

## **The removal of arsenic from drinking water and associated costs: the Chilean case**

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**Abstract** Arsenic found in drinking water sources in northern Chile is mainly of natural origin due to the hydrological characteristics of the area, and the predominance of Quaternary volcanism. Water treatment plants in northern Chile remove arsenic by a coagulation process, bringing levels of this contaminant in the treated water down to around  $0.04 \text{ mg l}^{-1}$ . This value is considered high so there is an interest in reducing it significantly. In this paper, a technical and economic evaluation demonstrates that it is possible to reduce the residual arsenic in drinking water to values in the range  $0.03\text{--}0.02 \text{ mg l}^{-1}$  at a very low cost, using the arsenic removal facilities currently operating in Chile. Consequently, exposure to arsenic could be reduced by 50%. To decrease arsenic levels below  $0.02 \text{ mg l}^{-1}$ , it would be necessary to use more advanced arsenic removal technologies, at a much higher cost. Reaching a standard at this lower level would lead to an estimated 83% increase in the price of water in Antofagasta. These results present the trade-off that the regulator faces between protecting health and the corresponding costs to society.

### **INTRODUCTION**

Arsenic is present in all ecosystems in the northern part of Chile, either due to natural conditions or from industrial processes mainly associated with copper mining. Raw water sources that serve the population in northern Chile have arsenic concentrations in the range of  $0.400\text{--}0.500 \text{ mg l}^{-1}$ , so they are treated to reduce the arsenic levels by 90%.

In Chile, the current regulations (INN, 1984) set the maximum arsenic concentration in drinking water at  $0.05 \text{ mg l}^{-1}$ , but new recommendations by international agencies such as the World Health Organization (WHO, 1993) and the US Environmental Protection Agency (Pontius *et al.*, 1994), have raised the need to review the current situation and investigate technologically feasible options for bringing residual arsenic concentrations in drinking water down to lower values. This paper analyses five scenarios of reduction targets to reach the range  $0.03\text{--}0.002 \text{ mg l}^{-1}$ . The  $0.04 \text{ mg l}^{-1}$  target is not considered because plants currently operating in northern Chile already produce drinking water with this level of residual arsenic (Sancha & Ruiz, 1984; Sancha *et al.*, 1992a).

## GENERAL BACKGROUND INFORMATION ON ARSENIC REMOVAL IN CHILE

To remove arsenic from water, classical methods can be used such as coagulation and softening, or certain advanced methods such as adsorption by activated carbon, activated alumina, ion exchange and membrane processes such as reverse osmosis, electro dialysis and nanofiltration. The only treatment used in Chile for large-scale arsenic removal is the coagulation method. There are four plants for removing arsenic from drinking water sources, with a total normal treatment capacity of 1730 l s<sup>-1</sup>. The operation of these plants requires the addition of an oxidant and coagulant. Chlorine and ferric chloride, respectively, are used for these purposes.

Some of the advanced systems mentioned in the literature could have significant shortcomings when applied on a large scale. The use of ion exchange is limited to sulphate rich waters, due to the exchange competition between arsenic and sulphate. The use of activated alumina is limited by competition between arsenic and sulphate, chloride, fluoride and orthophosphate, which reduces the removal capacity of alumina. The use of membranes requires pre-conditioning of the water being treated. In contrast, the coagulation method does not suffer from these limitations, but it is unable to achieve drastic reductions.

The coagulation method removes arsenic through processes of chemical sorption and particulate removal. The prior oxidation of the trivalent (III) form of arsenic (arsenite) into the pentavalent (V) form (arsenate) is an important stage in treatment since arsenate is removed more effectively than arsenite (Sancha *et al.*, 1992b).

During coagulation, the addition of coagulant in the form of aluminum or iron salts facilitates the conversion of arsenic types (V) and (III) into insoluble products that can subsequently be removed by sedimentation or filtration. The efficiency of arsenic removal depends on the formation of insoluble products and the removal of the resultant particulate material. Any problem that occurs during these processes can limit the amount of arsenic that is removed. Table 1 shows the effect of the different treatment processes involved in the coagulation method on arsenic removal.

Experience with coagulation to remove arsenic in Chile, along with the results of a study by González (1997), indicate that a residual arsenic level of 0.03 mg l<sup>-1</sup> could be achieved by optimizing current coagulation processes. To attain a residual level of 0.02 mg l<sup>-1</sup>, a double filtration system would have to be available. Residual arsenic values of 0.01 mg l<sup>-1</sup> or lower could only be achieved by using membrane methods like reverse osmosis, which requires water preconditioning by coagulation methods currently in use. Another alternative for attaining greater levels of arsenic removal is to mix the effluent from the current treatment system with desalinated sea water. These options are analysed in detail in the following section.

**Table 1** Effect of different treatment processes in removing arsenic from water.

Process	Effect
Pre-sedimentation	Removal of particulate As
Aeration	Oxidation of As <sup>+3</sup> to As <sup>+5</sup>
Pre-chlorination-oxidation	Oxidation of As <sup>+3</sup> to As <sup>+5</sup>
Coagulation	Removal of soluble As
Sedimentation	Removal of particulate As
Filtration	Removal of particulate As

## OPTIONS FOR REDUCING RESIDUAL ARSENIC IN DRINKING WATER IN ANTOFAGASTA AND CALAMA

Feasible options for reducing arsenic in drinking water in Antofagasta and Calama are shown in Table 2, taking into account: (a) the technology currently used in Chile and what is available on the international market; (b) the limits of arsenic removal with each technology; (c) problems of water scarcity in northern Chile; (d) the coastal location of Antofagasta; and (e) the distance of Calama from the sea. Each of the options is discussed below.

**Table 2** Feasible options for removal of arsenic from drinking water in Antofagasta and Calama.

Options	City	Targets (mg As l <sup>-1</sup> ):				
		0.03	0.02	0.01	0.005	0.002
Improvement of current system	Calama	×	×			
	Antofagasta	×	×			
Reverse osmosis	Calama	×	×	×	×	×
	Antofagasta	×	×	×	×	×
Desalination	Calama					
	Antofagasta			×	×	×

### Improvement of the current system

A schematic diagram of the current process for removing arsenic from water in treatment plants in Chile is shown in Fig. 1. This configuration shows the process used in a new plant at the Salar del Carmen complex in Antofagasta. Although the old plant in the same complex and the Cerro Topáter plant in Calama essentially have the same configuration, they do not have the pre-filtration stage.

The current system can be improved in two ways: (a) operating the plant more efficiently in terms of the automated dosage of chemical reactants and control of treatment parameters; and (b) improving existing units to separate out the insoluble products formed, or incorporating double filtration in plants that do not have this technology (i.e. the Cerro Topáter plant in Calama and the old Salar del Carmen plant in Antofagasta). Automation would make it possible to achieve residual arsenic concentration levels of 0.03 mg l<sup>-1</sup>, and double filtration would permit levels of 0.02 mg l<sup>-1</sup>.

### Reverse osmosis

This option involves the use of reverse osmosis units to further treat a portion of the effluent from the plants in Antofagasta and Calama. After passing through these units, the water is then mixed with the rest of the water treated by these plants. The configuration of this system is shown in Fig. 2.

The percentage of the flow treated by osmosis units will determine the concentration of arsenic that results from the system outflow. The osmosis process produces reject water which depends on the efficiency of the process and the quality of the water entering it. In this case the efficiency has been estimated at 75%, which

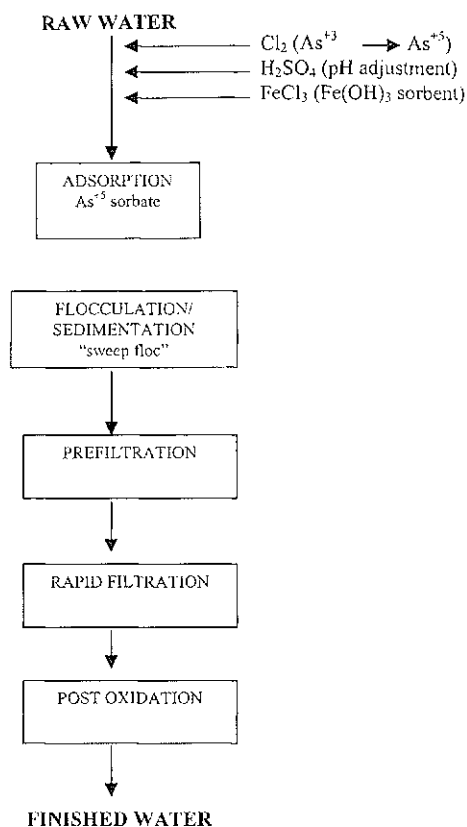


Fig. 1 Schematic diagram of the Nueva Salar del Carmen treatment plant.

means that 25% of the water entering the osmosis plant is lost as reject water, and 75% flows out with a residual arsenic concentration of  $0.001 \text{ mg l}^{-1}$ .

To obtain residual arsenic concentrations in drinking water in the  $0.03$  to  $0.002 \text{ mg l}^{-1}$  range, and to maintain the supply of drinking water, an increasing volume will have to be treated by both the reverse osmosis plant and the existing plant. In addition, new highly skilled staff will have to be hired to operate the system, and the quality control of the operation (i.e. laboratory costs) will need to be increased.

## Desalination

This option can only be applied in Antofagasta, which is a coastal city. It is not applicable to Calama because the city is more than 200 km from the coast. Water from the seawater desalination plant is mixed with the water treated in the Salar del Carmen complex. Water must be pumped from the coast up to the plant, 500 m a.s.l. Just as in the case of reverse osmosis used as a post-treatment, a large volume of water must be treated in the desalination plant to achieve the lower residual arsenic levels desired, while maintaining an adequate drinking water supply. This will produce water with concentrations of arsenic that are close to zero. Figure 3 shows this alternative.

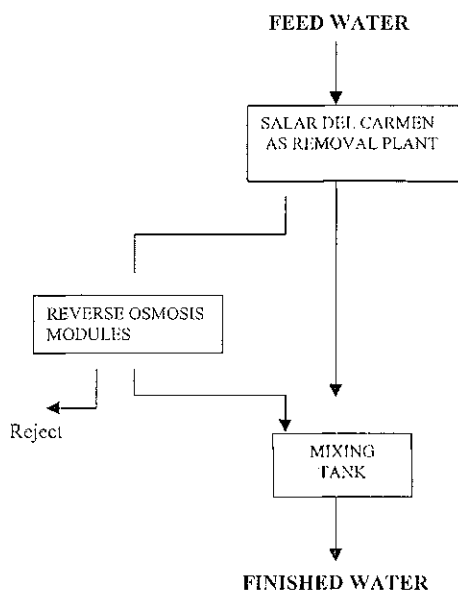


Fig. 2 Schematic diagram of the proposed reverse osmosis treatment plant.

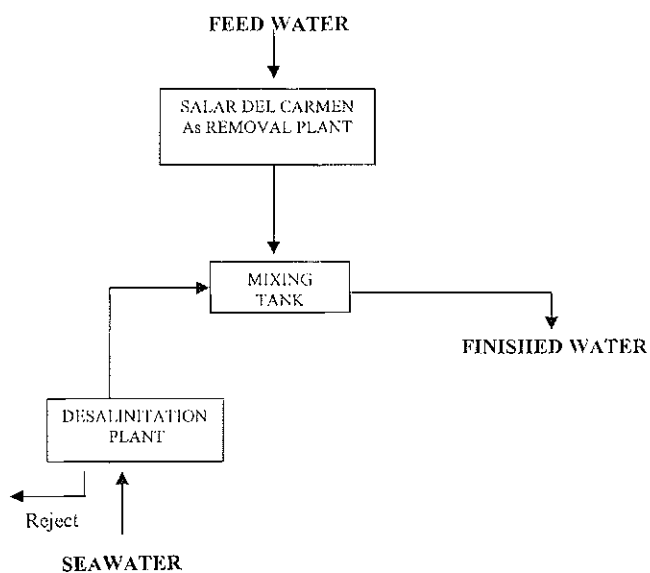


Fig. 3 Schematic diagram of a desalination plant.

### ECONOMIC EVALUATION OF OPTIONS FOR REDUCING ARSENIC IN DRINKING WATER IN ANTOFAGASTA AND CALAMA

To make an economic evaluation of each option for arsenic reduction, it is necessary to consider: (a) all the investments needed to implement the option, either in removal

technology or in related works; (b) the fixed and variable operating costs per year for the treatment plant to fulfill its function; (c) the repair and maintenance costs for the plant to be maintained fully operational (generally estimated as a percentage of invested capital); and (d) credits in terms of cost or investment reductions achieved when applying a given option.

To estimate the cost of each option for Antofagasta and Calama, multiple data sources were used to obtain technological, economic, demographic, hydraulic and geographic information. Data were collected on sanitary works, water quality, current water supply and demand, and projected water supply. The target arsenic concentration flowing out of the system determined the treatment volume of the plants using new technologies, for which a mass balance equation was used along with a continuity equation. The costs involved in each option included the removal technology as well as the construction work needed as a result of applying that technology. The application of new technologies included the upgrading of existing technologies. The assumptions and considerations used in analysing the different alternatives correspond mainly to information from the regional water and sanitation enterprise ESSAN. Budgets and input costs were requested from private firms.

The cost of reducing residual arsenic concentrations in drinking water using the options analysed for Antofagasta and Calama is shown in Figs 4 and 5. The gradient of each curve represents the incremental value of reducing pollutant concentration with each technology. For Antofagasta, the results show that if one wants to reduce arsenic levels to  $0.03 \text{ mg l}^{-1}$  from its present level of  $0.04 \text{ mg l}^{-1}$ , there are three possible alternatives with very different costs. Plant improvement produces an annualized net benefit (i.e. benefits exceed costs) of US\$22 000; with desalination there are annualized net benefits of US\$5 million, and reverse osmosis gives an annualized cost (i.e. costs exceed benefits) of US\$10 million. There are several reasons for these differences. In the case of automation, there are credits arising from an aggregate saving on chemical products in the first stage of the enhancement process. With desalination, new amounts of fresh water are generated, so the investments envisioned by the ESSAN water company to acquire new water sources (US\$170 million) are no longer necessary, thereby generating a large credit. On the other hand, no credit of any kind is produced with reverse osmosis; the only costs are related to the investment in technology and related construction work.

Thus, if one wants to reduce arsenic to  $0.03 \text{ mg l}^{-1}$  in Antofagasta, it is best to make improvements through automation and desalination. If the investment funds are not available, the first option would be most suitable. Otherwise it would be best to desalinate. If the aim is to reduce arsenic to  $0.02 \text{ mg l}^{-1}$  in the long run, double filtration is recommended. However, it should be pointed out that desalination produces about  $1300 \text{ l s}^{-1}$  of water in excess of the population's demand. If the high cost of this option can be offset by selling the water volumes generated, this could be a very attractive option. For example, the mining sector might be interested in acquiring these water volumes, as a water deficit of up to  $3000 \text{ l s}^{-1}$  is anticipated for the year 2000 in northern Chile. Of course, the cost of transporting the water would need to be assessed to make a complete evaluation of this option.

If the aim is to reduce arsenic to  $0.01 \text{ mg l}^{-1}$  in the long run, it is best to use reverse osmosis. For this level, desalination produces a surplus volume of up to  $3000 \text{ l s}^{-1}$  and

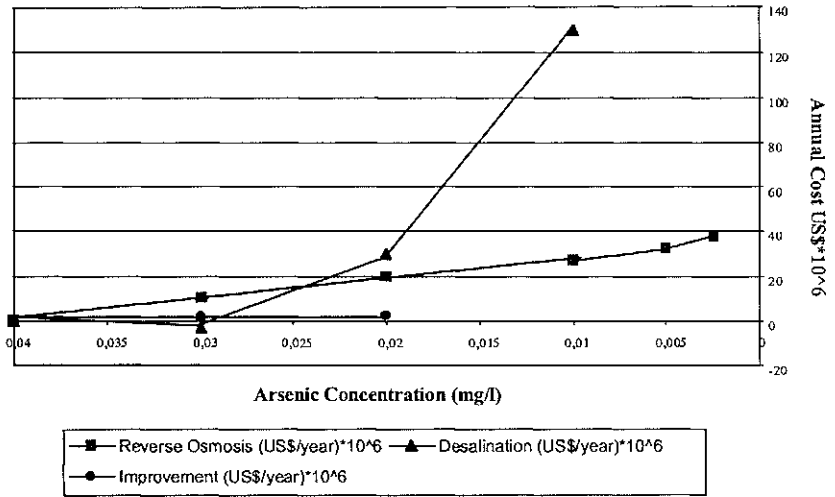


Fig. 4 Annual cost to reduce arsenic from drinking water in Antofagasta.

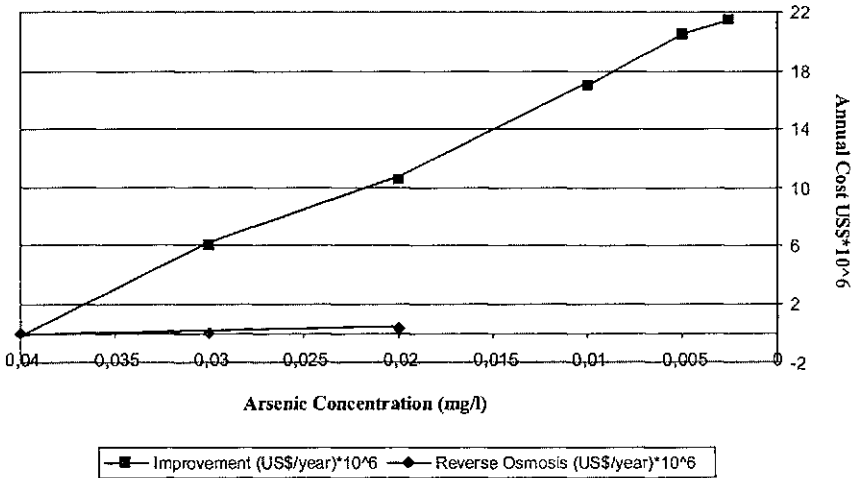


Fig. 5 Annual cost to reduce arsenic from drinking water in Calama.

the costs are very high, so this alternative is not attractive. It should be pointed out that osmosis generates a considerable water loss, which in this part of the country has a very high value due to its scarcity. These losses amount to 300 l s<sup>-1</sup>. However, if sensitivity analysis is applied to the results assuming cost of water triples, the results are maintained and reverse osmosis continues to be the best option.

The analysis for Calama is more simple, as there are only two alternatives for reducing arsenic from 0.04 mg l<sup>-1</sup> to 0.03 mg l<sup>-1</sup>: plant enhancement and reverse osmosis. In this case enhancement with automation is clearly recommended, with an annualized net benefit of US\$13 000. Equally, if the concentration target for arsenic is set at 0.02 mg l<sup>-1</sup>, enhancement with double filtration is best. For lower concentrations

the only option is reverse osmosis, with an annualized cost of US\$10 million for reductions from  $0.04 \text{ mg l}^{-1}$  to  $0.02 \text{ mg l}^{-1}$ , and US\$17 million to bring it down to  $0.01 \text{ mg l}^{-1}$ . Lowering to  $0.002 \text{ mg l}^{-1}$  has an annual cost of US\$22 million per year. This option has the disadvantage of generating a significant amount of reject water, which means new water sources will have to be sought. New sources will be very expensive, or they may not exist at all. Although sensitivity analysis with a tripling of the value of water does not significantly change the results, in practice it may be impossible to obtain the water needed to reach a level of  $0.002 \text{ mg l}^{-1}$ .

It is interesting to analyse the cost items that have the biggest effect on the total costs of arsenic abatement; namely, operational costs which, in the case of reverse osmosis, account for about 60% of the total. Energy is the biggest item in operational costs (60%). Thus, energy costs account for nearly 40% of the total annual cost of this option. Accordingly, lowering the cost of energy by introducing gas into the area could substantially alter the results. In the future, the impact of this must be analysed in detail.

Finally, introducing these treatment options into current processes will affect rates as indicated in Tables 3 and 4 because of the change in costs. Desalination will allow rates to be lowered by US\$0.13 per  $\text{m}^3$  of water (equivalent to 11% of the price of water in northern Chile), if a quality of  $0.03 \text{ mg l}^{-1}$  is required. The more stringent requirements would mean significant increases in rates of between US\$0.5 and US\$1 per  $\text{m}^3$ , equivalent to 41% and 83%, respectively, of the current price of water in northern Chile (US\$1.21  $\text{m}^{-3}$ ).

## CONCLUSIONS AND RECOMMENDATIONS

From this analysis it can be concluded that residual arsenic in drinking water in Chile can be substantially reduced, which would improve the current situation and mean a significant reduction in the population's total exposure to this pollutant. This is an important result considering that recent studies show that arsenic is even more hazardous to health than previously thought. Specific conclusions are:

- In Calama, the feasible options for reducing residual arsenic in drinking water are enhancement of current technology and reverse osmosis. Enhancement can be achieved by automating the dosage of coagulants and the introduction of double filtration, to achieve residual arsenic levels of  $0.03 \text{ mg l}^{-1}$  and  $0.02 \text{ mg l}^{-1}$ , respectively. With reverse osmosis, residual arsenic levels as low as  $0.002 \text{ mg l}^{-1}$  can be attained.
- In Antofagasta, the feasible alternatives for reducing residual levels are: enhancement with automatic coagulant dosage,  $0.03 \text{ mg l}^{-1}$ ; enhancement with double filtration,  $0.02 \text{ mg l}^{-1}$ ; reverse osmosis,  $0.005 \text{ mg l}^{-1}$ ; and desalination,  $0.002 \text{ mg l}^{-1}$ .
- Reducing arsenic in drinking water to levels in the range  $0.01\text{--}0.002 \text{ mg l}^{-1}$ , as recommended by the World Health Organization, will necessitate the use of advanced treatment technologies other than the current practice of coagulation. This will result in high treatment costs and will require careful operation. Reducing arsenic to a level of  $0.01 \text{ mg l}^{-1}$  in Antofagasta means a cost of nearly

**Table 3** Effect of reducing arsenic levels on water rates: Antofagasta.

Treatment alternative	Target concentration (mg l <sup>-1</sup> )	Rate increase (US\$ m <sup>-3</sup> )
Reverse 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

**Table 4** Effect of reducing arsenic levels on water rates: Calama.

Treatment alternative	Target concentration (mg l <sup>-1</sup> )	Rate increase (US\$ m <sup>-3</sup> )
Reverse osmosis	0.03	0.22
	0.02	0.37
	0.01	0.55
	0.005	0.66
	0.002	0.70

US\$30 million per year, which would raise water rates to users by almost US\$1 per m<sup>3</sup>. Bringing the level down to 0.002 mg l<sup>-1</sup> would cost nearly US\$ 40 million per year, and the amount of water needed might not even be available due to the high levels of reject water.

The results of this study show that the cost of reducing arsenic in water is high. Accordingly, before defining a standard, the Chilean authorities must take the cost into consideration, as well as evaluating the risk implied for the health of consumers by its presence in drinking water.

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