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ORIGINAL ARTICLE

Groundwater arsenic distribution in South-western Uruguay

A. Manganelli · C. Goso · R. Guerequiz · J. L. Fernández Turiel · M. García Vallès · D. Gimeno · C. Pérez

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Abstract This is the first specific information regarding arsenic distribution of groundwater in SW Uruguay. Twenty-eight wells were sampled on the aquifers of Mercedes, Raigón and Chuy in five localities. The pH, specific conductivity and temperature were determined in the field. The hydrochemical characterization (major and trace elements) was carried out by both inductively coupled plasma-optical emission spectrometry and inductively coupled plasma-mass spectrometry. The occurring arsenic concentrations exceed the recommended threshold for drinking water of the World Health Organization (10 μg/l of As) in 22 samples, with more than 50 μg/l of As in two cases. The median, minimum and maximum concentrations were 0.1, 16.9 and 58.0 μg/l of As, respectively. The studied aquifers present a horizontal and a vertical variation of the concentrations as a whole as well as individually. The highest values were observed in the Mercedes Aquifer in the areas near the Uruguay River.

A. Manganelli (✉) · C. Goso · R. Guerequiz · C. Pérez
Universidad de la República, Iguá 4225,
CP 11400 Montevideo, Uruguay
e-mail: albertomanganelli@yahoo.com

J. L. Fernández Turiel
Institute of Earth Sciences J. Almera,
CSIC, Barcelona, Spain
e-mail: jlfernandez@ija.csic.es

M. García Vallès · D. Gimeno
Fac. Geología, Universitat de Barcelona,
Barcelona, Spain
e-mail: maitegarciavalles@ub.edu

D. Gimeno
e-mail: domingo.gimeno@ub.edu

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Introduction

Interest in the arsenic content in groundwater has increased significantly in the last decade because millions of people around the world are exposed to its consumption. The major populations and largest affected areas are Bengal Gulf, Bangladesh and North-eastern India (Rahman et al. 2001; Bhattacharyya et al. 2003), Inner Mongolia in China (Guo et al. 2001), Taiwan and Vietnam (Smedley and Kinniburgh 2002), Western United States (BEST 2001), Mexico (Rodríguez et al. 2004), and Argentina and Chile (Fernandez-Turiel et al. 2005). Northern Chile and Central and Northern Argentina, between the Andes and the Parana River, are the main areas affected in South America. To date, no data have been published regarding the situation in Uruguay.

Epidemiological studies have demonstrated that health risks by natural arsenic groundwater contamination are serious (WHO 2004; Mead 2005). High arsenic water exposure may cause endemic regional chronic hydroarsenicism in humans. Furthermore, these studies also show harmful effects in cattle-raising. The discovery of new evidence of toxicological effects consumption to progressively decrease the recommended maximum thresholds of arsenic for drinking water. On the other hand, the economical consequences derived from the application of low thresholds of arsenic in large territories have produced an intense international debate to discuss the thresholds that can be actually implemented (Smith and Smith 2004; Hernández et al. 2005). The World Health Organization, Japan and the European Union recommend a maximum threshold of 10 μg/l of As for drinking water, as is proposed by the ''Maximum Contaminant Level Goal'' (MCLG) since January of 2006 by USEPA (WHO 2004; EU 1998; USEPA 2006).

In Argentina and Chile, 50 µg/l of As is the maximum concentration allowed for drinking water (Código Alimentario Argentino 1994, MS-ANMAT 2007; Norma Chilena Oficial 409/1 1984, Diario Oficial de la República de Chile 1984). In Uruguay, the government manages the hydrological resources (Art. 47, National Constitution). The Water Code (Law # 14.859) gives juridical support to the use of Uruguayan waters. In order to prevent environmental contamination, water control is managed by Decree 253/79 (Norms to prevent the environmental contamination through the water quality control) and the subsequent modifications introduced by Decrees 232/88, 698/89 and 195/91. According to its actual or potential use, four water categories are established in the latter regulations (Table 1; DINAMA 2007):

- Class 1 Drinking water susceptible to be treated conventionally. Maximum As concentration: 0.005 mg/l.
- Class 2a Water for irrigation of plants yielding vegetables for human consumption—when the products are wetted during this process. Maximum As concentration: 0.05 mg/l.
- Class 2b Water for recreation. Maximum As concentration: 0.005 mg/l.
- Class 3 Water for aquatic fauna and flora preservation, or irrigation of vegetables that are not directly consumed by people or when these products are not wetted during the process. Maximum As concentration: 0.005 mg/l.
- Class 4 Water belonging to streams draining urban or suburban areas, and water for irrigation of products that not will be consumed by people. Maximum As concentration: 0.1 mg/l.

Table 1 Water quality values (range of pH and maximum thresholds of studied elements) of the Decree 253/79 (and the subsequent modifications of Decrees 232/88, 698/89 and 195/91; DINAMA 2007)

Parameter	Unit	Decree 253/79				
		Class 1	Class 2a	Class 2b	Class 3	Class 4
pH	pH	6.5–8.5	6.5–9.0	6.5–8.5	6.5–8.5	6.0–9.0
As	µg/l	5	50	5	5	100
Cr	µg/l	50	5	50	50	500
Cu	µg/l	200	200	200	200	1,000
Ni	µg/l	20	2	20	20	200
P	µg/l	25	25	25	25	
Pb	µg/l	30	30	30	30	50
Zn	µg/l	30	30	30	30	300

See explanation of classes in the text

Domestic (in urban areas), industrial and agriculture demands in Uruguay are mainly satisfied by surface waters, but almost all dairy farm activities are supported by water wells. The use of groundwater resources has experimented a fast increase since the 1950s. A major impulse for the use of groundwater has been the implementation of the governmental project PRENADER (Natural Resources Management and Irrigation Development Program), funded jointly by the World Bank. This project permitted, between 1996 and 2001, the drilling of more than 3,000 wells throughout the country. In addition, a complete water well database including geological description and hydrogeological data became available. The PRENADER database was used to select the majority of the wells studied.

This article assesses the arsenic occurrence in the main South-western Uruguayan aquifers (Mercedes, Raigón and Chuy) and is the first published data regarding groundwater arsenic distribution. The only reference found (Montaño et al. 2006) simply indicates that the Quaternary ash-deposits are considered the probable source of high arsenic contents in Southern aquifers but provides no reference concerning the magnitude of such values. In this regard, the present study provides new data on this topic for both Uruguay and the regional situation towards the east of the Paraná River in this part of South America.

Geographical and geological setting

The studied aquifers are located in South-western Uruguay (Fig. 1; Heinzen et al. 1986; 2003). The de la Plata and Uruguay Rivers are the main drainage systems in the area. The relief is moderately undulated with low altimetry cotes (90 m) towards these rivers. The climate is humid and template with an annual average precipitation of 1,100 mm and a temperature of 22°C (Cfa type in Köppen classification, DINAME 2007). Agriculture and cattle raising are the main economical activities in the region.

The Cretaceous detrital Mercedes Aquifer samples were obtained from wells located near the cities of Nueva Palmira and Young (Colonia and Rio Negro departments, respectively). On the other hand, the Plio-Pleistocene detrital Raigón Aquifer was sampled in both proximal and distal fluvial-deltaic environments, near the cities of Canelones-Tala and Libertad (Canelones and San José departments). Finally, the Pleistocene detrital Chuy Aquifer was studied in Ciudad de la Costa (Canelones Department).

Mercedes Aquifer

The Upper Cretaceous Mercedes Formation (Goso and Perea 2003) is mainly composed of thick yellowish-white,

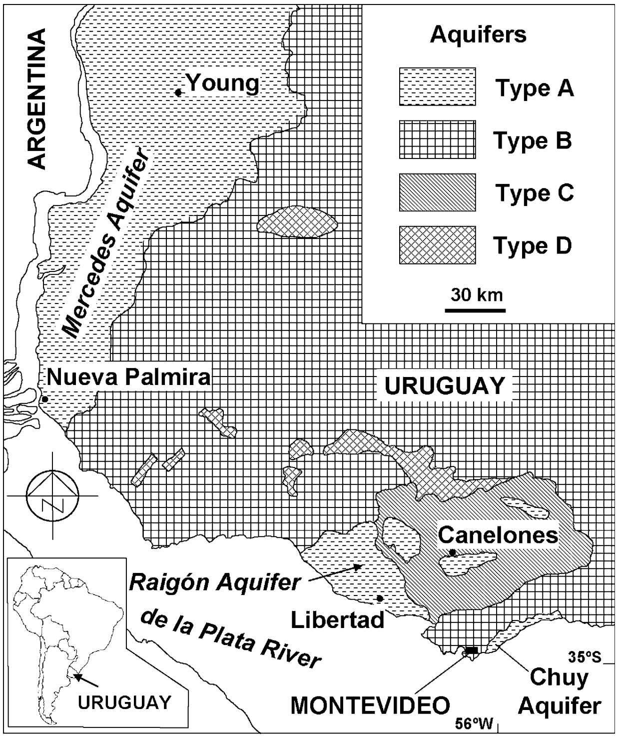

Fig. 1 Location of the study area in the hydrogeological setting of the SW of Uruguay (Heinzen et al. 2003). *Type A*, aquifers in consolidated and unconsolidated sediments with interstitial porosity; *Type B*, aquifers in rocks with fracture porosity or vuggy porosity due to weathering and/or karstic dissolution; *Type C*, aquifers in rocks with interstitial or small fracture porosity; *Type D*, mostly poor aquifers in igneous and metamorphic rocks or pelitic sediments

coarse conglomerates and coarse to fine sandstones and, secondarily, lenticular greenish mudstones. Erosion shapes, through cross, planar tabular and sigmoidal stratification of fluvial channels and sand barriers are the most common sedimentary structures observed. Alluvial and fluvial environments into an endorheic basin were interpreted. Detrital clasts are of both basaltic and granitic composition and come from North and South substrate provinces, respectively; thickness reaches a maximum of 100 m. These deposits were affected by intensive ferricrete, calcrete and silcrete processes during Early Tertiary periods (Paleocene–Eocene). This aquifer is intensively used in South-western Uruguay. Chemical analysis classifies these waters as calcium bicarbonate type (Montaño et al. 2006). Mercedes Aquifer, near the city of Paysandú, shows the hydrogeological parameters and properties shown in Table 2. Two areas of the Mercedes Aquifer were studied: one near Young and the other close to Nueva Palmira, in the centre and the southern extreme of the aquifer, respectively (Fig. 1). The corresponding samples are called Mercedes-Y and Mercedes-NP.

Table 2 Hydrogeological properties of the studied aquifers (after Montaño et al. 2006 and references herein and author observations)

Parameter	Mercedes Aquifer (Paysandú area)	Raigón Aquifer	Chuy Aquifer
Hydraulic conductivity (m/day)	0.12	25–50	5–40
Transmissivity (m^2/day)	5–100	300 to >600	<500
Storage coefficient	10^{-2}	2×10^{-4}–3×10^{-2}	10^{-2}–10^{-4}
Discharge rate (m^3/h)	15–25	20 to >30	10–20
Mean well depth (m)	40–100	30–40	<10

Raigón Aquifer

This aquifer—one of the most important in southern Uruguay—extends over 2,200 km^2 in the Santa Lucía Basin. The Raigón Formation (Bossi 1966), Plio-Pleistocene age, is mainly composed of conglomerates, sandstones and mudstones. Alluvial channel and bars, flood plain and deltaic front are the most common facies observed. Proximal deposits consist of coarse yellow polymictic orthoconglomerates, with centimetric clasts and sandy matrix, while the distal deposits are white ortho and paraconglomerates, occasionally cemented by calcium carbonate. Interbedded in the latter deposits, there are yellowish-white coarse to fine sandstones, wackes and green lenticular mudstones. These deposits reach 40–50 m in thickness. This aquifer supports an intensive exploitation for agriculture and dairy farm activities. Chemical analysis allows this groundwater to be classified as sodic bicarbonate type. The aquifer shows unconfined, semiconfined and confined behaviour as well as multilayer type characteristics. Two areas were sampled in the Raigón Aquifer to evaluate the differences between alluvial and deltaic depositional environments. The first area is near the cities of Canelones and Tala and the second close to Libertad. The samples have been named Raigón-C and Raigón-L, respectively. The main hydrogeological characteristics of the Raigón Aquifer are shown in Table 2.

Chuy Aquifer

This aquifer extends over nearly the entire de la Plata River and Atlantic Ocean coasts in Uruguay. The Pleistocene Chuy Formation (Goso 1972) is composed mainly of transitional detrital sediments. Tabular bed forms of metric yellowish-white conglomerates and sandstones are interbedded with some lenticular fossiliferous and pelitic sediments. These deposits show parallel, sigmoidal and herringbone cross-bedding structures together with intense bioturbation. The maximum thickness of these Quaternary transgressive cycles is about 60 m. The main uses of this aquifer are domestic and for farming. The water of this aquifer is of sodium bicarbonate and chloride type. Regional aspects of the hydrogeology and hydrochemical properties of Chuy Aquifer in South-eastern Uruguay were reported by Almagro et al. (1998) and Montaño et al. (2006). The main hydrogeological parameters of Chuy Aquifer are shown in Table 2.

Materials and methods

Twenty-eight wells were sampled on the aquifers of Mercedes, Raigón and Chuy in five localities of South-western Uruguay (Table 3). The wells of the Mercedes and Raigón aquifers were selected using the PRENADER Project database. Eleven samples correspond to Mercedes Aquifer (6 in Mercedes-Y area and 5 in Mercedes-NP area). Fourteen wells were sampled in the Raigón Aquifer (6 in Raigón-C area and 8 in Raigón-L area) and three in the Chuy Aquifer.

The pH, specific conductivity and temperature were determined in the field. The hydrochemical characterization (major and trace elements) was carried out by both inductively coupled plasma-optical emission spectrometry (ICP-OES) and inductively coupled plasma-mass spectrometry (ICP-MS). The samples were acidified (1% HNO_3, v/v) to analyse Na, K, Mg, Ca, SO_4^{2-}, Cl^-, Si, Al, As, B, Ba, Br, Co, Cr, Cu, Fe, Li, Mn, Mo, Ni, P, Pb, Rb, Sb, Sr, Th, U, V y Zn (Fernandez-Turiel et al. 2000a, b).

Table 3 Aquifers, field parameters and As concentration of the studied samples

Aquifer	Sample no.	Temperature (°C)	pH	Spec. cond. (µS/cm)	Arsenic (µg/l)
Chuy	14	21.5	7.52	306	20.6
Chuy	21	21	7.2	946	0.1
Chuy	22	21.5	9.13	220	41.1
Raigón-C	8	22.8	7.81	930	10.7
Raigón-C	9	21.4	7.97	663	10.4
Raigón-C	10	22.5	7.43	1,132	3.4
Raigón-C	11	21	8.13	944	11.8
Raigón-C	13	21.5	7.94	1,080	8.7
Raigón-L	1	19.3	7.04	774	16.3
Raigón-L	2	19.2	7.42	765	17
Raigón-L	3	18.2	7.84	1,099	18.9
Raigón-L	4	17.7	7.66	907	16.8
Raigón-L	5	16.8	8	936	17.6
Raigón-L	6	18.3	7.82	1,247	17.4
Raigón-L	7	17.6	7.4	717	14.3
Raigón-L	12	19.7	7.76	419	3.1
Raigón-L	29	22.5	7.27	1,581	13.5
Mercedes-Y	23	17.1	7.44	654	9.9
Mercedes-Y	24	18.1	7.18	1,569	21.9
Mercedes-Y	25	12.5	7.4	661	21.7
Mercedes-Y	26	17.4	7.48	475	11.8
Mercedes-Y	27	16.2	7.44	669	23
Mercedes-Y	28	ND	ND	620	18.1
Mercedes-NP	15	21.1	7.86	755	10.5
Mercedes-NP	16	19.5	8.13	950	50.4
Mercedes-NP	18	19.6	8.07	738	58
Mercedes-NP	19	21.2	8.61	780	29.1
Mercedes-NP	20	22	7.68	658	34.9

ND not determined

Results and discussion

The compositional variability of the studied groundwater in the South-western Uruguay is shown in the Chadha (1999) $[(Ca^{2+} + Mg^{2+}) - (Na^+ + K^+)]$ vs. $[(HCO_3^-) - (Cl^- + SO_4^{2-})]$ diagram (Fig. 2). The chemical analysis of Mercedes Aquifer waters indicates a composition of sodium bicarbonate type in Nueva Palmira and calcium bicarbonate type in Young. The only exception in the latter case was a sample with a composition of calcium sulphate type. The waters of Raigón and Chuy aquifers are classified as sodium bicarbonate and sodium chloride types. One sample near de la Plata River seems to be affected by marine water intrusion, a feature coherent with the observed high concentrations of Na, Cl and Br. Whereas the pH values of Chuy and Raigón-L (proximal depositional facies) are similar, Raigón-C (distal facies) registers a slightly higher value (medians 7.52, 7.54 and 7.88, respectively; Tables 3, 5).

A comparison between the obtained results and the thresholds of the Decree 253/79 (and the subsequent modifications of Decrees 232/88, 698/89 and 195/91; DINAMA 2007) shows as some pH values fall outside the 6.5–8.5 range recommended for drinking water. Such is the case of one sample in the Mercedes-NP aquifer and another in the Chuy aquifer (8.61 and 9.13, respectively) (Table 3). The pH variability is attributed to lithological variations in the aquifers. In addition, only the zinc concentrations in all the Chuy samples are lower than the threshold for drinking water (30 µg/l) while some sample always exceeds this value in the other aquifers. The highest observed value of Zn content (1,495 µg/l, sample 15) is interpreted as being related to the deterioration of well materials. In practically all cases, phosphorous concentrations exceed 25 µg/l, the maximum threshold recommended by the regulations for water uses of Classes 1, 2a, 2b and 3. Another parameter with a high value is manganese in the Chuy Aquifer

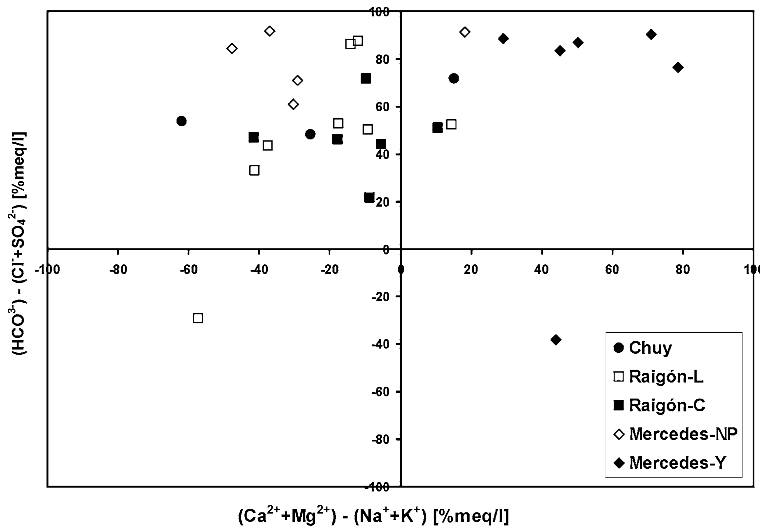

Fig. 2 Compositional variability of studied groundwaters in the diagram of Chadha (1999)

Table 4 Median, minimum and maximum values of parameters studied in the Mercedes Aquifer near the cities of Nueva Palmira (NP) and Young (Y)

Parameter	Unit	Mercedes-Y (n = 6)			Mercedes-NP (n = 5)		
		Median	Minimum	Maximum	Median	Minimum	Maximum
T	°C	17.1	12.5	18.1	21.1	19.5	22.0
pH	pH	7.44	7.18	7.48	8.07	7.68	8.61
Cond.	µS/cm	658	475	1,569	755	658	950
Ca	mg/l	82.9	67.3	218.2	44.2	35.9	58.2
Mg	mg/l	15.1	7.8	19.3	9.9	7.0	20.6
Na	mg/l	41.0	13.3	108.8	131.4	69.4	157.2
K	mg/l	3.0	0.9	5.8	5.8	5.1	6.4
Si	mg/l	37.9	21.0	43.7	37.0	31.4	43.1
Cl	mg/l	9.7	4.6	111.9	13.9	7.9	58.3
SO_4	mg/l	11.6	5.3	423.5	15.2	4.6	32.4
HCO_3	mg/l	368.9	296.7	419.1	501.9	443.6	524.7
Al	µg/l	0.9	0.2	3.6	1.6	0.7	4.4
As	µg/l	19.9	9.9	23.0	34.9	10.5	58.0
B	µg/l	86.9	45	239	224	118	253
Ba	µg/l	267.7	13.0	760.6	187.4	90.3	339.0
Br	µg/l	85.7	44.5	404.1	105.2	82.4	162.3
Co	µg/l	0.13	0.11	0.21	0.09	0.08	0.12
Cr	µg/l	1.7	1.6	2.0	3.6	2.2	24.9
Cu	µg/l	2.8	1.1	5.7	2.3	0.7	23.3
Fe	µg/l	3.0	1.4	8.0	4.4	3.7	7.9
Li	µg/l	15.7	10.1	34.8	17.1	11.4	20.3
Mn	µg/l	0.4	0.1	2.5	2.1	0.3	15.6
Mo	µg/l	0.9	0.1	1.5	1.6	0.3	4.2
Ni	µg/l	1.4	0.6	3.1	1.1	0.6	1.8
P	µg/l	39.3	23.3	46.7	48.3	2.8	66.8
Pb	µg/l	0.11	0.02	0.27	0.15	0.01	1.16
Rb	µg/l	2.00	0.29	2.54	1.71	1.39	2.54
Sb	µg/l	0.88	0.60	0.93	0.14	0.09	2.50
Sr	µg/l	581	428	1,390	393	330	623
Th	µg/l	0.01	<0.01	0.02	0.01	<0.01	0.03
U	µg/l	6.86	3.92	10.41	9.01	5.89	10.76
V	µg/l	68.9	30.1	105.0	84.0	34.6	122.6
Zn	µg/l	17	6	67	211	101	1495

(1,191 µg/l of Mn). This element is not included in the Uruguayan regulations. Its origin is related to the occurrence in the aquifer of reducing lagoon sediments (Almagro et al. 1998; Montaño et al. 2006).

As for arsenic concentration levels—the main subject of this study—only 3 samples out of the 28 studied showed lower concentrations than 5 µg/l, making them apt for the uses indicated in the regulated Uruguayan water Classes 1, 2b and 3 (Table 3). Two samples exceeded 50 µg/l of As, disqualifying them for the use of Class 2a (irrigation). Taking into account other regulations, only five samples showed lower concentrations than 10 µg/l of As (the recommended WHO threshold for drinking water, WHO 2004). Nevertheless, only two samples would be unsuitable for drinking water according to the recommendations of the neighbouring countries of Argentina and Chile (50 µg/l of As).

Regarding the distribution of arsenic concentrations in the aquifers, the Mercedes samples showed the highest values (Tables 3, 4, 5). The Nueva Palmira area requires special attention as samples with the highest values (50.4 and 58.0 µg/l of As in samples 16 and 18) were found in that region. The Raigón Aquifer shows slightly high concentrations in the distal depositional facies of the Libertad

Table 5 Median, minimum and maximum values of parameters studied in the Raigón Aquifer, near the localities of Canelones (C) and Libertad (L), and in the Chuy Aquifer

Parameter	Unit	Raigón-C (n = 6)			Raigón-L (n = 8)			Chuy (n = 3)		
		Median	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum
Temp.	°C	21.5	19.7	22.8	18.3	16.8	22.5	21.5	21.0	21.5
pH	pH	7.88	7.43	8.13	7.54	7.04	8.00	7.52	7.20	9.13
Cond.	µS/cm	937	419	1,132	922	717	1,581	306	220	946
Ca	mg/l	60.4	26.8	79.8	57.0	17.7	63.0	27.1	7.6	55.6
Mg	mg/l	15.3	9.7	18.8	16.1	13.5	28.4	7.3	0.7	11.9
Na	mg/l	132.1	58.0	197.4	129.7	74.8	269.0	41.2	31.6	138.9
K	mg/l	2.4	1.8	5.1	5.3	3.6	6.3	3.0	2.5	10.3
Si	mg/l	35.8	19.8	38.8	34.8	33.6	40.4	27.0	16.8	28.7
Cl	mg/l	59.6	12.1	100.9	65.2	11.0	259.6	15.5	14.5	92.2
SO_4	mg/l	46.5	15.5	91.2	24.5	12.2	115.3	2.1	0.2	6.1
HCO_3	mg/l	455.4	247.2	545.9	497.9	326.2	563.0	177.6	108.2	455.4
Al	µg/l	0.6	0.2	2.8	1.0	0.6	1.6	3.9	0.4	4.9
As	µg/l	9.6	3.1	11.8	16.9	13.5	18.9	20.6	0.1	41.1
B	µg/l	146	58	317	197	112	312	97	64	237
Ba	µg/l	98.0	35.0	189.6	201.0	6.2	266.8	23.9	6.3	44.0
Br	µg/l	368.1	131.2	581.6	349.0	135.4	877.5	89.1	79.0	579.1
Co	µg/l	0.06	0.05	0.08	0.08	0.05	0.11	0.14	0.03	0.15
Cr	µg/l	2.1	1.6	3.9	2.7	1.1	3.1	0.6	0.1	21.7
Cu	µg/l	1.7	0.7	2.9	2.3	0.6	7.4	1.4	0.9	3.9
Fe	µg/l	2.3	0.6	4.7	4.3	0.8	8.1	8.5	0.9	15.0
Li	µg/l	13.3	8.6	18.4	16.3	13.3	27.5	2.2	2.1	4.6
Mn	µg/l	0.4	0.2	3.8	0.3	0.1	1.3	279.4	2.8	1191.0
Mo	µg/l	0.8	0.2	1.1	1.1	0.6	1.9	2.1	0.5	4.2
Ni	µg/l	0.5	0.4	0.9	0.7	0.5	1.2	0.3	0.3	0.4
P	µg/l	28.4	11.7	70.4	52.9	32.3	101.6	88.2	7.4	845.9
Pb	µg/l	0.05	0.02	0.15	0.10	0.02	0.35	0.03	0.01	0.08
Rb	µg/l	1.19	0.13	1.35	1.43	0.49	2.07	3.51	1.48	4.38
Sb	µg/l	0.17	0.11	0.20	0.23	0.14	1.37	0.39	0.23	1.30
Sr	µg/l	513	226	639	466	78	548	150	28	370
Th	µg/l	0.06	0.03	0.22	0.04	<0.01	0.15	0.05	0.03	0.05
U	µg/l	7.17	0.84	17.31	6.44	2.19	18.73	0.08	0.05	0.33
V	µg/l	33.4	13.8	56.9	47.3	35.9	55.1	6.1	1.9	96.6
Zn	µg/l	5	3	300	14	3	79	6	2	9

area in comparison with those of the proximal depositional facies of Canelones-Tala, with medians of 16.9 and 9.6 μg/l of As, respectively. The concentrations of 20.6 and 41.1 μg/l of As found in the Chuy Aquifer are also noteworthy.

Conclusions

Groundwater quality observations in the main aquifers of South-western Uruguay indicate occurrences of arsenic that in some wells exceed Uruguayan regulations (Decree 253/79 and the subsequent modifications of Decrees 232/88, 698/89 and 195/91; DINAMA 2007) and WHO recommendations (thresholds of 5 and 10 μg/l of As for drinking water, respectively). The median, maximum and minimum determined in the studied groundwaters are 16.9, 58.0 and 0.1 μg/l of As (n = 28 samples).

Both lateral and vertical variations in arsenic concentration were observed along the assessed aquifers. The Cretaceous Mercedes Aquifer showed the highest values, the vicinity of Nueva Palmira city being the most affected area. More detailed studies are in progress to determine the origin of this arsenic in the groundwater.

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References

Almagro L, Custodio E, Rocha L, Abelenda D (1998) Hidrogeología del acuífero superior de la Formación Chuy (Hydrogeology of the Chuy Formation upper aquifer) Paper presented at the 4° Congreso Latinoamericano de Hidrología Subterránea, ALHSUD. Montevideo, Uruguay 1:374–390

BEST (Board on Environmental Studies and Toxicology) (2001) Arsenic in drinking water: 2001 update. National Academy Press, Washington DC, 225 pp. http://www.nap.edu/books/0309076293/html. Cited 9 Feb 2007

Bhattacharyya R, Chatterjee D, Nath B, Jana J, Jacks G, Vahter M (2003) High arsenic groundwater: mobilization, metabolism and mitigation—an overview in the Bengal Delta plain. Mol Cell Biochem 253:347–355

Bossi J (1966) Geología del Uruguay (Geology of Uruguay). Departamento de Publicaciones, Universidad de la República, Montevideo, 469 pp

Chadha DK, (1999) A proposed new diagram for geochemical classification of natural waters and interpretation of chemical data. Hydrogeol J 7:431–439

Diario Oficial de la República de Chile (1984) Norma Chilena Oficial N°409/1 Of. no. 84. Agua potable, Parte I: Requisitos (Drinking water, Part I: Requirements). Decree no. 11 of the Health Ministry (16 Jan 1984). Published 3 Mar 1984

DINAMA (Dirección Nacional de Medio Ambiente) (2007) Decree 253/79 and the subsequent modifications introduced by Decrees 232/88, 698/89 and 195/91. http://www.dinama.gub.uy/descargas/decretos/Dec.253_79.pdf. Cited 9 Feb 2007

DINAME (Dirección Nacional de Meteorología) (2007) Información climatológica (Climate information). http://www.meteorologia.com.uy/estadistica_climat.htm. Cited 9 Feb 2007

EU (European Union) (1998) Directive 98/83/CE relative to human drinking water quality, Official Journal of European Communities L330

Fernandez-Turiel JL, Llorens JF, López-Vera F, Gómez-Artola C, Morell I, Gimeno D (2000a) Strategy for water analysis using ICP-MS Fresenius' J Anal Chem 368:601–606

Fernandez-Turiel JL, Llorens JF, Roig A, Carnicero M, Valero F (2000b) Monitoring of drinking water treatment plants using ICP-MS. Toxicol Environ Chem 74:87–103

Fernandez-Turiel JL, Galindo G, Parada MA, Gimeno D, García-Vallès M, Saavedra J (2005) Estado actual del conocimiento sobre el arsénico en el agua de Argentina y Chile: origen, movilidad y tratamiento. (Current knowledge of arsenic in waters from Argentia and Chile: origin, mobility and treatment). In: Galindo G, Fernandez-Turiel JL, Parada MA, Gimeno D (eds) Arsénico en aguas: origen, movilidad y tratamiento (Arsenic in water: origin, mobility and treatment). II Seminario Hispano-Latinoamericano sobre temas actuales de hidrología subterránea—IV Congreso Hidrogeológico Argentino pp 1–22

Goso H (1972) El Cuaternario uruguayo (Uruguayan Quaternary). Proyecto Estudio Levantamiento de Suelos. Ed. Mimeogr., 12 pp

Goso C, Perea D (2003) El cretácico post-basáltico de la cuenca litoral del río Uruguay: geología y paleontología. (Post-basaltic Cretaceous sediments in littoral basin of the Uruguay River basin: geology and palaeontology). In: Veroslavsky G, Ubilla M, Martínez S (eds) Cuencas Sedimentarias de Uruguay. Geología, paleontología y recursos minerales. Mesozoico (Sedimentary basins of Uruguay: geology, palaentology and mineral resources). DIRAC-Fac. Ciencias, Montevideo, Uruguay, pp 141–169

Guo X, Fujino Y, Kaneko S, Wu K, Xia Y, Yoshimura T (2001) Arsenic contamination of groundwater and prevalence of arsenical dermatosis in the Henao plain area, Inner Mongolia, China. Mol Cell Biochem 222:137–140

Heinzen W, Velozo C, Carrión R, Cardozo L, Madracho H, Massa E (1986) Carta Hidrogeológica del Uruguay (Hydrogeologic Map of Uruguay) 1:200.000. DINAMIGE, Montevideo, Uruguay

Heinzen W, Carrión R, Massa E, Pena S, Stapff M (2003) Mapa Hidrogeológico del Uruguay. (Hydrogeologic Map of Uruguay) DINAMIGE. http://www.dinamige.gub.uy/ch25.htm. Cited 9 Feb 2007

Hernández MA, González N, Trovatto MM, Ceci JH, Hernández L (2005) Sobre los criterios para el establecimiento de umbrales de tolerancia de arsénico en aguas de bebida (Criteria to determine the arsenic tolerance threshold in drinking water). In: Galindo G, Fernandez-Turiel JL, Parada MA, Gimeno D (eds) Arsénico en aguas: origen, movilidad y tratamiento (Arsenic in water: origin, mobility and treatment). II Seminario Hispano-Latinoamericano sobre temas actuales de hidrología subterránea—IV Congreso Hidrogeológico Argentino, pp 167–172

Mead MN (2005) Arsenic: in search o fan antidote to a global poison. Environ Health Perspect 6:A378–A386

Montaño J, Gagliardi S, Montaño M (2006) Recursos hídricos subterráneos del Uruguay (Groundwater resources of Uruguay). Bol Geol Min 117(1):201–222

MS-ANMAT (Ministerio de Salud—Administración Nacional de Medicamentos, Alimentos y Tecnología Médica) (2007) Código Alimentario Argentino-Capitulo XII—Bebidas Hídricas, Agua y Agua Gasificada—Agua Potable—Artículo 982—(Res Msyas N° 494 Del 7.07.94) (Argentine Food Code of 1984). http://www.anmat.gov.ar/principal.html. Cited 9 Feb 2007

Rahman MM, Chowdhury UK, Mukherjee SC, Mondal BK, Paul K, Lodh D, Biswas BK, Chanda CR, Basu GK, Saha KC, Roy S, Das R, Palit SK, Quamruzzaman Q, Chakraborti D (2001) Chronic arsenic toxicity in Bangladesh and West Bengal, India—a review and commentary. J Toxicol Clin Toxicol 39:683–700

Rodríguez R, Ramos JA, Armienta A (2004) Groundwater arsenic variations: the role of local geology and rainfall. Appl Geochem 19:245–250

Smedley PL, Kinniburgh DG (2002) A review of the source, behaviour and distribution of arsenic in natural waters. Appl Geochem 17:517–568

Smith AH, Smith MMH (2004) Arsenic drinking water regulations in developing countries with extensive exposure. Toxicol 198:39–44

USEPA (United States Environmental Protection Agency) (2006) List of drinking water contaminants and MCLs, 28 November 2006. http://www.epa.gov/safewater/mcl.html. Cited 9 Feb 2007

WHO (World Health Organization) (2004) Guidelines for drinking-water quality, vol 1, 3rd edn, Recommendations. Geneva, 515 pp