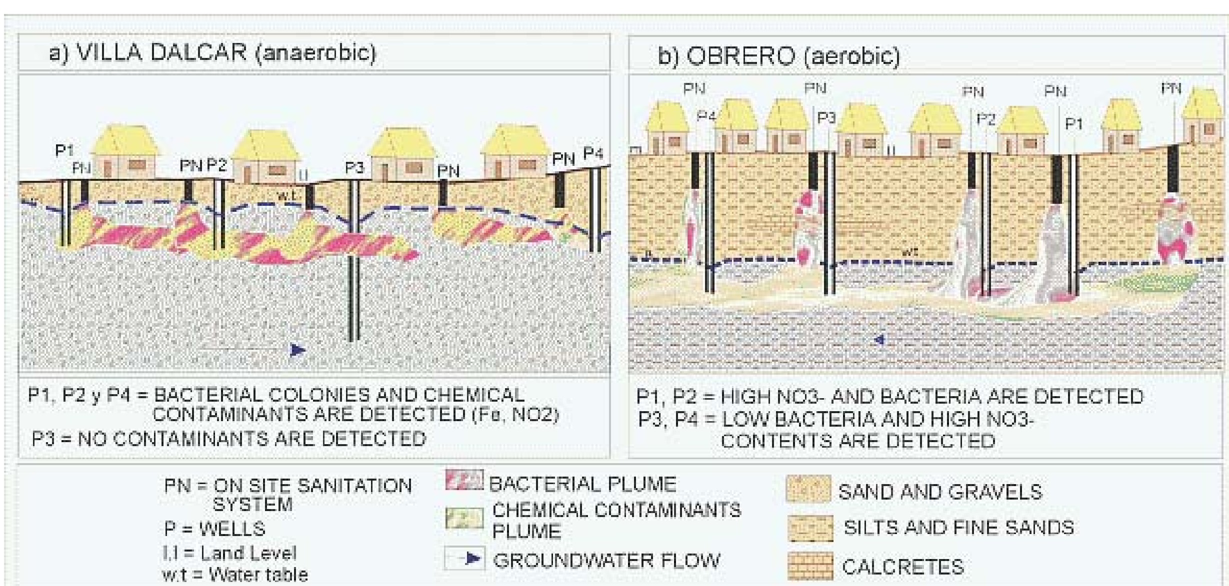

Figure 10. Contamination schemes. a) Villa Dálcar (anaerobic). b) Obrero (aerobic).

CONCLUSIONS

The best indicators in groundwater are the piezometric levels and water quality. Changes in these parameters may be early alarms of environmental problems that are necessary to solve or improve.

In the urban area, there is a need to define geoindicators and to monitor environmental changes in order to mitigate risks and damages. For the case of Río Cuarto city, and on the basis of pressure indicators synthesized through a load contaminant hazard map, and vulnerability and risk maps, monitoring areas and primary state indicators were selected and measured. Today, several of the primary state indicators that are proposed worldwide are being measured. These are: piezometric levels (to assess effects on buildings and groundwater resources) and EC, TDS, Cl, NO_3 and NO_2 (to assess hydrochemical processes and urban contamination). Experience in the city indicates that, related to these geochemical processes, the recount of *Escherichi coli* is a primary bioindicator of contamination due to untreated sewage.

The progressive rise of the water table was caused by an increasing trend of rainfall excess in the water balance, especially since 1998. To this increase, the permanent contribution of effluents coming from cesspools was added. Río Cuarto city does not have a history of monitoring of the water table, and the rise groundwater levels has occurred over the last two years. Even though the problem concentrated on the Pizarro neighborhood, and on nearby neighborhoods, it has caused very serious damage. Today there is a system for dewatering the aquifer using a well battery that is being permanently controlled and monitored to ensure that established levels should not be exceeded.

In relation to quality, the neighborhoods presented different contamination scenarios. Where aerobic conditions prevail, NO_3 was found in all the samples. Those with the highest values presented an increase in TDS and Cl. Where anaerobic conditions prevail (anoxic-postoxic- ferrous environment),

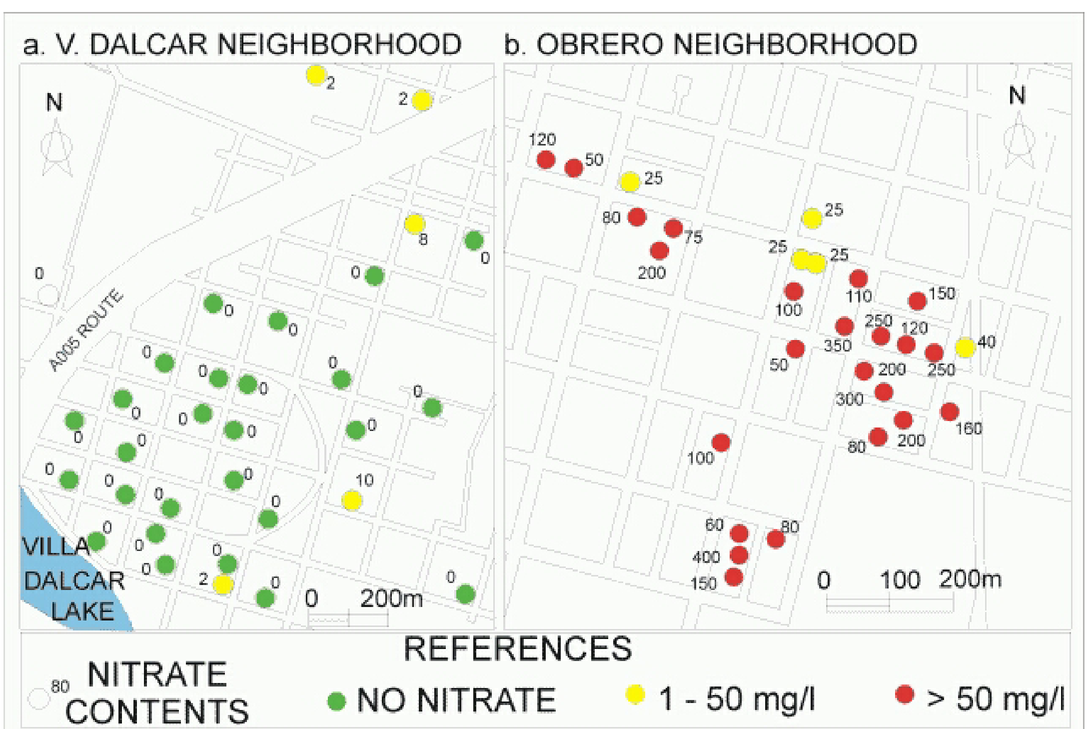

Figure 11. Nitrate contents. a) Villa Dálcar neighborhood. b) Obrero neighborhood.

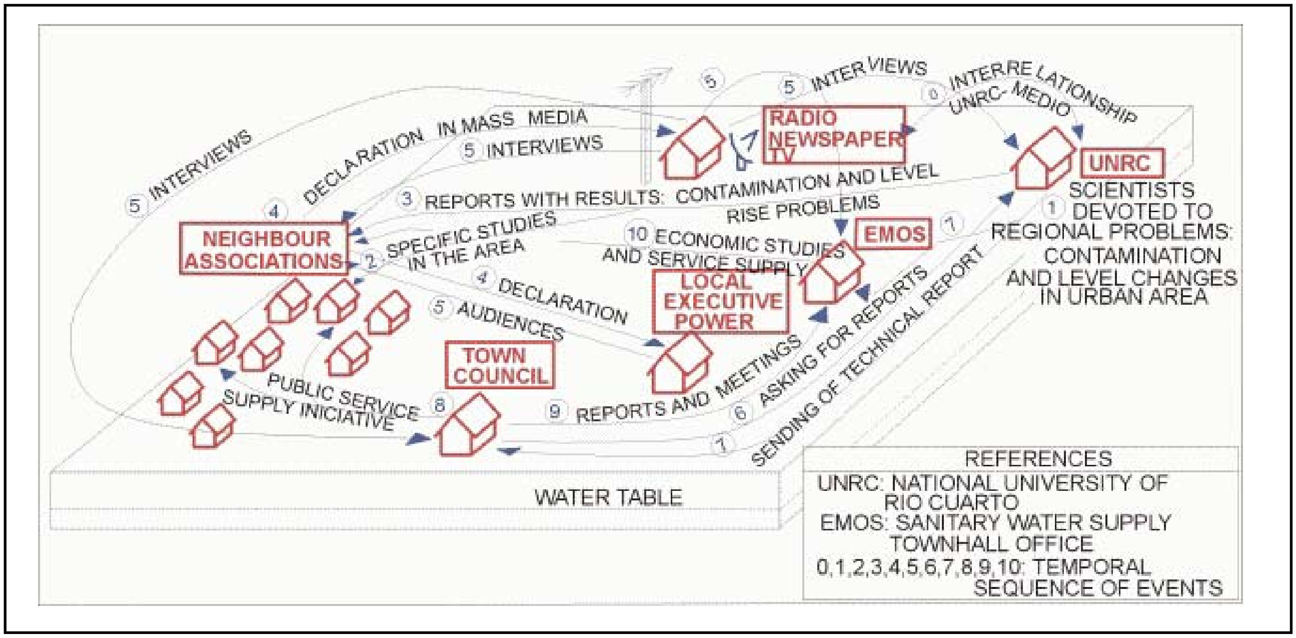

Figure 12. Agents involved in environmental problem and groundwater resource management.

NO_3 was not found (although NO_2 was found), there was dissolved iron and an evident increase in TDS and Cl in the most microbiological contaminated samples.

The most controlling natural factors in these contamination scenarios are water depth and the grain size of the unsaturated zone materials. The less thick the unsaturated zone is and the higher the permeability of the sediments (higher vulnerability), the more groundwater degradation is likely.

The most important anthropic factors in the described contamination models are cesspool density and the relative depth and location between sanitary systems and water wells in the different houses.

In both neighborhoods, more than 50% of the samples from domestic wells were not suitable for human consumption due to their microbiological characteristics. The presence of total coliforms, faecal coliforms,*Pseudomonas aeruginosa* and*Escherichia coli* in the aquifer is variable depending on the factors mentioned previously. The processes that eliminate bacteria were more effective where the unsaturated zone was thicker and made up of fine sediments.

Escherichia coli, nitrogenous species, and the increase in TDS and Cl were good indicators of contamination due to sanitary systems. In order to assess the redox state, NO_3 and dissolved Fe were very useful indicators.

Among the response indicators, as shown by social and political awareness of the problem, there are the diffusion measures of the media, management measures carried out by resident associations, and those conducted by the municipality. Taking into consideration that a great number of people was involved in this groundwater problem, the municipality provided more than 500 families with piped running water and/or sewerage system, or installed an abstraction well battery to dewater the aquifer where the water table levels were extremely high.

ACKNOWLEDGMENTS

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