EXTRA COST OF SALINE GROUND WATER TREATMENT: CASE OF LLOBREGAT RIVER DELTA (SPAIN)

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ABSTRACT

Each industry has settled its water depuration process to meet the quality of flow suppliers with its productive appliances. Correcting the process due to salinity increasing of ground water means the enlargement, modification or substitution of original installations with a subsequent important economic prejudice.

This report considers the global extra-cost resulting from depuration of water bound for industries situated in the Delta of Llobregat River by calculating the economic repercussion on a basis of two salinity sources affecting ground water. On one hand, it is considered the salinity increase caused by industrial exploitation of potash mines and on the other hand, the salinity due to sea water intrusion.

1 INTRODUCTION

1.1 Ground water of the Delta of the Llobregat River

Two aquifers co-exist in this delta:

(a) the upper one, minimally productive, used only on occasion for agricultural purposes,

(b) the lower one, having 41.8 10^6 m^3 of ground water extracted during 1986. Of this water, 61% was employed in industry, 38% for domestic use and 1% for agriculture.

The extensive hydrogeological information available on this delta makes it superfluous to enter into further discussion. They can be found elsewhere.

The exploitation of the lower aquifer began in 1883 in the municipality El Prat, which is situated in the center of the Delta. By 1909 the number of wells in operation already surpassed 300. Nevertheless, the amount of water extracted was minimal. During the same year, the Sociedad General de Aguas de Barcelona (SGAB) began supplying drinking water to the city of Barcelona from wells located in the recharge area of the hydrologic system.

The use of ground water by industry began in the 1920s and since then, the extractions destined for industry kept increasing up through the 1970s. This caused a drawdown of piezometric levels, which in turn produced the appearance of the first symptoms of the salinization due to the intrusion of sea water in deep wells near the cost.

In addition, ground water from the lower aquifer showed a salinity increase due to the exploitation of potash mines located upstream in the Llobregat River.

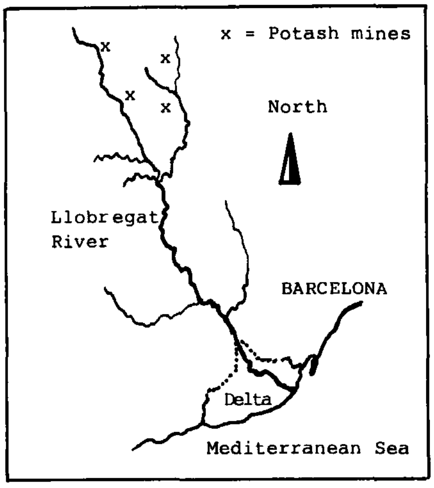
Given these facts, an estimate was later made of the additional costs to the industries of the zone caused by the need of treating extracted ground water.

This paper is only concerned with ground water salinity. It does not take into account the addional costs that might be occasioned by physical or bacteriological treatments for the correction of such waters.

1.2 Evaluation of the composition of ground water

At the beginning of the explotation of the waters of the lower aquifer of the delta, a self-renewal of the waters occurred without causing any notable incidence in the balance of the hydraulic system as a whole.

In 1923 the exploitation of potash mines situated at the upper part of the Llobregat River began, and of those situated at its affluent the Cardener River (Fig. 1).



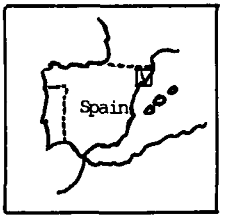


Fig. 1. Location of the potash mines in the basin of the Llobregat River, at about 130 km from the sea.

As a consequence of the mining activity being carried out, the saline content of the Llobregat river waters continued increasing, thus affecting both the surface as well as ground water. In the last few years, the Llobregat has been transporting 600 tons/day of salt from the potash mines to the sea. This causes technical problems related to the treatment of the water as well as a greater economic burden for those industries which need water of high purity in their production processes.

The annual flow of the Llobreat is approximately $600 \cdot 10^6\ m^3$ of water. About 15% of this volume is used by the industries in the area in the proximity of the river. Another 5% is pumped by the industries situated in the delta. The evolution of the salinity of the water of the river at the entrance to the delta is represented in Fig. 2.

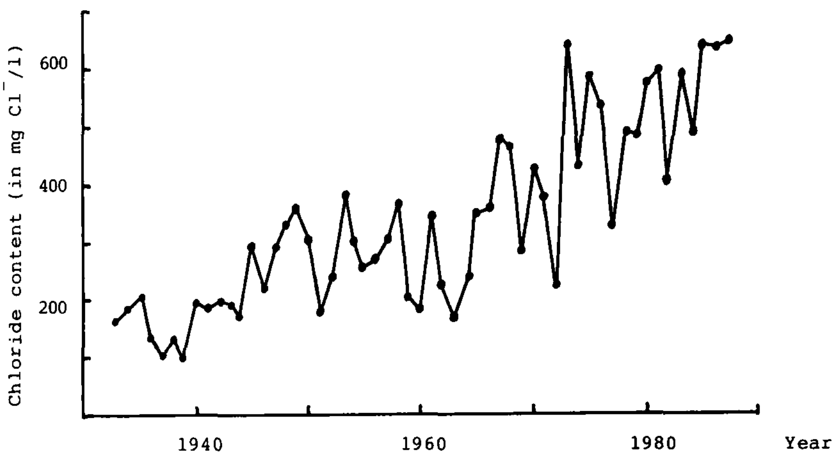


Fig. 2. Evolution of the chloride content of the surface water of the River Llobregat (mean yearly values).

The extraction of ground water reached a maximum at the beginning of the 1970s; this produced cones of depression within extensive areas, which in turn produced variations in the flow altering the quality of ground water. Later, the pumping rate became more stable due to the industrial recession resulting from the petroleum crisis of 1973, and in addition, as a result of the policy for a more rational use of water on the part of the main industries involved. Those who used ground water from the delta founded the first Water User's Community of Spain. Introduced savings contributed to the recovery of piezometric levels (Fig. 3.).

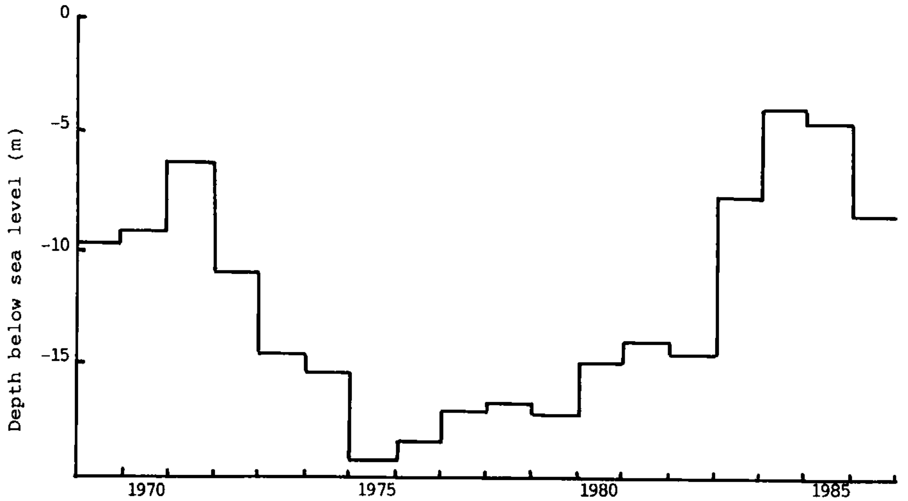


Fig. 3. Evolution of the piezometric level in Courtaulds Fibres, S.A., (CFSA) well water, 4 km from the coast.

The fall of the piezometric levels of ground water gave way to the intrusion of sea water landwards at three points as indicated in Fig. 4.

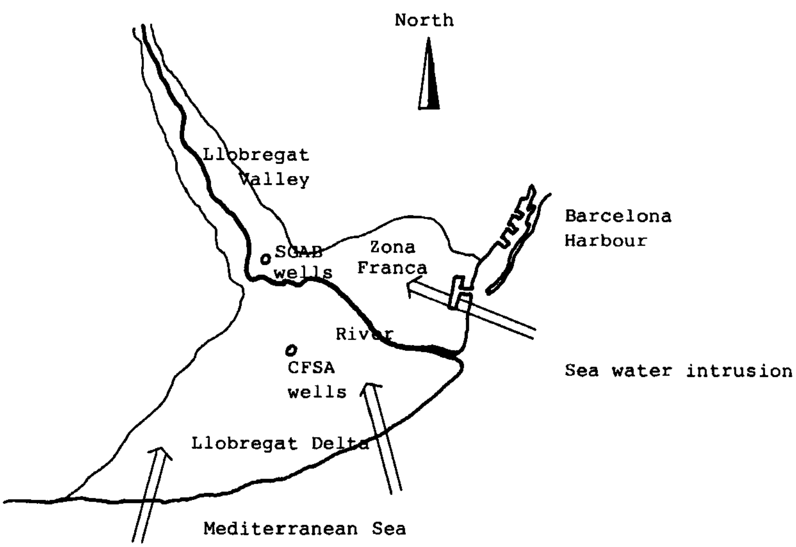


Fig. 4. Map of the situation of the Llobregat River Delta

Besides the two above-mentioned incidences, the composition of ground water has been altered due to greater use of river water in the area, and filtration from irrigation canals. The ground water of the delta had, at the beginning of this century, a stable ionic composition similar to that of the water of the Llobregat River. Today, only the industries closest to the recharge area of the river can claim a composition of ground water whose salinity parallels that of the surface waters of the Llobregat River. In Fig. 5 a graph shows the chloride content of the water from a well located in the recharge zone, and of other well at the center of the delta. The evolution in both wells shows a five year transit time under present ground water flow pattern.

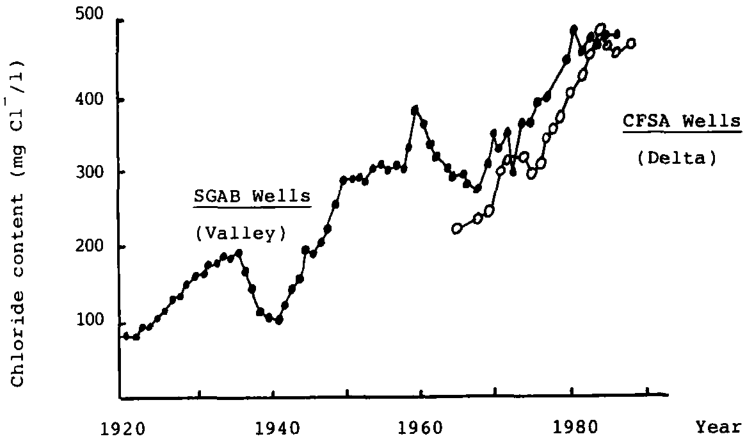


Fig. 5. Evolution of the chloride content in the water of two wells.

Those who use ground water contaminated by sea water have to deal with a fluctuating saline content, which depends on the volume of extraction, the distance from the contaminating source (the sea, in this case) and changes in recharge. Each user faces a different case of salinization for which he must adapt the water treatment most suitable to the changing conditions of salinity.

2 ECONOMIC STUDY

2.1 Ground water from the Llobregat River

Cost estimates for the depuration of water destined for industry in the following cases:

(a)	natural river water	(1915)	80 mg Cl^-/l
(b)	delta well water	(1968)	250 "
(c)	delta well water	(1987)	460 "
(d)	surface river water	(1987)	650 "

In the third part of this study, the extra costs of the depuration caused by the increase of salinity due to the mining operation will be calculated based on a comparison of the previous costs.

2.2 Ground water affected by intrusion of sea water

The irregularity of the saline content of these waters is reflected in the costs of the water treatment. So, in this case, the extra costs have been assessed using real data facilitated by some of the industries involved. The highest ground water salinity recorded is about 10,000 mg/l.

3 VARIABLE COST OF THE DEMINERALIZATION OF THE WATERS FROM THE LLOBREGAT RIVER

3.1 Point of departure

One example is the case of an industry situated in the center of the delta, which iniciated its activity in 1968. The demineralization plant was calculated on the base of the composition of the well water of that year (250 mg/Cl^-) by means of an ionic exchange process. The estimated capacity is 425 m^3/h in order to obtain deionized water with an electrical conductivity of 30 μS/cm at 25 ºC. This plant has been used as a reference in order to calculate the variable cost each of the cases cited in 2.1. All these calculations were based on constant local currency value of 1987. Wages and social benefits have not entered into consideration, since it is taken for granted that the number of workers remains constant. The consumption of electricity and compressed air have not been included either, since their incidence is minimal.

3.2 Pumping of well water

The cost in the central area of the delta corresponds to:
0.3 kwh/m^3 x 0.076\$/kwh = 0.023\$/m^3.

3.3 Taxes

For the year 1987 = 0.18&/m^3 water.

3.4 Cost of the hydrochloric acid used

The cationic composition in each case is, in meq/l:

Cation	(a) 1915	(b) 1968	(c) 1987	(d) 1987 (river)
Ca^{++}	5.2	7.4	9.8	8.5
Mg^{++}	2.8	4.7	4.6	4.2
Na^{+}	n.d.	6.0	10.1	14.5
K^{+}	n.d.	0.4	0.5	1.7
TOTAL	∼11.4	18.5	25.0	28.9

Based on the design of the installation (case b), the hourly production of each of the 5 available production lines is 85 m^3/h:

$$\frac{(127\ m^3/h \times 8\ h \text{ of service}) + (0 m^3/h \times 4\ h \text{ regenerating})}{8\ h \text{ of service} + 4\ h \text{ regenerating}}$$

The production hours plus the capacity of each line can be obtained from the following general formulae:

$$\frac{18.5\ meq/l}{\text{total } meq/l \text{ (in each case)}} = \text{production hours (p h)} \qquad (1)$$

$$\frac{127\ m^3/h \times p\ h}{p\ h + 4\ h \text{ regenerating process}} = \text{capacity in } m^3/h \qquad (2)$$

The cost of the hydrochloric acid has been estimated using this formula:

$$\frac{\$\ 209.44 \text{ regeneration}}{127\ m^3/h \times p\ h} = \$/m^3 \text{ decationated water} \qquad (3)$$

From the preceding formulas, the following values have been obtained.

	(a)	(b)	(c)	(d)
- production, hours	13	8	5.9	5.1
- capacity, m^3/h	98	85	76	72
- decat. water cost, $/$m^3$	0.31	0.21	0.28	0.32

3.5 Cost of caustic soda used

The anionic composition in each case is, in meq/l:

Anion	(a) 1915	(b) 1968	(c) 1987	(d) 1987 (river)
HCO_3^-	5.5	6.3	6.4	5.9
Cl^-	3.0	7.1	13.2	18.3
$SO_4^=$	2.9	5.1	5.4	4.6
NO_3^-	n.d.	0	0	0.1
Total	11.4	18.5	25.0	28.9

Using the same procedure for the estimate as in (3.4) and keeping in mind that the cost of each alkaline regeneration is $282.24:

	(a)	(b)	(c)	(d)
Cost of de-ionized water $\$/m^3$	0.17	0.28	0.38	0.43

3.6 Renewal of resin exchangers

The cost of the attrition that resins undergo is directly related to the number of regeneration cycles undergone. In case (b), for example, the result is $0.048 for each m^3 of treated water. The estimates correspond to:

	(a)	(b)	(c)	(d)
Cost in $\$/m^3$ water:	0.04	0.05	0.05	0.06

3.7 Rinsing of the resines

The consumption of water used to rinse anionic and cationic resins is about 5% of the water produced, which represents:

	(a)	(b)	(c)	(d)
Cost in $\$/m^3$ water	0.03	0.04	0.05	0.05

Example case (b)

$(0.02 + 0.18 + 0.28 + 0.05) \times 0,05 = 0.034\ \$/m^3$

3.8 Additional costs for reaching the desired capacity

The capacity of the plant diminishes as the salinity increases and surpasses the estimated limits. In case (c) and (d) further investments would have to be made in order to reach the needed capacity. In case (c) a new installation would have to be set up with a capacity of 45 m^3/h and for case (d) one of 67 m /h, in addition to the extra costs. This implies additonal costs estimated at:

	(a)	(b)	(c)	(d)
$\$/m^3$ water	0	0	~ 0.10	~ 0.17

3.9 Total variable cost

Table 1 sums up the total variable cost calculated in each case in $\$/m^3$ of demineralized water produced:

TABLE 1

	(a)	(b)	(c)	(d)
Pumping of well water	0.02	0.02	0.02	0.02
Taxes	0	0.18	0.18	0.18
HCl cost	0.13	0.21	0.28	0.32
NaOH cost	0.17	0.28	0.38	0.43
Resines replacement	0.04	0.05	0.05	0.06
Water rinsing	0.03	0.04	0.05	0.05
Additional costs	none	none	0.10	0.17
Total	0.39	0.78	1.06	1.23

3.10 Notes

(i) Fixed overhead such as maintenance costs, amortization, insurance and industrial material, have not been included in the above estimates.

(ii) The price of reagents in Spain is comparable to the prices in other European countries.

(iii) In case (a), since the waters in question are natural waters, the taxes have not been included in the estimate.

4 VARIABLE COST OF THE DEMINERALIZATION OF GROUND WATER CONTAMINATED BY SEA WATER

4.1 Point of departure

The irregularity of the composition of ground water due to the intrusion of the sea directly affects industry in varying degrees, from few mg/l Cl^- to more than 10,000 mg/l. Naturally, each industry takes into account the particular composition of its source of well water as well as the quality of water desired, of course, choosing the most economical treatment. To be considered below is the variable cost of the demineralization of ground water highly contaminated by sea water. Here a reverse osmosis (RO) process is employed, and the discussion refers to a given installation using a fixed type of membranes, receiving brackish water with salinity variable in a given interval.

4.2 Pumping of well water

$0.3\ kWh/m^3 \times 0.076\ \$/kWh = 0.023\ \$/m^3$

4.3 Taxes

$1987 = 0.18\ \$/m^3$

4.4 Cost of reagents

For an installation of RO of 250 m^3/h capacity:

H_2SO_4 = 0.4 kg/m^3 x 0.082 \$/kg =	0.033 \$/m^3
HMP = 0.01 kg x 1.44 \$/kg =	0.014 "
Flocculants and chlorine =	0.010 "
Total	0.056 \$/m^3

4.5 Electrical energy

1.2 kWh/m^3 x 0.076 \$/kWh = 0.09 \$/m^3

Inflow pressure is much higher than actual osmotic pressure. This explains the relative insensitivity of energy consumption to salinity changes in a given installation, without energy recovery (for brackish water this is not enough interesting).

4.6 Renewal of RO membranes

$$\frac{120000\ \$/\text{year}}{2500000\ m^3/\text{year}} = 0.048\ \$/m^3$$

4.7 Concentrated water to the effluent (2 arrays)

(0.02 + 0.18 + 0.06 + 0.09 + 0.05) x 0.25 = 0.10 \$/m^3

4.8 Total variable cost

The above costs come to the sum of 0.50 \$/m^3 water produced by reverse osmosis.

4.9 Notes

(i) The quality of the water obtained by RO is inferior to that obtained by ionic exchange. In order to desionize it to the level of 30 S/cm an additional cost of about 0.08 \$/m^3 should be added.

(ii) The total variable cost of a given system of water treatment based on RO scarcely varies with the increase of salinity of the water used, up to the maximum value acceptable by the plant performance.

5 VARIABLE COST IN RELATION TO THE TREATMENT

Fig. 6 illustrates the variable costs of the depuration of the water according to the treatment employed and the difference in ionic concentration. As seen below, the RO hardly influences the variable cost, even with an increase in salinity.

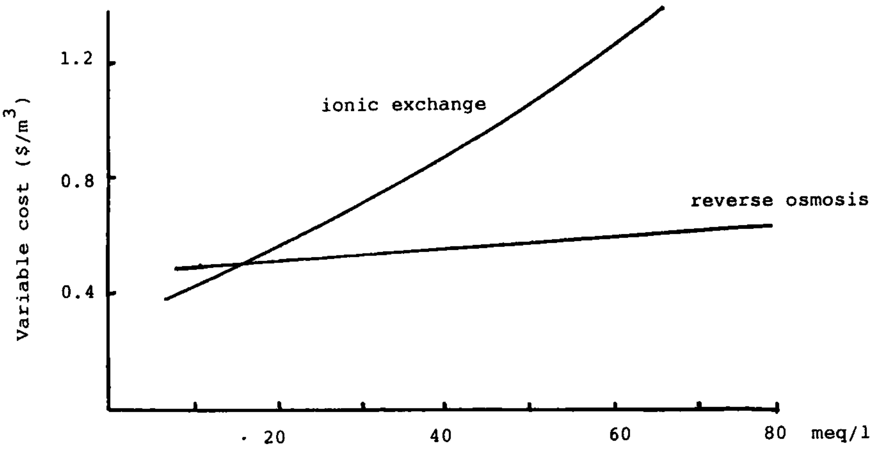


Fig. 6. Variable cost of water desalination versus variable salinity (in total meq/l) for a given installation according with existing experience in Prat de Llobregat.

As the graph shows, there is a point of intersection beyond which it becomes economically profitable to use RO (according to a greater saline content). The problem resides in the new investment involved in the change of the method of treatment. Nevertheless, it is worse for those industries that do not invest in changing the water method treatment, since they not only have to face an increase in cost, but their plants will experience a reduction in capacity. The moment will come when they will find it necessary to buy water because of non anticipating a solution to the problem earlier.

6 GROUND WATER OF THE DELTA

6.1 Quantity and use of the water pumped

The annual inquiry of the water User's Community of the Llobregat River Delta corresponding to 1986 provides the following summary:

TABLE 2

User	$10^6 m^3$/year	(%)	kWh/year
Supplier	15.7	(38)	3,256,000
Agriculture	0.4	(1)	undetermined
Industry	25.7	(61)	8,297,000
Total	41.8	(100)	11,553,000

The cost of the electrical energy needed to pump the water destined for suppliers and industry is:

11.553.000 x 0.076 $/kWh = $ 878.028

equivalent to: 0.021 $/m^3 of water pumped.

6.2 Treatment of the water destined for industry

Based on the inquiry of 1986, the water used by industry had the following destiny:

TABLE 3

Treatment	$10^6 m^3$/year	(%)
Decarbonated	0.66	2.6
Decationated	0.61	2.4
Reverse osmosis	2.24	8.7
Conventional ionic exchange	1.14	4.4
Mix bed	0.44	1.7
Direct consumption	20.61	80.2
Total	25.7	(100)

Based on this data calculations have been made to determine the extra cost of the depuration of ground water necessary because of the increase in salinity.

7 EXTRA COST OF THE TREATMENT OF GROUND WATER DUE TO AN INCREASE IN SALINITY

7.1 Case of saline contamination of river waters

In Table 4 the estimates are given of some cases that might occur in the event that all of the water of the delta became salinized due to the exploitation of potash mines only. The extra costs of water treatment shown in the table have been calculated based on the volumen of desionized water consumed by industry in 1986, that is:

2.22 (RO) + 1.14 (IE) + 0.44 (MB) = 3.82 $10^6 m^3$

TABLE 4

<table>
<tr><th rowspan="2"></th><th rowspan="2">DESMIN.WATER
$/m3
(price 1987)</th><th colspan="4">Incidence in $ million
(to purify 3.82 $10^6 m^3$ water per year)</th></tr>
<tr><th>(a)</th><th>(b)</th><th>(c)</th><th>(d)</th></tr>
<tr><td>(a) NATURAL RIVER WATER (1900)</td><td>0.39</td><td></td><td>(b-a)
1.46</td><td>(c-a)
2.56</td><td>(d-a)
3.23</td></tr>
<tr><td>(b) DELTA WELL WATERS (1968)</td><td>0.78</td><td>(a-b)
-1.46</td><td></td><td>(c-b)
1.10</td><td>(d-b)
1.78</td></tr>
<tr><td>(c) DELTA WELL WATERS (1987)</td><td>1.06</td><td>(a-c)
-2.56</td><td>(b-c)
-1-10</td><td></td><td>(d-c)
0.67</td></tr>
<tr><td>(d) SURFACE RIVER WATER (1987)</td><td>1.23</td><td>(a-d)
-3.23</td><td>(b-d)
-1.78</td><td>(c-d)
-0.67</td><td></td></tr>
</table>

7.2 Case of contamination by sea water

(1) Intrusion through the southwestern area of the delta. Of limited economic importance since it only affects a small part of industrial settlements, although town water supplies and agriculture have been badly damaged.

(2) Intrusion at the south of the river mouth. Their effect has been especially important in the industrial zone nearest the sea. In only a few years certain industries have got water with salinity increasing from 200 Cl^-/l to more than 3000 mg Cl^-/l. This has caused the collapse of the installations based on ionic exchange and they have had to recourse to on the spot costly supplies for fresh water. Some plants have enlarged their installations, while others have changed to inverse osmosis, which has called for significant investments.

(3) Intrusion in the delta Northern area. This is the most contaminated area, in which support an important part of the industrial settlements. Contents of more than 10,000 mg Cl /l are frequent. All of the industries needing water of high purity have had to abandon, either partially or completely, the exploitation of their wells, changing to the general water supply network, which has been extended and enlarged in this area. The diminishing rate of the extraction of ground water is as follows:

Year	$10^6 m^3$/year
1980	11.6
1983/84	6.4
1986	2.8

If the consumption of water had been stable during these years, the purchase of water in this zone during 1986 would have meant an additional cost of:

$$(11.6 - 2.8)\ 10^6\ m^3/year \times \left[0.76 - (0.18 + 0.02)\right]\ \$m^3 = 4.9\ 10^6\ \$/year.$$

Plans for saving on water have allowed industry to lower this additional cost. On the other hand, investments have been made in the installations of new equipments. It is not an exaggeration to assign an additional cost of some \$ 4.10^6 in 1987 for the purchase of water to substitute the salinized ground waters.

8 CONCLUSIONS

(a) The industries decided to establish themselves, in the delta of Llobregat River because of the abundance and high quality of ground water. As time went by, the water became more and more contaminated due to an increasingly high salinity content caused by the exploitation of potash mines located in middle Llobregat basin and also due to the intrusion of sea water in wide areas of the delta.

An excess in pumping has been the main cause of the intrusion mentioned above, together with a decreasing aquifer recharge due to a higher content suspended matter in the Llobregat river water at the main recharge area.

(b) In 1986 the industries located in the Delta of Llobregat River pumped $25.7 \times 10^6 m^3$ of ground water, of which $3.82 \times 10^6 m^3$ have been treated by chemical means in order to obtain the high-purity water needed for their manufacturing processes.

The extra cost of this treatment aimed at avoiding those problems and the ones developed by human activities, amounts to \$ 2.6 10^6 per year. This extra cost is equivalent to \$ 500/year per worker with a job in the local industry.

(c) Because of the contaminated ground water, industry must consider higher economic repercussions. Each type of industry has to bear an extra cost depending on the ion concentration in water.

Below we will consider three cases:

(a) Industries bearing moderated contamination which still treat ground water with ion exchange installations. In this case, it means a higher consumption of reagents and therefore a cost increase.

(b) Industries that had to alter or modify their installations because of the salinity increase. In this case new investments had to be made in order to deal with the problem.

(c) Those industries that had to give up partially or wholy the pumping and decided to take water from the general water supply network or, in some cases, even import water by truck. In the case of industries using the general water network, it means an extra-cost in raw material estimated in 0.56 $\$/m^3$. The ones with trucked water supplies, generally with low and irregular consumption, suffer an extra cost of 10 $\$/m^3$ of water.

The economic incidence ground water contamination by sea intrusion is difficult to estimate due to particular treatments led by each industry. In addition to this, the progressive salinity increase together with sudden fluctuations make estimations ineffective.

In the Zona Franca (Northern Sector), the most sea water contaminated area, the purchasing of water from the general network is evaluated at an extra cost of \$ 800/year per job. In the Prat industrial zone, less affected by water salinity increase and situated on the Llobregat

River right bank and nearer the sea, the complementary supplies of high quality water bound for treatment are estimated at $0.5 10^6 a year (extra cost of $100/year per job).

(d) Despite the extra costs mentioned before, there are some others difficult to estimate. They are listed and explained below, to provide a better understanding of the economic significance of ground water salinization:

(a) Increased corrosion of materials. It means a higher maintenance and in the replacement cost.

(b) New investments to deal with the loss of capacity in water treatment installations. Enlargements, modifications, new treatment installations, cooling towers, water re-use installations and so on.

(c) Industries with small capacity treatment facilities have higher extra costs.

(d) Industries, as well as agriculture and drinking water supplies, have had to give up taking water from wells because of corrosion or poor quality of water, and have had to open new well or move to more expansive water sources, if they are available.

(e) As a summary it can be said that, without accounting for the extra costs of difficult estimation that each industry in the delta has had to bear, nor the savings obtained by a better rationalization of water, the global extra cost in treatment of ground water in the Delta of the Llobreagt River due to salinity increase due to potash mines exploitation and sea intrusion amounts to \$ 5.6 10^6 /year (equivalent about \$ 1100/year per industrial job). This extra cost is six times higher than the cost of electrical energy used for pumping ground water.

9 ACKNOWLEDGEMENTS

This paper has been possible thanks to the information given by the main water user's of the Delta of the Llobregat River. The author is grateful to them and he recognizes that without this priceless colaboration this paper could not have been issued.