
Review of Coagulation Technology for Removal of Arsenic: Case of Chile

Ana María Sancha

*Department of Civil Engineering, Division of Water Resources and Environment,
University of Chile, Blanco Encalada 2002, Santiago, Chile*

ABSTRACT

Coagulation technology has been used since 1970 in northern Chile for removing arsenic from drinking-water. This experience suggests that coagulation is an effective technology for the removal of arsenic. It is currently possible to reduce arsenic from 400 $\mu\text{g/L}$ to 10 $\mu\text{g/L}$ at a rate of 500 L/sec, assuming pH, oxidizing and coagulation agents are strictly controlled. The Chilean experience with the removal of arsenic demonstrates that the water matrix dictates the selection of the arsenic-removal process. This paper presents a summary of the process, concepts, and operational considerations for the use of coagulation technology for removal of arsenic in Chile.

Key words: Arsenic; Arsenic removal; Coagulation technology; Drinking-water; Chile

INTRODUCTION

The presence of hazardous concentrations of arsenic in drinking-water and the serious health effects this situation is causing to untold hundreds of millions of people across the planet, have led the World Health Organization (WHO) to recommend that the maximum concentration of arsenic in human drinking-water not exceed 10 $\mu\text{g/L}$. Researchers in many countries are studying to identify the most feasible technologies for the removal of arsenic in their particular situations. Some removal systems recommended in the international water market involve advanced or emerging technologies which generally require extensive pre-treatment processes and/or very high construction, operation and maintenance costs. For many affected populations, neither they nor their governments are able to afford such expensive investments in infrastructure.

Chile, a small but emerging nation with significant arsenic exposure through water, has faced the challenge of removal of arsenic with large-scale water-treatment

plants since the 1970s and has developed a strategy using the conventional technology which is both very effective and relatively inexpensive to build, operate, and maintain.

This study presents a summary of the Chilean experience in removal of arsenic from water, including an overview of the problems and variables involved and a discussion of our investigations and results at the level of large-scale water-treatment facilities.

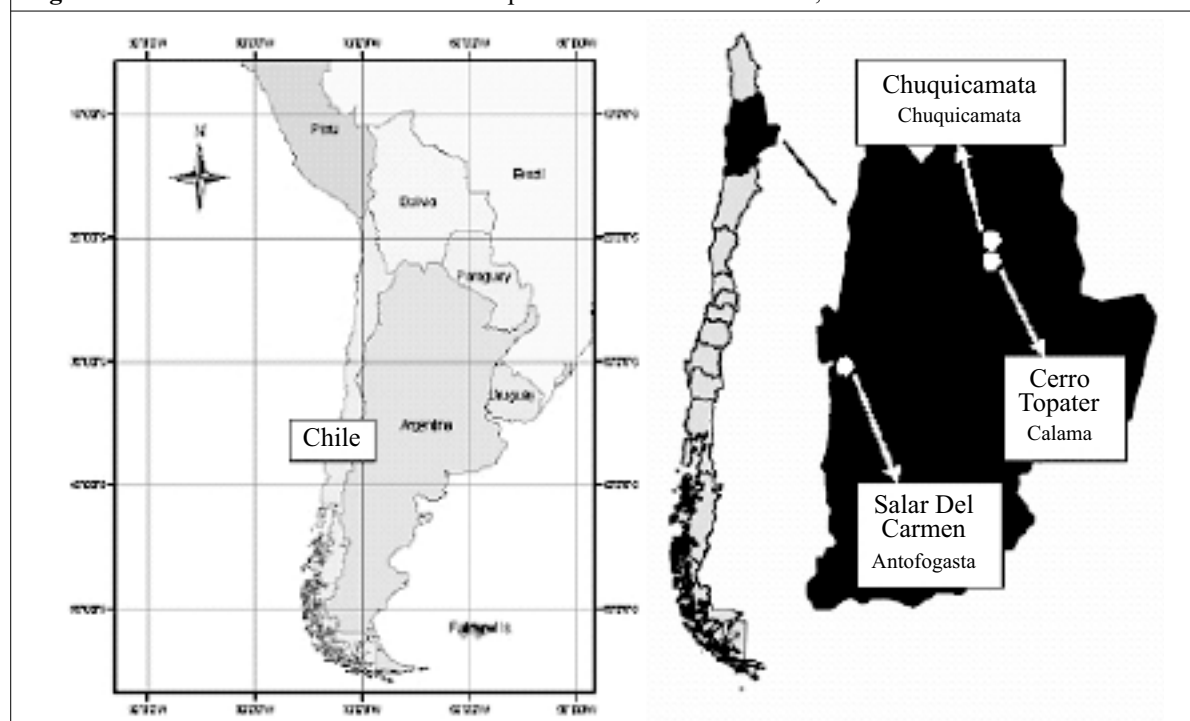
BACKGROUND

Chile, located along a 4,320-km strip in southwestern South America (Fig. 1), with a population of approximately 15,400,000, has extensive experience in the removal of arsenic from drinking-water supplies (1,2). Due to the particular geological characteristics of Chile and its intensive mining activity, many water sources in the northernmost area and central zones of the country are contaminated with arsenic (3).

In the late 1960s, it became evident that the consumption of water from the Toconce River—with concentrations of arsenic in the range of 600-900 $\mu\text{g/L}$ —was causing serious problems for residents of the northern zone (4). The Chilean Government commissioned a study by German researchers from Berkefeld Filter concerning the removal of this contaminant from drinking-water. Working together with Chilean colleagues, these researchers ascertained the parameters required to remove arsenic from water by means of

Correspondence and reprint requests should be addressed to:
Prof. Ana María Sancha
Department of Civil Engineering
University of Chile
Blanco Encalada 2002
Santiago
Chile
Email: amsancha@ing.uchile.cl
Fax: 56 2 6894171

Fig 1. Name and location of water-treatment plants for removal of arsenic, Chile



coagulation (5). The first plant was built and began operations in 1970. Four arsenic-removal plants (Table 1)

currently investigating the coagulation process, and their results indicate that further improvements are viable

Table 1. Water-treatment utilities for removal of arsenic in Chile. Chuquicamata is owned by a mining company and has limited availability of public data

Utility	Capacity (L/sec)	Water source	Arsenic range ($\mu\text{g/L}$)
Salardel Carmen Complex*			
Old plant (1970)	500	Toconce	600-900
New plant (1978)	520	Lequena	150-350
		Quinchamale	100-250
		Siloli Polapi	<50
Cerro Topater* (1978)	500	Toconce	600-900
		Lequena	150-350
		Quinchamale	140-250
Chuquicamata* (1989)	210	Colana	70-90
		Inacaliri	80-90
Taltal** (1998)	32	Agua Verde	60-80

*Surface water; **Groundwater

that use the same process have been built in the northern zone in subsequent years (6-9).

Experience has confirmed that the coagulation process is a good device for both quality of water (Table 2) and volumes of water to be treated. Recently, the WHO identified the coagulation process as being the most appropriate technology to remove arsenic in large volumes (10). Numerous researchers are cur-

(11-16). Some new knowledge became apparent during Chile's long experience with full-scale arsenic-removal treatment plants.

The Chilean drinking-water standard permitted a maximum arsenic concentration of 50 $\mu\text{g/L}$ until 2004. Currently, the Chilean drinking-water standard has been modified to reach a goal of 30 $\mu\text{g/L}$ in 2010 and 10 $\mu\text{g/L}$ in 2015 (17). The WHO recommended that water for

Coagulation technology for arsenic removal

Table 2. Quality of water in the northern zone of Chile. The process only removes arsenic. Other parameters are essentially the same in the effluent

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	µg/L	400-600	60-80
Sulphate	mg/L	80-100	-
Chloride	mg/L	120-140	-
Alkalinity	mg/L CaCO ₃	100-120	50-60
Hardness	mg/L CaCO ₃	130-150	350-400
Silica	mg/L SiO ₂	20-30	20-30
Boron	mg/L	3-4	2-5
Dissolved organic carbon	mg/L	Negligible	Negligible

human consumption should not contain more than 10 µg/L (18). Currently, 99.98% of the Chilean population have access to potable water with arsenic <50 µg/L, but only 52.69% have access to potable water with arsenic <10 µg/L. To meet the new Chilean standard and the WHO guidelines, Chile will need to treat significantly more water for removal of arsenic in other zones of the country.

REMOVAL OF ARSENIC

The coagulation process consists of the addition of metal-based coagulant, such as ferric chloride (FeCl₃), to arsenic-contaminated water. FeCl₃ hydrolyzes in water to form positively-charged ferric hydroxide [Fe(OH)₃]. Arsenic must be in oxidized form [As(V)] for effective removal. Thus, if any arsenite [As(III)] is present, it may be necessary to oxidize it to As(V) using chlorine as a pre-treatment process. Arsenate [As(V)] is a negatively-charged anion and sorbs to the positively-charged Fe(OH)₃ particles or flocs. The sedimentation and filtration processes then remove arsenic particulate. A general schematic diagram of the arsenic-removal treatment process is given in Fig. 2.

The arsenic-removal system by means of coagulation in the 1970s delivered water with a residual arsenic concentration of 120 µg/L to the population of the northern Chile. The delivery concentration decreased to 50 µg/L in the 1980s and to as low as 10 µg/L in the 2000s. This increase in efficiency in the removal of arsenic has been achieved by improving the treatment-system follow-up, including control of pH and adjustment of reagent doses (19). Table 3 lists some principal arsenic-removal conditions at Salar del Carmen, Cerro Topater, and Taltal.

The coagulation processes are typically used for removing turbidity. When the same processes are used for removing arsenic from surface water, the design of the treatment system should maximize the formation of a floc with characteristics of size, cohesion, and sedimentation speed that favour stable arsenic adsorption onto it. In this way, arsenic changes from a dissolved species into a particulate species that can be separated or removed from water by means of sedimentation and filtration. In the case of groundwater, the removal process often includes only oxidation, coagulation, adsorption, and filtration. Regardless of the method of re-

Fig 2. General schematic Chilean arsenic-removal treatment process: (a) Surface water and (b) Groundwater

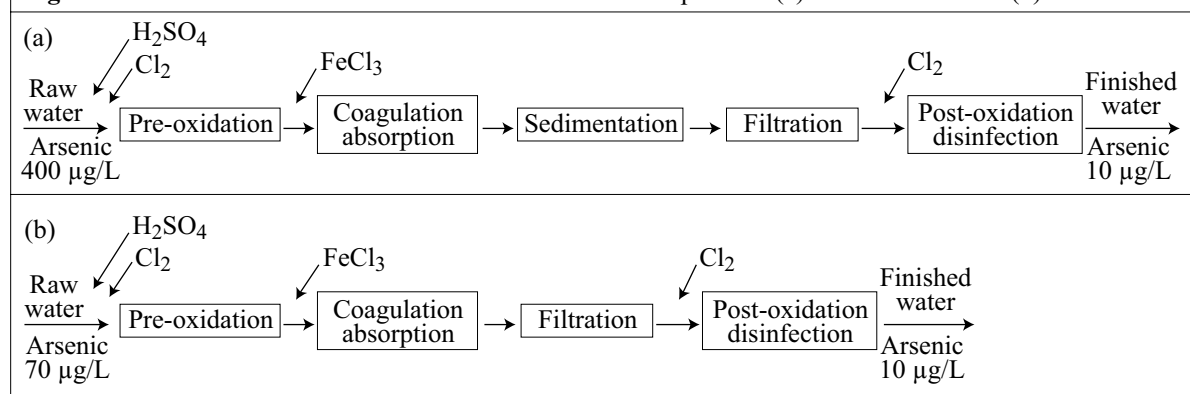


Table 3. Arsenic-removal conditions: Salar Del Carmen, Cerro Topater, and Taltal, Chile

Arsenic-removal conditions	Salar del Carmen	Cerro Topater	Taltal
Arsenic in raw water ($\mu\text{g/L}$)	400	400	70
Chemical dosage			
Oxidant (mg/L Cl_2)	1.0	1.0	1.0
Coagulant (mg/L FeCl_3)	56.1*	40.5*	8.0
Decantation rate ($\text{m}^3/\text{m}^2/\text{day}$)	70-75	70-75	-
Filtration rate ($\text{m}^3/\text{m}^2/\text{day}$)	143	143	150
Sludge generation (kg/day)	25-30	20-30	-
Arsenic in finished water ($\mu\text{g/l}$)	10	10	10

* H_2SO_4 for adjustment of pH

moval, the arsenic-removal process becomes a simple device for removal of suspended material. Arsenic speciation, pH, coagulant doses, and agitation speed are important parameters in this process (7,19). Any problems that may originate in the process of floc formation and separation by sedimentation and/or filtration may limit the efficiency of removal of arsenic from water.

Recent studies demonstrated that the presence of hardness in water to be treated could favour removal of arsenic, but that some anions, especially phosphate, carbonate, and silicate, may compete with arsenic for the sorption sites, thus interfering with removal of arsenic (20,21). Chilean water has both hardness and these competitive anions. The efficiency of the process is, thus, sensitive to the water matrix in this condition.

Quick and accurate measurement of concentrations of arsenic in water has also been a fundamental factor in improving the efficiency of the removal process. It has always been important to use the analytical method which has best responded to the requirements of the control process, to the country's economic situation, and to the abilities of its technicians. Initially, the Gutzeit method was used (22), but later, in the 1980s, the silver diethyldithiocarbamate colorimetric method was used (23), since the 1990s, hydride generation-atomic absorption spectrometry has been used (24). This has allowed more frequent adjustment of the process and the reduction of the detection limits.

Achieving higher efficiency in the removal of arsenic from water has involved greater expenditure for increasing coagulant dosage and dose automation, continuous control of pH, and more frequent monitoring of concentrations of arsenic. The FeCl_3 dose may be reduced if pre-treatment of pH is applied (19). Greater investment, operations and maintenance costs also require additional resources to train and maintain teams of highly-qualified technicians to operate the plants.

Finally, the disposal of arsenical sludge generated during treatment of water has always been and will always be difficult due to its dangerous characteristics. In the case of Chile, the problem has been solved by carrying out this process in the desert. During the first years, this sludge was disposed of without taking any special precautions. In recent years, the process has taken place in specially-engineered sites using a geotextil as component of a landfill bottom and capping barrier systems (25)

The price of drinking-water in Chile is determined, in part, by the cost of infrastructure for treatment of water, the chemical reagents used, and the system's operation and maintenance costs. In Antofagasta, where arsenic is removed from water, the cost for a family that consumes 20 m^3 of water per month is currently US\$ 46.48, or 2.3¢ per litre. The cost for a family in Santiago, where arsenic is not removed, amounts to US\$ 16.18, or about a third of the cost in Antofagasta, for the same volume of water. These figures reflect partially the relatively high cost of removal of arsenic in Northern Chile.

FUTURE OF ARSENIC REMOVAL

Chile is making efforts to find cost-effective solutions to achieve lower levels of residual arsenic concentration in drinking-water from surface and underground water supplies. In this new scenario, another possibility that has been considered, for Northern Chile, is to replace some current sources of surface water with de-salinized sea water (26,27). This option would only be applicable in coastal cities, but not in plants located farther from the ocean, i.e. in Salar del Carmen Plant (Antofagasta), but not in Cerro Topater (Calama).

In the central zone of Chile, where some surface waters have concentrations of arsenic in the range of 14 to 16 $\mu\text{g/L}$, modifications to the current coagulation process used for removing turbidity could meet a 10- $\mu\text{g/L}$ standard. In the case of groundwater with concen-

trations of arsenic in the range of 20 to 80 $\mu\text{g/L}$, coagulation-filtration also would be the selected process to remove arsenic (28). Because of the afore-mentioned characteristics of water quality, adsorption processes are inefficient in the removal of arsenic. In addition, most manufacturers of sorbents do not provide regeneration instructions.

CONCLUSION

The Chilean experience in removal of arsenic demonstrates that the water matrix dictates the selection of the arsenic-removal process. The coagulation process has been proven to be an effective arsenic-removal process for surface and groundwater. Moreover, it has the advantage that it does not typically require excessive pre-treatment or conditioning of influents and chemicals used that are not made in Chile.

The Chilean water industry has gained significant operational experience in the removal of arsenic by coagulation and will rely on achieving a residual arsenic concentration of 10 $\mu\text{g/L}$ by coagulation technology through adjustment of pH and control of coagulant dose.

The Chilean experience in the removal of arsenic at water-treatment plants demonstrates that the processes of coagulation/adsorption-sedimentation-filtration can remove arsenic up to the WHO-recommended standards for drinking-water. These processes do not require complex pre-treatment of water, but only pre-oxidation and pH adjustment. This technology for the removal of arsenic can be simplified by eliminating the sedimentation process if the conditions of water permit.

The inputs of this technology—oxidizing agent, coagulant, filtering medium—can be of local origin, and the operation of the removal system requires personnel with an intermediate level of training. The handling and disposing of the sludge generated must always be done with special precautions.

ACKNOWLEDGEMENTS

This paper is based on studies supported by Universidad de Chile and FONDEF-CONICYT through Project FONDEF 2-24. The author is grateful for the many contributions of her students, whose cooperation made these studies possible.

REFERENCES

1. Sancha A. Removal of arsenic from drinking water supplies: Chile experience. *Water Supply* 2000;18:621-5.
2. Sancha A. Removing arsenic from drinking water. A brief review of some lessons learned and gaps arisen in Chilean water utilities. *In: Chappell W, Abernathy C, Calderon R, Thomas D, editors. Arsenic exposure and health effects. Amsterdam: Elsevier B.V., 2003:471-81.*
3. Alonso H. Arsenic enrichment in superficial waters. II. Región Northern Chile. *In: Sancha A, editor. Proceedings of the International Seminar on Arsenic in the Environment and Its Incidence on Health. Santiago: Universidad de Chile, 1992:101-8.*
4. Borgoño J, Greiber R. Estudio epidemiológico del arsenicismo en la ciudad de Antofagasta. *Rev Med-Chile* 1971;99:702-9.
5. Latorre C. Estudio físico-químico para la remoción del arsénico en el río Toconce. Santiago: *Revista Ingeniería Sanitaria* 1966:12-21.
6. Sancha A. Experiencia Chilena en remoción de arsénico en fuentes de agua potable. Santiago: Sección Ingeniería Sanitaria y Ambiental, Universidad de Chile, 1986. 44 p. (Publ 0-18).
7. Sancha A, Ruiz G. Estudio del proceso de remoción de arsénico de fuentes de agua potable empleando sales de aluminio. *In: Proceedings XIX Congreso Interamericano de Ingeniería Sanitaria y Ambiental (AIDIS) Chile, Tema I Agua Potable, 1984;2:380-410.*
8. Sancha A. Full-scale application of coagulation processes for arsenic removal in Chile: a successful case study. *In: Chappell W, Abernathy C, Calderon R, editors. Arsenic exposure and health effects. Amsterdam: Elsevier Sciences B.V., 1999:373-8.*
9. Ruiz G, Perez O, Sancha AM. Filtración directa para el Tratamiento de Aguas Subterráneas con arsénico. *In: Proceedings XXIII Congreso de la Asociación Interamericana de Ingeniería Sanitaria y Ambiental (AIDIS), La Habana: AIDIS Cuba, 1992:729-39.*
10. World Health Organization. Arsenic in drinking water. Chapter VI. Safe water technology. Geneva: World Health Organization, 2002. 98 p.
11. Edwards M. Chemistry of arsenic removal during coagulation and Fe-Mn oxidation. *J AWWA* 1994;86:64-78.
12. Hering J, Chen P, Wilkie J, Elimelech M, Liang S. Arsenic removal by ferric chloride. *J AWWA* 1996;88:155-67.

13. Hering J, Chen P, Wilkie J, Elimelech M. Arsenic removal from drinking water during coagulation. *J Environ Eng* 1997;123:800-7.
14. McNeill L, Edwards M. Predicting As removal during metal hydroxide precipitation. *JAWWA* 1997;89:75-86.
15. Karcher S, Cáceres I, Jekel M, Contreras R. Arsenic removal from water supplies in northern Chile using ferric chloride coagulation. *Water Environ Manage* 1999;13:164-8.
16. McNeill L, Edwards M. Soluble arsenic removal at water treatment plants. *JAWWA* 1995;87:105-13.
17. Instituto Nacional de Normalización Chile. NCh 409/1.Of 2005 drinking water. Pt. 1. Requirements. Santiago: Instituto Nacional de Normalización, 2005. 9 p.
18. World Health Organization. Guidelines for drinking-water quality. V. 1. Recommendations. 2d ed. Geneva: World Health Organization, 1993. 188 p.
19. Granada J, Cerda W, Godoy D. ESSAN: El camino para reducir notoriamente el arsénico en el agua potable. *Revista AIDIS-Chile* 2003;(34):44-9.
20. Holm T. Effects of CO₃-2/bicarbonate, Si, and PO₄-3 on arsenic sorption to HFO. *JAWWA* 2002;94:174-81.
21. Meng X, Bang S, Korfiatis G. Effects of silicate, sulfate and carbonate on Arsenic removal by ferric chloride. *Water Res* 2000;34:1255-61.
22. American Public Health Association. Métodos normales para los exámenes de aguas, aguas negras y desechos industriales. México: División de Salubridad, Bienestar y Habitación del Instituto de Asuntos Interamericanos, 1955:57-8.
23. American Public Health Association. Standard methods for the examination of water and wastewater. 14th ed. Washington, DC: American Public Health Association, 1975: 283-6.
24. American Public Health Association. Standard methods for the examination of water and wastewater. 14th ed. Washington, DC: American Public Health Association, 1980:160-3.
25. Cerda W, Gatica R, Veneros M. Sistema de recuperación de aguas de descarte y disposición final de lodos arsenicados. *Revista AIDIS-Chile* 1999;(24):26-31.
26. Gonzalez K. Alternativas de remoción de arsénico desde fuentes de agua potable en la II Región Antofagasta y costos asociados. Santiago: Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, 1997. 246 p. (Dissertation).
27. O’Ryan R, Sancha A. Controlling hazardous pollutants in a developing context: the case of arsenic in Chile. In: Lehr JH, editor. McGraw-Hill Standard handbook of environmental science, health and technology. Chapter 22. Global perspectives and trends. New York, NY: McGraw-Hill, 2000:22.13-22.28.
28. Fuentealba C. Planta piloto para remover arsénico en una fuente subterránea de agua potable. Santiago: Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, 2003. 136 p. (Dissertation).