Managing Hazardous Pollutants in Chile: Arsenic

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Contents

1 Introduction

Chile is one of the few countries confronted with environmental challenges posed by extensive arsenic pollution, which exists in the northern part of the country. Naturally occurring arsenic in Chile derives from volcanic activity in the Andes Mountains and affects water, air, and soils. Additionally, copper mining and smelting activities, major economic activities in Chile, are important anthropogenic sources

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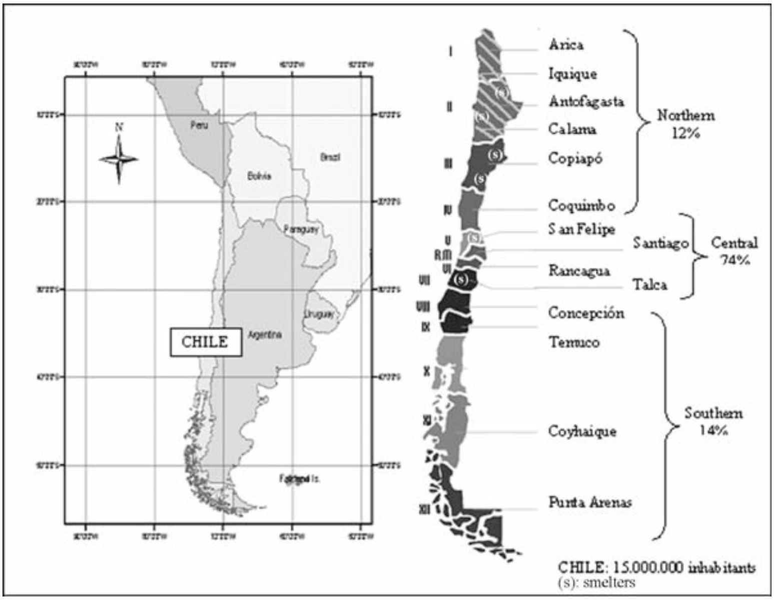

Fig. 1 Geographic distribution of population (% by zone), main cities, and smelters in Chile

of arsenic. The high levels of arsenic contamination in the north of Chile, and the economic consequences of mitigating the contamination in water and air, have not allowed copying standards applied in other countries.

In Chile, approximately 1.8 million people, representing about 12% of the total population, live in arsenic-polluted areas (Fig. 1). Until recently, water consumed by the urban population contained levels of arsenic that were much higher than the values recommended by the World Health Organization (WHO). The air near many large cities is also contaminated with arsenic in variable amounts, which derives from both natural sources and intensive mining activity near those cities. In rural areas, indigenous populations are exposed to arsenic by consuming polluted water and various foods grown locally in arsenic-contaminated soils.

The health effects of arsenic were first discovered in the 1950s, when vascular, respiratory, and skin lesions from drinking arsenic-contaminated drinking water were observed in children and adults. Methodologies were evaluated and technology developed to mitigate arsenic in polluted water sources, which was accomplished at a relatively low cost. Abatement began in the 1970s, with construction and operation of treatment plants designed to remove arsenic from contaminated water supplies. An exacerbating factor is that water is extremely scarce in northern Chile, where the Atacama Desert exists; this desert is among the driest in the world.

During the 1980s and early 1990s, epidemiological studies showed that the rate of lung and bladder cancer in the northern zone was considerably higher than the mean cancer rate of the general Chilean population. Exposure to arsenic was regarded to be the source of this increased incidence of cancer.

In the 1990s, the presence of high arsenic levels in the vicinity of copper smelters gave rise to action by Chile's Health Ministry to regulate arsenic smelter emissions.

The measures undertaken to reduce atmospheric arsenic levels by regulating emissions from copper smelting plants in northern Chile were prompted, to some extent, by international pressures and concerns.

The process of establishing emission standards to abate arsenic was unique for a developing country. The process included an extensive evaluation of both risks and costs for various abatement options. The evaluation was challenging because of a general lack of systematic information on health effects, emission and contamination levels, control technologies, and related costs. To address this dearth of information, a research project entitled "Protection of the Competitiveness of Chile's Mining Products: Antecedents and Criteria for Environmental Regulation of Arsenic" (FONDEF 2–24 1997) was undertaken from 1994 to 1996. In this project, the independent Universidad de Chile, working with the Ministries and mining and sanitary companies involved, developed the required information. As a result, considerable experience was gained on how to manage this type of hazardous pollution, particularly in the context of evaluating trade-offs among production, control costs, and health improvement.

More recently, the local community has pushed for more significant reductions of arsenic concentrations in air and water, mainly because of their increasing awareness and knowledge concerning risks from exposure to arsenic.

In this chapter, we present a historical assessment of arsenic contamination in Chile. Levels of arsenic in air, water, soils, and vegetables, together with the implications to health and patterns of exposure, are reviewed. Moreover, we relate the important lessons learned on how a developing country approaches regulation of a hazardous pollutant in the face of scarce financial, technical, and human resources.

2 Arsenic Contamination in Chile

2.1 Arsenic Levels in Air, Water, Soil, and Food

Background Levels

Knowledge of background levels of a particular contaminant in its ambient state is a fundamental requirement before the pollutant can be regulated. In Chile, the regional geology and extent of mining activities determine what relative environmental arsenic levels are likely to be encountered in Chile's northern, central, and southern zones (Enriquez 1978). In this section we review what is known of arsenic levels in Chile's air, water, soil, and food.

Air

The literature provides scant information on arsenic levels in air, regardless of country, although data from work sites are available (EHC 1981). A detailed study of airborne arsenic concentrations in principal Chilean cities was made during the period 1994–1995 (Ulriksen and Cabello 2004). Levels of breathable particulate airborne arsenic (PM-10) were determined by taking 24-hr samples for a 7-d period

Table 1 Concentrations of arsenic (As) in atmospheric particulate matter for selected Chilean cities

Cities	Period (yr)	No. of samples	Concentration (μg/m^3)	
			Average	Maximum
Northern zone				
Arica	01/96–02-96	10	0.004	0.007
Iquique	06/94–06/95	85	0.025	0.037
Antofagasta	06/94–06/95	93	0.057	0.088
Central zone				
Viña del Mar	06/94–03/95	84	0.026	0.051
Santiago	07/94–06/95	83	0.02	0.037
Rancagua	06/94–06/95	85	0.038	0.081
Talca	06/94–06/95	84	0.003	0.007
Southern zone				
Concepción	06/94–06/95	84	0.007	0.016

once each month for an entire year. These measurements were designed to determine average annual values, seasonal variations, and day-to-day variations while optimizing use of resources and minimizing monitoring and analysis costs. In the southern zone, samples were taken only at the city of Concepción, because it is known that, in this region, neither natural geological nor anthropogenic sources of arsenic contamination exist. Table 1 presents the results of this airborne arsenic contamination study.

Sampling results indicate that the lowest levels of arsenic were found in Arica, Talca, and Concepción, cities relatively distant from mining activities. The highest arsenic concentrations were registered at Antofagasta, a city in the northern zone, where geological sources of arsenic have been exacerbated by anthropogenic contamination from smelting emissions.

In the central zone, the city of Rancagua also registered high airborne arsenic levels from nearby copper smelting activity. Although distant from such activity, Santiago recorded midrange arsenic levels, influenced both by combustion of coal and petroleum and, probably, by other unidentified industrial sources.

The reported analytical results for arsenic have the usual sources of uncertainty. Other than the standard sampling uncertainty, there are variations over time, both in the mineral composition of the ore smelted and in patterns of production utilized, as well as in seasonal variability and meteorological factors. However, for cities unaffected by mining activity, we presume reported airborne arsenic levels reasonably represent actual historic levels of arsenic pollution.

Water

The natural quality of water in Chile is closely related to the geochemical characteristics of the soils and rocks with which it comes into contact. Table 2 shows arsenic levels that exist in a variety of rivers in Chile. These results show that

Table 2 Arsenic concentrations in water of selected Chilean rivers, by geographic zone

Rivers	Arsenic range (μg/L)
Northern zone	
San José	50–100
Lluta	600–700
Toconce	600–900
Lequena	150–350
Colana	70–90
Siloli	20–50
Inacaliri	80–90
Central zone	
Elqui	50–60
Blanco	20–30
Aconcagua	10–20
Maipú	10–20
Mapocho	10–20
Southern zone	
Bío-Bío	<5
Valdivia	<5

hydrological resources in the north of Chile generally have elevated, if variable, arsenic levels. To satisfy water quality criteria, these rather high levels require water treatment before consumption by urban residents of this zone. However, among indigenous peoples of the Altiplano, most still consume untreated waters (Sancha et al. 1995, 1997; Queirolo et al. 2000a).

Studies of arsenic speciation in water indicate that arsenic generally exists as As^{+} (V) (Sancha et al. 1992a,b). In addition to arsenic, many northern waterways also contain boron (B), an element whose deleterious effects on public health is only recently beginning to be explored. Both elements are of concern to regional authorities.

Soils and Vegetables

Several studies (De Gregori et al. 2003, 2004; Queirolo et al. 2000b) demonstrate that a wide range of arsenic concentrations are found in Chilean soils (Fig. 2). Elevated arsenic levels are encountered in nearly all soils in the northern zone. Such contamination is of geological origin and is distributed and enhanced through crop irrigation, and it is also a by-product of mining activity.

Studies of arsenic residues in vegetables and fruit sold in farmers' markets and grocery stores reveal significant concentration differences among zones (Fig. 3). High arsenic levels were found in irrigated vegetables and in soils of indigenous communities of the Altiplano (Table 3). It was noted that the concentration of

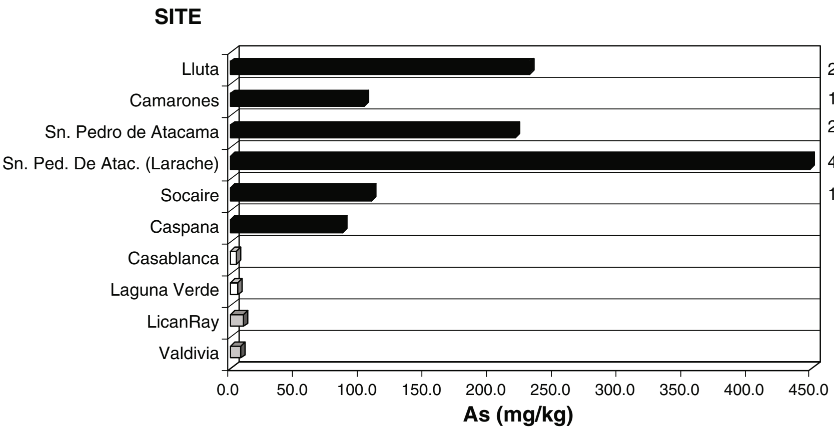

Fig. 2 Arsenic levels in soils from various Chilean cities

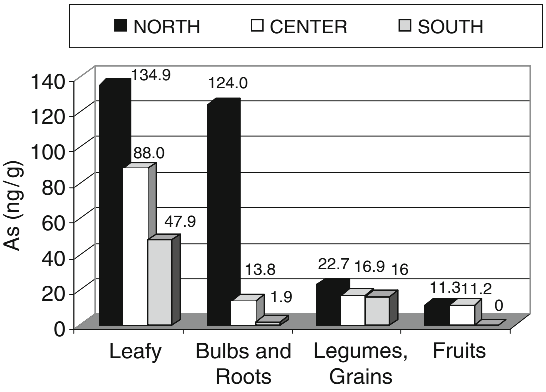

Fig. 3 Arsenic in vegetables and fruits grown in Chile. Leafy vegetables include Swiss chard, lettuce, parsley, spinach, etc. Bulbs and roots include garlic, beets, carrots, onions, potatoes, etc. Legumes and grains include beans, corn, peas, etc. Fruits include apples, pears, grapes, and peaches

Table 3 Arsenic concentrations in water, soil, and vegetables cultivated in the Altiplano

					Vegetables (As µg/g)				
Site[a]	Water (As µg/L)	Soil (As µg/g)	Cabbage	Radish	Beet	Chard	Potato	Garlic	Onion
1	2	86.0	–	–	–	0.218	–	0.018	0.036
2	172	220.5	0.054	0.207	–	0.282	0.040	–	0.106
3	220	108.5	0.033	–	0.156	–	0.044	0.050	–
4	619	448.0	0.715	0.938	0.520	0.718	–	–	–

[a] *Sites*: 1, Caspana; 2, San Pedro de Atacama (Condeduque); 3, Socaire; 4, San Pedro de Atacama (Larache).

arsenic in the same crop varieties depended on arsenic levels in irrigation water and soil in which these crops come into contact (Sancha et al. 1995). Although these results are interesting, they do not define a clear cause-and-effect relationship.

Agricultural production in such Altiplano communities is very limited because of high water and soil salinity, characteristic of the zone. For this reason, crops grown here are consumed locally and do not reach the larger cities of Chile's north.

Studies of arsenic levels in vegetables from As-endemic areas have increased in recent years (Queirolo et al. 2000a; Muñoz et al. 2002; Díaz et al. 2004). However, comparisons of results from one study to another are challenging, because, as some studies point out, arsenic levels found may depend on bioavailability of arsenic in soil (Flynn et al. 2002; Roychowdhury et al. 2002, 2003; Alam et al. 2003). Such bioavailability is known to be affected by soil pH, organic matter content, clay content, and clay type, among other variables. Another factor that may affect residue levels is the irrigation method utilized; drainage that cleanses soil could diminish bioavailability (Ayers and Westcot 1994).

2.2 Population Exposure

Chile's particular geological conditions and anthropogenic activities result in higher levels of environmental exposure to arsenic than levels considered normal in the literature. This is particularly true in Chile's northernmost region, but less so in the central zone (see Fig. 1). The cities of Antofagasta and Calama are especially affected by this contaminant.

Early estimates of arsenic exposure to the Chilean population were obtained in the 1990s. These data opened the way for evaluating the relative contribution to human arsenic exposure provided by various environmental media (air, water, and food) (Sancha et al. 1997; Sancha and Frenz 2000). Additionally, available tools were utilized to make approximations of total arsenic intake from food, water, and air (Table 4). Among arsenic exposure data used were surveys of schoolchildren and adolescents (Ivanovic et al. 1986, 1987), and model diet data on adults recommended by the Ministry of Health. Although measures of consumption were indirect, the tools and surveys used represent good estimates of Chilean food consumption founded upon national cultural eating patterns. Rates used to estimate water and air

Table 4 Total arsenic exposure by geographic zone among Chilean population groups

	Total arsenic exposure (ng person d^{-1})		
Zone	Adults	Adolescents	Preadolescents
Northern	85.1	52.8	60.9
Central	42.2	29.0	23.3
Southern	23.2	17.7	12.9

intake were also those established by the Chilean Ministry of Health. Once estimates for air, water, and food intake were assembled, calculations of human exposure were made using arsenic concentrations found in these substrates at different points in the country.

Results reveal that, when compared to international standards, individuals living in Chile's northern zone have arsenic exposures that are abnormally high and unhealthy. Results also show a clear tendency of decreasing total arsenic exposure as one progresses from the north to the south of Chile; this decline in exposure appears to closely correlate with the abundance of naturally occurring elements (arsenic, etc.) and the proximity to anthropogenic mining activities.

The relative proportion of total arsenic exposure to adults accounted for by air, food, and water is presented in Table 5. Drinking water constitutes the most important exposure pathway for urban populations in both northern and central Chile. In the south, exposure is similar to that in other countries that do not have the Chilean combination of natural geological arsenic pollution coupled with anthropogenic sources of arsenic (Dabeka et al. 1993). Results show that, nationwide, airborne arsenic is the least significant exposure source for people. However, the situation can be very different at or near mining sites, where this contamination is a relevant health issue. Finally, in contrast to the pattern in Chile, foodstuffs typically represent a high percentage of total arsenic exposure in most countries. This distribution of arsenic exposure by source (air, water, food) correlates closely with the nature of Chilean geology and mining activities, and the fact that Chilean urban populations are supplied with foodstuffs from agricultural and livestock breeding areas that are generally not contaminated by arsenic.

Table 5 Percent contribution of total arsenic exposure by intake pathway for residents of various Chilean cities

		Arsenic contribution (%)		
Zone	Cities	Water	Air	Foods
Northern	Arica	56.91	1.58	41.51
	Iquique	89.15	0.4	10.45
	Antofagasta	81.77	1.46	16.78
	Calama	82.91	2.77	14.32
	Copiapó	33.21	12.29	54.5
	Coquimbo	46.82	1.95	51.23
Central	San Felipe	25.3	1.3	73.4
	Santiago	72.7	0.9	26.4
	Rancagua	69.3	2	28.7
	Talca	46.2	0.3	53.5
Southern	Concepción	19.2	1.3	79.5
	Temuco	19.4	0.4	80.2
	Coyhaique	19.4	0.4	80.2
	Puntas Arenas	19.4	0.4	80.2

The evolution of arsenic exposure in Antofagasta was evaluated under the assumption that levels in air and foodstuffs have remained nearly constant whereas those in water have varied. The evaluation indicated that, until the 1980s, water contributed more than 90% of total arsenic exposure; since 2004, that figure declined so that approximately 50% of total exposure comes from water. Simultaneously, the percentage contribution of foodstuffs to arsenic exposure has increased. Before 1990, air represented less than 1% of total arsenic exposure in Antofagasta, whereas since 2004 its contribution to overall arsenic exposure has increased to about 3.3% (Table 6).

2.3 *Health Effects*

High exposure in Chile's north to arsenic during 1950–1970 produced early health effects, including increased rates of infant mortality. Table 7 provides a historic record of average arsenic concentrations in Antofagasta drinking water.

The excess incidence of death for the period 1958–1965 was estimated to be between 18% and 24% (Hopenhayn-Rich et al. 2000). Children were reported to suffer from arsenicosis (Borgoño and Greiber 1971; Bruning 1968) and from arsenicosis associated with respiratory symptoms, including diffuse and segmentary bronchiectasis (Borgoño and Greiber 1971). In the general population, excessive rates of respiratory symptoms and vascular disorders associated with arsenic exposure appeared (Borgoño et al. 1977; Zaldivar 1980; Puga et al. 1973; Rosenberg 1974).

Table 6 Historic relative contributions of arsenic exposure from water, air, and food among the population of Antofagasta

	Arsenic contribution (%)		
Period	Water	Air	Food
1930–1957	92.47	0.59	6.94
1958–1970	99.16	0.07	0.78
1971–1979	93.76	0.49	5.80
1981–1987	90.53	0.74	8.73
1988–2003	84.53	1.20	14.26
2004–2006	57.73	3.29	38.97

Table 7 Average concentrations of arsenic in the drinking water of Antofagasta (northern Chile) for various periods since 1930

Period	Arsenic (μg/L)
1930–1957	90
1958–1970	860
1971–1979	110
1980–1987	70
1988–2003	40
2004–2007	10

The high risk of death from lung cancer in Antofagasta was first reported and described for the period 1976–1978. Standard Mortality Rates (SMRs) from lung cancer in Antofagasta were five times greater than was the national average (Haynes 1983).

An epidemiological study conducted in 1994–1996 generated data on arsenic exposure and death rates from cancers of the lung, bladder, kidney, and skin for the period 1950–1996. The study authors concluded that the most significant public health effect of the presence of arsenic in drinking water was lung cancer (Ferreccio et al. 2000). The main causes of relative excess of mortality, adjusted for age and sex, in Antofagasta during 1985–1992 were from bladder cancer, followed by lung cancer. The high risk for lung cancer in Antofagasta persisted for 20–30 yr after operation of water treatment plants, built to remove arsenic, began. From 1993 to 2002, the risk of dying from bladder or lung cancer in Antofagasta was four and seven times higher, respectively, than in the rest of Chile (Ferreccio and Sancha 2006). Other epidemiological investigations produced similar results (Smith et al. 1998; Rivara et al. 1997).

These rates are expected to decrease, in the coming years, because of significant diminution of arsenic concentrations in drinking water. However, the impact of increased arsenic emissions into the atmosphere—mitigated somewhat by the trapping of gases in recent years—may have negative consequences in the coming decades.

3 Removing Arsenic from Water

3.1 Arsenic Removal Technologies Used in Chile

High arsenic water levels exist in the north of Chile, a region characterized by water scarcity. For this reason, water treatment must preserve as much usable water as possible. The literature discloses that the most commonly available technologies for removing arsenic from water are founded on one or more of the following principles: coagulation/precipitation, adsorption, ionic exchange, or membrane filtration. The first, coagulation and precipitation, is a classic process for treating water to remove arsenic; the others are advanced processes of more recent development. Some of the latter processes have the disadvantage of consuming large amounts of water.

Removal of arsenic from water can be a very expensive process. Costs may exceed the means of those benefited, requiring careful selection of the technology to be utilized. The selection must first consider the characteristics of the water to be treated. Characteristics of surface waters and groundwater may be similar or different (Table 8). Some waters contain ions that compete with arsenic for adsorption sites or ionic interchange and thereby may reduce the efficiency of the removal process (Holm 2002; Meng et al. 2000; Clifford 1999).

In Chile, studies undertaken in the 1960s made it possible to appreciate the potential of the coagulation/precipitation process for effectively removing arsenic from water (Latorre 1966). This process was widely known and used at the time, and is still used today. A main feature of the process is that it allows suspended solids removal

Table 8 Principal characteristics of water found in northern Chile

		Water source	
Parameter	Unit	Surface water Range	Groundwater Range
pH		8.0–8.4	7.0–8.0
Total dissolved solids	mg/L	700–800	730–790
Arsenic	ug/L	400–600	60–80
Sulfate	mg/L	80–100	—
Chloride	mg/L	120–140	—
Alkalinity	mg/L CaCO3	100–120	50–60
Hardness	mg/L CaCO3	130–150	350–400
Silica	mg/L SiO2	20–30	20–30
Boron	mg/L	3–4	2–5
Dissolved organic carbon	mg/L	Negligible	Negligible
Dissolved arsenic	µg/L	400–600	60–80
Particulated arsenic	µg/L	Negligible	Negligible

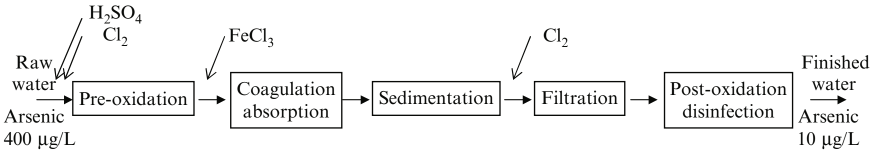

Fig. 4 General schematic for the most common Chilean arsenic-removal process for surface water

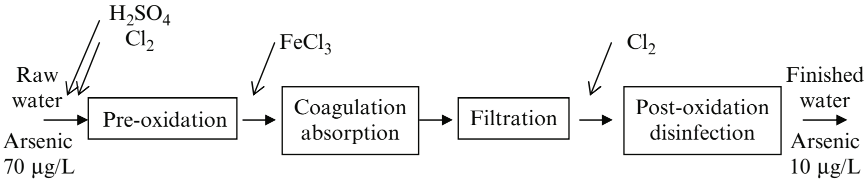

Fig. 5 General schematic for the most common Chilean arsenic-removal process for groundwater

from water by forming aluminum or iron oxyhydroxides. Research demonstrated that arsenic is adsorbed by such oxyhydroxides, resulting in removal of arsenic in its particulate form. The coagulation/precipitation process removes only arsenic.

Beginning in the 1970s, coagulation was used in Chile for large-scale arsenic removal from both surface waters and groundwater (Figs. 4, 5). In 1990, there were four treatment plants for removing arsenic from surface drinking water sources in Antofagasta and Calama, with a total combined normal treatment capacity of 1,730 L/sec. In 1998, a small plant of 32 L/sec was placed in operation in Taltal to treat groundwater (Table 9).

The efficiency of coagulation in removing arsenic from water depends on such factors as pH of the waters treated, dose of coagulant, and filtrate flux and backwash interval. These factors can all be controlled and adjusted, as required, in the operation of treatment plants. Other factors, such as mixing times and energy usage levels,

Table 9 Water treatment facilities for arsenic removal in Chile

Utility	Capacity (L/sec)	Water sources[a]	As range (μg/L)
Salar del Carmen Complex[b]			
Old plant (1970)	500	Toconce	600–900
		Lequena	150–350
New plant (1978)	520	Quinchamale	100–250
		Siloli Polapi	<50
Cerro Topater[b] (1978)	500	Toconce	600–900
		Lequena	150–350
		Quinchamale	140–250
Chuquicamata[b] (1989)	210	Colana	70–90
		Inacaliri	80–90
Taltal[c] (1998)	32	Agua Verde	60–80

[a] The names in this column for surface water sources refer to rivers.
[b] Surface water.
[c] Groundwater.

must be considered in the basic design of the plant. Numerous investigators have studied this first factor (McNeill and Edwards 1995, 1997; Scott et al. 1995; Cheng et al. 1994; Edwards 1994). For treatment purposes, it is necessary to know the As(III)/(V) speciation ratio in the water. As(III), which is a uncharged molecule and a weak ligand, is much more difficult to remove from water than are the anionic As(V) forms, which are readily removed by adsorption onto aluminum or iron oxyhydroxides formed during coagulation processes (Clifford 1999).

Recent studies conducted in Chile, using waters of low turbidity, compared efficiencies and costs of arsenic removal using coagulation and adsorption onto different media. Results show that, in Chile, coagulation is the more cost-effective technology (Fuentealba 2003). In the early years after 2000, the coagulation process was improved to further reduce amounts of arsenic from water in all Chilean water treatment plants (Granada et al. 2003). For Chile, coagulation is a viable technology for meeting the arsenic Maximum Contaminant Level (MCL) of 10 μg/L.

An alternative process, adsorption, has been judged to be disadvantageous for Chile because of both the volume of water consumed during treatment and the high cost of adsorbent material. The limited information available on regenerating absorbent media, and media disposal problems, are additional factors that detract from use of adsorption processes.

Disposal of residuals generated by arsenic removal processes is another important issue and consideration. In Chile, these arsenic residuals were disposed of in the desert during the early years without taking special precautions. Beginning in approximately 2000, disposal began at specially engineered sites. These sites use a geotextile barrier lining beneath disposed arsenic waste, and are then covered with a capping barrier system (Cerda et al. 1999).

3.2 Costs

As previously discussed, there are currently four large plants in Chile that treat raw water to remove arsenic for the purpose of producing safe drinking water. The operation of these plants requires the addition of an oxidant and coagulant (chlorine and ferric chloride, respectively) to produce clean water. These plants have successfully met drinking water standards set by different regulations from the 1970s (120 μg/L) to the present (10 μg/L).

In 1997, a goal of the FONDEF project was to evaluate the costs of further reducing arsenic concentrations in drinking water. Table 10 summarizes options developed to effect such reductions for arsenic in drinking water in Antofagasta (Sancha et al. 2000). When judging feasibility, we considered (i) the technology currently used in Chile and its availability on the international market; (ii) the effectiveness of arsenic removal with each technology; (iii) the special problem of water scarcity in northern Chile; and (iv) the coastal location of Antofagasta.

Experience in Chile with coagulation to remove arsenic, along with the results of a new study by González (1997), indicated that coagulation could achieve a residual arsenic level of <0.030 mg/L, if an improved process were used. Technical experience suggested that, to attain a residual level of <0.020 mg/L, a double filtration system would have to be used. Residual arsenic values of 0.010 mg/L or lower could only be achieved using membrane filtration such as reverse osmosis, which requires water preconditioning by coagulation. Another alternative for attaining greater levels of arsenic removal is to mix the effluent from the current treatment system with desalinated seawater.

Figure 6 presents annualized costs of removing arsenic from drinking water in Antofagasta, as evaluated in 1997. These costs include (i) all capital investments needed to implement the removal operation or related costs; (ii) fixed and variable operating costs per year; (iii) repair and maintenance costs; and (iv) any economic credits received as a result of increased water availability, when applying a given option.[1]

Table 10 Feasible options for removing arsenic from drinking water in Antofagasta

	Targets (mg arsenic/L)				
Options	0.03	0.02	0.01	0.005	0.002
Improvement of current system	X	X			
Reverse osmosis	X	X	X	X	X
Desalination			X	X	X

Source: FONDEF 2-24 Project.

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[1] To estimate the cost of each option multiple data sources were used. The assumptions and considerations used in analyzing the different alternatives correspond mainly to information from the regional water and sanitation enterprise (ESSAN). Budgets and input costs were requested from private firms.

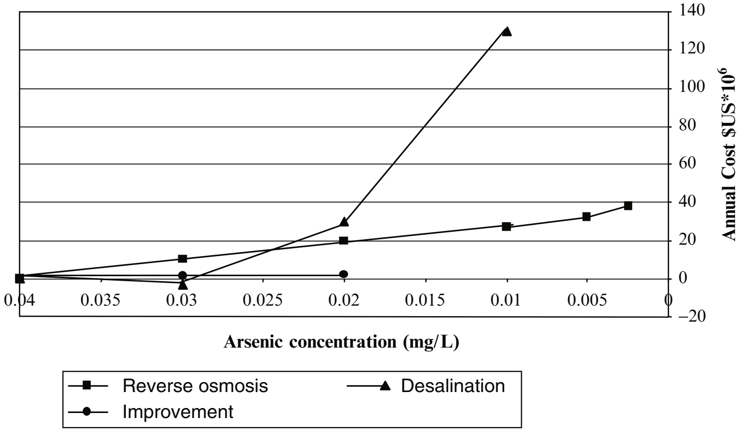

Fig. 6 Annual cost to treat arsenic in drinking water from Antofagasta

Results show that in, Antofagasta, there were three alternatives, each with its associated costs, to reduce arsenic to 0.03 mg/L from its prevailing 1997 level of 0.04 mg/L. Simple plant process improvement related to the automation of processes produced an annualized total profit increase to the Antofagasta treatment plant of $US 22,000; by incorporating a mixing step with desalinized seawater, there were annualized benefits of $US 5 million; reverse osmosis gives an additional annualized cost of $US 10 million. Savings were achieved from credits arising from an aggregate saving on chemical treatment products; with desalination, greater volumes of freshwater were generated, which negated the need for new investments ($US 170 million) envisioned by the ESSAN (regional water sanitation enterprise) water company to acquire new water sources. On the other hand, no credit was produced with reverse osmosis, which had only costs relating to technology investment and construction.

Consequently, to reduce arsenic to 0.03 mg/L in Antofagasta, it was best to make process improvements or to include the desalination step. If capital investment funds are unavailable, the first option would be most suitable; otherwise desalination is the best approach. If the aim is to reduce the arsenic content in treated water to 0.02 mg/L, double filtration was the option recommended to achieve it. However, using the equipment installed, desalination produces about 1300 L/sec of water in excess of the population's demand. Therefore, it would be attractive if the high cost of installing desalination could be offset by selling excess water volumes generated. The mining sector was a candidate to acquire such water, because they faced a deficit in Chile's north of up to 3000 L/sec for the year 2000. Since then, a small desalinization plant has been built, and currently an expansion is being undertaken to satisfy the increasing demand from mining activity.

The best known option during the 1990s to reduce arsenic levels in treated water to 0.01 mg/L was reverse osmosis. However, to achieve this lower concentration consumes an amount of water equal to an additional 300 L/sec, which in this part

Table 11 Effect of arsenic level reduction on tariff rates[a]: Antofagasta

Treatment alternative	Target concentration (mg/L)	Rate increase ($US/m^3)
Inverse osmosis	0.03	0.27
	0.02	0.53
	0.01	0.68
	0.005	0.79
	0.002	0.83
Desalination	0.03	–0.13
	0.02	0.45
	0.01	1.03

Source: FONDEF 2–24 Project.

[a] Tariff rates refer to the periodic charges made to households to cover the cost of treated water.

of the country, where water is scarce, has a very high value. The higher water consumption renders this alternative unattractive from an economic perspective.

In Chile, water tariffs (or costs) are paid at the household level and are based on the costs of the water provided to the user. Consequently, the costs of the different options discussed above had a potential impact on water tariffs. The effect on tariffs is depicted in Table 11. The price of water in the north of Chile was $US 1.21/m^3 in 1997.[2] Desalination allows tariff rates to be lowered by $US 0.13/m^3 of water (equivalent to 11% of the price), if a quality of 0.03 mg/L is required. More stringent requirements (lower arsenic concentration) translates as significant increases in rates of between $US 0.5 and $US 1/m^3, equivalent to a premium of 41% and 83%, respectively, over current water prices in Chile's north.

In conclusion, results show that residual arsenic in Chile's drinking water could be substantially reduced in the late 1990s; however, costs increased significantly as arsenic removal rates increased, particularly when arsenic concentrations approached 0.01 mg/L. For this reason, evaluation of lower cost options for Antofagasta continued. In recent years, optimization of the coagulant process has resulted in achieving considerably lower arsenic concentrations in treated water (0.01 mg/L) at a relatively lower cost (Granada et al. 2003). Consequently, beginning in 2006, the more stringent standard of 0.01 mg/L was imposed, and it is now complied with in all treatment plants in the north of Chile.

4 Reducing Airborne Arsenic Emissions

In 1995, nearly 90% of Chile's copper was produced by seven smelters using pyrometallurgy. Air concentrations of arsenic in the vicinity of smelters were particularly high. The high levels derive both from high arsenic content in Chile's copper ore, typically reaching 1% (more or less the same as the copper content), and the fact that the smelting process did not incorporate antipolluting technologies.

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[2] (Source: ESSAN).

Consequently, in 1995, air concentrations of arsenic reached average annual values of about 1 μg/m^3 in the area of many smelters. In the worst case, average annual values in air reached 10 μg/m^3, with daily maximums of 100 μg/m^3. Total emissions from smelters in 1992 reached almost 9,000 t/yr.

4.1 Control Options

Two primary approaches are generally used to reduce arsenic air emissions. The first employs technology aimed at reducing both chimney stack and fugitive emissions. The aim of the second approach is to reduce the exposure of people to arsenic air levels. Technology improvements are designed to modernize existing processes and implement systems for capturing and treating effluent gases. Such technological changes permit better control of gas emissions. If capture and treatment of metallurgical gases is insufficient in any one plant, more profound technological measures may be used, including replacement of older smelters with more modern technology.

The second approach, designed to reduce arsenic exposure to the population, includes changes in the arsenic content of ores fed into the smelter, reduction in daily activity levels for people in arsenic-polluted areas, and even relocation of local populations, if necessary. Indeed, it is possible to reduce arsenic emissions by feeding the smelter with a mix of copper ores with different arsenic content, pre-roasting of concentrated feed, or by reducing the quantity of concentrate fed into the process. Finally, by relocating the affected population it is possible to reduce air arsenic exposure without modifying smelter operations.

Table 12 summarizes ranges of air emission reduction achievable by implementing each of the foregoing options.

Table 12 Summary of reduction efficiencies for various As reduction approaches

Option	Capture efficiency (%)
Electrostatic precipitators	10–50
Acid plants	+99
Flash Inco Oven	95
Contop technology	95
Isasmelt Process	95
Flash Converting-Flash Smelting	+99
Mitsubishi	+99
Multi-story roaster	90
Dust treatment plant	80–90
Secondary hood	94–99
Matte and slag launder cover	99
Smelter shutdown	100
Change of concentrate feed	Variable
Reduction of activity	Variable
Population relocation	Variable

Source: FONDEF 2–24 Project.

4.2 Costs to Reduce Arsenic Air Pollution

Reducing pollution always has associated costs and benefits, and both must be considered when choosing and implementing programs to achieve lower exposures. Of course, there is a trade-off between costs and degree of reduced arsenic exposure that is achievable: the lower the cost input, the higher the exposure. To inform policymakers of their options, a detailed cost analysis was conducted at different levels of arsenic emission reduction. This analysis allowed decision makers to choose the most cost-effective approach that would offer protection to exposed populations at levels considered to be acceptable.

Costs of options include capital investment expenditures, as well as the operating and maintenance costs, with possible benefits, such as credits arising from generation of additional sulfuric acid, being factored in. Costs were calculated for each smelter based on literature information, data from national and international experts, and data from smelter operations. Indirect costs such as job loss, reduction of ancillary services, etc., were not considered.

Annualized costs were determined by calculating the comparative net present value (NPV) of the existing smelter operation with and without the emission reduction project. An investment horizon of 25 yr with a 12% discount rate was used in the NPV calculation. Table 13 presents a typical smelter cost profile. Similar data

Table 13 Cost of reducing emissions with technology and by relocation of population: an example showing private costs and incomes before tax

Option	Description of option	Emissions (t/d)	Maximum concentration ($\mu g/m^3$)	Incremental investment ($US millions)	Net cost (PV) ($US millions)	Net cost/ annum ($US thousands)	Net cost of anodes (US cents per lb)
0	Base case	1.4	6.01	0	0	0	0
1	Improved base case	0.43	1.4	5.1	4.1	518	0.2
2	Teniente converter	0.65	2.1	72.9	−29.6	−3,773	−1.1
3	Contop	0.21	0.82	54.7	−100.1	−12,773	−3.6
4	Flash furnace	0.74	2.14	159.1	103	13,139	3.7
5	Continuous smelting	0.08	0.46	352	150.7	19,200	5.4
6	Smelter shutdown	0	0.08	0	49.9	6,361	2.3
7	Relocation of population	1.4	0.08	–	30	3,800	1.4

PV, present value.
Source: FONDEF 2–24 Project.

were prepared for each smelter.[3] The smelter depicted in Table 13 had two dominant options. In the first option, the plant could switch to Contop Technology with net benefits of $US 13 million, a result of net credits from selling sulfuric acid, a production by-product. Emissions of arsenic would be reduced to approximately one-seventh of the original value. However, such levels are still rather high. So, if additional reduction is required, the best option for this smelter is to relocate the affected population (workers and their families), comprising 3,000 people. This latter alternative was the one finally adopted; this relocation was completed in 2007.

5 Setting Environmental Standards for Arsenic: Present and Future

5.1 Air

Until 1990, there was no regulation in Chile for airborne arsenic emissions. In that year, the new democratic government declared that environmental issues would be a main concern for the administration (O'Ryan and Lagos 2005). One of the priority environmental problems facing the new administration was that of arsenic emissions from copper and gold smelters. In particular, the Health Ministry was pushing for a strict ambient emissions standard. A special Interministerial Commission for Air Quality (CICA) was established with participation from four ministries: Agriculture, Health, Economics, and Mining (Camus and Hajek 1998). A deliberative group was formed that included public and private institutions, and also included private mining firms and the State-owned National Copper Corporation (CODELCO).

Based on available information, a first regulation was established at the end of 1991 through "Decreto 185." This regulation imposed an emission standard on all sources of emitted arsenic. It was recognized that, before developing more elaborate emission standards, a great deal of additional information would be required. Such information included emissions and dispersion data, health effects, control options, and associated costs. The FONDEF project was proposed, and two relevant regulatory questions were posed: (1) What is the appropriate regulatory approach: an ambient standard or emissions standard for each source? and (2) How strict should the standards be? The first question was hotly debated, because an ambient standard was preferred by many institutions who were most concerned about the high arsenic concentrations observed in the north of Chile. Others, however, were concerned about the high economic costs and social consequences of imposing a uniform ambient standard[4] that would universally apply, even in localities with very low population exposure. A quantitative evaluation was made to answer open

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[3] For detailed results see O'Ryan and Diaz (2000).

[4] Ambient standards aimed at protecting health must be uniform in the whole country.

Table 14 Permissible arsenic emission air standards in Chile

Location or Province	Capacity (t/yr)	Arsenic emission allowed (t/yr) 2000	2001	2003
El Loa	≤1,400,000	1,100	800	400
Antofagasta	≤350,000	126		
Copiapó	≤200,000	42		34
Chañaral	≤500,000	1,450	800	150
Del Elqui	≤80,000	200		
San Felipe de A.	≤350,000	95		
Valparaíso	≤400,000	120		
Cachapoal	≤1,100,000	1,880	375	

questions by studying the main profile of each smelter, including costs, emissions, and arsenic concentrations at the most affected locations (O'Ryan and Díaz 2000).

Results showed that a unique ambient standard could not be too stringent without jeopardizing smelter operations; in fact, stringent standards would result in a shutdown of operations for some smelters. However, it was also recognized that lax ambient standards would encourage plants that had high emissions (and their future investors) to wrongly believe that it would be permissible to build plants with relatively low emission controls. Consequently, it was decided to regulate using emission standards specific to each region in which pollution sources where located. Using a reference ambient quality standard for local residents (between 0.1 and 0.2 μg/m^3), regulators imposed the emission standards presented in Table 14. This regulation was passed on June 2, 1999, as Decree 165/1999 MINSEGPRES (Ministerio Secretaria General de la Presidencia, or in English, Ministry General Secretariat of the Presidency), and it is currently in force.

5.2 Water

Regulating permissible levels of arsenic in potable water has been a constant concern in Chile (Table 15). Given Chile's special geological conditions, adopting the MCL recommended by the WHO has been impossible, both technically and economically. Instead, over a period of four decades, Chile has established a series of ever-lower feasible MCLs to improve standards for arsenic in drinking water, and these standards have continued to be modified downward as scientific studies and techniques for optimizing removal processes have progressed.

Thus, in 1970, the Chilean standard for permissible arsenic in drinking water was set at 0.12 mg/L, because that was the level of arsenic removal achieved by the first treatment plant built in Chile. Gradually, after Chilean researchers determined how to reduce residual levels of arsenic to 0.05 mg/L by means of small modifications in plant design and operation, this value became the legal limit in 1984. Finally, at the beginning of 2000, the reliability of the optimized coagulant process permitted reaching 0.01 mg/L, allowing imposition of this level as the standard.

Table 15 Evolution of Chilean regulations governing arsenic content of drinking water

Year	Standard	MCL (mg/L As)
1970	NCh 409Of70 Drinking water: Requirements	0.12
1984	NCh 409Of84 Drinking water: Part 1: Requirements	0.05
2005	NCh 409/1Of2005 Drinking water: Part 1: Requirements	0.01

MCL, Maximum Contaminant Level.

Arsenic of no more than 0.01 mg/L in potable water became established as the Chilean standard in 2005. This standard governs practices of arsenic removal in plants constructed since 2005. Plants constructed before to 2005 have adopted timetables for eventual compliance with the new norm, and indeed some of these reached the new standard by 2004. Those few plants constructed before 2005 that have not yet achieved the norm of 0.01 mg/L have a 5-yr window in which to achieve a residual arsenic level of 0.03 mg/L and a maximum of 10 yr to reach 0.01 mg/L.

6 Concluding Remarks

Regulating hazardous pollutants requires a careful weighing of environmental and economic trade-offs and, often, gradualism in implementing needed changes. Research fitted to the context of developing countries is particularly important, because copying standards from other countries may neither be affordable nor necessarily produce appropriate risk reductions. In the context of developing countries, it is essential that compliance be affordable and feasible.

It is important to prioritize environmental risks and to focus on the most important ones first. Following this concept, ex post studies in Chile show that it was appropriate (for arsenic) that priority first be given to regulation of water and subsequently of air. Of course, it would be particularly convenient that riskcost analysis be performed *ex ante* to most effectively allocate resources.

Arsenic regulation in Chilean water was preceded by development of appropriate technologies to adequately address and reduce arsenic content. This effort began over 40 yr ago, when this pollutant was first identified as a health hazard. Average concentrations of arsenic in drinking water have fallen from 860 µg/L, more than four decades ago, to 110 µg/L after 1971; currently, average concentrations are ~10 µg/L.

In air, the regulatory process has developed much more recently and has been centered on copper smelters. In regulating air emissions of arsenic for application to copper smelters, technical feasibility costs and risks of proposed standards were all weighed. As a result, different emission standards were applied to each smelter, and application of a universal and uniform ambient standard was discarded until more definitive information becomes available.

The regulatory process and associated research needed to create regulations has been a joint effort among university researchers, regulatory agencies, and entities in the private sector, particularly the mining industry. This collaboration has allowed a fruitful interchange of information and experience and has enhanced the regulatory process. However, much progress is yet to be made, in particular, to meet the established arsenic standard for all Chilean water sources and also to make progress in achieving goals for reductions in airborne arsenic concentrations.

7 Summary

Chile is one of the few countries that faces the environmental challenge posed by extensive arsenic pollution, which exists in the northern part of the country. Chile has worked through various options to appropriately address the environmental challenge of arsenic pollution of water and air. Because of cost and other reasons, copying standards used elsewhere in the world was not an option for Chile.

Approximately 1.8 million people, representing about 12% of the total population of the country, live in arsenic-contaminated areas. In these regions, air, water, and soil are contaminated with arsenic from both natural and anthropogenic sources. For long periods, water consumed by the population contained arsenic levels that exceeded values recommended by the World Health Organization. Exposure to airborne arsenic also occurred near several large cities, as a consequence of both natural contamination and the intensive mining activity carried out in those areas. In rural areas, indigenous populations, who lack access to treated water, were also exposed to arsenic by consuming foods grown locally in arsenic-contaminated soils.

Health effects in children and adults from arsenic exposure first appeared in the 1950s. Such effects included vascular, respiratory, and skin lesions from intake of high arsenic levels in drinking water. Methods to remove arsenic from water were evaluated, developed, and implemented that allowed significant reductions in exposure at a relatively low cost. Construction and operation of treatment plants to remove arsenic from water first began in the 1970s.

Beginning in the 1990s, epidemiological studies showed that the rate of lung and bladder cancer in the arsenic-polluted area was considerably higher than mean cancer rates for the country. Cancer incidence was directly related to arsenic exposure.

During the 1990s, international pressure and concern by Chile's Health Ministry prompted action to regulate arsenic emissions from copper smelters. A process began in which emission standards appropriate for Chile were set; this process included careful evaluation of risks versus mitigation costs for abatement options. Such options were developed and implemented.

More recently, local communities have pressed for more significant reductions of arsenic in air and water. Considerable experience was gained with the arsenic experience on how to manage this type of hazardous pollutant, in a context of trade-offs among production, jobs, income, and health. In this review article, we cover arsenic levels in Chile's air, water, and soils and discuss health impacts and patterns of exposure. We also describe the process followed to set arsenic regulatory standards, as well as abatement options for air and water and the associated costs.

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