Author's personal copy

WATER RESEARCH 44 (2010) 5828–5845

Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/watres

Emerging mitigation needs and sustainable options for solving the arsenic problems of rural and isolated urban areas in Latin America – A critical analysis

Jochen Bundschuh [a,b,k,*], *Marta Litter* [c,d], *Virginia S.T. Ciminelli* [e], *María Eugenia Morgada* [c], *Lorena Cornejo* [f,g], *Sofia Garrido Hoyos* [h], *Jan Hoinkis* [a], *Ma. Teresa Alarcón-Herrera* [i], *María Aurora Armienta* [j], *Prosun Bhattacharya* [k]

[a] *Institute of Applied Research, Karlsruhe University of Applied Sciences, Moltkestrasse 30, 76133 Karlsruhe, Germany*
[b] *Department of Earth Sciences, National Cheng Kung University, University Road, Tainan City 701, Taiwan*
[c] *Gerencia Química, Comisión Nacional de Energía Atómica, Av. Gral. Paz 1499, San Martín, 1650, Prov. de Buenos Aires, Argentina*
[d] *Instituto de Ingeniería e Investigación Ambiental, Universidad Nacional de General San Martín, Av. Gral. Paz 5445, 1650 San Martín, Prov. de Buenos Aires, Argentina*
[e] *Department of Metallurgical and Materials Engineering, Federal University of Minas Gerais, Av Antonio Carlos, 6627-Belo Horizonte-31.270.901, Minas Gerais, Brazil*
[f] *Departamento de Química, Facultad de Ciencias, Universidad de Tarapacá, Casilla 7-D, Arica, Chile*
[g] *Laboratorio de Investigaciones Medioambientales de Zonas Áridas, LIMZA, Centro de Investigaciones del Hombre en el Desierto, CIHDE/CODECITE, Universidad de Tarapacá, Casilla 7-D, Arica, Chile*
[h] *Instituto Mexicano de Tecnología del Agua, Paseo Cuauhnáhuac 8532, Col Progreso, Jiutepec, Morelos 62550, Mexico*
[i] *Centro de Investigación en Materiales Avanzados (CIMAV), Ave. Miguel de Cervantes 120, Complejo Industrial Chihuahua, C.P. 31109 Chihuahua, Chih., Mexico*
[j] *Universidad Nacional Autónoma de México, Instituto de Geofisica, Ciudad Universitaria Del. Coyoacán México D.F. C.P. 04510, Mexico City, Mexico*
[k] *KTH-International Groundwater Arsenic Research Group, Department of Land and Water Resources Engineering, Royal Institute of Technology (KTH), Teknikringen 76, SE-100 44 Stockholm, Sweden*

ARTICLE INFO

Article history:
Received 14 January 2010
Received in revised form
31 March 2010
Accepted 5 April 2010
Available online 10 April 2010

Keywords:
Arsenic
Water resources
Latin America

ABSTRACT

In this work, current information about the contamination of ground- and surface-water resources by arsenic from geogenic sources in Latin America is presented together with possible emerging mitigation solutions. The problem is of the same order of magnitude as other world regions, such as SE Asia, but it is often not described in English. Despite the studies undertaken by numerous local researchers, and the identification of proven treatment methods for the specific water conditions encountered, no technologies have been commercialized due to a current lack of funding and technical assistance.

Emerging, low-cost technologies to mitigate the problem of arsenic in drinking water resources that are suitable for rural and urban areas lacking centralized water supplies have been evaluated. The technologies generally use simple and low-cost equipment that can easily be handled and maintained by the local population. Experiences comprise (i)

* *Corresponding author*. Institute of Applied Research, Karlsruhe University of Applied Sciences, Moltkestrasse 30, 76133 Karlsruhe, Germany.

E-mail addresses: jochenbundschuh@yahoo.com (J. Bundschuh), litter@cnea.gov.ar (M. Litter), ciminelli@demet.ufmg.br (V.S.T. Ciminelli), mariaeugenia.morgada@gmail.com (M.E. Morgada), lorenacp@uta.cl (L. Cornejo), sgarrido@tlaloc.imta.mx (S.G. Hoyos), jan.hoinkis@googlemail.com (J. Hoinkis), teresa.alarcon@gmail.com (Ma.T. Alarcón-Herrera), victoria@geofisica.unam.mx (M.A. Armienta), prosun@kth.se (P. Bhattacharya).

0043-1354/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.watres.2010.04.001

Author's personal copy

Rural areas
Isolated urban areas
Emerging remediation methods
Decentralized water supply

coagulation/filtration with iron and aluminum salts, scaled-down for small community- and household-scale-applications, (ii) adsorption techniques using low-cost arsenic sorbents, such as geological materials (clays, laterites, soils, limestones), natural organic-based sorbents (natural biomass), and synthetic materials. TiO_2-heterogeneous photocatalysis and zerovalent iron, especially using nanoscale particles, appear to be promising emergent technologies. Another promising innovative method for rural communities is the use of constructed wetlands using native perennial plants for arsenic rhizofiltration. Small-scale simple reverse osmosis equipment (which can be powered by wind or solar energy) that is suitable for small communities can also be utilized.

The individual benefits of the different methods have been evaluated in terms of (i) size of the treatment device, (ii) arsenic concentration and distribution of species, chemical composition and grade of mineralization in the raw water, (iii) guidelines for the remaining As concentration, (iv) economical constrains, (v) complexity of installation and maintenance, and infrastructure constraints (e.g. electricity needs).

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

The contamination of ground- and surface water resources in Latin America by arsenic (As) (Fig. 1) is of the same order of importance to that of Southeast Asia, where much research has been done, especially during the last two decades. However, very few publications reflect the problem in this continent, where As contamination has been known for nearly 100 years.

In many regions of Latin America, a lack or shortage of fresh water is a very important problem that is continuously increasing, due to a growing population and expanding economies. In many regions, groundwater resources contain several natural pollutants at toxic levels, such as As, fluoride or heavy metals. In other areas, where the ground- and surface water resources are affected by the weathering of sulfidic ore deposits (sometimes accompanied by mining activities), As is often found with an assemblage of high concentrations of Fe, Mn, Pb, Zn, Cd, and other contaminants. Examples are the Andes and the Middle American Cordillera. Further, in many parts of Latin America with arid to moderate climate (i.e. practically the entire Latin American continent with the exception of the tropical areas of Central America, Brazil, Colombia, and Venezuela), groundwater resources contain natural or anthropogenic contaminants or are highly mineralized, which limits partially or completely the suitability of this water for drinking purposes. This is also valid for rivers, where quality of natural waters has been affected by pollution, rendering unusable these water resources.

The mitigation of the As problem can be faced by either tapping of alternative water resources or treating the As-contaminated water (Litter et al., 2010). Several classical treatment processes are currently available, such as those based on membrane technologies, use of adsorbents, coagulation/coprecipitation, and ion exchange (for overviews see Newcombe and Möller, 2006; Pirnie, 2000; Bianchelli, 2004; Mohana and Pittman, 2007; Jekel and Amy, 2006; Kabay et al., 2010). Their individual benefits, in terms of ease of use and of cost –e.g. in the case of drinking water treatment–depend on numerous factors, such as the size of the treatment device, As concentration and distribution of species, chemical composition and grade of mineralization in the raw water, guidelines for the remaining As concentration, and economical constraints, among others. Since many of these technologies comprise very advanced technologies, they are applied in most of the cases at an industrial scale, and have been used to solve the As problem in urban areas of Latin America or other smaller areas with access to centralized water supplies.

The above-described technologies are not suitable, or not suitably modified to be useful in small communities or dispersed rural settlements. These isolated urban and rural areas – which lack a centralized water supply – require simple and low-cost equipment that can be easily handled and maintained by the population (Litter et al., 2010).

The current lack of funding and technical assistance have slowed down the commercial development of low-cost remediation methods for small communities or single houses, despite the various sustainable solutions for rural and urban dispersed areas developed by local researchers.

In this paper, a short overview on the distribution and genesis of As-contaminated water resources in Latin America and the situation of As in drinking water resources of Latin America will be presented. The remediation needs for isolated urban and rural areas, together with remediation options for As removal in these regions will also be addressed. At the end, some recommendations aimed to solve the Latin American As problem in these disadvantaged areas will be given.

2. Genesis of arsenic contamination in ground- and surface waters of Latin America

Most of the problems of water contamination with As around the globe are the result of its mobilization and retention, under natural conditions, in a wide variety of environmental systems, under both oxidizing and reducing conditions. Arsenic is predominantly released from rocks with primary or secondary As or As-containing minerals due to physical, chemical or microbiological weathering into the hydrosphere, biosphere and atmosphere. There are numerous geogenic As sources, including over 200 As bearing minerals, and the As release and mobility in each environment is controlled by different geochemical, biogeochemical, geological,

Author's personal copy

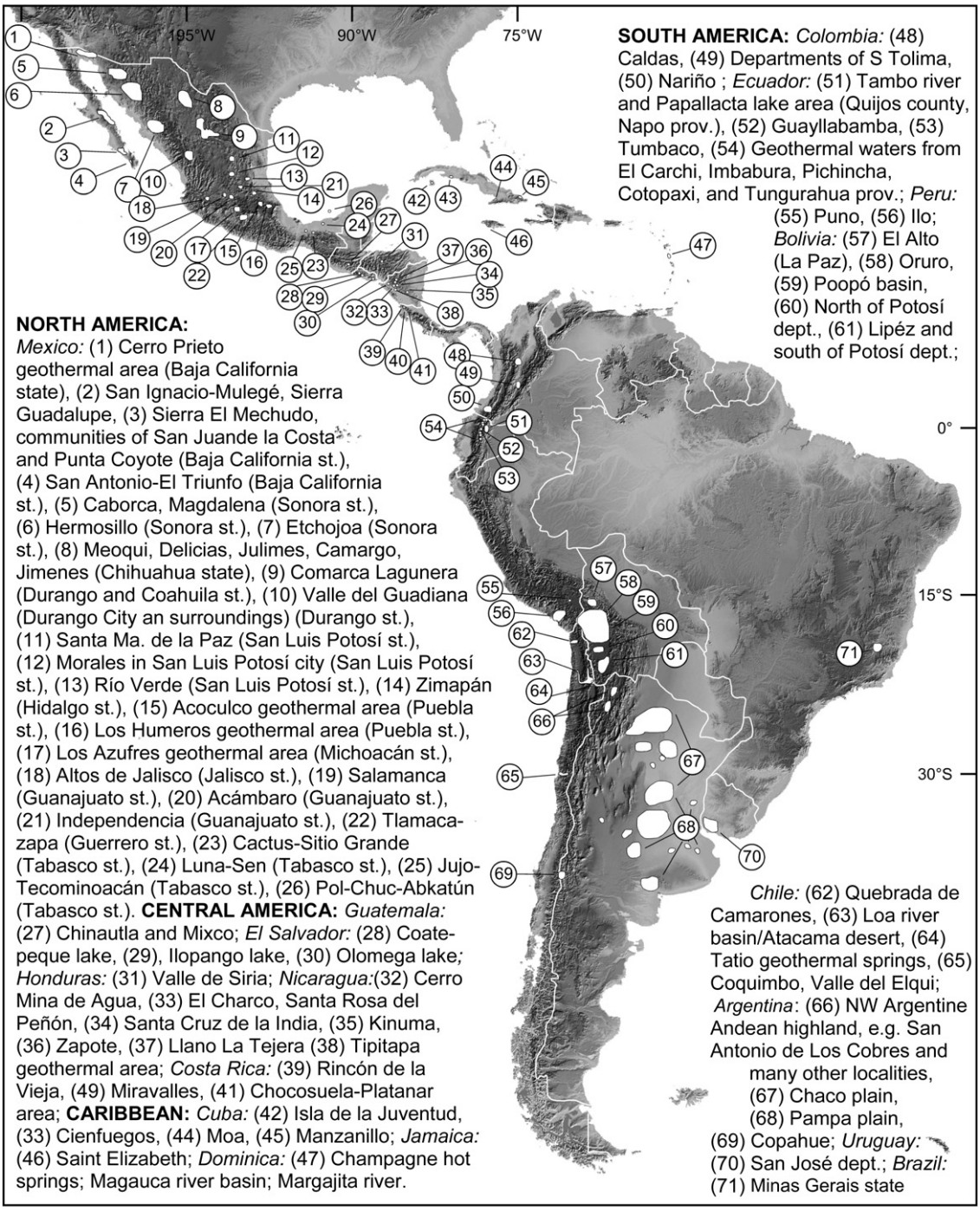


Fig. 1 – Latin America: distribution of aquifers and surface water bodies with high concentrations of dissolved As as known today. Adapted from Armienta et al. (2008), Bundschuh et al. (2008, 2009a, b) and from unpublished information of the authors. Abbreviations: st: state, prov.: province, dept.: department. The digital elevation model of the world PIA3388 (http://photojournal.jpl.nasa.gov) is courtesy of NASA/JPL-Caltech.

hydrogeological, geomorphological and climatic conditions and settings. Thus, in Latin America, young volcanic rocks of Tertiary to recent age and their weathering products form numerous sedimentary (mostly oxidizing) aquifers with high concentrations of As in the groundwater. Examples are the Andes (WHO, 2001; Farías et al., 2003; Quintanilla et al., 2009) and its continuation in Central America (López et al., 2009; Altamirano Espinoza and Bundschuh, 2009) and Mexico (Armienta et al., 2008) (Fig. 1). The weathering products derived from rocks of the circumvolcanic belt may eventually be transported by eolic and fluvial processes over large distances, contributing to the sediments of aquifers far away from its original source and, therefore, to the genesis of high As groundwater (e.g., the Chaco-Pampean plain of Argentina;

Author's personal copy

Fig. 1) (Smedley et al., 2005, 2009; Bundschuh et al., 2004; Bhattacharya et al., 2006).

Arid and semiarid climates can further contribute to the genesis of As-rich groundwater due to the evaporative increase of the As concentration in the water. The group of climate influenced or climate controlled examples of aquifers with high concentrations of As in the groundwater comprises the Atacama desert, northern Chile (Fig. 1) (e.g., Borgoño and Greiber, 1972; Bundschuh et al., 2008, 2009a,b) and the Chaco-Pampean plain, Argentina (Fig. 1) (e.g. Bundschuh et al., 2000, 2004, 2008, 2009a,b; Bhattacharya et al., 2006).

At several sites in Latin America, As-rich geothermal waters, which mix with aquifers used for water supply or which flow into surface water bodies, form an important source of geogenic As. Numerous examples are found along active plate boundaries and other tectonically active zones in young volcanic areas. Examples are described from Chile (Cusicanqui et al., 1976; Ellis and Mahon, 1977), Ecuador (Cumbal et al., 2009), Costa Rica, (Hammarlund and Piñones, 2009), El Salvador (Lopéz et al., 2009) and Mexico (Birkle and Bundschuh, 2009; Birkle et al., 2010) (Fig. 1). Additionally, other geothermal manifestations, such as fumaroles or volcanic emissions, contribute to the As influx into ground- and surface water bodies.

In an oxidizing environment, As mobilization from solids into water is mainly due to (1) desorption of As at high pH values (pH $\geq$ 8) and (2) sulfide oxidation at low pH values (pH $\ll$ 7). Under reducing conditions, As can also be mobilized due to reductive dissolution at circumneutral pH. These processes are controlled by local redox, geomorphological, geological, hydrogeological and other conditions (such as climate and land use patterns). Arsenic desorption under oxidizing conditions and high pH explains the high As concentrations in the groundwater of extended areas of the Chaco-Pampean plain in Argentine (Smedley et al., 2005; Bundschuh et al., 2004; Bhattacharya et al., 2006) and its continuation into the adjacent plains of Uruguay (Guérèquiz et al., 2006) (Fig. 1), Paraguay and Bolivia. Examples of As release from sulfide minerals under oxidizing conditions are the Andes, the Middle and North American cordillera, and the Transmexican volcanic belt. The presence of sulfidic ore bodies also explains groundwater As concentrations in classical mining areas, (e.g. in Mexico) (Armienta et al., 2008).

The released As may again be immobilized under specific geochemical conditions (pH and Eh), by coprecipitation with (oxy)hydroxides of iron and other metals, or adsorption on different substrates. Arsenic immobilization usually involves a combination of these two mechanisms. The immobilization may occur either *in situ* or in places far away from the original source, if redox conditions change from oxidizing to reducing.

3. Current status of remediation efforts for Latin American rural and urban isolated areas

In contrast to the large urban areas, which rely on a centralized water supply, practically no solutions could be found for the problem due to the already mentioned lack of funding and technical assistance for mitigation in isolated Latin American rural and urban population not connected to a centralized water supply. Two zones in Argentina, not strictly considered a poor country in Latin America, reflect the enormous contrasts often found in the Latin-American region: (i) the Chaco-Pampean plain and (ii) the Matanza-Riachuelo basin in the urban area of Buenos Aires. In the Chaco-Pampean plain, covering more than 1 million km^2, about 12% of the population lives in dispersed settlements with less than 50 inhabitants (who are often the poorest in the region). In these areas, where people live in dramatic conditions of poverty, extreme lack of education and bad water quality, several cases of Regional Endemic Hydric Arsenicism (HACRE in Spanish) have been documented. The Matanza-Riachuelo basin, placed in the industrialized zone of the Buenos Aires Province, covering 2240 km^2 in urban, suburban and semirural areas, is inhabited by 3.5 million people from all socioeconomic levels. In the slum neighborhoods of this basin, people live without piped water or sewage services. Arsenic was documented to reach values above the WHO and local regulation for drinking water (10 μg L^{-1}). Moreover, these two quite distinct groups of rural and urban poor communities are typically not aware of the As toxicity but both require low-cost remediation methods that are suitable for small communities from 50 inhabitants down to single households. Thus, low-cost and robust methods, simple to handle and maintain are required, provided such options are locally sustainable.

The problem of As in drinking water used by large or medium populations has already been dealt with in most of the larger Latin American urban areas by installing treatment plants. For example, plants were installed in northern Chile in Antofagasta (since 1970; Sancha et al., 2000), Calama (since 1978; Rivara et al., 1997), San Pedro and other cities, where drinking water was successfully treated by flocculation by $FeCl_3$ followed by filtration. Another example is the installation of a conventional As removal plant in the urban development of Naranjo County, located in the municipality of Mixco, Guatemala, since 2008, with a flow of 24.5 L s^{-1} (Fig. 1) The treatment includes $FeCl_3$ and a polymer as coagulant and flocculant, respectively, and a ceramic media filter. The plant produces drinking water with an As concentration of 7 μg L^{-1}, a value that meets the Guatemala standard (Garrido and Avilés, 2008; Garrido et al., 2009).

In cities and some big towns of Argentina, in the provinces of La Pampa, Santa Fe and Santiago del Estero (all located in the Chaco-Pampean plan), coagulation methods and reverse osmosis (RO) are applied to remove As from drinking water. All these methods are expensive and often not efficient for As removal due to the complex groundwater chemical characteristics (Sancha and Fuentealba, 2009; Sancha et al., 2000, Sancha, 2003).

4. Tapping alternative water resources

In the past, alternative water resources, found locally or tapped far away and transported by canals or pipelines to the site, were used at many sites in Latin America to supply the population with water in sufficient quantity and apparent good quality. Some problems arose from these actions. In 1958, in Antofagasta, a new drinking water supply, tapping water from

Author's personal copy

the Loa river and its tributaries, containing about 800 μg L^{-1} of As, was introduced (Fig. 1) (Bundschuh et al., 2009b). As a consequence, in 1962, the first cases of chronic As-related health effects were reported, and, in the entire NW Chile, a total of 500,000 people were exposed to As (based on the 50 μg L^{-1} limit; Castro de Esparza, 2009). In Antofagasta alone, 130,000 persons were exposed for 12 years to As-containing drinking water (>50 μg L^{-1}) until 1970 when an As removal plant was installed.

A large number of people in many rural communities in northern and central Mexico are exposed to As through drinking water. In the Lagunera region (Fig. 1), which includes several communities from two states (Durango and Coahuila), it was estimated that the number of people at risk for As exposure was around 400,000 (WHO, 2001) (Fig. 1). In Chihuahua state (Fig. 1), 67% of the municipalities were exposed to concentrations above the 50 μg L^{-1} limit in force at that time. At the same time, more than 200 RO plants were installed in different rural communities. There, people can get treated water in 20 L capacity bottles, which is used only for drinking and cooking (Calderón-Fernández, 2006). The problem was only partially solved, because RO is a process that generates 50% rejected water, resulting in a stream of concentrate or brine containing concentrated As and other impurities. If this rejected water is not treated or disposed of properly, another problem is generated.

Nicaragua is another negative example, where to improve the water quality, the source of the water supply of a rural community was changed without testing the As concentration. Here a well was drilled in 1994 to provide water to the community of El Zapote (Fig. 1) without recognizing during the following two years that the well water contains high concentrations of arsenic (in average 1.32 mg/L). The water consumption from this well resulted in the poisoning of the population for 2 years with As-rich drinking water (Barragne, 2004; Bundschuh et al., 2007a; Altamirano Espinoza and Bundschuh, 2009).

In other cases, tapping of alternative water resources was successful. In Argentina, water with low As concentrations was transported by a canal from Salta province to Monte Quemado in Santiago del Estero province, where groundwater is highly contaminated by As (Mandal and Suzuki, 2002). In Antofagasta (Chile), As was firstly removed by a suitable plant, placed about 400 km from the tapping sites, close to the Andean mountain chain (east of the Atacama desert). Some decades ago, these installations were the only economically and technically available water resource to supply Antofagasta and other communities in northern Chile. However, today, seawater desalination has become an alternative source to supply the coastal cities, such as Antofagasta and Taltal, with drinking water, as will be shown in Section 6.1.

At Zimapán, Mexico, the authorities constructed an aqueduct to pump As-free water from a well located about 35 km in distance and 400 m lower in altitude with respect to the town (Armienta and Segovia, 2008; Armienta and Rodríguez, 2004). However, the abstracted water was not enough to supply the population, and it had to be mixed with contaminated well water from Zimapán (0.394 mg L^{-1} As) giving variable As concentrations over time (e.g. 0.087 mg L^{-1} in September 2009; unpublished data Armienta et al., 2009). Currently, a new well close to the first one, is being drilled so that more As-safe water can be transported through the aqueduct to Zimapán and the As-contaminated well in Zimapán can be shut down.

5. Emerging conventional and innovative technologies suitable for small-scale applications in Latin American isolated rural and urban areas

Classical As removal technologies have been applied successfully by central water supplies in some parts of Latin America and they can be consulted in other references (Argentina: Martin, 1997; Muñoz et al., 2005; Chile: Sancha, 2002, 2006; Peru: Esparza, 2004; Litter et al., 2010). They will not be discussed in this article.

During the last two decades, scientific and technological work targeted the development of a number of new or emerging technologies for As remediation. Some of these technologies are in fact just conventional methods using coagulation/filtration, adsorption, membrane and thermal desalination, and ion exchange processes. These methods have been adapted for use in downsized equipment, technically simplified or modified from their original industrial version. For example, in the case of technologies based on coagulation, the process was modified to electrocoagulation, to optimize As removal and limit the quantity of residues (sludge) generated. For adsorption processes, low-cost adsorbents were employed, and membrane technologies were adapted to lower pressures and lower energy requirements.

A large number of emerging innovative technologies for As removal, focused on low-cost and medium to small-scale communities, have been explored and proposed. Some of them are based on biological processes, like phytoremediation, through constructed wetlands and biomass adsorption. Others are based on physicochemical processes, like clay or lime adsorption and solar oxidation (Alarcón-Herrera et al., 2007; Morgada de Boggio et al., 2006; Morgada et al., 2008). In the following sections, we will discuss some emerging options tested in Latin America, principally at a laboratory scale and in a few pilot field applications. They are designed to mitigate the As problem in rural areas, for towns with about 10,000 inhabitants, down to isolated houses and for isolated urban areas. However, these remediation methods should only be seen as short-term emerging, palliative solutions.

5.1. *Combined coagulation/flocculation, adsorption and ion exchange methods*

Different technologies for As removal in single households were developed or adapted by scaling down and simplifying the oxidation, adsorption and coagulation sequence (e.g., Sastre et al., 1997; Castro de Esparza and Wong de Medina, 1998; Litter et al., 2008). The main goal is now to adapt them in such a way that they can be used and maintained by the inhabitants of a household for a long period.

Author's personal copy

A household scale, low-cost As removal methodology was developed by CEPIS-PAHO[1] in Peru, using a product called ALUFLOC, which is a mixture of an oxidant (hypochlorite), activated clays (As adsorbents and ion exchangers) and a coagulant ($Al_2(SO_4)_3$ or $FeCl_3$) (Bedolla et al., 1999). $Fe(OH)_3$ and $Al(OH)_3$ precipitates are the final hydrolysis products of the coagulants, with an optimal precipitation efficiency at pH 6.5–7.0 and 7.5–8.0, respectively. This methodology removes up to 98% of the dissolved As (As concentration in raw water: 1000 $\mu g\ L^{-1}$), though at higher concentrations, the removal efficiency decreases. The methodology involves different processes whose individual importance strongly varies with water chemistry (e.g. the presence and concentration of competing ions for sorption sites, pH and Eh). This requires a careful examination of solution composition together with validation experiments of the technology considering the specific conditions of the water to be treated.

Iron salts have been used for As removal from the water of a polluted well in Zimapán (Hidalgo state, Mexico, Fig. 1) (from 1000 $\mu g\ L^{-1}$ to 25 $\mu g\ L^{-1}$) (Armienta et al., 2007). Based on these results, the performance of a conventional (flocculation with Fe salts, sedimentation and filtration) mobile treatment plant was also tested. A flow of 50.9 L min^{-1} was considered adequate for its operation, using a dose rate of 38.8 mg L^{-1} $Fe_2(SO_4)_3$. The As content was decreased from 780 to 40 $\mu g\ L^{-1}$ which was below the drinking water standard at the time the tests were done (Armienta et al., 2007). This plant was later installed at Zimapán to treat polluted well water (400–500 $\mu g\ L^{-1}$ As) used as a drinking water supply. However, instead of iron salts, the filters were filled with activated alumina. NaOCl was added for the oxidation of As (III) to As(V) and HCl added to lower the pH to 5.5–6.0 before filtration. The plant produced good-quality water (4–9 $\mu g\ L^{-1}$ As) and treated 600 m^3 during the 5 months of operation (Rivera et al., 2000).

Luján and Graieb (1994, 1995) and Luján (2001) showed the suitability of a hydrogel of activated aluminum hydroxide, which can be added directly to the water, to remove As in a household scale application, independent of the As species. The hydrogel is prepared using hydrated aluminum sulfate, calcium hypochlorite, ammonium hydroxide and demineralized water. After a 3-h settling time, the clear water can be drawn off. Sixty four artificial water samples (As: 100–5000 $\mu g\ L^{-1}$) and 200 groundwater samples (As: 40–800 $\mu g\ L^{-1}$) from the Tucumán province (NW Argentina), were tested. The final As concentration of all samples was below 10 $\mu g\ L^{-1}$. The cost of each liter of treated water was calculated to be US$ 0.08 when the hydrogel is produced on a sufficient scale to supply a population of 30,000 inhabitants. However, the costs are not affordable by the isolated population of the Chaco-Pampean plain.

Goethite (α-FeO(OH)) was tested as an adsorbent for As(V) spiked tap water from Comarca Lagunera (Mexico) (Alvarez-Silva et al., 2009). The removal process consists of As(V) adsorption/coprecipitation onto goethite obtained by the hydrolysis of Fe(III). The highest efficiency was obtained for a Fe/As molar ratio of 20. This ratio was used for treating a well water containing 210 $\mu g\ L^{-1}$ of As (3% as As(III), circumneutral pH) from El Mayrán, Coahuila state, Mexico (Fig. 1). Experiments performed with ferric sulfate and ferric chloride as goethite precursors lowered the As concentration to 16 and 10 $\mu g\ L^{-1}$, respectively.

Cumbal and SenGupta (2009) evaluated polymer-supported Fe(III) oxide particles as an As-selective sorbent. These authors harnessed nanoscale hydrated Fe(III) oxide (HFO) particles within polymeric beads to overcome the unsuitability of HFO for plug flow configurations due to excessive pressure drops and poor durability. Commercially available cation and anion exchangers were used as host materials for dispersing HFO particles within the polymer phase, the latter exhibiting a much higher As removal capacity. Since hybrid anion exchanger-macroporous (HAIX-M) beads were amenable to efficient regeneration, their reuse for several cycles could be confirmed. This technology seems interesting for As removal for small communities upwards, but due to economic limitations not for household scale.

5.2. *Adsorption methods using natural low-cost adsorbents*

The use of natural geological materials (soils and sediments) for As removal at a household level is an emerging solution for poor people in remote rural settlements, especially if the materials are locally available and can be collected by the local population. Their low or zero cost makes these materials very attractive for As removal compared to synthetic or commercial materials. Sometimes, this may be the only option to provide safe water to very poor settlements. Their suitability for As removal from water is mainly due to adsorption, coprecipitation and ion exchange processes involving Fe- and Al-rich minerals and clay minerals included in the soils or sediments. However, one aspect that should be addressed prior to its implementation for regular use is the acceptance by the local people, since some of the materials (like soils) may be associated with the pollution rather than with the decontamination. The cost-benefit depends mostly on the availability of the material at places close to the polluted zones.

Several geological materials, such as hematite (α-Fe_2O_3), goethite (α-FeO(OH)), gibbsite (γ-$Al(OH)_3$), and soils or sediments containing these minerals (e.g., oxisols, laterite) were tested in Latin America at a laboratory scale either with laboratory or natural waters, as will be seen later. Other As sorbents tested were limestone and iron-coated zeolites. Clay minerals such as montmorillonite (and clays such as bentonite, consisting predominantly of montmorillonite) have been used in a colloidal form as absorbents.

In Zimapán (central Mexico, Fig. 1), crushed indigenous limestone (Soyatal limestone) with 41.4% CaO, with a 34% loss on ignition and trace amounts of Fe, Al and Mn, was tested in batch and column tests for As removal from well water (around 500 $\mu g\ L^{-1}$ of As) (Romero et al., 2004; Armienta et al., 2009). Batch experiments using limestone (10 g L^{-1} in the raw water) showed 90% As removal within the first 5 min and the same particles could be used for five separate cycles. This locally available limestone has been proved to be suitable for

[1] Centro Panamericano de Ingeniería Sanitaria y Ciencias del Ambiente (Panamerican Center of Sanitary Engineering and Environmental Sciences, Panamerican Health Organization).

Author's personal copy

domestic water treatment in batch-mode as proposed earlier by Ongley et al. (2001) and alternatively, in packed columns to remove As-contaminated water flowing from a well (Armienta et al., 2009).

Rivera and Piña (2004) tested natural zeolites to remove As from drinking water jointly with Fe and Mn in a small-scale pilot study. The zeolite was of the clinoptilolite type ($Na_6((AlO_2)_6(SiO_2)_{30})\cdot 24H_2O$), where Na is the main exchangeable cation. In their experiments, Rivera and Piña used zeolites already coated by Mn oxide, obtained from a Mn removal plant. The authors used a well water supplying Mazatlán (Sinaloa state), an important city in Mexico (As: 0.021–0.032 mg L^{-1}, Fe: 0.41–3.18 mg L^{-1}, Mn: 1.1–1.3 mg L^{-1}, pH: 6.5–7.3, electrical conductivity 446–500 μS cm^{-1}). In the process, ion exchange is followed by an oxidation process using Cl_2, which forms a Mn oxide coating on the zeolite. This coating then adsorbs dissolved Fe and Mn (Petkova-Simeonova et al., 1995). During these processes, 19–60% of As was removed due to coprecipitation as insoluble Fe and Mn compounds, physical entrapment in the zeolite bed and adsorption on the Mn oxide coating.

Different clay-rich soils and sediments have been tested and compared as adsorbents at a laboratory scale in Santiago del Estero province (SDE, NW Argentina) to remove As from the groundwater of the Río Dulce alluvial aquifer (Claesson and Fagerberg, 2003; Mellano and Ramirez, 2004; Storniolo et al., 2005; Lindbäck and Sjölin, 2006). In laboratory experiments (Claesson and Fagerberg, 2003), high As removal at a household scale was achieved using a Fe-rich laterite, an acidic soil from the Misiones province (NE Argentina). The major components of laterite were hydrous oxides of Fe, Al, with a pH_{zpc} of 7–9. In experiments with natural SDE groundwaters (500 μg L^{-1} As; 1:10 laterite:water mass ratio), the initial As concentration was decreased to 10–30 μg L^{-1} within 40 min, corresponding to a removal efficiency of 94–98%. Approximately 48 h were required for complete sedimentation and the removal of turbidity. The main economic limitation was the transport costs of the laterite to SDE (Misiones is 1100 km far from SDE), estimated to be US$ 43 (year 2003) for a household of ten persons (daily consumption: in average 4 L water/person).

Mellano and Ramirez (2004) evaluated natural clays from SDE and Misiones provinces as adsorbents for As removal from groundwater. Batch experiments (solid/liquid ratio of 1:10 wt/wt) with laboratory water at different initial pH values (4.5, 5.6, 8.6) and different initial As(V) concentrations (0.5, 1.0, 2.0 mg L^{-1}) were performed. Higher As(V) removal was obtained with the Misiones laterite sample (99% as compared to 40–53% with the SDE clays), which can be related to lower Al and Fe contents in the SDE samples compared with those in the laterite sample.

Lindbäck and Sjölin (2006) studied the effectiveness of five samples of sediments and soil from different sites in the Argentine provinces of Santiago del Estero, Tucumán, Salta and Misiones. The high Fe content and low pH values from the laterite sample favored As adsorption and made it the most suitable material to remove As. The other soils were unfavorable.

Ladeira and Ciminelli (2004) and Ladeira et al. (2002) studied the adsorption and desorption of As(III) and As(V) by oxisol samples from Brazil (Paracatu, Minas Gerais) and its main constituents, goethite, gibbsite and hematite. The highest As (III) and As(V) uptake was correlated with the highest content of aluminum and iron oxyhydroxide in the oxisol samples (app. 26% gibbsite and 11% goethite with minor hematite) and the highest specific surface area. Oxisol and goethite were superior to gibbsite with respect to As immobilization. As an example of an industrial application, oxisol liners have been used in tanks providing containment for sulfide tailings (app. 15% S, as pyrite and arsenopyrite, 100 mg L^{-1} of dissolved As) generated in gold cyanidation of flotation concentrates (Esper et al., 2007). Over 15 years of groundwater monitoring has proved that the enriched Fe- and Al-oxisol liner is an efficient system for the retention and attenuation of tailings dam seepage at this mining site. This successful, large-scale experience supports the possibility of using these materials for As removal in rural and remote areas.

In a further development of the previous studies, Brazilian soils enriched in Fe and Mn were investigated. In addition to As removal, the aim was to promote a direct As(III) oxidation to As(V). The soil samples were composed of Mn minerals (todorokite, birnessite, cryptomelane, lithiophorite) and Fe oxides (goethite, hematite, and magnetite) (Deschamps et al., 2003). Column experiments were performed with As-spiked (100 μg As(III) L^{-1}) tap water percolating through 1 mm particles of the soil (Deschamps et al., 2005). A very efficient elimination of As(III) was achieved, and the 10 μg L^{-1} limit was only exceeded after 7400 bed volumes (BV) total throughput. The As-loaded residue was classified as non-toxic, thus making the spent material suitable for discharge in landfills.

The mechanism of As(III) oxidation and removal using nanosized birnessite (Mn(IV)) was investigated. It was shown to involve a reduction to hausmannite (Mn(II) and Mn(III)). Precipitation of $Mn_3(AsO_4)_2.4H_2O$ was also indicated and correlated with the very high As removal (up to 110 mg g^{-1} or 33 μmol m^{-2}) (Dias et al., 2008), one order of magnitude higher than typical values reported for As adsorption on metal oxyhydroxides (Deschamps et al., 2003).

Column experiments using natural hematite (α-Fe_2O_3) and zeolite samples were tested with polluted well water after adjusting the pH to 6.6. A removal to less than 50 μg L^{-1} of As (from app. 1000 μg L^{-1}) proved the suitability of using the adsorbents for small to middle-sized communities (Petkova Simeonova, 1999).

Other studies conducted by Garrido et al. (2008, 2009) optimized As removal from capacitive deionization reject water (see Section 6.2) onto natural goethite. At a laboratory scale, 99 and 65% of As was removed from water with initial As concentrations of 900 and 10,000 μg L^{-1}, respectively, by adding 1 g goethite L^{-1} at pH 6 (agitation time 60 s). The sorption process of total As onto goethite fitted a Langmuir equation. Due to the fast adsorption, it is assumed that transport in the external boundary layer of the surface of the goethite prevails and that intraparticle diffusion can be discarded.

5.3. *Natural and modified organic materials*

In Latin America, different types of low-cost organic materials have been tested for their suitability to remove As from water, including cellulose, milled bones, sedges, sorghum biomass and waste biomass.

Author's personal copy

Muñiz et al. (2009) developed filters using a combination of iron-enriched activated carbon from lignite (1.8 μm < particle diameter <8.7 μm; surface area: 1500 m^2 g^{-1}; 3% iron as oxide) and acetylated cellulose (triacetate cellulose) synthesized from low-cost cotton and Kraft cellulose. Acetylated cellulose-activated films with different carbon loadings were tested in a continuous flow cell (4 bar; flux: 47–49 L m^{-2} h^{-1} bar^{-1} as typical for microfiltration membrane processes) with synthetic As solutions (200 and 400 μg L^{-1} As(V)). A maximum of 63% As removal was reported.

Czerniczyniec et al. (2007) studied the effects of pH, hardness, alkalinity, salinity and bone calcination temperature for As(V) adsorption onto natural biogenic hydroxyapatite (HAPb) obtained from charred cow bones. Up to 75% As(V) removal from a laboratory solution was obtained after 24 h contact with a 5 g L^{-1} suspension of the biogenic HAPb (from 325- to 400-mesh fraction). The chemical composition of water significantly modified the HAPb capacity for As and the conditions for the optimum treatment of arsenical water with HAPb correspond to high salinities, low pH and high hardness.

Teixeira and Ciminelli (2005) developed an activated waste biomass with a high fibrous protein content (rich in keratin), obtained from chicken feathers, for the selective removal of As(III). Arsenic removal increased as pH decreased from 10 to 2. Arsenic uptake reached values of 270 μmol As(III) g^{-1} of biomass (or 20 mg g^{-1}). The reaction involves the replacement of OH groups in the neutral arsenite molecule, $As(OH)_3$, by S atoms from the sulfhydryl groups (SH) present in the biomass. Therefore, cysteine-rich biomass, which is a cheap available waste product found in animal skin, hair, nails, horns or feathers, appears to be an option for As removal from waters where As(III) is present in significant amounts.

Hansen et al. (2004) studied As(V) biosorption using dried algae (*Lessonia nigrescens*) collected in Valparaiso bay, Chile. Experiments were performed with laboratory solutions containing 200 mg L^{-1} As(V) at low pH values (2.5, 4.5 and 6.5), since the focus of the research was on As removal from wastewater released from a copper smelting plant. Maximum adsorption capacities were estimated to be 45.2, 33.3, and 28.2 mg g^{-1} at pH values of 2.5, 4.5, and 6.5, respectively. Though the experimental conditions do not correspond to those found generally in waters used for drinking water purposes, the use of *L. nigrescens* may be interesting for small-scale drinking water treatment and deserves further investigation.

Bundschuh et al. (2007b) investigated the effectiveness and suitability of dried macro-algae (*Spyrogira* spp.) for As removal from water and compared it with those of totora (*Schoenoplectus californicus*) and paja brava (*Festuca orthophylla*) for As removal from acid mine drainage (AMD) and other contaminated waters in the Poopó lake basin (Bolivia, Andean highlands, Fig. 1). Experiments were performed with prepared metal solutions (As: 7.5, Zn: 8.0, Pb: 3.4, Fe: 4.5 and Cu: 9.4 mg L^{-1}) and a real AMD effluent taken from the Bolivar mine (40 km SE of Oruro, As: 5.75, Zn: 9.2, Pb: 2.1, Fe: 7.2 and Cu: 8.7 mg L^{-1}). Both solutions gave similar results regarding As removal. Macro-algae (*Spyrogira* spp.) has been found to be the most effective adsorption material to remove As, Pb, Fe, Cu and Zn from AMD, compared to totora which is less effective, and to paja brava, which is unsuitable. Within 4 days, macro-algae removed 80–90% of As, 90–100% of Pb, 83–87% of Fe and 82–83% of Cu initially present in the solutions. Therefore, the use of macro-algae seems to be the best method for a household scale As removal.

A detailed investigation of As complexation with an iron-loaded vegetable biomass (dried lettuce leaves) was carried out by Silva et al. (2009). A maximum sorption capacity of 9.74 mg g^{-1} or 0.13 mmol g^{-1} As(V) was achieved using media with an iron content of 12.0 mg Fe g^{-1} (or 0.22 mmol Fe g^{-1}).

Haque et al. (2007) studied the suitability of sorghum biomass (SB) for As removal from aqueous solutions. They determined two potential binding sites associated with carboxyl and hydroxyl groups. The equilibrium time for As adsorption on SB was 12 h. The effect of pH on As adsorption to SB was investigated over a pH range of 2.0–10.0. They found a strong influence of pH with a maximum removal of As at pH 5.0. The Freundlich model fitted the equilibrium data. Through column experiments, it was found that for both non-immobilized and immobilized sorghum biomass, the maximum adsorption capacities were 2.76 and 2.43 mg of As g^{-1}, respectively. Therefore, sorghum biomass can be used as a material for As(V) removal from waters.

5.4. *Constructed wetlands*

Artificial wetlands are considered cost-effective technologies for water and wastewater treatment. They offer great advantages over conventional treatment systems; they operate on solar energy, require low external energy input, can achieve high levels of treatment, and involve inexpensive technology that is easily operated and maintained.

The implementation process involves several steps. It starts with the selection of the most promising plants capable of removing the contaminants from water and retaining them in their roots; this process, called rhizofiltration, is quite successful for the removal of As. This study determined the As tolerance and removal capacity of two Cyperaceae species, *Schonoeplectous americanus* and *Eleocharis macrostachya* (Alarcón-Herrera et al., 2009). The studies were conducted in a subsurface wetland prototype system with three units (2 units with plants, one without plants) operated in parallel under continuous flow. The design of the prototype was based on the hydraulic factors of the system, considering the minimum width–length ratio required for plug flow (3:1).

Water solutions with an added As concentration of 1000 μg L^{-1}, in the form of sodium arsenate, were prepared and continuously pumped through the three units using peristaltic pumps. The hydraulic retention time of the solution in the wetlands was 8 days, and the test period was 40 days. The artificial wetland prototype units planted with *Schoenoplectus americanus* were 90% efficient in removing As from water. This means that the system was capable of reducing, without saturation, the As concentration from 1000 to 100 μg L^{-1}.

Another experiment was performed under the same physical conditions, this time with *Eleocharis machrostachya*. The study was conducted over a period of 7.5 months (Olmos-Márquez et al., 2009). Several influx As concentrations (from 100 to 500 μg L^{-1}) and two retention times (2.3 and 1.0 days) were used during the experiment. 99% As removal from the treated water was obtained during the test period with the

Author's personal copy

highest As feedwater concentration (500 μg L^{-1}), and 89% As removal for the test stage with the lowest As concentration (100 μg L^{-1}). In both cases, the required concentration of As for drinking water according to Mexican regulations (25 μg L^{-1}) was obtained. All these tests show that the use of artificial wetlands as an alternative for the removal of As from water is an important technique that has proven effective in prototype systems and should be considered for pilot projects aimed at treating water intended for human consumption.

5.5. *Zerovalent iron*

Methods using zerovalent Fe (metallic iron) are suitable low-cost methods to remove As at a household scale. Zerovalent iron (ZVI) is an emergent material having several advantages compared to other adsorption materials: (i) it is cheap and widely available in many forms, (ii) the intermediates formed during ZVI corrosion can oxidize As(III) to As(V), which eliminates the need of an additional oxidation, and (iii) iron corrosion produces ferric oxyhydroxides (FHO), which strongly sorb As. Removal by ZVI takes place mainly by adsorption and coprecipitation onto these FHO, through a mechanism involving Fe(0) corrosion to Fe(II) and Fe(II)/(III) oxides or hydr(oxides) (iron rusts, magnetite, lepidocrocite, maghemite, ferrous hydroxide ($Fe(OH)_2$) and ferric hydroxide ($Fe(OH)_3$)), depending on the redox conditions and pH. Then, in the presence of dissolved O_2, reactive oxygen species (ROS) like $HO^{\bullet}$, $O_2^{\bullet-}/HO_2^{\bullet}$, H_2O_2 are formed, leading to oxidation of reduced iron species to Fe(III). Fenton reactions and species of higher oxidation state like Fe(IV) were also proposed (Morgada et al., 2009).

There are already results from basic experiments using zerovalent iron, which use local iron materials, iron wool and packing wire, as well as iron nanoparticles, many of them coming from Latin American groups. These will be discussed in more detail in Section 5.7, because the use of ZVI is often improved by solar irradiation (Cornejo et al., 2004, 2008; Litter, 2006; Litter and Jiménez González, 2004; Litter and Mansilla, 2003; Morgada de Boggio et al., 2006, 2010; Morgada et al., 2008, 2009).

A method using the electrochemical corrosion of a fixed bed of metallic iron was developed and applied in San Juan, Argentina (Cáceres, 2007; Litter et al., 2008). The procedure is ideal for small scale applications (households to a few hundred people) and consists of a first oxidative chlorination step, a second step using a bed filled with iron filings or small pieces of iron, conditioning of the flocs and filtration. Arsenic removal rates above 90% were obtained.

5.6. *Solar technologies*

Very cheap technologies based on the use of solar light, abundant in many regions where the problem of As is dramatic, can be adapted for As removal. The use of solar or artificial light and dissolved iron has been the object of several studies in the last decade, especially to facilitate the oxidation of As(III) to As(V). To effectively remove As, a two-step process has to be designed: one for As(III) oxidation and the second one for elimination of the produced As(V). These two steps can be simultaneous or consecutive.

5.6.1. *Solar oxidation and removal of arsenic (SORAS) and modified SORAS*

SORAS (RAOS, *Remoción de Arsénico por Oxidación Solar*, in Spanish) follows the classical treatment sequence of water treatment plants and combines oxidation, adsorption, coagulation and decantation (e.g. Wegelin et al., 2000; García et al., 2004a,b). There exist different versions of the SORAS method. All have in common the oxidation of As(III) to As(V) by active species formed by sunlight irradiation in the presence of oxygen. Therefore, the raw water is filled in transparent PET bottles and exposed to sunlight. Citrate, added to the raw water in form of lemon juice, reacts with Fe(III), which is either present in the natural raw water or added in different options, such as iron packing wire, iron wool, or iron filings and, as a result, a precipitate of iron oxyhydroxides is obtained, where As(V) is adsorbed or coprecipitated. Then, the bottle is put in a vertical position to decant the precipitate, or the water is filtered by a cloth or ceramics to obtain clear drinking water. Tests of this technology have been performed in Nicaragua, Bangladesh, Chile and Argentina (Cornejo et al., 2008; Emett and Khoe, 2001; García et al., 2004a,b; Hug, 2000; Hug et al., 2001; Hug and Leupin, 2003; Lara et al., 2006; Litter, 2002, 2006; Litter and Jiménez González, 2004; Litter and Mansilla, 2003).

SORAS has been applied with relative success to the natural waters of Bangladesh (removal of As(III) between 50 and 70%). There, the As concentrations range between 100 and 150 μg L^{-1}, and the process uses Fe(III) naturally present in the water, with lemon juice addition and solar light irradiation (Hug et al., 2001). However, groundwaters of most regions of Latin America do not have enough iron to make the SORAS technology efficient. For this reason, SORAS was modified to be applied to natural waters of the Camarones river (Arica, Chile; Fig. 1), where As(V) (1250 μg L^{-1}) has been successfully decreased by up to 95%, helped by the external addition of Fe (II) (Cornejo et al., 2004; Lara et al., 2006). In further experiments, steel wool was used. Response surface method analysis was used to optimize the amount of zerovalent iron (steel wool) and the citrate concentration (lemon juice) to be used. The optimal conditions for natural water from the Camarones river were: 1.3 g L^{-1} steel wool and one drop (ca. 0.04 mL) of lemon juice. Under these conditions, removal percentages were higher than 99.5% and the final As concentration was below 10 μg L^{-1} (Cornejo et al., 2008).

Experiments with natural well waters from Los Pereyra (Tucumán, Chaco-Pampean plain) and similar laboratory waters were performed in Argentina, adding iron externally. Some natural Fe-containing minerals from the region, iron wool, packing wire or zerovalent iron nanoparticles were tested. It was proved that, under the same conditions, removal was more effective in natural waters than in laboratory samples due to the presence of natural dissolved organic matter, which promoted Fenton reactions. For this reason, it was not necessary to add lemon juice. A recent study was performed using extremely reactive commercial nanoparticles (NZVI) produced by an Argentine industry. It found a rapid As(V) removal using very low amounts of iron (0.005–0.1 g L^{-1}). Over 90% As removal was obtained after 150 min of contact time at the optimal NZVI concentration. The commercial NZVI showed an outstanding ability to

Author's personal copy

remove As from waters, due not only to a high surface area and low particle size but also to a high intrinsic activity. After a 3-h contact time between the iron nanoparticles (0.025 mg L^{-1}) and a real groundwater sample (initial As concentration: 174 μg L^{-1}, circumneutral pH), the As concentration was decreased to 42 μg L^{-1} in the dark, and to levels lower than the Argentine regulatory limit (10 μg L^{-1}) under UV irradiation (García et al., 2004a,b; Litter et al., 2008; Morgada et al., 2008, 2009; Morgada de Boggio et al., 2009, 2010).

5.6.2. *Photocatalytic oxidation using TiO_2 under UV light irradiation*

The photocatalytic method using TiO_2 as photocatalyst, followed by iron addition, is another recently developed, low-cost technology, suitable for As removal from water. PET plastic bottles impregnated with TiO_2 (Meichtry et al., 2007) were used to remove As from well waters of Las Hermanas (SDE) (initial As concentration: 500–1800 μg L^{-1}, circumneutral pH). More than 94% removal of As(III) and As(V) was obtained when the bottles were exposed to artificial UV light in the presence of Fe(III) salts (Litter, 2006; Litter et al., 2008; Mateu, 2007; Morgada de Boggio et al., 2006, 2009, 2010; Morgada et al., 2008). Fostier et al. (2008) obtained similar results.

6. Desalination technologies

6.1. *Conventional reverse osmosis desalination plants*

Desalination can be a good option to remove As from water or can be used to tap alternative water resources, such as saline (or otherwise chemically unsuitable) groundwater or seawater. We can use the example of the seawater desalination plant of Antofagasta city, northern Chile. There, the As-rich surface water resources, which are presently tapped close to the Andes and transported via a 400 km pipeline across the Atacama desert to Antofagasta and other cities and towns, cannot supply additional water. This makes desalinated seawater the only supply to cover the future water needs of northern Chile to support population growth (expected to grow about 40% from 2000 to 2020, IADB, 2003), and the needs of the expanding mining industry, which is the primary economic base of northern Chile. The Company of Sanitary Services (Empresa de Servicios Sanitarios de Antofagasta, S.A., ESSAN) installed a seawater RO desalination plant, 11 km from Antofagasta (Fig. 1), with an initial water production capacity of 13,000 m^3 day^{-1} each (IADB, 2003) which has been expanded to 52,000 m^3 day^{-1} and is the largest in Latin America. Also in Chile, in the small town of Taltal (Fig. 1), a desalination plant was installed in 2007, with a capacity of 5 L s^{-1}. In 2007, the first desalination plant was installed in Los Cabos, Mexico, with a capacity of 21,000 m^3 day^{-1}. Another desalination plant will be installed in northern Chile, in the copper-gold mine Esperanza (180 km from Antofagasta). Here, desalinated seawater will be pumped 150 km to the mine site, which is 2300 m a.s.l. A seawater desalination plant will also be built in Escondida mine (170 km SE of Antofagasta, 3200 m a.s.l.), one of the worlds greatest sources of copper (Petry et al., 2007).

In Argentina, in different sites, As is removed by RO, e.g. in the Chaco-Pampean plain in the provinces of Santa Fe, Córdoba and La Pampa (D'Ambrosio, 2005). The demineralized water is remineralized by adding $Ca(OH)_2$ or NaOH or bringing the effluents in contact with calcite. As an alternative, the demineralized water can be mixed with raw waters in such a ratio that the As concentration of the final product remains below the regulatory limit.

6.2. *Desalination combined with locally available renewable energy resources (wind, solar, geothermal)*

Desalination methods using RO plants require large amounts of energy in the form of electricity. Therefore, the use of locally available energy sources, such as wind, solar and geothermal energy can significantly increase the range of water resources available for use by a community.

In Latin America, desalination is one of the most promising fields for the application of geothermal energy due to the coincidence, in many places, of water scarcity or unsuitability, with geothermal availability. Therefore, it is necessary to look in more detail at geothermal desalination using low-enthalpy geothermal resources (minimum required temperature 60 °C, e.g. for membrane distillation). Electrodialysis (ED) and RO are not suitable for using geothermal heat directly, but they can be run by electricity produced from geothermal resources, which, however, require a greater temperature of the geothermal fluids (> 85 °C). Another membrane-based technology is membrane distillation (MD), which, in contrast to both previous membrane techniques, can directly use the heat from the geothermal water (Shih, 2005).

Small-scale marine RO units (known as watermakers), used to produce drinking water from seawater on boats, can also possibly be used for As or heavy metal removal. Some of these units can be powered by sustainable energy sources such as photovoltaic, wind wheels, or can be operated manually. Small scale RO units are currently being tested at the Karlsruhe University of Applied Sciences for their efficiency at As removal (Geucke et al., 2009) and, in an ongoing work, their suitability for Latin American conditions will be evaluated in Argentina. The most salient feature of these desalinators is the very low energy consumption; 80% less power is needed than for conventional RO watermakers. Field studies in Argentina are scheduled to start in 2011. Using the information about the chemical compositions and grades of mineralization of water to be treated together with information on available infrastructure, the cost of the treated water was estimated to be as follows: the capital cost for units producing 1.4–2.4 m^3 day^{-1}, which can supply high quality drinking water to 300–500 people is 5000–6000 Euro. The operating cost per liter of drinking water is less than 0.01 Euro.

Garrido et al. (2008, 2009) applied a Canadian advanced electrochemical technology (the capacitive deionization) to remove ion species from contaminated groundwater. This system is an electrostatic charging cell, which behaves as a capacitor and is comprised of carbon electrodes. During the first stage of the process, the capacitor is energized using

Author's personal copy

Table 1 – Advantages and disadvantages for emergent technologies for arsenic removal from drinking water in rural and isolated urban areas.

Technologies	Main features	Limitations
Small-scale oxidation/ coagulation/sorption	Simple operation. Low cost. Simultaneous disinfection, As(III) oxidation and turbidity removal.	Chemicals should be delivered. Susceptible to water chemistry.
Geological materials as natural sorbents	Household or small community scale. Site-specific materials selected according to local availability. Low cost. Simple operation. No additional chemicals needed. May be modified to increase efficiency. As(III) oxidation if manganese is present.	Variable efficiency according to the characteristics of materials. It may become clogged. Amount of residues may be large due to low adsorption capacity. Possible growth of microorganisms. Susceptible to water chemistry.
Organic sorbents	Similar as above. Environmental compatibility and possible cost-effectiveness. May be specific for As(III) or As(V) removal.	The same as above but often with lower efficiency of As removal and higher sensitivity to water chemistry. Need of material preparation (e.g. drying, grinding) adds costs. Much research still needed.
Zerovalent iron	Household or small community scale. Widely available local iron materials at low cost. Simple operation. Simultaneous disinfection and As(III) oxidation. Nanosized materials significantly increase loading capacity and reactivity, thus requiring lower amount of iron.	Acid addition may be needed. May require special care to assure removal of nanosized, colloidal materials.
Constructed wetlands for arsenic removal	Small community scale. Native perennial plants (Sedges, Cyperaceae family). Simple operation and maintenance.	Requires a good design, and large superficial area. Residues (plants): the levels of arsenic have to be measured and, when needed, they have to be disposed off appropriately
Modified Solar Oxidation and Removal of Arsenic (SORAS)	Household scale. Higher efficiency of As (III) and As(V) removal. Ability to handle natural waters with high levels of dissolved solids. Environmentally friendly and non-expensive technology. Successfully tested in remote areas in Latin America. Simultaneous disinfection and As(III) oxidation. Low cost (4 cents US$ per liter, in Chile).	Iron and citrate addition often required. Requires removal of colloidal material resulting from the process. The highest removal efficiencies are related to geographical areas with high levels of insolation.
Oxidative or reductive TiO_2 heterogeneous photocatalysis	Oxidative photocatalysis requires solar or artificial light. Low cost TiO_2. Simultaneous As(III) oxidation and removal of natural organic pollutants, toxic metals and microbiological contamination can be achieved.	Further addition of iron is needed. Addition of organic donors is required in reductive photocatalysis. Much research is still needed.
Innovative small-scale membrane technologies	Small community level, several families sharing treatment device. Simple operation. Comparably low energy consumption. Modularity and flexibility. Very high water quality due to removal of other dissolved contaminants, particulates, bacteria, viruses along with As. Low treatment cost due to long life-time of device and membranes.	Lower rejection of As(III) therefore pre-oxidation or double pass unit needed at higher As(III) feed concentration. Capital cost comparably high. Brine treatment or disposal necessary.

direct current, creating positive and negatively charged surfaces. Ionic compounds such as As are attracted to and electrostatically adsorbed onto the surface of the electrodes. To regenerate the electrode surfaces, the polarity of the cell is automatically reversed during stage two, causing the capacitor to release the contaminants into the cell channels. The third stage of the process is to remove the contaminants from the cell by flushing with a small quantity of liquid forming a concentrated solution. This technology is recommended for water containing less than 3000 mg L^{-1} of total dissolved solids. The advantages of capacitive deionization over reverse osmosis, nanofiltration and electrolysis are the following: (i) only small amounts of chemical reagents are required for the cleaning of cells or membranes; (ii) both As(V) and As (III) can be removed; (iii) high ion removal efficiencies; (iv) low volume of rejected water (between 3 and 7% of the total treated volume); (v) low operation and maintenance costs.

Author's personal copy

7. Comparison of methods: suitability for specific conditions

Emerging, low-cost technologies to mitigate the problem of As in drinking water resources suitable for rural and urban areas lacking centralized water supplies have been evaluated. These comprise several alternatives such as the direct treatment of ground- and surface water, or tapping of other water resources including rainwater collection and artificial aquifer recharge. It is necessary to remark that in many rural areas of Latin America, groundwater with high As concentrations is the only available drinking water resource, and, although surface water may be locally accessible, in many cases it is only seasonably available.

Emerging technologies for As removal from drinking water in rural or urban areas without a centralized water supply are considered appropriate if they fulfill the following four basic requirements:

(1) Technology is suitable for small-scale equipment.
(2) Technology is inexpensive and affordable for a population with a low economic income.
(3) Technological design is simple, so that installation and maintenance can be performed by the local population or, in the case of single household, by the consumer.
(4) Technology relies on local materials and local, renewable energy resources (e.g. wind, sunlight, biomass) rather than on a supply of more expensive fossil fuels, which often must be transported over large distances to be used in fossil fuel power generators.

Table 1 shows the emerging technologies for As removal applied or tested at a laboratory or field scale in Latin America. Advantages and disadvantages are given considering the community size for which it is designed to serve (down to a household-scale), socioeconomic conditions (affordability), maintenance demand, requirement for an electricity supply, characteristics of water to be treated (As only, additional contaminants, high mineralization, As species and concentration in raw water, amount and toxicity of waste product generation).

Coagulation/filtration with iron and aluminum salts is a well-established, efficient method for large scale water treatment, in either the absence or the presence of As. The method has been scaled-down for household applications. The addition of chlorine assures disinfection, which is an important advantage in many rural and remote areas of Latin America. Simple operation and basically no maintenance needs make this option attractive to remote, domestic applications, if the reagents (e.g. iron and aluminum salts) can be provided at low cost.

Alternative sorbents (clays, laterites, soils, limestones) have been investigated and tested at laboratory and pilot plant scales. The most efficient sorbents rely on the presence of iron and aluminum oxyhydroxides in the material. Some manganese minerals enhance the oxidation of As(III) to As(V). Untreated soils and ferruginous clay materials may be selected according to their availability by the affected community at basically no cost. The performance in terms of As removal per g of material depends on the nature, concentration and specific surface area of the active constituent. Again, the operation is simple with essentially no need for maintenance and electricity, which makes it affordable and applicable in small communities. When sorption methods are used alone to treat water, they depend more on the components of the water than when they are combined with coagulation/coprecipitation processes. This is due to the fact that sorption sites will be also available to other anions (e.g., sulfate, phosphate and silicate which are quite often present in higher concentrations than As in the water to be treated). Therefore, these methods would be attractive for niche applications considering mainly their availability close to the site.

Organic-based sorbents, such as those from natural biomass, are possible alternatives. However, they are even more affected by water chemistry than inorganic sorbents. Many of these materials often require special preparation (e.g. drying, grinding), which may increase costs or create additional effluents to be treated. Organic-based sorbents become attractive in specific operations where other options (e.g. Fe- or Al-based sorbents) are not available.

Synthetic materials may be prepared with high specific surface areas, which results in lower dosage requirements. On the other hand, complex preparations will have some impact on the overall costs. An efficient solid–liquid separation should also be provided otherwise the ingestion of As-loaded colloidal or nanosized particulates may become a source of contamination. Modifications of existing materials in order to improve the efficiency of As removal, bed permeability, fixation to adequate supports or selectivity have been also investigated.

Perhaps the material that better combines many of the advantages of natural, low-cost materials, with the simple operation of sorption processes (no need of electricity and consumables) is *zerovalent iron*. The natural oxidation of iron to colloidal, nanoscale oxy(hydr)oxides provides an *in-situ* production of a highly efficient material for As removal. Considering the climate characteristics of many regions in Latin America affected by As contamination in groundwater, this is probably the best option for many remote, rural areas. The application has been well investigated and tested in many places. When associated with *photocatalytic oxidation* (i.e. using sunlight in the process) the method also offers the advantage of providing As(III) oxidation and water disinfection. Fixed bed, ZVI operation combined with chlorination is one of the emerging technologies deserving special attention, when the supply of water on a community-scale basis is considered. The use of zerovalent nanoparticles results in an outstanding increased removal rate, but more research is needed.

Another promising innovative method for rural communities is the use of *constructed wetlands for arsenic removal*. When the process is well designed, it can work by gravity and if combined with native perennial plants for As rhizofiltration, the cost and efficiency of the system can be improved. The system does not require maintenance by highly-trained personnel.

TiO_2 *heterogeneous photocatalysis* is also a promising, emergent technology which allows the simultaneous oxidation of As(III) and removal of natural organic pollutants, toxic metals and microbiological contamination. An iron source should be added to retain As on a solid surface.

Author's personal copy

Regarding water supply on a large scale for remote small or medium size communities, one cannot overlook the possibilities offered by *reverse osmosis*, especially when salinity is an issue, as occurs in many parts of Latin America (e.g. Argentina, Chile and Mexico). Since the removal efficiency for As(V) is much better than that for As(III) (Shih, 2005), RO is especially favored for the Latin American region where most arsenic is present as As(V) species. Moreover, the most salient feature of RO is that As can be removed along with other contaminants such as particulates, bacteria, viruses, salt, heavy metals, organic micropollutants etc., resulting in a very high water quality. This distinguishes RO from other removal technologies which predominantly remove only As.

The advances in membrane technology have reduced the costs of reverse osmosis to a level that makes it a viable choice for potable water production. A supply of energy, capital investment, chemicals (only small amounts for cleaning), and only low-level operator skills are necessary. The production of rejected water, which will require further treatment and/or appropriate disposal, is another point of concern. The combination with locally available renewable energy resources makes the method more attractive.

Reverse osmosis units can be powered by alternative energy resources, such as wind wheels or photovoltaic, though this will depend upon the local situation (sun radiation, wind) and economic aspects. However, such small-scale RO desalinators are generally not suitable for a single household, which is not due to technical reasons, but due to unaffordability. Membrane distillation (MD) can be powered by alternative heat energy sources, such as solar and geothermal and the equipment is small. Despite the benefits as a technically simple low-cost device, ideal for rural areas and isolated urban areas without centralized water supply, and the studies by numerous academic experimentalists and theoreticians, it has not yet been commercialized (Lorenz et al., 2007).

It is not possible at present to include the performance of the individual technologies (e.g. by giving data of percentage of removal) as has been done in Bangladesh by Murcott (2001). The authors consider that the comparison of the available data on As removal would be misleading because the data were obtained using different methods applied to different water samples. More importantly, the removal cannot be directly associated to the final As concentration, which is the most relevant performance indicator regarding potable water treatment. In addition, much less data are available in Latin America in comparison to other affected areas, and most of these data are derived from laboratory rather than field-scale experiments, meaning that conclusions in terms of overall performance are still premature.

8. Conclusions

The main features and limitations of the emerging As removal technologies investigated in Latin America over the last few decades are analyzed. Technologies rely on adaptation and improvement of methods involving simple physicochemical processes like adsorption, coagulation/precipitation and ion exchange, all of them being more suitable for As(V) removal, which usually implies a preliminary oxidation step.

The technologies best suited for application at the community level will be those that are robust, operate well under a wide range of environmental conditions, and can be effectively operated and maintained by people without extensive technical training. For rural communities in Latin America, small-scale and household level As removal systems are the only feasible short-term solution. Specific reactants used in coagulation/sorption processes for As removal are suitable for addition to small volumes of water and can be easily applied at a household level.

Natural geological materials like iron oxides and hydroxides, calcite, clays, and soils may yield effective, simple and low-cost As removal at the household level and for small communities. The As removal efficiency of natural geological materials (e.g. zeolites) may be artificially improved, but this reduces direct availability to the communities and increases costs.

Natural organic materials are also the basis for suitable low-cost technologies. Sorption agents coming from plants and animal residues are more attractive for small-scale, rural, household applications, while the use of As-tolerant and As-accumulating plants is more suitable for community applications, since care must be paid to the growth, harvest, and disposal of the specimens.

Procedures using zerovalent iron from diverse materials are affordable and easy to operate and maintain. They require daily attention, but most of them are nevertheless adequate for family use and furthermore, sunlight may be used to improve their effectiveness. Relatively inexpensive UV lamps can be used if solar radiation is not sufficient and there is access to electricity.

Other alternatives, like desalination and capacitive deionization, require electricity that may be produced from environmental-friendly sources like wind or sunlight.

Emergent small-scale RO is adequate at a community level since no specially trained technicians are needed.

Since experiences with innovative emerging As removal processes in Latin America remain scarce, and are generally limited to laboratory studies, there is a great need for further research to determine how the technologies for As removal described previously can be effectively applied as As mitigation interventions in rural and urban isolated communities. Their use in a regular treatment, however, depends upon the economic level of the communities and the continuous availability of the reactants at the contaminated sites. The effectiveness of the specific reactants should be tested, like many of the treatment options, with the untreated water of every site.

Social knowledge and acceptability of treatment technologies by the local population are important issues in Latin America. The role of women must be considered in particular, since they are the primary procurers and users of the water. To provide them fast and easy technologies to get clean and safe water can result in a better profit of their time, which can be devoted to educational and leisure activities with their children.

Acknowledgments

The authors greatly acknowledge support provided by the CYTED Network 406RT0282 IBEROARSEN, JB thanks the

Author's personal copy

National Science Council of Taiwan for the financial support. MIL thanks CNEA, CONICET and ANPCyT agencies in Argentina. L. Cornejo thanks the Convenio de Desempeño Universidad de Tarapacá (UTA-MINEDUC, 2008–2010) for financial support. V. Ciminelli acknowledges the support from CNPq, Fapemig and INCT-Acqua (Brazil). PB would like to thank Sida and the Strategic Environmental Research Foundation (MISTRA) for their financial support through the respective grants, contribution 73000854 and 2005-035-137 for studies on global advocay on arsenic in drinking water and searching safe groundwater sources for drinking water supplies. We also thank two anonymous reviewers for their constructive suggestions to the earlier draft of the manuscript.

REFERENCES

Alarcón-Herrera, M.T., Martín-Domínguez, I.R., Benavides-Montoya, A., 2007. Wetlands for arsenic removal. In: WETPOL 2007 2nd International Symposium on Wetland Pollutant Dynamics and Control, 16–22 September 2007, Tartu, Estonia.

Alarcón-Herrera, M.T., Núñez-Montoya, O.G., Melgoza-Castillo, A., Royo-Márquez, M.H., Rodriguez Almeida, F.A., 2009. Potential use of sedges (Cyperaceae) in arsenic phytoremediation. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 649–655.

Altamirano Espinoza, M., Bundschuh, J., 2009. Natural arsenic groundwater contamination of the sedimentary aquifers of southwestern Sébaco valley, Nicaragua. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 109–122.

Alvarez-Silva, M., Uribe-Salas, A., Nava-Alonso, F., Pérez-Garibay, R., 2009. Adsorption of As(V) onto goethite: experimental statistical optimization. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 527–534.

Armienta, M.A., Rodríguez, C.R., Ongley, L.K., Brust, H., Morales, F., Aguayo, A., Cruz, O., Ceniceros, N., 2007. Origin and fate of arsenic in a historic mining area of Mexico. In: Trace Metals and Other Contaminants in the Environment, vol. 9. Elsevier, Amsterdam, The Netherlands, pp. 461–486.

Armienta, M.A., Amat, P.D., Larios, T., López, D.L., 2008. Central America and Mexico. 13 978-84-96023-61-1. In: Bundschuh, J., Pérez-Carrera, A., Litter, M.I. (Eds.), Distribution of Arsenic in the Iberian and Iberoamerican Region (in Spanish). Editorial Programa Iberoamericano de Ciencia y Tecnologia para el Desarrollo, Buenos Aires, Argentina, pp. 187–210 (in Spanish). Available at:. http://www.cnea.gov.ar/xxi/ambiental/iberoarsen/ (accessed 10.09) (in Spanish).

Armienta, M.A., Micete, S., Flores-Valverde, E., 2009. Feasibility of arsenic removal from contaminated water using indigenous limestone. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 505–510.

Armienta, M., Rodríguez, R., 2004. Metals and metalloids, study case: contamination by arsenic in groundwater of Zimapan, Hidalgo: environmental issues and methodologic Scope. In: Jiménez, B., Marín, L. (Eds.), Water in Mexico from an Academic Point of View. Academia Mexicana de Ciencias, México D.F., pp. 79–98 (in Spanish).

Armienta, M.A., Segovia, N., 2008. Arsenic and fluoride in the groundwater of Mexico. Environmental Geochemistry and Health 30, 345–353.

Barragne, P., 2004. Contribution to the Study of Five Zones Contaminated Naturally by Arsenic in Nicaragua. UNICEF, Managua, Nicaragua (in Spanish).

Bedolla, L., Avilés, M., Tirado, L., Cortés, J.M.C., 1999. Removal of Arsenic from Drinking Water by Coagulation–Flocculation at Household Level. Instituto Mexicano de Tecnología del Agua (IMTA), Jiutepec, Morelos, Mexico (in Spanish).

Bhattacharya, P., Classon, M., Bundschuh, J., Sracek, O., Fagerberg, J., Jacks, G., Martin, R.A., Storniolo A del, R., Thir, J. M., 2006. Distribution and mobility of arsenic in the río Dulce alluvial aquifers in Santiago del Estero Province, Argentina. Scince of the Total Environment 358, 97–120.

Bianchelli, T., 2004. Arsenic Removal from Drinking Water. Nova Science Pub. (Inc).

Birkle, P., Bundschuh, J., 2009. The abundance of natural arsenic in deep thermal fluids of geothermal and petroleum reservoirs in Mexico. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 145–153.

Birkle, P., Bundschuh, J., Sracek, O., 2010. Mechanisms Of arsenic enrichment in geothermal and petroleum reservoirs fluids in Mexico. Water Research 44 (19), 5691–5703.

Borgoño, J.M., Greiber, R., 1972. Epidemiological study of arsenism in the city of Antofagasta. Trace Substances in Environmental Health 5, 13–24.

Bundschuh, J., Bonorino, G., Viero, A.P., Albouy, R., Fuertes, A., 2000. Arsenic and other trace elements in sedimentary aquifers in the Chaco-Pampean plain, Argentina: origin, distribution, speciation, social and economic consequences. In: Bhattacharya, P., Welch, A.H. (Eds.), Arsenic in Groundwater of Sedimentary Aquifers; Pre-Congress Workshop, International Geological Congress, Rio de Janeiro, Brazil, pp. 27–32. http://www.lwr.kth.se/Personal/personer/bhattacharya_prosun/KTH_DU_Special_Publication.pdf (accessed 06.09).

Bundschuh, J., Farias, B., Martin, R., Storniolo, A., Bhattacharya, P., Cortes, J., Bonorino, G., Albouy, R., 2004. Groundwater arsenic in the Chaco-Pampean plain, Argentina: case study from Robles County, Santiago del Estero Province. Applied Geochemistry 19, 231–243.

Bundschuh, J., Altamirano Espinoza, M., Cumbal, L., 2007a. Geogenic arsenic in sedimentary aquifers of southwestern Sébaco valley, Nicaragua. Geological Society of América Annual meeting, Denver, 28–31Oct, 2007, Session No. 192: arsenic: from nature to human I. Geological Society of America Abstracts with Programs 39 (6), 518.

Bundschuh, J., García M.E., Alvarez, M.T., 2007b. Arsenic and heavy metal removal by phytofiltration and biogenic sulfide precipitation - a comparatibe study from Poopó Lake Basin, Bolivia. Abstract Volume 3rd International Groundwater Conference IGC-2007, Water, Environment & Agriculture – Present Problems & Future Challenges, 7–10 February 2007, Tamil Nadu Agricultural University, Coimbatore, India, 152.

Author's personal copy

Bundschuh, J., Pérez-Carrera, A., Litter, M.I. (Eds.), 2008. Distribution of Arsenic in the Iberian and Iberoamerican region. Editorial Programa Iberoamericano de Ciencia y Tecnologia para el Desarrollo, Buenos Aires, Argentina Available at: http://www.cnea.gov.ar/xxi/ambiental/iberoarsen/ (accessed 12.09) (in Spanish).

Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), 2009a. Natural arsenic in groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands.

Bundschuh, J., García, M.E., Birkle, P., Cumbal, L.H., Bhattacharya, P., Matschullat, J., 2009b. Occurrence, health effects and remediation of arsenic in groundwaters of Latin America. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 3–15.

Cáceres, R.E., 2007. Metallic Iron Fix Bed Process for Arsenic Removal from Water in Small Plants. Universidad Nacional de San Juan, San Juan, Argentina. Available at: http://www.cnea.gov.ar/xxi/ambiental/iberoarsen/docs/Tesis%20Roberto%20E.%20Cáceres.pdf (accessed 12.09) (in Spanish).

Calderón-Fernández, M.L., 2006. Purification of Water for Human Consumption in the Chihuahua State by Alternative Technologies. Documents World Water Forum. Junta Central de Agua y Saneamiento de Chihuahua, Mexico City, Mexico (in Spanish).

Castro de Esparza, M.L., 2009. The presence of arsenic in drinking water in Latin America and its effect on public health. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 17–29.

Castro de Esparza, M.L., Wong de Medina, M., 1998. Reduction of arsenic in groundwater for rural areas. In: XXVI Congreso Interamericano de Ingeniería Sanitaria y Ambiental, 1–5 November 1998, Lima, Peru. (in Spanish).

Claesson, M., Fagerberg, J., 2003. Arsenic in Groundwater of Santiago del Estero – Sources, Mobility Patterns and Remediation with Natural Materials. Master Thesis, Dept. of Land and Wat. Res. Eng., KTH, Stockholm, Sweden, TRITA-LWREX-03-05.

Cornejo, L., Mansilla, H.D., Arenas, M.J., Flores, M., Flores, V., Figueroa, L., Yánez, J., 2004. Removal of arsenic from water of Río Camarones, Arica, Chile, using the modified SORAS technology. OAS AE 141 Project. In: Litter, M.I., Jiménez-González, A. (Eds.), Advances in Economic Solar Technologies for Disinfection, Decontamination, and Removal of Arsenic from Water of Rural Communities of Latin America. Digital Graphic Publisher, La Plata, Argentina, pp. 43–56. http://www.cnea.qov.ar/xxí/ambiental/agua-pura/LibroBN.Pdf (accessed November 2009).

Cornejo, L., Lienqueo, H., Arenas, M., Acarapi, J., Contreras, D., Yañez, J., Mansilla, H.D., 2008. In field arsenic removal from natural water by zero-valent iron assisted by solar radiation. Environmental Pollution 156, 827–831.

Cumbal, L., Bundschuh, J., Aguirre, V., Murgueitio, E., Tipán, I., Chavez, C., 2009. The origin of arsenic in waters and sediments from Papallacta lake in Ecuador. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 81–90.

Cumbal, L.H., SenGupta, A.K., 2009. Polymer-supported Fe(III) oxide particles: an arsenic-selective sorbent. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 571–580.

Cusicanqui, H., Mahon, W.A.J., Ellis, A.J., 1976. The geochemistry of the el Tatio geothermal field, northern Chile. In: 2nd United Nations Geothermal Symposium Proceedings, Lawrence Berkeley Laboratory. Univ. of California, Berkeley, CA.

Czerniczyniec, M., Farías, S., Magallanes, J., Cicerone, D., 2007. Arsenic(V) adsorption solution composition effects. Water Air and Soil Pollution 180, 75–82.

D'Ambrosio, C., 2005. Evaluation and selection of technologies available for arsenic removal. In: Galindo, G., Fernández-Turiel, J.L., Parada, M.A., Gimeno Torrente, D. (Eds.), Arsenic in Water: Origen, Mobility and Treatment. Taller II Seminario Hispano-Latinoamericano sobre temas actuales de hidrología subterránea - IV Congreso Hidrogeológico Argentino. Río Cuarto, 25–28 October 2005, Argentina (in Spanish).

Deschamps, E., Ciminelli, V.S.T., Weidler, P.G., Ramos, A.Y., 2003. Arsenic sorption onto soils enriched with manganese and iron minerals. Clays and Clay Mineral 51, 197–204.

Deschamps, E., Ciminelli, V.S.T., Höll, W., 2005. Removal of As(III) and As(V) from water using a natural Fe and Mn enriched sample. Water Research 39, 5212–5220.

Dias, A., Sá, R.G., Spitale, M.C., Athayde, M., Ciminelli, V.S.T., 2008. Microwave-hydrothermal synthesis of nanostructured Na-birnessites and phase transformation by arsenic(III) oxidation. Materials Research Bulletin 43, 1528–1538.

Ellis, A.J., Mahon, W.A.J., 1977. Chemistry and Geothermal Systems. Academic Press, New York, NY.

Emett, M.T., Khoe, G.H., 2001. Photochemical oxidation of arsenic by oxygen and iron in acidic solutions. Water Research 35, 649–656.

Esparza, M.L., 2004. Presence of arsenic in drinking water in Latin America and its effect on the public health. In: Sancha, A.M. (Ed.), Third International Seminar on Evaluation, and Management of Drinking Water Resources Contaminated by Arsenic (Proceedings Available as CD), Universidad de Chile, November 8–11, 2004 (Santiago de Chile, Chile) (In Spanish).

Esper, J.A.M.M., Amaral, R.D., Ciminelli, V.S.T., 2007. Cover design performance at a Kinross gold mine in Brazil. In: XXII Encontro Nacional de Tratamento de Minérios e Metalurgia Extrativa, Proceedings VII Meeting of the Southern Hemisphere on Mineral Technology, Ouro Preto, Vol. II, Ouro Prieto, Brazil, 607–612.

Farías, S.S., Casa, V.A., Vazquez, C., Ferpozzi, L., Pucci, G.N., Cohen, I.M., 2003. Natural contamination with arsenic and other trace elements in ground waters of Argentine Pampean plain. Science of the Total Environment 309 (1–3), 187–199.

Fostier, A.H., Silva Pereira, M.S., Rath, S., Guimarães, J.R., 2008. Arsenic removal from water employing heterogeneous photocatalysis with TiO_2 immobilized in PET bottles. Chemosphere 72, 319–324.

García, M.G., Lin, H.J., Custo, G., d'Hiriart, J., Hidalgo, M. del, V., Litter, M.I., Blesa, M.A., 2004a. Advances in arsenic removal by solar oxidation from water of Tucumán, Argentina. OAS AE 141 Project. In: Litter, M.I., Jiménez-González, A. (Eds.), Advances in Economic Solar Technologies for Disinfection, Decontamination, and Removal of Arsenic from Water of Rural Communities of Latin America. Digital Graphic Publisher, La Plata, Argentina, pp. 43–56. http://www.cnea.gov.ar/xxi/ambiental/agua-pura/LibroBN.Pdf (accessed 12.09).

Author's personal copy

García, M.G., d'Hiriart, J., Giullitti, J., Lin, H., Custo, G., Hidalgo, M. del, V., Litter, M.I., Blesa, M.A., 2004b. Solar light induced removal of arsenic from contaminated groundwater: the interplay of solar energy and chemical variables. Solar Energy 77 (5), 601–613.

Garrido, S., Avilés, M., 2008. Analysis of Technical Information and Evaluation of the Functionality of the Arsenic Removal Plant, Mixco, Guatemala. Final Report TC 0832.3. Instituto Mexicano de Tecnología del Agua, Jiutepec, Mexico (in Spanish).

Garrido, S., Segura, N., Avilés, M., 2008. Optimization of high arsenic concentration removal in the reject water from capacitive deionization. In: 2nd International Congress Arsenic in the Environment: Arsenic from Nature to Humans, 21–23 May 2008, Valencia, Spain.

Garrido, S., Avilés, M., Ramírez, A., Calderón, C., Ramírez-Orozco, A., Nieto, A., Shelp, G., Seed, L., Cebrian, M., Vera, E., 2009. Arsenic removal from water of Huautla, Morelos, Mexico using capacitive deionization. In: Bundschuh, J., Armienta, M. A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 665–676.

Geucke, T., Deowan, S.A., Hoinkis, J., Pätzold, Ch, 2009. Performance of a small-scale RO desalinator for arsenic removal. Desalination 239, 198–206.

Guérèquiz, A.R., Mañay, N., Goso Aguilar, C., Bundschuh, J., 2006. Assessment of the environmental risk caused by the presence of arsenic in the western area of the Raigón aquifer, department of San José, Uruguay. Taller de distribución del As en Iberoamérica, 27–30 November 2006, Red Temática 406RT0282 Iberoarsen, Centro Atómico Constituyentes, San Martín, Buenos Aires, Argentina, 111–112.

Hammarlund, L., Piñones, J. 2009. Arsenic in Geothermal Waters of Costa Rica —A Minor Field Study. TRITA-LWR MSc Thesis, LWR-EX-09-02. Department of Land and Wayer Resources Engineering, Royal Institute of Technology, Stockholm, Sweden.

Hansen, H.K., Rojo, A., Oyarzun, C., Ottosen, A.R., Mateus, E., 2004. Biosorption of arsenic by *Lessonia nigrescens* in wastewater from cooper smelting. In: Sancha, A.M. (Ed.), Third International Seminar on Evaluation, and Management of Drinking Water Resources Contaminated by Arsenic (Proceedings Available as CD), Universidad de Chile, November 08–11, 2004, Santiago de Chile, Chile Available at: http://www.cepis.ops-oms.org/bvsacd/arsenico/Arsenic2004/theme3/paper3.6.pdf (accessed 11.09). (In Spanish).

Haque, M.N., Morrison, G.M., Perrusquía, G., Gutierréz, M., Aguilera, A.F., Cano-Aguilera, I., Gardea-Torresdey, J.L., 2007. Characteristics of arsenic adsorption to sorghum biomass. Journal of Hazardous Materials 145, 30–35.

Hug, S., 2000. Arsenic contamination of groundwater: disastrous consequences in Bangladesh. EAWAG News 49, 18–20.

Hug, S., Canonica, L., Wegelin, M., Gechter, D., Von Gunten, U., 2001. Solar oxidation and removal of arsenic at circumneutral pH in iron containing waters. Environmental Science and Technology 35, 2114–2121.

Hug, S.J., Leupin, O., 2003. Iron-catalyzed oxidation of arsenic(III) by oxygen and by hydrogen peroxide: pH-dependent formation of oxidants in the Fenton reaction. Environmental Science and Technology 37, 2734–2742.

IADB, 2003. Antofagasta desalination plant. Project Abstract, CH-0171. Interamerican Development Bank, Washington, DC. http://www.iadb.org/pri/projDocs/CH0171_A_E.pdf (accessed 17.09).

Jekel, M., Amy, G.L., 2006. Arsenic removal during drinking water treatment. In: Newcombe, G., Dixon, D. (Eds.), Interface science in drinking water treatment —Theory and application. Interface Science and Technology, vol. 10, pp. 193–206.

Kabay, N., Bundschuh, J., Bruce, H., Bryjak, M., Yoshizuka, K., Bhattacharya, P., Anaç, S. (Eds.), 2010. Global arsenic problem and challenges for safe water. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 2. CRC Press/Balkema Publisher, Leiden, The Netherlands.

Ladeira, A.C.Q., Ciminelli, V., 2004. Adsorption and desorption of arsenic on an oxisol and its constituents. Water Research 38, 2087–2094.

Ladeira, A.C.Q., Ciminelli, V.S.T., Nepomuceno, A.L., 2002. Soil selection for arsenic immobilization. Ouro Preto. REM: Revista Escola Minas 55 (3), 215–221.

Lara, F., Cornejo, L., Yañez, J., Freer, J., Mansilla, H.D., 2006. Solar-light assisted removal of arsenic from natural water: effect of iron and citrate concentrations. Journal of Chemical Technology and Biotechnology 81, 1282–1287.

Lindbäck, K., Sjölin, A.M., 2006. Arsenic in Groundwater in the Southwestern Part of the Río Dulce Alluvial Cone, Santiago del Estero Province, Argentina. Master Thesis. Dept. of Land and Wat. Res. Eng., KTH, Stockholm, Sweden, TRITA-LWREX-06-26.

Litter, M., 2002. Prospect of Latinamerican Rural Communities for Application of Low Cost Technologies for Water Potabilization. OAS Project AE141. Digital Grafic, La Plata, Argentina. Available from:. http://www.cnea.gov.ar/xxi/ambiental/agua-pura/ (accessed 06.05).

Litter, M.I. (Ed.), 2006. Workshop on the Distribution of Arsenic in Iberoamerica. CYTED, Buenos Aires, Argentina Available at: http://www.cnea.gov.ar/xxi/ambiental/iberoarsen/docs/taller06/libroresumenes-taller-2006.pdf (acessed 12.09).

Litter, M.I., Fernández, R.G., Cáceres, R.E., Grande Cobián, D., Cicerone, D., Fernández Cirelli, A., 2008. Low-cost Technologies for Arsenic Removal at Low- and Mediun Scale. Revista Ingeniería Sanitaria y Ambiental 100. published by AIDIS, Buenos Aires, Argentina (in Spanish) 41–50.

Litter, M.I., Morgada, M.E., Bundschuh, J., 2010. Possible treatments for arsenic removal in Latin American waters for human consumption. Environmental Pollution 158, 1105–1118.

Litter, M.I., Jiménez González, A. (Eds.), 2004. Solar Water Disinfection in Latinamerican Rural Communities, OAS Project AE/141. Digital Grafica, La Plata, Argentina Available from: http://www.cnea.gov.ar/xxi/ambiental/agua-pura/ (accessed 12.09).

Litter, M.I., Mansilla, H. (Eds.), 2003. Arsenic Removal Assisted by Solar Light in Rural Communities of Latin America, OAS Project AE/141. Digital Grafic, La Plata, Argentina Available from: http://www.cnea.gov.ar/xxi/ambiental/agua-pura/ (accessed 12.09).

López, D., Ramson, L., Monterrosa, J., Soriano, T., Barahona, J., Bundschuh, J., 2009. Volcanic arsenic and boron pollution of Ilopango lake, El Salvador. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 129–143.

Lorenz, M.G., Izquierdo-Gil, M.A., Sanchez-Reillo, R., Fernández-Pineda, C., 2007. Single CMOS sensor system for high resolution double volume measurement applied to membrane distillation. In: Proc. SPIE 6491.

Luján, J.C., 2001. Arsenic Removal from Water Using Activated Hydrogel of Aluminium Hydroxide. Ciencia, Tecnologia y Medio Ambiente 1(1), Unversidad Tecnológia Nacional, Tucumán, pp. 9–13. (in Spanish).

Author's personal copy

Luján, J.C., Graieb, O.J., 1994. Elimination of Arsenic from Water by Distillation a Household Scale in Rural Areas. Revista Médica 1, Tucumán, Argentina, pp. 247–255. (in Spanish).

Luján, J.C., Graieb, O.J., 1995. Elimination of arsenic from water by distillation a household scale in rural areas. Revista Ciencia y Tecnología 3(7), Universidad Tecnológia Nacional, Tucumán, Argentina, p. 13. (in Spanish).

Mandal, B.K., Suzuki, K.T., 2002. Arsenic round the world: a review. Talanta 58 (1), 201–235.

Martin, A.P., 1997. Optimization of arsenical groundwaters of the north of Santiago del Estero by the use of calcium hydroxide. Congreso Internacional sobre Aguas, Buenos Aires, Argentina, p. II-7. (in Spanish).

Mateu, M. 2007 Arsenic removal by heterogeneous photocatalysis. Master Thesis. University of Buenos Aires, Buenos Aires, Argentina. (in Spanish).

Meichtry, J.M., Lin, H., de la Fuente, L., Levy, I.K., Gautier, E.A., Blesa, M.A., Litter, M.I., 2007. Low-cost TiO_2 photocatalytic technology for water potabilization in plastic bottles for isolated regions. Photocatalyst fixation. Journal of Solar Energy Engineering 129, 119–126.

Mellano, M.F., Ramirez, A.E., 2004. Groundwater Arsenic in the Area Around Maria Elena in Santiago del Estero Province, Northwestern Argentina. Department of Land and Water Resources Engineering KTH, Stockholm, Sweden. TRITA-LWR-EX-04-40.

Mohana, D., Pittman Jr., C.U., 2007. Arsenic removal from water/wastewater using adsorbents—a critical review. Journal of Hazardous Materials 142 (1–2), 1–53.

Morgada de Boggio, M.E., Levy, I.K., Mateu, M., Litter, M.I., 2006. Economic technologies based on heterogeneous photocatalysis and zerovalent iron for arsenic removal in Chacopampean Plain, Argentina. In: Litter, M.I. (Ed.), Final Results of OAS/AE141 Project: Research, Development, Validation and Application of Solar Technologies for Water Potabilization in Isolated Rural Zones of Latin America and the Caribbean, Buenos Aires, Argentina, pp. 11–37 (Chapter 1), OAS (ed). Available at: http://www.cnea.gov.ar/xxi/ambiental/agua-pura/ (accessed 12.09).

Morgada de Boggio, M.E., Levy, I.K., Mateu, M., Litter, M.I., Bhattacharya, P., Bundschuh, J., 2009. Low-cost technologies for arsenic removal in the Chaco-Pampean plain, Argentina. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 677–683.

Morgada de Boggio, M.E., Levy, I.K., Mateu, M., Meichtry, J.M., Farías, S., López, G.D., Bahnemann, D., Dillert, R., Litter, M.I., 2010. Low-cost solar technologies for arsenic removal in drinking water. In: Kabay, N., Bundschuh, J., Bryjak, M., Yoshizuka, K., Bhattacharya, P., Anaç, S. (Eds.), Global Arsenic Problem and Challenges for Safe Water Production. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 2. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 209–218.

Morgada, M.E., Mateu, M., Bundschuh, J., Litter, M.I., 2008. Arsenic in the Iberoamerican region. The IBEROARSEN Network and a possible economic solution for arsenic removal in isolated rural zones. e - T e r r a. Revista Electrónica de Ciências da Terra, Geosciences On-line Journal. ISSN: 1645-0388 5 (5). ISSN: 1645-0388. http://e-terra.geopor.pt.

Morgada, M.E., Levy, I.K., Salomone, V., Farías, S.S., López, G., Litter, M.I., 2009. Arsenic (V) removal with nanoparticulate zerovalent iron: effect of UV light and humic acids. Catalysis Today 143, 261–268.

Muñiz, G., Manjarrez-Nevárez, L.A., Pardo-Rueda, J., Rueda-Ramírez, A., Torres-Muñoz, V., Ballinas-Casarrubias, M.L., 2009. Filter development from low cost materials for arsenic removal from water. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 657–663.

Muñoz, M.A., Buitrón, J.A., De Ormaechea, B., 2005. Removal of arsenic and fluor; a case study from the locality of Eduardo Castex, La Pampa. In: Galindo, G., Fernández-Turiel, J.L., Parada, M.A., Gimeno Torrente, D. (Eds.), Arsenic in Water: Origen, Mobility and Treatment. Taller. II Seminario Hispano-Latinoamericano sobre temas actuales de hidrología subterránea - IV Congreso Hidrogeológico Argentino. Río Cuarto, 25–28 October 2005, (Argentina) (in Spanish).

Murcott, S., 2001. A comprehensive review of low-cost, tubewell water treatment technologies for arsenic removal. In: Chappell, W., Abernathy, C., Calderón, R.I. (Eds.), Arsenic Exposure and Health Effects IV. Elsevier Science Ltd., pp. 419–429.

Newcombe, R.L., Möller, G., 2006. Arsenic Removal from Drinking Water: a Review. Blue water technologies, Inc., Hayden, ID. http://www.blueh2o.net/docs/asreview%20080305.pdf (accessed 07.09).

Olmos-Márquez, M.A., Benavides-Montoya, A., Rosette, M., Alarcón-Herrera, M.T. 2009. The arsenic removal efficiency of Eleocharis Macrostachya in constructed wetlands with subsurface flow. In: Proceedings of the 3rd Wetland Pollutant Dynamics and Control WETPOL, 20–24 September 2009, Barcelona, Spain.

Ongley, L.K., Armienta, M.A., Heggeman, K., Lathrop, A., Mango, H., Miller, W., Pickelner, S., 2001. Arsenic removal from contaminated water by the Soyatal Formation, Zimapán mining district, Mexico—a potential low-cost low-tech remediation system. Geochemistry: Exploration, Environment, Analysis 1, 23–31.

Petkova Simeonova, V., 1999. Pilot studies for arsenic removal, State of Hidalgo. Revista de Ingeniería Hidráulica en México 14, 65–77 (in Spanish).

Petkova-Simeonova, V.M., Rivera-Huerta, M.L., Piña-Soberanis, M., 1995. Removal of Iron and Manganese by Adsorption on Non-conventional Conact Media. Final Report TC-9531. Instituto Mexicano de Tecnología del Agua, Jiutepec, Morelos, Mexico (in Spanish).

Petry, M., Sanz, M.A., Langlais, C., Bonnelye, V., Durand, J.-P., Guevara, D., Mantovani Nardes, W., Homma Saemi, C., 2007. The El Coloso (Chile) reverse osmosis plant. Desalination 203, 141–152.

Pirnie, M., 2000. Technologies and Costs for Removal of Arsenic from Drinking Water. US EPA Report 815-R-00–028.

Quintanilla, J., Ramos, O., Ormachea, M., García, M.E., Medina, H., Thunvik, R., Bhattacharya, P., Bundschuh, J., 2009. Arsenic contamination, speciation and environmental consequences in the Bolivian plateau. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 91–99.

Rivara, M., Cebrian, M., Corey, G., Hernandez, M., Romieu, I., 1997. Cancer risk in an arsenic contaminated area of Chile. Toxicology and Industrial Health 13 (2–3), 321–338.

Rivera, M., Cortés, J., Soberanis, M., Domínguez, A., 2000. Removal of iron and arsenic from water for human consumption by precipitation and adsorption in Zimapán, Hidalgo, Mexico. In: XXVII Congresso Interamericano de Engenharia Sanitária e Ambiental, Porto Alegre, Brazil, 3–8 December 2000. (in Spanish).

Rivera, M.L., Piña, M., 2004. A pilot study for arsenic removal from water by adsorption in natural zeolite adsorption in presence

Author's personal copy

of iron and manganese. In: Sancha, A.M. (Ed.), Third International Seminar on Evaluation, and Management of Drinking Water Resources Contaminated by Arsenic (Proceedings Available as CD), Universidad de Chile, 8–11 November 2004, Santiago de Chile, Chile, 2004 Available at: http://www.cepis.ops-oms.org/bvsacd/arsenico/Arsenic2004/theme3/paper3.14.pdf (accessed 12.09). (in Spanish).

Romero, F.M., Armienta, M.A., Carrillo-Chavez, A., 2004. Arsenic sorption by carbonate-rich aquifer material, a control on arsenic mobility at Zimapán, Mexico. Archives of Environmental Contamination and Toxicology 47 (1), 1–13.

Sancha, A.M., 2002. Removal of arsenic from drinking water supplies: Chile experience. Water Supply 18 (1), 621–625.

Sancha, A.M., 2003. Removing arsenic from drinking water. A brief review of some lessons learned and gaps arisen in Chilean water utilities. In: Chappell, W., Abernathy, C., Calderón, R., Thomas, D. (Eds.), Arsenic Exposure and Health Effects. Elsevier B.V., New York, pp. 471–481.

Sancha, A.M., 2006. Review of coagulation technology for removal of arsenic: case of Chile. Journal of Health, Population, and Nutriation 24 (3), 267–272.

Sancha, A.M., O'Ryan, R., Pérez, O., 2000. The removal of arsenic from drinking water and associated costs: the Chilean case. In: Interdisciplinary Perspectives on Drinking Water Risk Assessment and Management, vol. 260. IAHS Publ., pp. 17–25.

Sancha, A.M., Fuentealba, C., 2009. Application of coagulation–filtration processes to remove arsenic from low-turbidity waters. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 687–697.

Sastre, M.S., Rodríguez, H., Varillas, A., Salim, B., 1997. Endemic Chronic Regional Hydroarsenism (ECRH) and Community. Congreso Internacional sobre Aguas, Buenos Aires, Argentina, p. W-13 (in Spanish).

Shih, M.C., 2005. An overview of arsenic removal by pressure-driven membrane processes. Desalination 172, 85–97.

Silva, G.C., Vasconcelos, I.F., Carvalho, R.P., Dantas, M.S.S., Ciminelli, V.S.T., 2009. Molecular modeling of iron and arsenic interactions with carboxyl groups in natural biomass. Environmental Chemistry 6, 1–7.

Smedley, P.L., Kinniburgh, D.G., Macdonald, D.M.J., Nicolli, H.B., Barros, A.J., Tullio, J.O., Pearce, J.M., Alonso, M.S., 2005. Arsenic associations in sediments from the loess aquifer of La Pampa, Argentina. Applied Geochemistry 20, 989–1016.

Smedley, P.L., Nicolli, H.B., Macdonald, D.M.J., Kinniburgh, D.G., 2009. Arsenic in groundwater and sediments from La Pampa province, Argentina. In: Bundschuh, J., Armienta, M.A., Birkle, P., Bhattacharya, P., Matschullat, J., Mukherjee, A.B. (Eds.), Natural Arsenic in Groundwater of Latin America. In: Bundschuh, J., Bhattacharya, P. (Eds.), Arsenic in the Environment, vol. 1. CRC Press/Balkema Publisher, Leiden, The Netherlands, pp. 35–45.

Storniolo, A., Martín, R., Thir, M., Cortes, J., Ramirez, A., Mellano, F., Bundschuh, J., Bhattacharya, P., 2005. Reduction of the arsenic content in water using natural geological materials. In: Galindo, G., Fernández-Turiel, J.L., Parada, M.A., Gimeno Torrente, D. (Eds.), Arsenic in Water: Origen, Mobility and Treatment. Taller. II Seminario Hispano-Latinoamericano sobre temas actuales de hidrología subterránea - IV Congreso Hidrogeológico Argentino. Río Cuarto, 25–28 October 2005. Argentina, 173–182 (in Spanish).

Teixeira, M.C., Ciminelli, V.S.T., 2005. Development of a biosorbent for arsenite: structural modeling based on X-ray spectroscopy. Environmental Science & Technology 39 (3), 895–900.

Wegelin, M., Gechter, D., Hug, S., Mahmud, A., Motaleb, A., 2000. SORAS—a simple arsenic removal process. In: Water, Sanitation, Hygiene: Challenges of the Millennium. 26th WEDC Conference, Dhaka, Bangladesh, 379–382.

WHO, 2001. Guidelines for Drinking-water Quality: Arsenic in Drinking Water. Fact Sheet No. 210. World Health Organization, Geneva, Switzerland.

View publication stats

ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/45271138

Emerging Mitigation Needs and Sustainable Options for Solving the Arsenic Problems of Rural and Isolated Urban Areas in Latin America – a Critical Analysis

Article *in* Water Research · November 2010

DOI: 10.1016/j.watres.2010.04.001 · Source: PubMed

CITATIONS
119

READS
793

10 authors, including:

Jochen Bundschuh
University of Southern Queensland
352 PUBLICATIONS **9,102** CITATIONS

SEE PROFILE

Marta I Litter
National University of General San Martín
228 PUBLICATIONS **10,808** CITATIONS

SEE PROFILE

V. Ciminelli
Federal University of Minas Gerais
152 PUBLICATIONS **4,446** CITATIONS

SEE PROFILE

Maria eugenia Morgada
National University of Technology
24 PUBLICATIONS **1,031** CITATIONS

SEE PROFILE

Some of the authors of this publication are also working on these related projects:

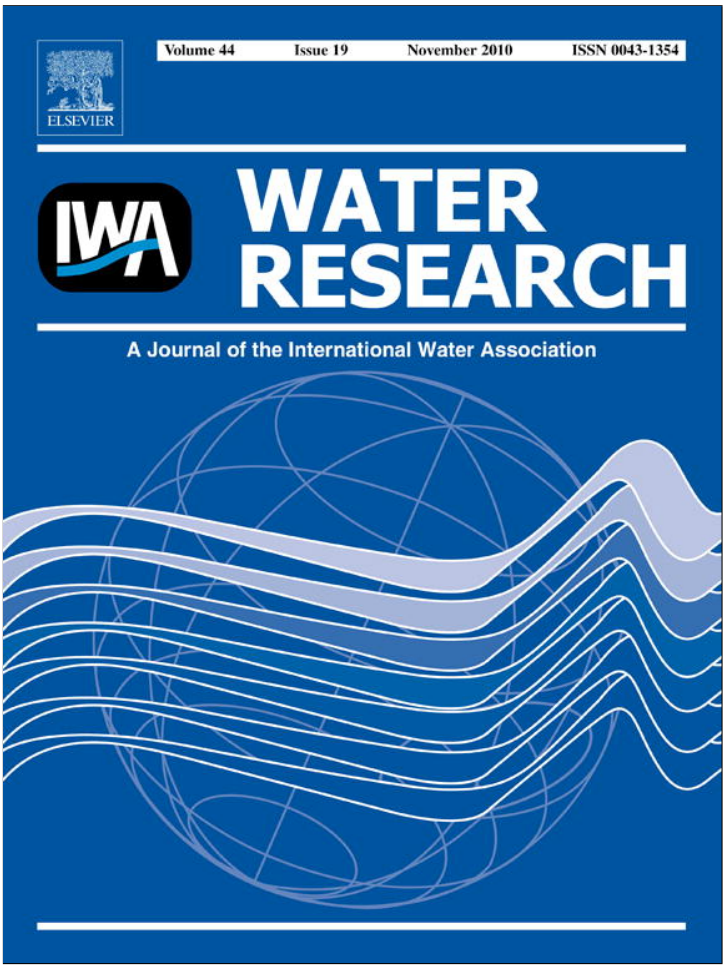
Project Environment and neotectonics View project

Project Geogenic and Pathogenic Contamination: Issues and Innovation in the Post- COVID-Anthropocene View project

All content following this page was uploaded by Sofia Garrido Hoyos on 29 June 2018.

The user has requested enhancement of the downloaded file.

Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright