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Groundwater chromium pollution in the Río Turbio Valley, Mexico: Use of pollutants as chemical tracers

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RESUMEN

La calidad del agua subterránea del Valle del Río Turbio en el estado de Guanajuato, México ha sido afectada por la incorporación de compuestos de cromo, Cr(VI), al sistema acuífero. Cuatro fuentes potenciales de contaminación han sido detectadas en la región, afectando el 90% de los pozos. Este estudio se basa en monitoreo vertical de agua, estratigrafía de detalle y análisis piezométrico con el uso de cromo como un trazador químico. El proceso de contaminación permite inferir el comportamiento hidraúlico del acuífero en el área de Buenavista. La variación espacial y temporal de la calidad del agua subterránea también permite una parametrización hidraúlica inicial. En el área más afectada se propone un programa de rehabilitación acuífera basado en extracción - tratamiento después de la relocalización de una fuente de compuestos de cromo.

PALABRAS CLAVE: Compuestos de cromo, contaminación acuífera.

ABSTRACT

Groundwater quality in the Río Turbio Valley in Guanajuato, Mexico is affected by chromium compounds, Cr(VI), in the aquifer system. Four potential pollution sources affecting 90% of the wells were detected. Vertical groundwater sampling and detailed stratigraphic and piezometric analysis is used to study aquifer behavior with Cr as a chemical tracer. Time - space changes in groundwater quality permitted an initial hydraulic parameterization. In the most affected area, Buenavista, an aquifer remediation program is proposed based on pumping and treating after chromium source removal.

KEY WORDS: Chromium compounds, aquifer pollution.

INTRODUCTION

In the Río Turbio Valley in Guanajuato, Mexico (Figure 1), four potential sources of pollution by chromium compounds were reported in a previous hydrogeological study (Rodríguez *et al.*, 1991). Chromium affects the groundwater quality and the urban water supply of the cities of Leon, Silao and San Francisco del Rincón. Trivalent chromium Cr(III) is stable and non toxic: it is believed to be necessary for glucose metabolism in humans (Yassi *et al.*, 1988; Doisy, 1976; Mertz, 1974). Hexavalent chromium Cr(VI) may affect human health in different ways; gastro-intestinal and liver diseases, nasal septum perforation, allergic contact dermatitis and lung cancer (Merian E., 1991; Royle, 1975). Lewis and Taken (1980), reported that high doses of up to 350 g of Cr(III) had no adverse effects on human health when taken orally. Gaur and Bhuttacherjee (1990), in a microbial bioassay found that Cr (III) produced no evidence of DNA damage whereas Cr(VI) compounds (K_2CrO_4 and $K_2Cr_2O_7$) caused damage to plasmid DNA.

Groundwater is the main source of water supply in Guanajuato state. This region is an important industrial area for leather processing and shoe manufacture. Agriculture is based on sorghum production. About 90% of the wells show abnormal chromium content, the highest concentration being 50 mg/l; the international standard for human consumption is 0.05 mg/l total chromium (EPA US, 1984; Galvao and Corey, 1987). Most wells have Cr concentrations below 0.05 mg/l. The most contaminated area is Buenavista to the west of the valley, where a plant for refining chromium compounds is located (Figure 2). Local well pollution was first reported in 1975 when the groundwater became yellow owing to a chromium concentration over 0.10 mg/l.

The Turbio river valley is covered by Quaternary alluvium. To the west, ignimbrites and rhyolites are related to the Guanajuato Range. Sediment grain size is larger in piedmont areas and consequently permeability is greater there. Former lacustrine and fluvial environments are the source of sediments that define the local aquifer system, such as clay lenses and gravel and sand layers with a very irregular distribution.

CHROMIUM POLLUTION SOURCES

In the Río Turbio valley, four sources of chromium pollution have been detected, one of which is natural while the other three are anthropogenic (Table 1). The natural source consists of leachings from Jurassic ultramafic rocks (San Juan de Otates Formation) containing pyroxenites and hornblendites (Jpsj, Figure 1). Pyroxenites contain chromite, nickel and iron. However, chromite concentration in these rocks is low from the economic point of view. Pyroxenites crop out in Cerro Pelón, about 30 km NE of the Buenavista study area (Figure 1); hydraulic communication between these two areas is not possible because of an intervening regional cone of depression (Servais *et al.*, 1982).

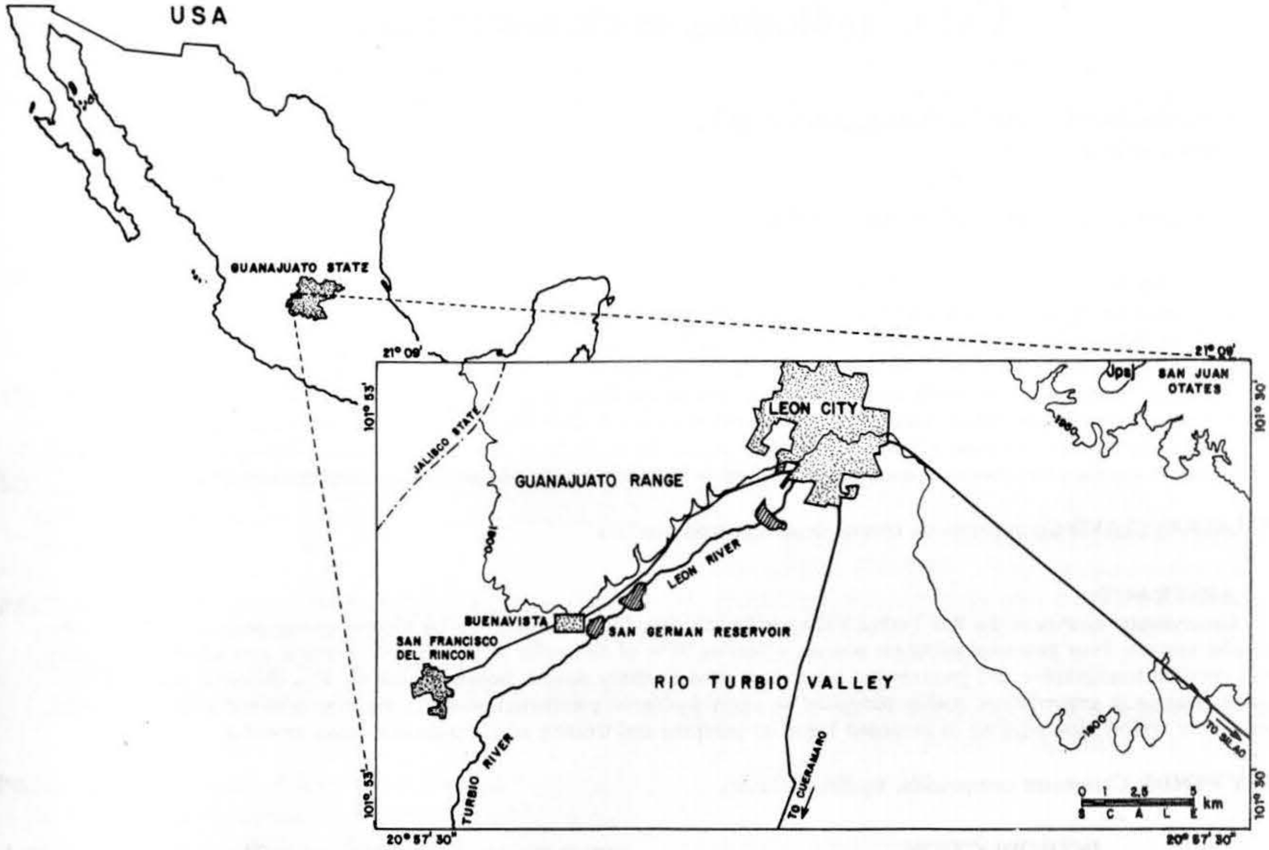

Fig. 1. Localization of study area in Guanajuato state. Turbio river valley. (Jpsj, San Juan de Otates Piroxenite Outcrop).

Table 1

Chromium compounds sources and Cr(VI) concentration levels in groundwater, GW.

Source of Chromium	Chromium content	GW concentration level
1 Pyroxenites	Cr(III)>>Cr(VI)	0.005-0.015 mg/l
2 Brick factory ashes	Cr(III) > Cr(VI)	0.005-0.04 mg/l
3 Tannery waste water	Cr(III)	0
4 Industrial wastes	Cr(VI) > Cr(III)	0.05-55.0 mg/l

In the Río Turbio valley there are brick factories that traditionally use waste leather, derived from different processes such as tanning and shoe manufacturing, for fuel in brick furnaces. Residual leather is cheap and brick manufacturers believe that bricks acquire a better coloration. Although leather contains chromium as Cr(III), the combustion process oxidizes Cr(III) to Cr(VI). The residual ashes are spread over agricultural lands as a fertilizer, becoming the second reported source of chromium pollution (Rodríguez *et al., op cit.*). Irrigation and/or precipitation facilitates chromium leaching into the groundwater. Urban well extraction in the center of the valley has generated a large cone of depression where the water table is at 80m depth compared to the valley margins where it is 10-20m deep. In the central area, only shallow aquifer units show chromium pollution; the intermediate-depth wells in this area have no chromium (Armienta *et al.*, 1993). It is possible that Cr(VI) migration through the non-saturated zone is slowed by clay adsorption or other physical-chemical water-rock interactions. Cr is incorporated to deep aquifer formations in valley margins where permeability is greater due to the low clay content. Dispersion in the aquifer system is controlled by flows induced by the pumping regime. This is the main regional pollution mechanism, influencing the largest valley area. In the Buenavista area, however, there are no brick factories. Thus the groundwater chromium must have a different origin.

In León city a great number of tanneries have been established. The tanning process uses large volumes of water. Tannery waste waters contain organic material, salt (NaCl), Cr(III) and sulfides. While these waters do not contain significant amounts of Cr(VI) they were considered by the local population as the main source of chromium in the valley. Untreated tannery wastes are mixed with urban sewage and discharged into the Turbio river. In such a reducing environment, from the chemical point of view, it is hardly possible to transform Cr(III) to Cr(VI). Cr(III) can be oxidized to Cr(VI) by manganese dioxide (Eary and Ral, 1987; Richard and Bourg, 1991), but in Buenavista area there is no evidence for such a process (Armienta *et al.*, 1995). Sewage is used for irrigation. Trivalent chromium may not affect plants but some crops do not tolerate high sodium concentrations. Tannery waste waters have a high sodium content. Tanneries discharge about 100 ton of salt/day. Our previous study (Rodríguez *et al.*, 1991) reported high Cl concentrations in groundwater around the Turbio river drainage area, 500-1500 mg/l yet Cr(VI) was not detected in either deep or shallow wells in this zone (Armienta *et al.*, 1993).

The highest chromium contents originate in the plant for refining chromium compounds located in Buenavista (Figure 1). This is the fourth and main Cr pollution source in the valley. The plant is located near San Germán Dam, one of three water reservoirs used as oxidation ponds (Figure 2), fed by the León River. The industrial plant started its operation 20 years ago. The polluted area related to this source is not larger than 5 km^2 and includes up to ten active wells. The maximum Cr(VI) concentration in this zone is found in well 37. Its chromium concentration may vary between 30 to 55 mg/l, depending on the pumping rate. The source of hexavalent chromium in this area has been traced to leaks from an industrial solid waste container next to San Germán Dam. Local water pumping results in a westward-moving contaminant plume that has migrated to well 40. Pumping of polluted water from well 40 has prevented Cr migration from extending beyond the Buenavista area (Figure 2).

MIGRATION PROCESS OF POLLUTANTS

The Cr concentrations that define the contaminated plume geometry (Figure 2) allow us to suppose that the migration process of pollutants in the Buenavista area is controlled by the geological framework and by the well pumping regime. Column experiments were carried out with rock samples from the piezometer wells drilled in Buenavista (Figure 2). These experiments showed that adsorption-desorption capacity is present in clay lenses, but adsorption capacity is saturated at the concentration levels found in the most highly polluted wells (Armienta, 1992).

A monitoring system consisting of five piezometers was cored to 30m depth (Piezometers I-V, Figure 2) around

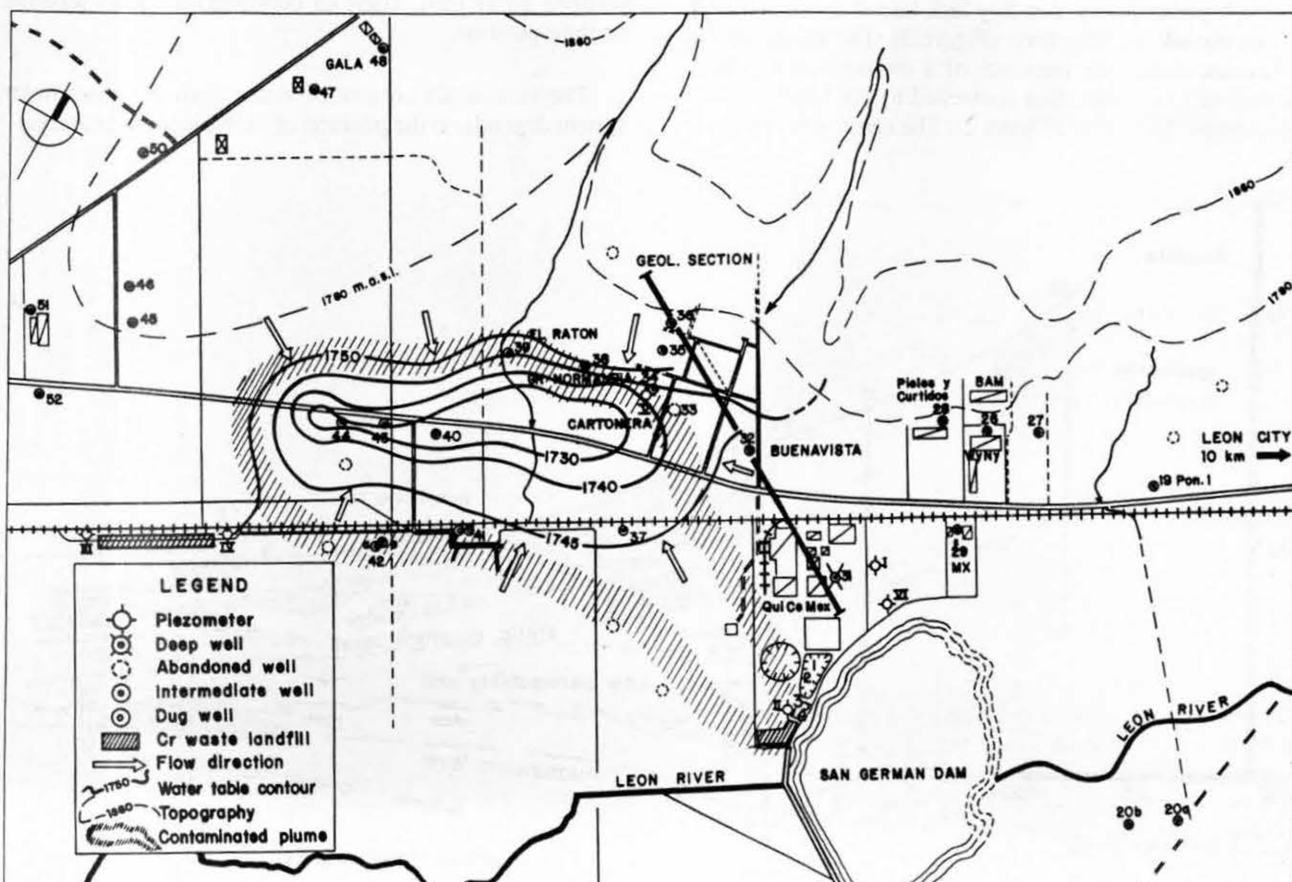

Fig. 2. Piezometric depression at the Buenavista area. Schematic geometry of the contaminant plume.

the plant. A piezometer nest consisting of six observational points (site VI) was drilled to depths of 3, 5, 7, 9,11 and 13m around San Germán Dam. These wells were drilled with a pneumatic hammer and unaltered and non-contaminated rock samples were obtained. Drilling fluid was avoided because Cr(VI) has a high solubility. After drilling, a polyethylene closed casing was introduced to a 6m depth below which a sawed and slotted PVC casing covered by a fiberglass filter was installed. Groundwater sampling depths were selected to match sand and gravel layers. Vertical sampling at three different depths is currently being carried out every two weeks.

Originally we suspected leakage from two solid waste landfills, one of them 700m outside the plant. Chemical results from piezometers III and IV suggested, however, that chromium had not migrated from these landfills because the water had a Cr(VI) content lower than 0.05 mg/l. Piezometer II, within the most critical area, had a Cr(VI) concentration of 60 mg/l (Rodríguez *et al.*, 1991). Chromium came from a solid waste landfill which contains industrial wastes rich in alumina (point 4, Figure 2) and chromium compounds. These wastes contain 6% Cr(VI) and 50% moisture. Chromium is leached through sand, gravel and clayey sand. There are clay and silt layers of very low permeability, but they lack lateral continuity and cannot impede Cr migration (Figure 3). The migration of pollutants causes the presence of a contaminated plume moving in a flow direction controlled by the local cone of piezometric depression (Figure 2). The chromium distribution for January 1991 shows a Cr gradient within a sandy layer at 15m and 18m depth. Cr concentrations are larger at 15m than at 18m, due to more sand in the 15m layer. In this area, the piezometric level of the semiconfined aquifer is located also at 15m. This concentration gradient, vertical and horizontal, indicates a preferential horizontal flow for pollutants and also denotes that the advective transport is dominant over the dispersive one. Similar configurations were obtained for other periods of time (Figures 4.a, 4.b).

LOCAL PIEZOMETRIC BEHAVIOR

In the Buenavista area there are four kinds of wells: deep, intermediate, shallow dug wells and controlled piezometers. This is one of the first observational systems for groundwater pollution by industrial wastes in Mexico.

One well is as deep as 600m. It was specially designed with 100m closed casing to prevent surface chromium pollution. It is placed in the factory (well 31). Its water does not contain chromium above the limit of detection (0.005 mg/l). Intermediate wells have depths between 50 to 100m. Their chromium content depends on their position relative to the plant. Shallow wells are large diameter with depths between 10 to 15m. Their Cr concentration also depends on their position.

The vertical Cr content of water from the piezometer system depends on the position of each piezometer and on

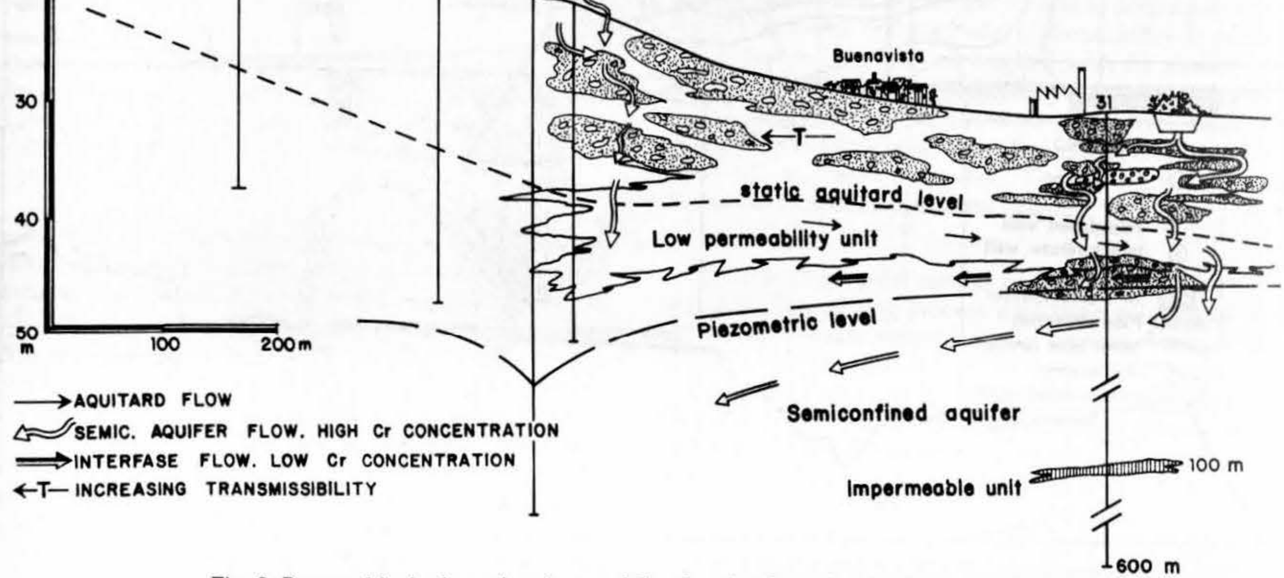

Fig. 3. Proposed hydrodynamic scheme of Cr migration from the alumina waste disposal.

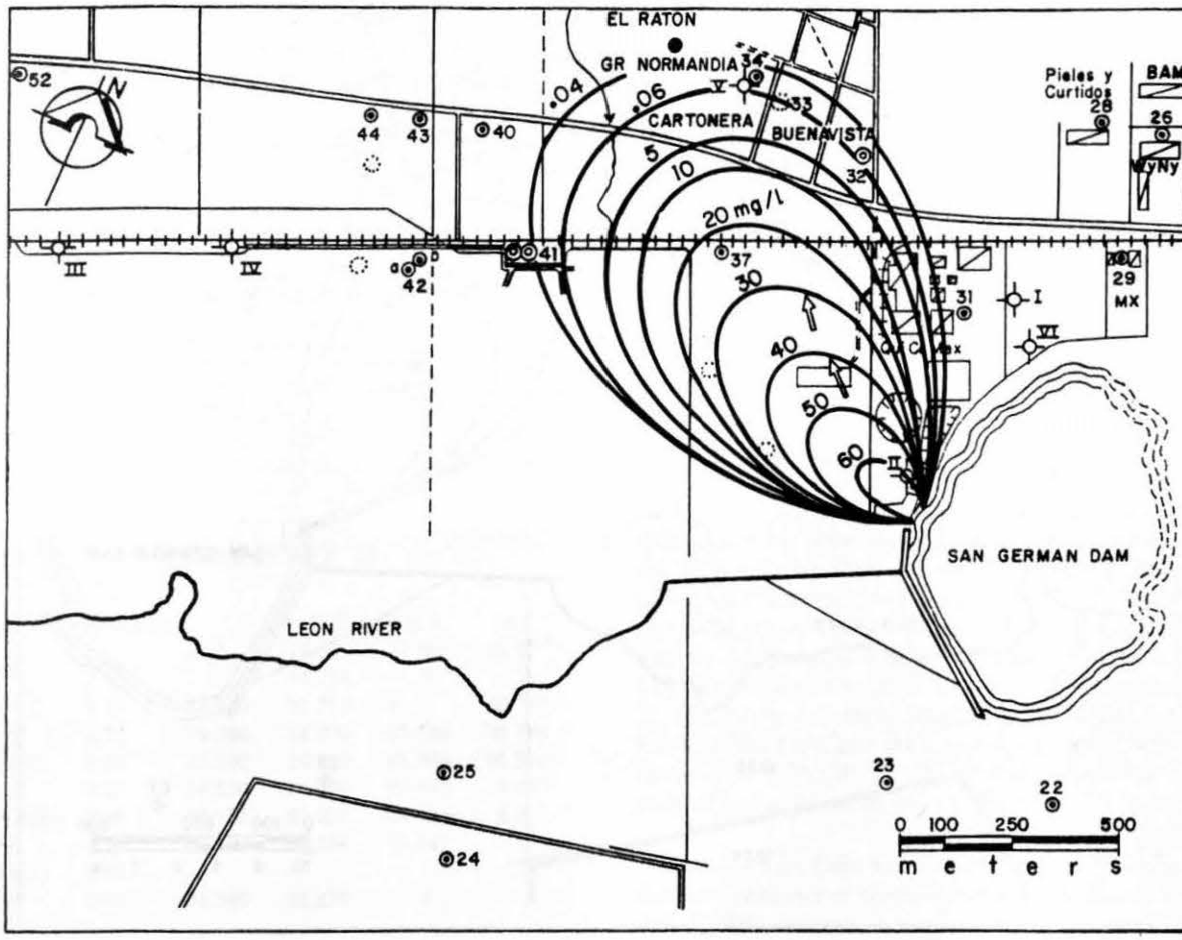

Fig. 4a Cr(VI) [mg/l] Distribution for January 1991, 15 m depth.

the lithological column. Control well I does not show any detectable amounts of chromium. Piezometers III and IV have low Cr content. Piezometers II and V feature the most important Cr concentrations (Table 2).

In Buenavista wells, the piezometric level of the deepest well (31) is at a depth of 35m. The intermediate wells are about 15m deep in the valley to 30m in the piedmont (well 34, Figure 2). The water table of the shallow wells varies between about 10m in the valley and 15m in the hills. The well 31 corresponds to the regional piezometric level of the aquifer formation actually pumping (a low permeability formation) and the last well (34) depends of the elevation over the valley level.

Deep and intermediate wells do not show the influence of precipitation. One week after rainfall the water table of shallow wells rises indicating flow between the surface and relative shallow aquifer formations due to the irregular distribution of permeable and impermeable layers.

LOCAL AQUIFER SYSTEM

Initially the high concentrations of Cr(VI) in well 34, located 10m above the factory and 600m away from the Cr sources, seemed puzzling. This well had a Cr(VI) content of 10 mg/l whereas well 41 located at the same distance from the source had only 1 mg/l. Both tapped the same aquifer. Piezometer V is 10m away from well 34. Its depth is 50m. Its Cr content is always larger than that of piezometer V.

Water from well 34 is used for cardboard manufacturing, pig farming and irrigation. The local high permeability allows Cr(VI) leakages from untreated waste water from the cardboard manufacturing plant, which flows in an open ditch into León River. Seepage from irrigation acts as an aquifer Cr feedback: polluted water is fed back into the aquitard and to the semiconfined aquifer, thus increasing the chromium concentration. The multiaquifer system also explains the presence of Cr(VI) in well 34. Wells 34 and 37 have approximately similar pumping regimes, but more water is extracted from well 34 due to higher permeability as a consequence of piedmont material with a variable grain size. The permeability of this material plays an important role in chromium migration.

The only deep well (# 31) has no Cr. It was drilled in 1970. It taps a confined deep aquifer. The confining formation might be a rhyolite layer related to the Guanajuato range, or some other impermeable unit.

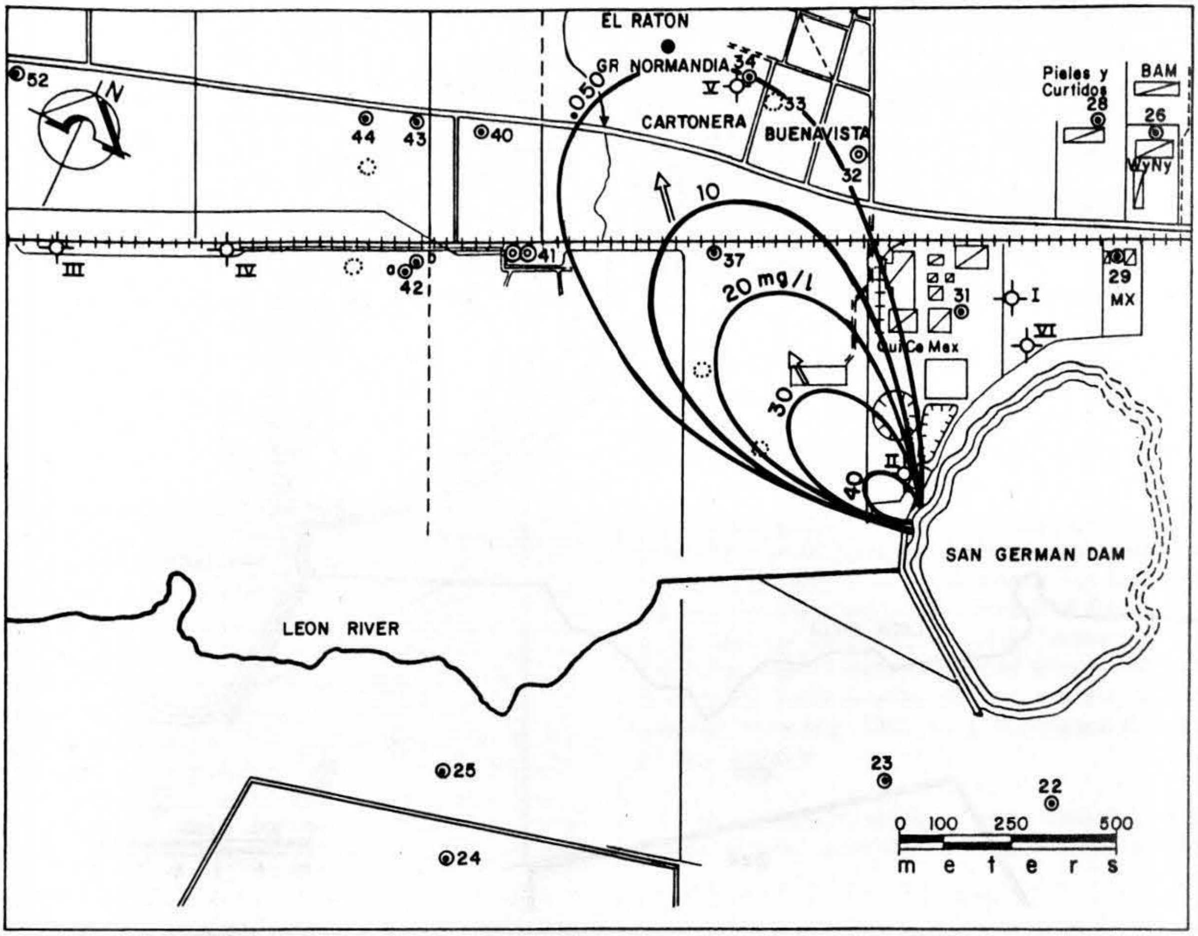

Fig. 4b. Cr(VI [mg/1] Distribution for January 1991, 18 m depth.

Except for well II, piezometers have lower Cr concentrations than intermediate wells. Vertical Cr distribution reflects the local stratigraphy. Maximum Cr contents are correlated with sand and gravel, and minima with to clay and silt. Their stratigraphy defines a low permeability unit (aquitard). A local flow to the piezometric depression occurs in some thin layers of gravel and sand (Rodríguez *et al.*, 1991; Castelan *et al.*, 1995). The non-contaminated groundwater flow from piedmont to valley is related to local recharge. A mean flow velocity of 100 m/year is estimated, though gravels and sands could have greater values. The shallow dug wells tap this layer.

A semiconfined aquifer underlies this low permeability layer. Its stratigraphy features are sand and gravel layers. Its clay content is lower than the aquitard's. In this permeable layer, the local flow has an opposite direction to that observed in the aquitard-from the valley to the piedmont (Figure 3). Its water velocity is the largest of the different aquifer types. Intermediate wells tap this aquifer which accounts for about 90% of the total yield. Some intermediate-depth wells intercept both the aquitard and the semiconfined aquifer.

The major volume of polluted water from the contaminated plume is moving in the interface between the aquitard and the semiconfined aquifer and in the upper part of the latter. Its spatial and temporal evolution is controlled by the pumping regime of wells 37 and 34. When pumping stops at well 37 the groundwater flow is affected by pumping at well 34, and the plume is pulled towards this well. Pumping tests carried out in both wells yield different permeability values. At well 37 the mean permeability is $k = 5 \times 10^{-5}$ m s^{-1} and at well 34 $k = 3 \times 10^{-4}$ m s^{-1}. This difference implies a significant influence of well 34 on the flow direction and on chromium migration in the Buenavista area.

HYDRODYNAMIC MODEL

The observed chromium distribution and evolution leads to a hydrodynamic model of the aquifer system which explains groundwater pollution dynamics. The concentration gradient from vertical groundwater sampling confirms local flow direction obtained by piezometry in the semiconfined aquifer, horizontally and radially to the piezometric depression. Cr(VI) was used like a groundwater tracer. The origin and time-space evolution of Cr(III) and Cr(VI) in Buenavista area are related to the role of the different potential pollution sources in the valley, especially the chromium plant.

Table 2

Cr(VI) [mg/l] Groundwater concentrations. Piezometer system. January-May 1991. (W. L. water table)

PIEZOMETER I

MONTH	W.L.(m)	DEPTHS (m)			
		11.3	14.00	17.00	20.00
JAN	11.20	0.0497	-	-	-
JAN(2)	10.95	0.0136	0.0044	0.0226	0
FEB	10.95	0	0	0	0
FEB(2)	11.06	0.0310	0.0044	0.0040	-
MAR	11.30	0	0.018	0.0130	0
MAR(2)	11.56	0.0180	0	0.0090	0.0090
APR	11.80	0	0.0056	0	0
APR(2)	12.00	0.0124	0	0.0033	0.0034
MAY	12.12	0	0	0	0

PIEZOMETER II

MONTH	W.L.(m)	DEPTHS (m)			
		11.3	14.00	17.00	20.00
JAN	8.11	-	94.730	0	0
JAN(2)	8.25	55.330	81.710	0	40.730
FEB	8.22	49.780	18.670	03.780	03.780
FEB(2)	9.00	43.100	10.910	01.590	01.210
MAR	9.23	26.830	06.420	02.640	0.095
MAR(2)	9.46	02.102	01.627	01.433	0.022
APR	9.76	01.103	01.537	03.447	0
APR(2)	9.93	-	-		0
MAY	10.0	01.360	01.270	0	0

PIEZOMETER III

MONTH	W.L.(m)	DEPTHS (m)		
		10.0	12.00	15.00
JAN	9.62	0.0362	0	0
JAN(2)	9.10	0.0045	0.0045	0.0814
FEB	9.70	0	0	0
FEB(2)	9.59	0.0580	0.0090	0
MAR	9.68	0	0	00090
MAR(2)	9.60	0	0	0
APR	9.48	0	0	0
APR(2)	9.50	0.0147	0	0.0450
MAY	9.53	-	-	0

PIEZOMETER IV

MONTH	W.L.(m)	DEPTHS (m)		
		11.0	13.00	16.00
JAN	10.58	0.0728	-	-
JAN(2)	10.57	0.0315	0.0045	0
FEB	10.68	0.0090	0	0
FEB(2)	10.56	0	0	0
MAR	10.47	0.0940	0.0720	0.0670
MAR(2)	10.48	0.1950	0.1760	0.0270
APR	10.40	0.3120	0.3979	0.3627
APR(2)	10.40	0.2000	0.1615	0.1142
MAY	10.30	0.4740	0.5830	0

PIEZOMETER V

MONTH	W.L.(m)	DEPTHS (m)		
		18.0	20.00	23.00
JAN	-	-	-	-
JAN(2)	17.20	0.0723	0.0362	0.0452
FEB	17.70	0	0.0580	0.0180
FEB(2)	16.65	8.4500	7.2200	1.6700
MAR	17.45	11.350	9.6800	7.3900
MAR(2)	19.50	-	1.6720	0
APR	12.85	6.6000	7.5700	7.3400
APR(2)	13.83	-	-	0
MAY	17.90	5.1900	4.8400	3.7800

The piezometric depression generated by local pumping of the semiconfined aquifer explains the plume geometry. Below the chromium waste landfill (point 4, Figure 2) the geological medium is saturated; a vertical flow is established from the *alumina* container to the aquitard. Within the aquitard, Cr flow moves horizontally toward the piezometric depression (Figure 3). The Cr(VI) concentration differences between 15 and 18m sampling depths (20 mg/l in 3m) supports this assumption (Figures 4.a and 4.b). Wells located to the E do not show Cr content (wells 22, 23). Neither do those located to the SE (wells 24, 25). San Germán Dam and the León River act as a hydraulic barrier. NE wells (26, 27, 28) have no Cr; neither do those situated to the W, wells 46, 45, 50, 47.

San Germán Dam has no influence on the recharge or chemical behavior of shallow wells. Wells placed around it lack Cr(III) content. León River water contains large amounts of NaCl, but piezometers and Buenavista wells do not reflect NaCl pollution. NaCl infiltration is reduced by shallow clay lenses. The irregular distribution of soil Cr content is associated with absorption by roots. Cr(III) concentration is highest in soils irrigated with tannery waste waters.

The piezometric head of observational site VI is not affected by seasonal variations of dam level; this suggests no hydraulic connection between the dam and shallow permeable layers. The absence of Cr(VI) and Cr(III) supports this assumption. The dam receives untreated waste water from two tanneries. The chemical oxygen demand is a measure of organic pollution. Oxygen demand values of 981 mg/l for tannery waste water and 90 mg/l for plant sewage were obtained. The high organic matter content of the discharge into the dam has formed a thick bottom slime wich modifies soil permeability and delays the flow of pollutants to the aquifer.

Some agricultural lands have been affected by salt (NaCl). Seepage due to irrigation is limited by the clay content of soils. Evaporation is increasing the salt concentration in soils.

Chromium compounds do not reach the confined aquifer partly because of the local extraction regime, which causes mainly horizontal flow in the saturated zone.

Regional flow has an E direction, whereas in the semiconfined aquifer, at present, local flow has a SW direction. This flow is controlled by the pumping regime. The flow is radial to well 40. Local recharge from the Guanajuato Range originates a SE shallow flow in the aquitard (Beltrán, 1991). This flow contributes to Cr dilution in the aquitard, which accounts for low Cr concentrations in some shallow wells and in piezometer V (Figure 3).

Pumping regime variations cause oscillations of the piezometric level of the semiconfined aquifer inducing vertical flow from the aquitard to the former, draining it. This contributes to move some Cr retained in clay lenses. Where the water table fluctuates, the piezometer gradient concentrations change; higher concentrations are found at the deeper sampling levels.

AQUIFER REMEDIATION

Groundwater chemical treatment *in situ* is not recommended, because it requires chemical stabilization of chromium as Cr(III) from Cr(VI) dissolved in the water. The stabilization of industrial waste waters consists of Cr(VI) reduction in an acid medium with iron or another reductant such as SO_2 ,followed by precipitation with lime (Besselievre, 1969). This procedure would be very difficult to carry out *in situ* in view of the various steps involved and also because of the alteration of the aquifer by the addition of chemicals. The reduction might be done by organic matter; but this procedure may not be effective because of the high chromium concentration in the water. It would also deteriorate the groundwater quality. A remediation program based on pumping and treating is thus to be preferred. The polluted water is pumped and conducted to a treatment plant. The treated water is reused or reinjected into the aquifer.

An aquifer remediation program based on controlled pumping has been proposed as follows. Wells 37 and 34 are to increase pumping for industrial plant water supply. An additional well between well 37 and piezometer II at 20m depth is planned. At present, water from well 37 is used only in the chromium plant. Industrial processes of this plant do not produce waste water, yet they have a treatment plant. Water surplus from wells 37 and 40 will be treated and used for green areas irrigation around the factory, thereby increasing the hydraulic head in the margins of the piezometric depression.

The identification of the Cr pollution source (*alumina* wastes, point 4), facilitated its elimination. This landfill has a depth of 8m and an area of 400 m^2. The proposed remediation program will start after shutting down the landfill and treating the solid wastes. At present the wastes are being removed to a temporary container. A new landfill for the treated chromium wastes, with a strongly reduced Cr(VI) content, will start operation in late 1996. Unless the pollution source is deactivated, groundwater pollution cannot be stopped.

The Buenavista population was drinking water with Cr(VI) content between 0.05 - 0.10 mg/l until 1989. In order to establish Cr uptake by the exposed population, an epidemiological study was carried out (Armienta and Rodríguez, 1995). The only adverse effect observed was perforated nose walls in 2.4% of the plant workers in the last ten years. At present local groundwater is not used in this zone for human consumption. Buenavista water supply comes from the Cañada de Soto well system, 6 km away from the chromate plant (outside Figure 1, NW from well 50). The factory owners have financed drilling and well equipment for this new water supply system.

Some of the solid wastes will be used for brickmaking after Cr(VI) reduction and precipitation. This process has some technical limitations especially in terms of efficiency of Cr(VI) removal.

Groundwater vertical monitoring in piezometers will continue in order to observe Cr concentration evolution and to detect eventual problems in the aquifer remediation program.

CONCLUSIONS

Groundwater Cr pollution in Río Turbio Valley is caused by four different potential sources. In Buenavista only one source is active, a solid waste landfill. In this area pollutants were used as tracers with some success. The geological structure and the hydrodynamics of the local aquifer were inferred from the spatial and temporal distribution of Cr concentrations and from piezometric analysis; this also accounts for plume geometry. The difference in chemical behavior and in origin of the two types of chromium pollution in the region, Cr(III) and Cr(VI), facilitate tracing the pollution sources. The presence of different chromium oxidation states in different permeable units leads to a hydrodynamic model of the Buenavista aquifer.

A local piezometric depression controls plume migration. Fluctuation in the pumping in wells 37 and 40 causes flow changes towards well # 34, placed 10m above the topographic level of the pollution source, where the permeability is greater.

Grain size differences cause permeability changes and different hydrodynamic responses to pumping, thus controlling pollutant migration. The irregular distribution of permeable layers did not allow us to make a zoning map of the permeability. It was only possible to define general trends.

This study is part of a research program based on vertical sampling in the piezometer system built in Buenavista in 1990. The cost of the piezometers was relatively high. The installation of this observational system is relevant in developing countries, where the solution to groundwater pollution problems does not necessary involve research and investment. In many cases, when the pollutant is detected, the solution is to stop pumping. For the first time in Mexico (Rodríguez *et al.*, 1991) a special monitoring system for a contaminant plume from industrial waste disposal was financed by local government agencies (National Water Commission, CNA, and the Municipal Water Supply and Sewage System of León City, SAPAL), the industry responsible (Química Central de México, QC) and university research institute (Institute of Geophysics of UNAM).

Knowledge of the hydrodynamics has enabled us to propose an aquifer remediation program based on waste relocalization and programmed pumping. Polluted water is used in plant processes whereas treated water will be conducted to León River and some will be used for green areas irrigation. The first step was to remove 20,000 tons of chromium wastes. The wastes have been placed in a temporary container. A new landfill is being planned. The Cr content of the waste will be lowered before disposal in the new container. An *in situ* treatment scheme was also considered but presents some operational complications and is not totally safe.

ACKNOWLEDGMENTS

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