ENVIRONMENTAL ASPECTS OF WATER USES IN THE LLOBREGAT RIVER BASIN

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Abstract

The Llobregat basin covers a large part of the province of Barcelona (Catalunya, Spain). Its chief watercourse is the river Llobregat, with a length 156 Km (average flow: 10-15 m^3/s). It is a Mediterranean-type river basin with a water regimen characterised by large fluctuations in volume of flow owing to the geography and climate of the area.

The Llobregat basin was 3000 years ago the cradle of civilisation in what now is know as Catalunya. The Llobregat delta played 2000 years ago, a key role in the establishment of the initial tribal settings which developed in what is now Barcelona city. During the end of the 18th century, and at the beginning of the 19th century, the Llobregat basin was the centre of the 2nd. largest industrial development in Europe, closely following the boom of the textile industry in Manchester area. In the last 40 years, the Llobregat delta area (known as Baix Llobregat) has shown one of the largest growth on GIP (Gross Industrial Product) of Spain.

Consequently, the basin's resources are scarce as they are widely tapped for irrigation, industry and water supply. The exploitation of Llobregat water resources starts already at the high parts of the basin and continues with increasing pace all the way down to its delta. One notable use is in mini-hydropower stations, which affect the sustainability of the river during dry periods and droughts. In the lower reaches of the basin there are two major drinking-water plants (Sant Joan Despí and Abrera) which supply Barcelona, among other towns. There are also considerable groundwater resources in the area. The combined use of ground and surface waters through replenishment techniques is becoming a reasonable way of utilising these two resources in a sustainable fashion..

Furthermore, the quality of the water resources at the Llobregat river is low due to the large input of industrial and urban waste entering into the system. A particularly acute problem has been caused by the uncontrolled potash mining activity at the medium part of the basin which has created a large increase in salinity. These problems have severely affected both the quality and quantity of surface and ground waters at the Llobregat basin. A few projects are underway to palliate some of these problems under the Catalonian Drainage Plan (Plan de Saneamiento de Catalunya) – construction of a brine collector, rationalisation of water use, introduction of new automatic quality control
joint scheme to reuse wastewater – are already showing some beneficial effects.

The objective of this case study is to present the typical situation arising from a Mediterranean basin with scarce and extremely irregular resources which are largely overexploited on a densely populated area. Further to this, we would like to discuss the management strategies to be implemented in order to return the use of the Llobregat river to sustainable horizons.

1. Physical description of the river Llobregat : basic data

The Llobregat river basin is in the north-east of the Iberian Peninsula, fully contained in Catalunya and forming what is the backbone of the province of Barcelona (Figure 1). The river Llobregat is 156.5 km long, part of the Pyrenean-Mediterranean network, constituting its largest basin (4,948.4 km^2).

Table 1 shows data regarding the Llobregat's main tributaries (Linati-Bosch 1977).

Table 1 – The river Llobregat's main tributaries

Name	Area (km^2)	Length (km)
Cardener	1,373.2	87.0
Noia	929.4	66.5
Gabarresa	449.6	60.0
Marlés	173.0	46.8
Rubí	122.1	31.0

On its route from the Pyrenees to the Mediterranean, the river Llobregat and its tributaries cross successive geographical and geological zones of a highly diverse nature which, coupled with factors such as relief, climate and vegetation along with the often vital influence of human activity, confer some very particular characteristics on the basin. In geological terms, this river network runs through various morpho-structural units ranging from the Pyrenees and sub-Pyrenean zone to the Mediterranean System, crossing what is known as the Central Catalonian Depression (Depresión Central Catalana) from north to south. This area has a major influence on the properties of water in the basin as it contains several large deposits of potassium salts.

As to the area's relief, the highest altitudes are in the mountain ranges bordering the basin – around 2,000 m. So the headwaters of the Llobregat and Cardener river basins lie in a sub-alpine climate

As to the distribution of the basin area, 21% is above 1,000 m, 24% between 1,000 and 500 m, and 55% at altitudes below 500 m. The vegetation at each level is typically Mediterranean, from meadowland to woods of firs and pines, oaks, holm oaks and other deciduous trees, and shrubs. A large variety of crops are grown, though broadly speaking there is a predominance of traditional Mediterranean staples, i.e., vines and olive and fruit trees, the latter concentrated near rivers and canals. There is also an abundance of cereals and, especially in the Llobregat delta, irrigated crops (Catalan *et al.* 1971).

Temperatures are linked to altitude and range from a few degrees below zero in winter to nearly 40°C in summer (July-August) in some areas. Overall we may say that average monthly temperatures are all above zero degrees, within a range from minimum levels of 5°C to maximum of 25°C.

Rainfall in the Llobregat river basin is variable; it averages between some 500 and 1,000 mm/year, while the maximum values tend to be in the months of May, June and September and the minimum levels in winter and then again in summer. It is worth noting that rainfall is very unevenly distributed both in time and space.

It may be deduced from the above that the outstanding hydrological feature of the river Llobregat is its low and highly irregular flow. Figure 2 shows the evolution of the river's flow volumes over recent years at Sant Joan Despí, site of the Aigües de Barcelona (Agbar) Water Treatment Station and Abrera, site of the Aigües Ter-Llobregat Water Treatment Station. It is worth noting that extreme flows at this point range from low flow periods of less than 1 m^3/s to highs of more than 1,000 m^3/s, with the consequent floods. One of the worst floods in our memories, in September 1971, brought a flow of 3,100 m^3/s at Sant Joan Despí. In 1998, the flow of the river Llobregat at Sant Joan Despí fluctuated from 0.1 to 102 m^3/s, with an average daily flow of 5.1 m^3/s. Table 2 shows the river's average annual flow (1996) along with average and minimum flows for a dry year (1989) at various gauging stations in the Llobregat basin (Prat 1997a). This data shows up one of the characteristics of this basin and, in general, of most of the rivers in eastern Spain.

Table 2 - Flows (m^3/s) at various points in the Llobregat river basin

Gauging point	**Altitude (m)**	**Average annual flow**	**Average flow (dry year)**	**Minimum flow (dry year)**
Mediona	375	0.19	0.13	0.10
Anoia	121	2.29	1.02	0.22
Rubí	35	1.1	1.1	0.5
Castellbisbal	155	17.6	9.5	5.2
Martorell	44	20.7	7.6	1.7
St. Joan Despí	11	15.4	6.2	2.4

For many years the only regulating reservoir in the Llobregat basin was that of Sant Pons on the river Cardener, with a capacity of 24.7 hm^3. Since 1976 there has been another reservoir at La Baells with a capacity of 125 hm^3, vital to regulating the river's flow and improving its overall utilisation. Finally, the construction of a new dammed reservoir, known as La Llosa del Cavall, has been finished on the river Cardener upstream of Sant Pons, with a capacity of 80 hm^3 (Figure 1).

2. Geochemical description of the Llobregat basin: Basic data

As we have already pointed out the Llobregat river basin flows through three very differentiated geological settings, this has a clear implication on the geochemical characteristics of the river and, in particular, what constitutes one of its main characteristics its increasing chloride content.

Figure 3 is a plot of the evolution of chloride content as a function of the distance from the river sources. The data are from a series of sampling campaigns performed in May-June 1996 (Freixes et al, 1996, Prat 1997b) and correspond to a season with relatively few disturbances in flow. Therefore, the data should be representative of the average geochemical behaviour of the basin. The sampling points are geographically located in Figure 1.

Figure 3, clearly indicates the influence of the Catalan Central Depression in the increased chloride

The geochemical evolution of the major component geochemistry of the Llobregat river is given in Figure 4. This Piper plot gives a clear indication of the main chemical evolution of the river from the relatively low mineralised, calcium bicarbonate type of waters at the upper part of the basin, to the highly mineralised sodium chloride, sulphate type of waters from the intermediate part of the basin, down to the delta.

According to Custodio and Queralt (1981) there are two main contributions to the salinity content in the Llobregat river:

- the natural input of salinity due to the fact that halite and carnalite are at the surface and contacting the Cardener river both in Suria and Cardona. According to some analytical data from 1912, prior to the mining activities, this background content in the river was around 80 mg Cl^{1-}/l (0.002 mole dm^{-3}). This is in agreement with the range of values estimated from the chloride content (80-100 mg/l) inferred from the chlorine intrusion in the delta groundwaters older than 100 years (Custodio and Queralt, 1981).
- The anthropogenic input, mainly due to the mining activities around Suria, Cardona and Balsareny, which has largely disturbed both the geomorphology, the hydrology and consequently the geochemistry of the intermediate part of the basin. This issue will be thoroughly discussed in the discussion concerning the usage of Llobregat river resources.

3. Water usage at the Llobregat basin

The water resources from the Llobregat river and its tributaries is intensively used right from the source down to its delta. These resources are used for power production, industrial processes, agricultural irrigation and as municipal water supply.

The Llobregat river basin contains some of the largest towns in Catalunya. The total basin population is estimated to be 960,000 inhabitants (Matia *et al.* 1993). This population is fully all of supplied with water from the basin, both for domestic and industrial uses. The water from the Llobregat river is used and contaminated and cleaned to a varying degree, and then returned to the basin. It is also worth noting that the Abrera and Sant Joan Despí Water Treatment Plants in the lower Llobregat basin contribute to the water supply for Barcelona and its metropolitan area, populated by some 3 million people.

In the last few decades there has been a large rise in water demand owing to population growth and the requirements of agriculture and industry. All this has affected water quality. The numbers in the boxes in Figure 5 show the population upstream of each point on the various rivers in the basin. The geographical distribution of the main activities in the basin is also shown.

The waters of the river Llobregat are so intensively utilised that only the initial 9 km of its course are thought not to have undergone any kind of transformation, while 12 km have been altered by dams, 4 km by agricultural irrigation channels and 130 km tapped for various uses, especially hydropower stations (Prat 1997a).

Irrigation

There are numerous dams along the course of the river Llobregat that deviate the circulating surface water by drawing it off through canals for irrigation and/or industry.

The areas of irrigable land are not very large, and they are indeed steadily decreasing due to increasing urbanisation, the construction of new road and railway infrastructure and the decline in local agriculture. Thus in 1971, according to local Associations of Irrigators (Comunidades de Regantes), the total area of irrigated land was 6,939 ha (Catalan *et al.* 1971), corresponding to 80% of the lower Llobregat basin, from Molins de Rei to the delta (20 km). Today the total area is thought to be 2,800 ha, just 40% of 1971 levels. This does not include the irrigated areas of the Llobregat delta, where groundwater is used.

The canals that currently draw off the largest flow are Canal de la Derecha (up to 1,800 l/s) and Canal de la Infanta, which was built in 1907 and is currently capable of tapping up to 1,300 l/s of water from the Llobregat and the Rubí rivers.

Hydropower stations

The presence of mini-hydropower stations is one of the basin's specific problems, owing to the functional regimen of its waters. These are small dams just a few metres high that use a certain volume of river water to generate electricity then return it a few hundred metres or some kilometres downstream. As a result, some stretches of the rivers are left without sufficient water, especially in dry seasons, to support the rivers flora and fauna (ecologically sustainable flow). It is therefore impossible to maintain the ecosystems of these areas.

Many mini-stations on the river Llobregat were set up to power old textile industries. According to data from 1965 there were 56 stations on the Llobregat river, 35 on the Cardener river and 7 on the Anoia river. The total installed capacity was 22,655 kW (Catalan *et al.* 1971). At present, there are 55 mini-stations on the Llobregat, the first at 50 km from the source. On the Cardener there are 25 power stations (Prat, 1997a).

The problem is exacerbated by the fact that the flow and volume concessions for many mini-stations were reviewed in 1996 with a view to increase electricity production. As there were no proper studies of the minimum ecological flow required in the river, a number of bypassed sections are left dry. According to Prat (1997a) in the period 1991-1992 some stretches of the river Llobregat were dry for more than 200 days per year.

Hence, a dedicated effort is needed to make electricity generation sustainable by defining the ecological flows of the Llobregat river and consequently preserving this vital basin.

Drinking-water supply

As we have previously discussed the whole local population is supplied with water from the basin.

The two most important collection points are on the lower reaches of the river Llobregat (Abrera and Sant Joan Despí) (Figure 1). A large portion of the water collected is supplied to municipalities outside the basin, in particular Barcelona.

- Sant Joan Despí Treatment Plant (Agbar 1996).

Cumulative growth in water demand, due largely to development in Barcelona and its metropolitan area, meant that in 1953 it became necessary to utilise the Llobregat's surface waters. This led to the first concession granted to Agbar to tap 2.2 m^3/s and the construction of the Sant Joan Despí Treatment Plant. The original plant was enlarged in 1957 and 1960 to cater for further flow volume concessions, up to a total capacity of 5.3 m^3/s. The volumes constant rise in water demand made it necessary also to turn to other basins in order to supply the Barcelona area. The plant now treats some 120 hm^3 of water a year, accounting for 36% of Barcelona's water supply. A further 4.5% corresponds to groundwater collected from the Llobregat aquifer in wells situated mainly in the vicinity of the plant (municipalities of Cornellá and Sant Joan Despí).

Initially, standard conventional methods were used to treat the water : pre-chlorination, coagulation, flocculation, decanting, sand filtering and final post-chlorination.

However, pollution in the Llobregat's untreated waters started to increase considerably once the plant came on stream. This and the pursuit of better quality in treated water led to the progressive introduction of new treatment techniques. Thus in 1968 the addition of carbon powder was introduced, then in 1977 sand filtering was replaced with filtering by granular active carbon (GAC). Finally the treatment line was extended in 1992 with the introduction of a double filtering process using sand and GAC, with intermediate ozonisation and a maximum ozone production capacity of 96 kg/h. Further changes have been made more recently, such as feeding groundwater to the plant at the ozonisation stage and replacing pre-chlorination, used chiefly in the removal of ammonium, with chlorine dioxide and nitrification treatment. Figure 6 shows a diagram of the plant.

- Abrera Treatment Plant (Valero 1996).

This plant lies in the municipality of Abrera 30 km from Barcelona, upstream of Sant Joan Despí (Figure 1).

Built to a smaller scale than the initial project, which was to treat 6 m^3/s, it came on stream in 1978 to supply water to a number of municipalities in the area. Since 1985 it has been publicly owned and has undergone various improvements.

The stages of the current treatment process are pre-chlorination, coagulation/flocculation, decanting, sand filtering, GAC filtering and final post-chlorination. One major change to improve the quality of the water treated was the introduction of 10 GAC filters in 1995. surface area of 100 m^2 each, a 1.5 m layer of GAC and a maximum filtering speed of 10.7 m/h with a contact time of 8 min. Work is under way to introduce chlorine dioxide to replace pre-chlorination.

Average water production in 1996 stood at 65,000 m^3/day. There is a tendency to increase. Some of the water is now also supplied to Barcelona and other municipalities outside the basin.

4. Groundwater : the aquifer of the Llobregat delta

The aquifer of the Llobregat delta is a unitary hydrogeological formation stretching from Martorell to the sea, widening progressively from a few hundred metres to several kilometres along a total length of 110 km^2 (Figure 7).

In the upper reaches (between Pallejá and Cornellá), the aquifer is unconfined and up to 2,100 wide and over 40 m thick. At Cornellá it splits into two : an unconfined upper arm and an enclosed lower one.

The deep aquifer (from Cornellá to the sea) is unquestionably the most important part, consisting of quaternary gravel and sand. Its thickness ranges from 30 to 45 m and the maximum useful reserves along its whole length are estimated at 114 hm^3 (Agbar 1990).

- Uses of the aquifer.

The groundwater was first used for water supply and irrigation at a local level. The first intensive utilisation began in 1905 when Agbar began to use it for water supply. Later, especially from 1930 onwards, water demand for domestic, industrial and irrigation purposes rose increasingly (in 1954 Agbar extracted over 70 hm^3 for water supply). Utilisation of the deep aquifer grew over the 60 s mainly as result of industrial development, peaking at the extraction of 130 hm^3 in 1973 (a very dry year). From then on the utilisation of the aquifer fell back to more rational levels, due especially to the combined and co-ordinated use of ground and surface waters in the basin and efforts on the part of industry to save water. This was largely due to the creation of the users community called "Comunidad de Usuarios del Delta del Río Llobregat" (Llobregat Delta Water Users' Association) (Miralles 1994).

The increasing control of the overexploitation of the aquifer has led to more rational utilisation. Accordingly, the current availability stands at 8-10 hm^3/year for agriculture, 35-45 hm^3/year for industry and 8-40 hm^3/year for water supply (Miralles 1994).

- Combined use of ground and surface waters.

The first project of this type started in the 50s, boosting the recharge of surface water from the aquifer by scarifying the river bed in the area where the aquifer is unconfined. The scarified area is opposite the town of Pallejá (figure 7). The technique involves preparing the river bed then scarifying it with a tractor equipped with ripper of less than 50 cm. It is applied when the river flow is between 10 and 35 m^3/s, water turbidity is less than 150 NTU and the quality of the water is suitable (break point $Cl_2 < 12$ mg/l, chlorides < 700 mg/l, etc.). At present it is possible to percolate a flow of 0.5 m^3/s.

In 1996, while the availability of resources was sufficient to ensure water supply, Agbar decided to start projecting and building deep artificial recharge facilities, taking advantage of the existing wells in the Cornellá area plus some other new ones. These are used for collection and recharge alike. The water for recharge comes from the Sant Joan Despí Treatment Plant via a system with a recharge capacity of 1 m^3/s. Descaling and cleaning operations need to be carried out periodically, and the quality of the recharged water must fulfil certain quality criteria (chlorine > 500 mg/l, turbidity < 0.6 NTU, etc.) (Agbar 1990). In wet years it has been possible to replenish over 7 hm^3 of water.

5. Main stresses on the Llobregat river basin

The peculiar characteristics of the Llobregat river basin with dense population, extensive salt extraction, pre-industrial development, etc, in addition to the irregularity of its hydrological cycle make this river basin very prone to acute contamination problems.

In Figure 5 we show a summary of the location of the main contaminant activities. The main sources of industrial pollution are diverse: salt and coal mining, textile industry, galvanic industry, tanning, paper, chemical industry, detergents, pharmaceutical industry, etc., and the effects of uncontrolled dumping imply the water is subject to large fluctuations in quality.

Due to the circumstance that the Llobregat river is extensively used for water supply, the main stresses in the river waters are reflected on the quality of the liquid that is used as raw water to produce drinking water.

Figure 8 shows, as an example, the evolution of ammonium levels in the river Llobregat at Sant Joan Despí since 1960. An improvement in water quality is apparent from the seventies on.

The pollutants that have caused most problems, especially as regards the utilisation of water for drinking supply, have been salinity, (chlorides, sodium, potassium), ammonium, detergents, oil and grease, colorants, heavy metals (chromium), cyanides, and organic compounds (taste and odour).

Table 3 shows some parameters of water quality in the river Llobregat in 1998 at the Sant Joan Despí Water Treatment Plant. Clearly some pollution problems remain despite the drainage work carried out. These problems currently arise in the form of pollution episodes that on occasion lead to shutdowns at the treatment plant. As an example of this, table 4 shows pollution episodes that caused the Sant Joan Despí Plant to be shut down in 1993 (Matia *et al.* 1995).

Table 3 – Quality of water from the river Llobregat at Sant Joan Despí

Parameter	**Minimum**	**Average**	**Maximum**
Conductivity (μS/cm)	741	1515	3050
Chlorides (mg Cl/l)	63	328	865
Sodium (mg Na/l)	114	186	240
Ammonium (mg NH_3/l)	< 0.1	1.02	11.1
COT (mg C/l)	3.1	5.9	26.4
Surfactants (mg LSS/l)	0.02	0.2	3

Table 4 - Pollution episodes that brought about shutdowns in the Sant Joan Despí Plant

Cause	**Number**	**Time (h)**
Taste and odour	2	16
Ammonia	8	73
Turbidity	8	83
Surfactants	1	5
Grease and oil	1	18
Ammonia and TOC	11	98
Ammonia, TOC and UV abs.	5	75
Turbidity, ammonia, TOC and UV abs.	13	244
Turbidity, colour, odour, ammonia and TOC	1	21
TOTAL	50	633

In 1998 there were 656 hours of shutdown at the Plant due to 35 pollution episodes. A large number of these were caused by polluted waters from tributaries of the river Llobregat – the Anoia and the Rubí (Figure 1, Figure 5), especially the latter. These waters, particularly those from the Rubí, are normally drawn off the Llobregat and by-passed through a system of canals under the Sant Joan Despí Water Treatment Plant. Pollution episodes arise when, for various reasons (such as a rise in volume of flow), these waters run into the Llobregat. All this requires exhaustive, systematic and periodical quality control on the untreated water of the Llobregat.

As regards to organic pollutants, a wide range of compounds have been found in the water, including halogenous compounds, aromatic hydrocarbons, phenols and quinones, acids and ethers, alcohol, ketones and aldehydes, plasticisers, pesticides and herbicides, amines and amides, detergents and their derivatives, etc. (Rivera *et al.* 1988).

- The salinity problem.

As we have already discussed, one particular problem concerning the quality of water a large portion of the Llobregat basin is caused by saline mining operations (chloride, sodium and potassium) in the upper area of the basin (Cardona, Suria, Sallent and Balsareny) (Figure 1). These activities started in 1923 and caused a gradual build-up in the salinity of both the ground and surface waters, mainly due to brine dumping in the basin. This is a particularly problematic contamination as they are used downstream for water supply.

This has been one of the major problems for quality of the Llobregat river for quite some time. Particularly, in the period 1960 to 1989, when a collector was installed to gather the brine from mining activities and preventing its dumping in the Cardener and the Llobregat rivers. The brine collector has reduced the salinity of the water, although the problem is not fully solved. Table 5 shows the evolution of salinity levels in the river Llobregat at Sant Joan Despí (Martín 1994 ; Agbar 1996). The large variability is due to the wide fluctuations in volume of flow as mentioned earlier.

Table 5 - Chloride content and flow average in the river Llobregat

Year	**Average Flow (m^3/s)**	**Chloride (mg Cl^{1-}/l)**		
		Max.	**Min.**	**Average**
1985	10.2	1495	163	640
1986	6.1	1053	353	751
1987	15.1	1121	92	641
1988	20.1	1085	121	568
1989	6.2	1624	128	924
1990	7.9	1496	92	570
1991	16.2	1855	114	452
1992	30.7	553	43	271
1993	13.3	801	85	360

In Figure 9, we show the evolution of annual average chlorine concentration in the Llobregat river, from pre-mining times (data of 1912, according to Custodio and Queralt, 1981), to present times.

It is very noteworthy to see the immediate impact of mining operations from 1925 on, the decrease on chlorine content due to the slowdown of salt mining during the Spanish Civil War and the 2nd World War (period 1936-46), the reduced impact of the construction of the regulating reservoir at La Baells (1973), and the very positive influence of the construction of the Brine Collector from 1990 till present. If this tendency is kept, the Llobregat river could be back to pre-mining levels in the forthcoming decades.

- Groundwater contamination

The pollution of surface water, especially with regards to salinity, has also affected groundwater. Meanwhile there have been other groundwater pollution problems due to direct contamination of the aquifers, particularly through the use of industrial waste to backfill pits left by aggregate extraction for construction

➢ Chlorine solvent pollution.

This problem was detected in 1974 in one of Agbar's wells (Pozo Estrella 4) in the municipality of Sant Feliu (Figure 7) owing to the odour of the water. First, a presence of perchlorethylene was identified. Later on other solvents were found (trichlorethylene, 1,1,2-trichlorethane, etc.).

This episode has been connected to the unauthorised use of industrial waste to backfill the aggregate quarries located upstream. To prevent the pollution spreading a hydraulic barrier was established by pumping out several wells. Today, more than twenty years on, the contamination persists, especially when the piezometric level of the aquifer rises. Figure 10 shows the situation over recent years as regards the presence of 1,1,2-trichlorethane (Luque 1998).

- Heavy metal inputs in the Llobregat river.

The imprint from the extensive usage of metals in the Llobregat river can be seen in the heavy metal content at different locations in the Llobregat river bed. The data collected by Ballbé and Queralt (1989) at diverse locations throughout the basin are shown in Figure 11. The increased content on heavy metals with increased distance from the source is an indicator of the extent of past and present metal input into the river system. This has severely affected the quality of the Llobregat water in some acute contamination episodes.

In January 1986, a presence of hexavalent chromium (Cr VI) was detected in some of Agbar's 25 extraction and replenishing wells in the municipality of Cornellá.

Studies traced the pollution to a galvanisation company that was dumping its wastewater in a pit linked to the Llobregat Delta aquifer (side intake). The water in the pit contained 7 mg /l of chromium.

Though the source of the pollution was removed, the concentration of Cr (VI) in the contaminated wells rose steadily to a peak of 60 μg/l in 1989, before falling to 5 μg/l (Luque 1996).

- Contamination from petrol spillage.

In December 1991, petrol contamination was detected in some of the above-mentioned Estrella wells in the municipality of Sant Feliu, used for water supply.

Studies traced the pollution to petrol spillage caused by a terrorist attack on a pipeline that runs parallel to the river Llobregat.

To limit the damage it was decided to set up several hydraulic barriers, two with the existing wells and another two with newly built ones. Meanwhile the ground (soil and groundwater) where the spillage had happened was cleaned up, which entailed removing 23 tm of petrol. The barriers have been working totally or partially for four years, extracting 4 hm^3 of water (Luque 1998). Figure 12 shows the affected area of the pollution damage.

Currently no petrol contamination is detected at any of the collection points. Nonetheless, exhaustive monitoring of water quality continues.

6. Projects to control and improve water quality

As has been seen, environmental problems in the Llobregat river basin have been severe and complex, bringing sometimes serious difficulties in water management, in terms of both quantity and quality. These problems have been due largely to the hydrogeological features of the basin, its dense population and industrial activity and the utilisation of its water. It is worth noting that 39% of the organic material from industrial dumping in Catalunya is concentrated in the Llobregat river basin (Junta de Sanejament 1996). Each specific problem has had to be remedied by a specific solution, and while some have been more effective than others, all have ultimately worked. Measures taken in recent years, especially at overall level, have been more in the field of prevention. Their effects have been felt above all in a substantial improvement in the quality of water in the basin. Some of the measures considered most important are outlined below.

The Drainage Plan

The Catalonian Drainage Plan (Plan de Saneamiento de Catalunya) seeks to raise the quality of water to specific levels. Achieving this aim entails developing a number of projects based on the overall planning of water quality, establishing an eco-finance system for the various plans and projects, and then carrying them through. Lastly it is necessary to control water quality and encourage participation and joint responsibility on the part of all sectors in averting and remedying pollution. All this is currently being carried out by the Agència Catalana de l'Aigua (previously Junta de Sanejament), a body dependent on the Catalonian government (Generalitat de Catalunya). The projects carried out so far in the Llobregat basin have been centred on the construction of drainage networks and wastewater treatment plants, introducing and improving systems for treating and dumping water from industrial activity, and establishing the relevant control systems.

By year 1998, the treatment of urban wastewater corresponding to 764,880 people was implemented treatment plants (WTP) in service, 14 under construction and 3 were being projected (Junta de Sanejament 1998).

Concerning industrial wastewater, gradual decontamination programmes, sector co-operation agreements and subsidised grants to improve the waste water quality of many companies have been given.

One highly important aspect of water treatment in this basin, especially in the lower part, is the reuse of treated wastewater. Wastewater reuse should be considered for green areas and sport grounds, for cooling and other industrial uses, for replenishing aquifers and irrigating certain crops, and also for maintaining environmentally friendly water levels.

This water reutilization market in Catalunya is still limited. Thus in 1999 only 3.75% of treated water is being reused, as against a projection of 41% of total treated wastewater (Junta de Sanejament 1999).

For the metropolitan area of Barcelona there has been a viability study on reusing the resources of current plants through various networks of water for industrial use. With these it would be possible to reuse 51,700 m^3/day of treated water (Aigües Ter-Llobregat 1998). Meanwhile the future WTP of Prat del Llobregat (the biggest in Catalunya), which will treat wastewater mostly generated outside the basin, may allow the reuse of 325,000 m^3/day (Junta de Sanejament 1998). A good example of wastewater reuse for irrigation has been given this summer in the lower reaches of the Llobregat. The drought has made it necessary to reduce the flow tapped by the Canal de la Derecha to 800 l/s. So to ensure that water needs are met, 400 l/s of water from the Sant Feliu treatment plant has been added to the flow, thereby enabling 1,000 ha to be adequately irrigated. This water is moreover undergoing various forms of quality control (El Periódico 1999).

The Brine Collector

It was mentioned above that one of the major problems regarding water quality in the Llobregat basin was salinity owing to mining activity.

In order to palliate this problem, a collector to draw off brine and channel it to the sea was proposed as early as 1931. Yet work on such a pipeline did not start until 1983, and its construction was finished by 1989.

Figure 13 shows the layout of the collector. It is in a "Y" shape with one branch on the river Cardener and another on the Llobregat. Its total length is 120 km. The pipes are made of fibercement (diameter: 250 mm) and fibreglass-reinforced polyester (diameter: 350 and 450 mm) and are hydraulically operated by 13 towers and 8 load-breaker boxes along the route. The collector's maximum capacity is to convey 150 l/s of brine with a transit time of 50 hours. It draws off brine from mining industries, from leachates in tips and from natural mine outflows (Agbar y Junta de Sanejament 1996, Matia 1994).

Table 5 and, with more detail, Table 6 show the improvement in water quality since the collector came into operation (Agbar, Junta de Sanejament 1996). This improvement has also affected groundwater.

Table 6 - Effect of the Brine Collector on water quality in the Llobregat river
at Sant Joan Despí

Parameters	**Average values 1987-89**	**Average values 1991-93**	**% Improvement**
Conductivity (µS/cm)	2726	1625	40
Chlorides (mg Cl^{1-}/l)	711	359	49
Sodium (mg Na^{1+}/ l)	346	187	46
Potassium (mg K^{1+}/l)	161	45	65

The automatic quality control network for surface water

Problems regarding the variable quantity and quality of water from the river Llobregat, especially due to its use for public water supply, gave rise in early 1989 to a pilot programme to install automatic water quality alert stations. This programme later became a project carried out by Agbar (a private company) and the Junta de Sanejament (a public company) to construct a network of stations throughout the Llobregat river basin. Its aims were as follows (Matia *et al.* 1995) :

- Warning, indicating the occurrence of a contamination episode and upgrading the overall safety of the treatment plants.
- Controlling, by showing the evolution of the parameters indicating contamination and their compliance with the applicable regulations or other approaches.
- Informing, by creating a database capable of assessing water quality and its evolution.

The project included the design of the stations, paying special attention to the treatment of the sample and the choice of analysers.

In this project, three kinds of warning station were defined, depending on the number and type of parameters to be analysed :

- basic : temperature, pH, conductivity, turbidity, dissolved oxygen, TOC and sampling equipment.
- complete : with the addition of ammonia and phosphate measurement.
- special : with the addition of, depending on the station, measurements of cyanides, UV absorption, chromium, detection of hydrocarbons and equipment for extracting organic compounds.

Figure 14 shows the distribution of these stations about the Llobregat river basin.

Control centres were also designed ; these enable the management in real time of the overall situation of the stations, monitoring the state of the station, receiving alarm and warning messages, the management of station maintenance and the analysis of information.

Since this network of stations came on stream there has been a notable improvement in water quality control, making it possible to detect and control various contamination episodes. The following are worth noting in particular (Godi *et al.* 1997) :

- Salinity episodes due to breaks in the Brine Collector.
- Spillage due to overflowing of drainage networks.

- Chromium spillage from galvanisation industries and other industrial dumping.

Figure 15 shows the record of one case of urban wastewater spillage detected by an alert station.

Moreover, through this network of stations it is possible to monitor episodes, to study the movement of pollutants and to predict their possible consequences, especially as regards water collection for drinking supply.

7. Conclusions

The river Llobregat basin in Catalunya (Spain) may, with its peculiar natural characteristics (geography, climate, hydrology, etc.) and anthropocentric features (demography, industrial activity, etc.), may be regarded as quite a special case in terms of the water running through it and its management and utilisation. It is worth to be put forward as case study on how a river basin's intrinsic characteristics together with environmental factors affect its water and the utilisation of it. The basin's small area and high concentration of activity are two factors that heighten these problems.

The volumes of flow running through its rivers are not large and they are moreover subject to wide fluctuations in line with wet and dry seasons. This circumstance itself gives rise to environmental problems in view of the multiple and somewhat contradictory uses made of the water.

The resources of the river Llobregat and its tributaries are tapped intensively right from their headwaters for irrigation, industry and water supply, especially the latter two uses. In the lower part of the basin there are two water treatment plants (Abrera and Sant Joan Despí) with a current capacity to collect up to nearly 7 m^3/s of water, much of which is exported out of the basin. Meanwhile the presence throughout the basin of many mini-hydropower stations may, especially during droughts, have negative effects on the sustainability of the rivers' ecosystems and leave some stretches dry. A constant effort is needed to make the management and utilisation of surface water sustainable.

The Llobregat basin contains sizeable underground resources, particularly in its lower part (delta). These resources are strategic in terms of a large reservoir of water for the Barcelona area, with

Growing awareness of the consequences of overusing the basin's resources, especially in the 70s, has led to more rational water use based on control, reductions in exploitation and the combined utilisation of ground and surface waters. Interesting developments have been implemented to encourage replenishment of the aquifer by scarifying the bed of the river Llobregat, and artificially through wells using surface water treated at the Sant Joan Despí Plant. The maximum replenishment flow is 1.5 m^3/s.

The dense population and intense activity in the basin together with the functional regimen of its waters have given rise to another problem : water contamination. In this context there have been numerous episodes affecting both the ecosystem and the quality for drinking water. However, the high salinity content remains the most serious and challenging problem, due to mining activities in the central part of the basin. The groundwater has also been subject to various acute contamination problems chiefly as a result of polluted industrial waste used to fill quarry pits or direct contamination of the aquifer.

This situation has led to the need for various projects to avert and prevent contamination episodes. These projects are based on the Catalonian Drainage Plan (Plan de Saneamiento de Catalunya) and involve the construction of drainage networks and wastewater treatment plants in virtually all the towns in the basin, the introduction and improvement of industrial wastewater treatment and dumping systems and the establishment of control systems. One crucial project has been the construction of the Brine Collector, which has made it possible to a large extent to correct the salinity of water in the basin by averting saline spillage from mining activity.

With a view to the future, and with the aim of improving the basin's insufficient resources and using them in a sustainable fashion, the practice of treated wastewater reutilization is progressively being introduced. Initially it is being used for irrigation, while there are plans to use it in industry, replenishing aquifers and maintaining environmentally friendly water levels.

Finally we should highlight the efforts made to improve the water quality control in the basin. This control has been intensive and exhaustive over the years, especially in view of the presence in the basin of drinking-water treatment plants. In this context, the installation in recent years of a network of 14 automatic stations for water quality analysis in real time has been instrumental to control the quality and avert contamination episodes even more effectively.

We believe that under these premises the environmental status of this crucial (and historically important) basin for Catalunya has reached a turning point in terms of its evolution towards more sustainable horizons. The sustainability of the Llobregat river basin is critical for the continuous habitability and growth of the region that constitutes the backbone of the industrial and post-industrial development of Catalunya.

BIBLIOGRAPHY

- Agbar (1990). Recarga artificial de acuíferos en los deltas de los ríos Llobregat y Besos. Monografía nº 3. Aguas de Barcelona, Barcelona. 14 pp.
- Agbar (1996). Planta de tratamiento del río Llobregat en Sant Joan Despí. Aguas de Barcelona. Barcelona. 23 pp.
- Agbar and Junta de Sanejament (1996). Colector de Salmueras de la cuenca del río Llobregat. Aguas de Barcelona y Departament de Medi Ambient. Barcelona. 16 pp.
- Aigües Ter-Llobregat (1998). Possibilitats d'estalvi d'aigua i de reutilització d'aigua regenerada a l'ambit d'ATLL. Informe. Barcelona.
- Ballbe, E. and Queralt, I. (1989). Mineralogía y elementos pesados de los sedimentos actuales del Río Llobregat (Barcelona). Acta Geològica Hispànica 24, 1, 1-5.
- Freixes, A., Monterde, M., Ramoneda, J. (1996). Geochemistry of the surface and groundwaters at the upper basin of the river Llobregat. Pirineos, 147-148, 41-59, Jaca.
- Catalan, J.G., Oliver, B. y Alonso, J.J. (1971). Estudio hidrológico del río Llobregat. Publ.: por Comité Asesor y de Estudios del Abastecimiento de Agua de Barcelona y por el Centro de Estudios, Investigación y Aplicaciones del Agua, Barcelona, pp. 7-196.
- Custodio, E. and Queralt, R, (1981), Contaminación salina de los acuíferos del delta del Llobregat por vertidos de la minería potásica. Actas de Sesiones de las Jornadas sobre Análisis y Evolución de la Contaminación de las Aguas Subterráneas en España. 19-23 Octubre de 1981, Barcelona, pp. 605-622.
- El Periódico (1999). El Baix empieza a regar con agua tratada. Diario El Periódico, 14 de agosto de 1999. Barcelona. pp18.
- Godi, Ll., Serena, C., Matia, Ll. and Ariño, R. (1997). Redes automáticas de control de la calidad de las aguas superficiales. Tecnología del Agua, September, pp. 23-32.
- Junta de Sanejament (1996). Pla de Sanejament de Catalunya. Departament de Medi Ambient. 1ª Edició. Barcelona. 64 pp.

- Junta de Sanejament (1998). Balanç del sanejament a Catalunya 1992-1998. Departament de Medi Ambient, Barcelona. 24 pp.

- Junta de Sanejament (1998). Memòria de 1997. Departament de Medi Ambient, Barcelona. - Linati-Bosch, D.J.A. (1977). El problema de la contaminación en la cuenca del río Llobregat. La contaminación en cauces públicos. Comisión Intercolegial de Medio Ambiente. 1st Ed. Publ. LAIA. Barcelona, pp. 75–80.

- Luque, F. (1996). Episodios de contaminación en los acuíferos del bajo Llobregat. Workshop "La contaminació i regeneració de sòls i aqüífers". Associació d'Enginyers Industrials de Catalunya, Barcelona. 12 pp.

- Luque, F. (1998). La contaminación de las aguas subterráneas por actividades urbanas e industriales : la visión de los usuarios. In : "La contaminación de las aguas subterráneas : un problema pendiente". Ed. Samper, J., Sahuquillo, A., Capilla, J.G., Gómez, J.J. Inst. Técn. Geominero de España. Valencia, pp. 211-223.

- Martin, J. (1994). Barcelona's water supply improvement : the brine collector of the Llobregat River. Wat. Sci. Tech., 30, 10, pp. 221-227.

- Matia, Ll., Martín, J. and Lloret, R. (1993). Pollution control of surface waters for drinking water production : towards the setting up of protected areas. In : Proceedings of International Conference on Environmental Pollution (ed. B. Nath, L. Candela, L. Hems, J.P. Robinson) vol.1, ECPR, London, pp. 136–143.

- Matia, Ll., Cantó, J., Lupon, J., Salvatella, N., Prats, N. and Alonso, J. (1995). The integral management of quality control in a public water supply through automatic control stations : a future perspective. XX International Water Supply Congress and Exhibition. IWSA. Durban, pp. SS 13, 9–13.

- Miralles, J.M. (1994). L'aquífer : una infraestructura natural. Informe Aguas de Barcelona. Barcelona. 15 pp.

- Prat, N. (1997a). Gestió de l'aigua a Catalunya i conservació dels rius com ecosistemes. V Jornades sobre la millora de la gestió de l'aigua a Catalunya, A.S.A.C., Reus (Spain), pp. 135-158.

- Prat, N., Rieradevall, M., Munné, A., Solà, C. and Chacón, G., (1997b) La Qualitat Ecològica del Besòs i el Llobregat. Informe 1996. Diputació de Barcelona.

- Rivera, J., Fraise, D., Ventura, F., Caixach, J., Figueras, A. (1988). GC/MS, HPLC and FAB Mass spectrometric analysis of organic micropollutants in Barcelona Water Supply. Intern J. Environ. Anal. Chem, 29, pp. 15–35.

- Valero, F. (1996). Explotación de la ETAP de Abrera (Barcelona) Evolución, estado actual y planes de futuro. Tecnología del Agua, 148, 6 pp.

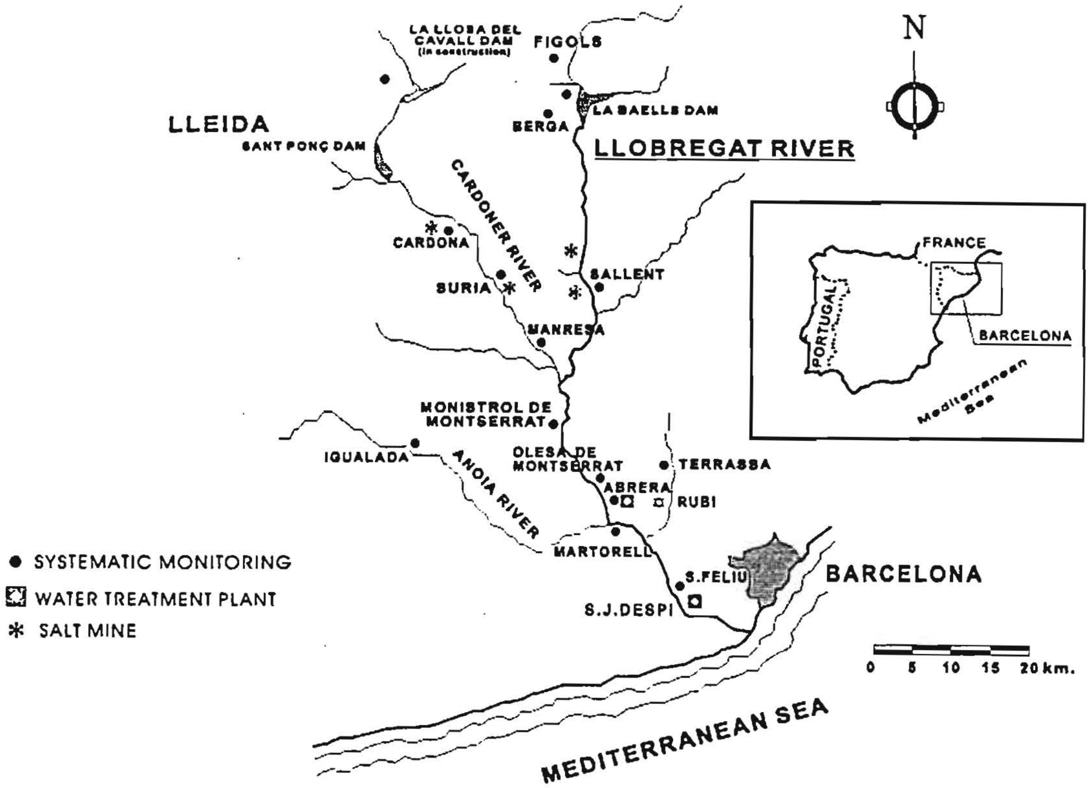

Figure 1 - Geographical situation of Llobregat River Basin.

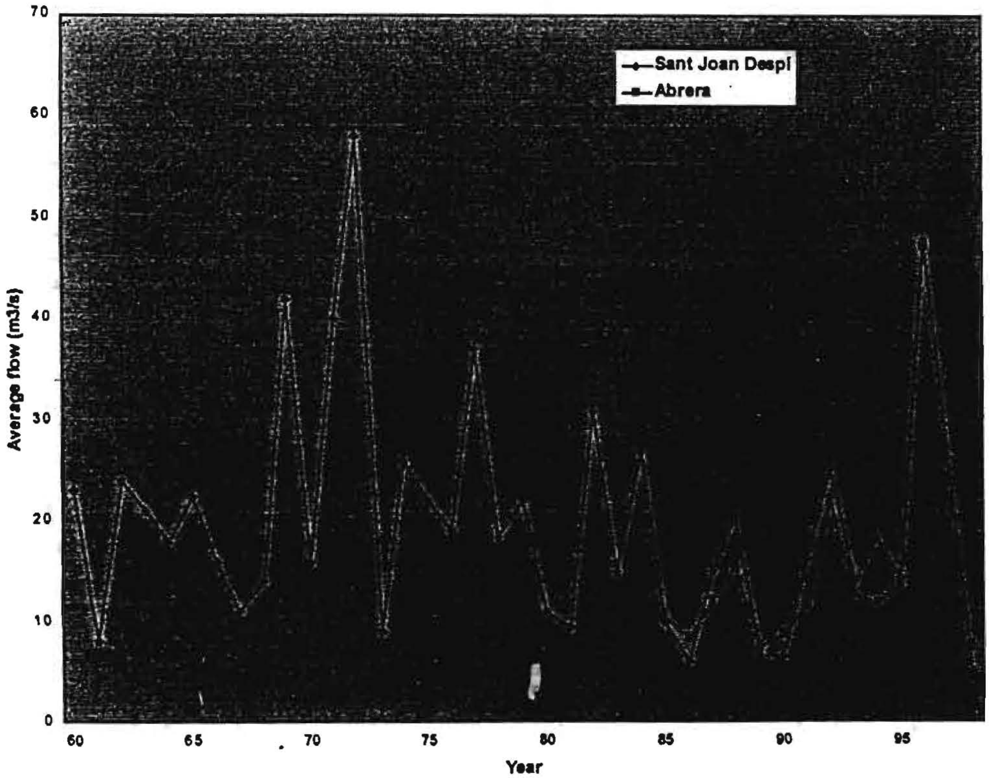

Figure 2 - Evolution of waterflows of Llobregat River in Sant Joan Despí and Abrera.

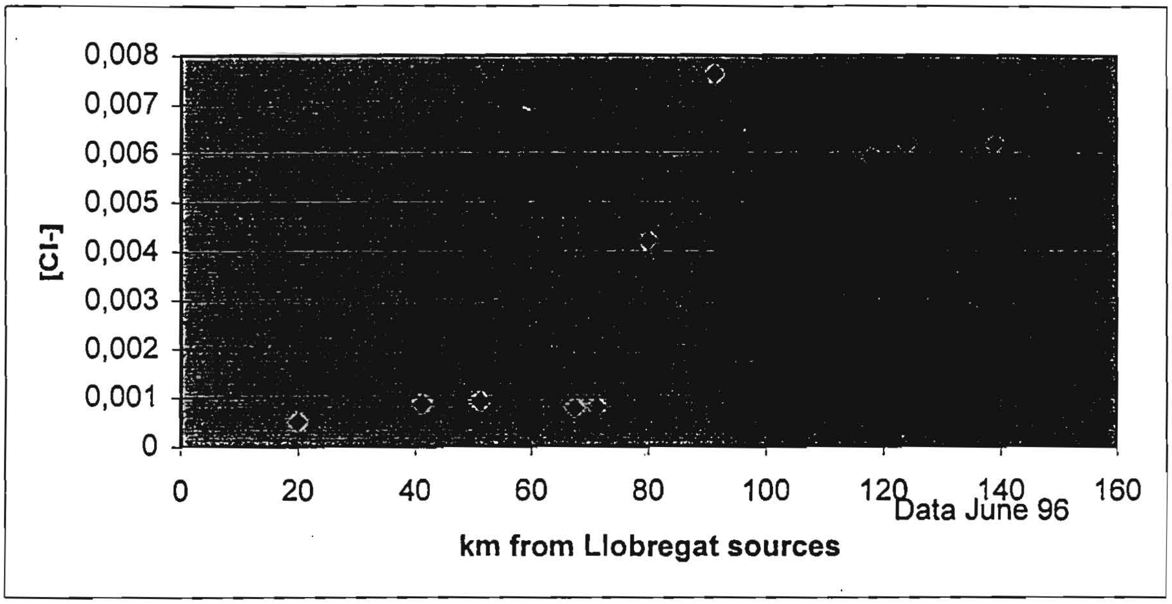

Figure 3 - Evolution of chloride with distance from source.

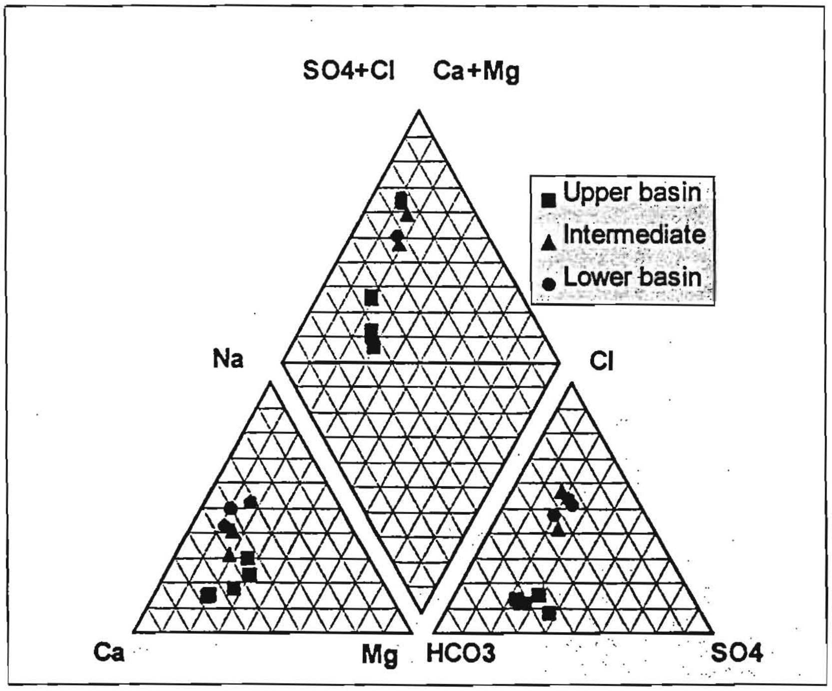

Figure 4 - Chemical evolution of the river water from the low to high mineralisation in a Piper diagram.

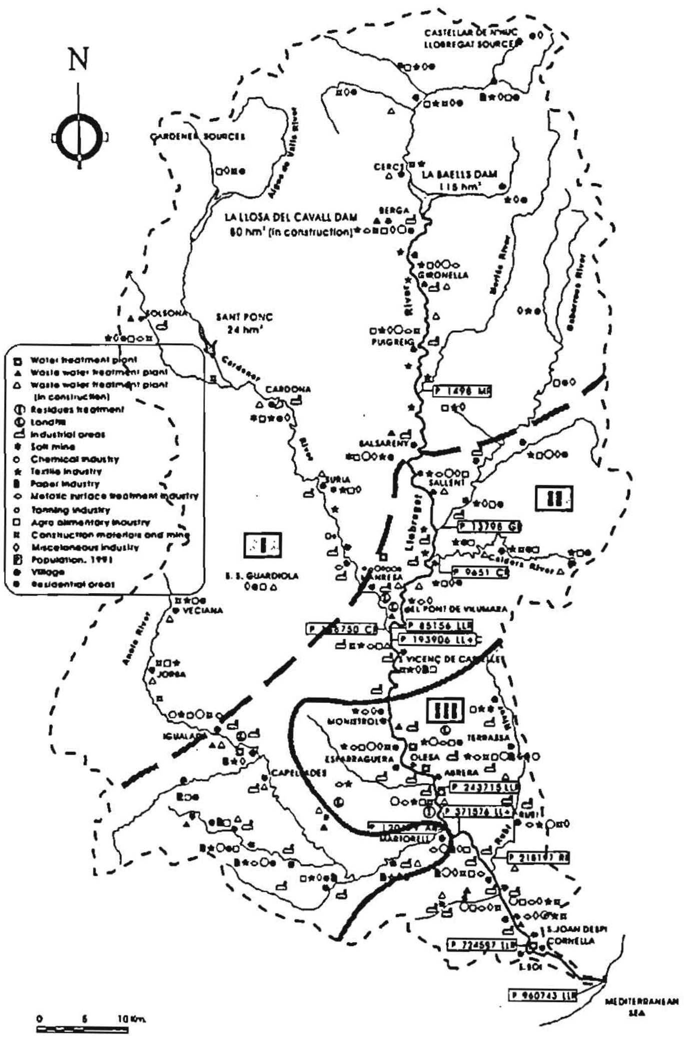

Figure 5 - The Llobregat River Bassin : population and potentially pollution activities. The heavy lines show the proposal of protection areas (levels I, II and III) for the water treatment plants of Abrera and Sant Joan Despí.

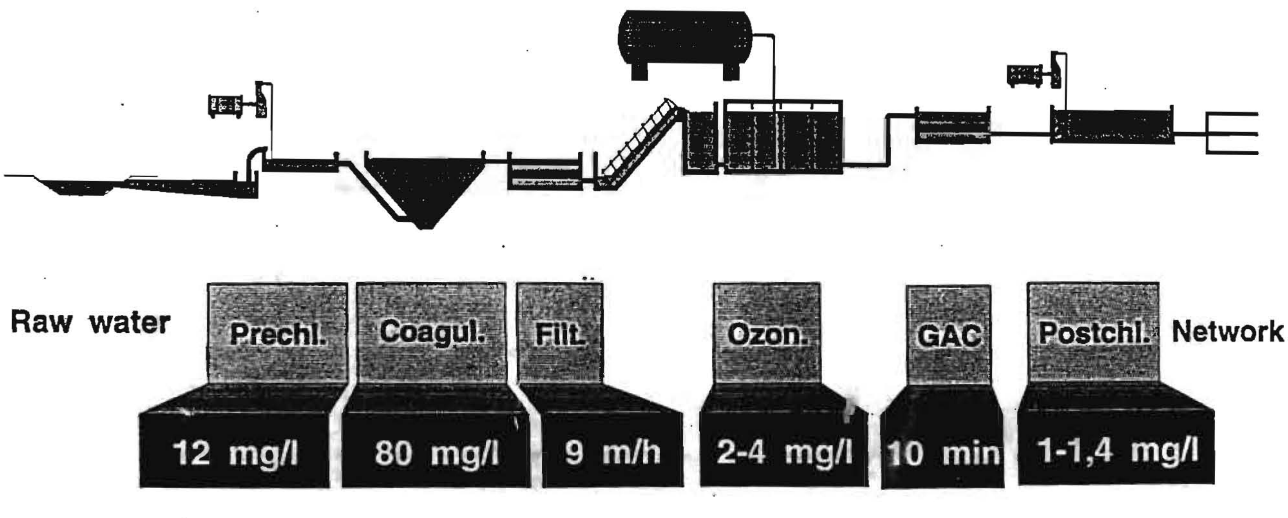

Figure 6 - Diagram of the Sant Joan Despí Water Treatment Plant.

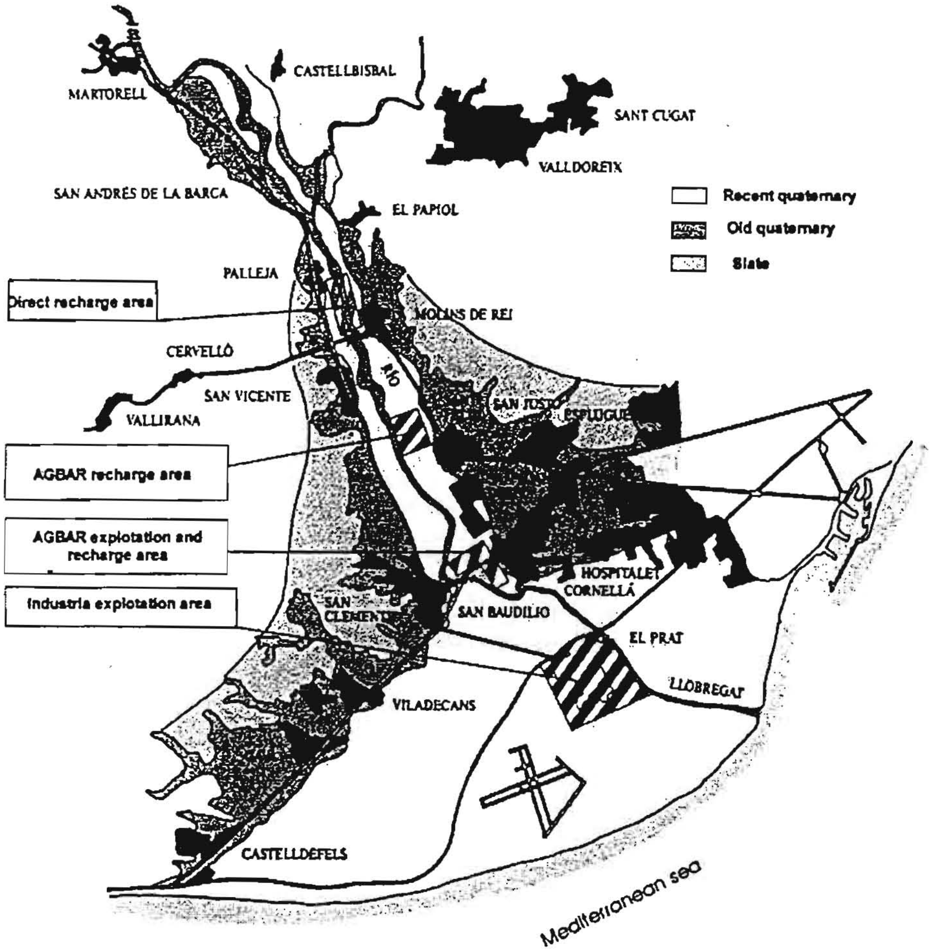

Figure 7 - Delta Llobregat River Aquifer : areas of explotation and recharge.

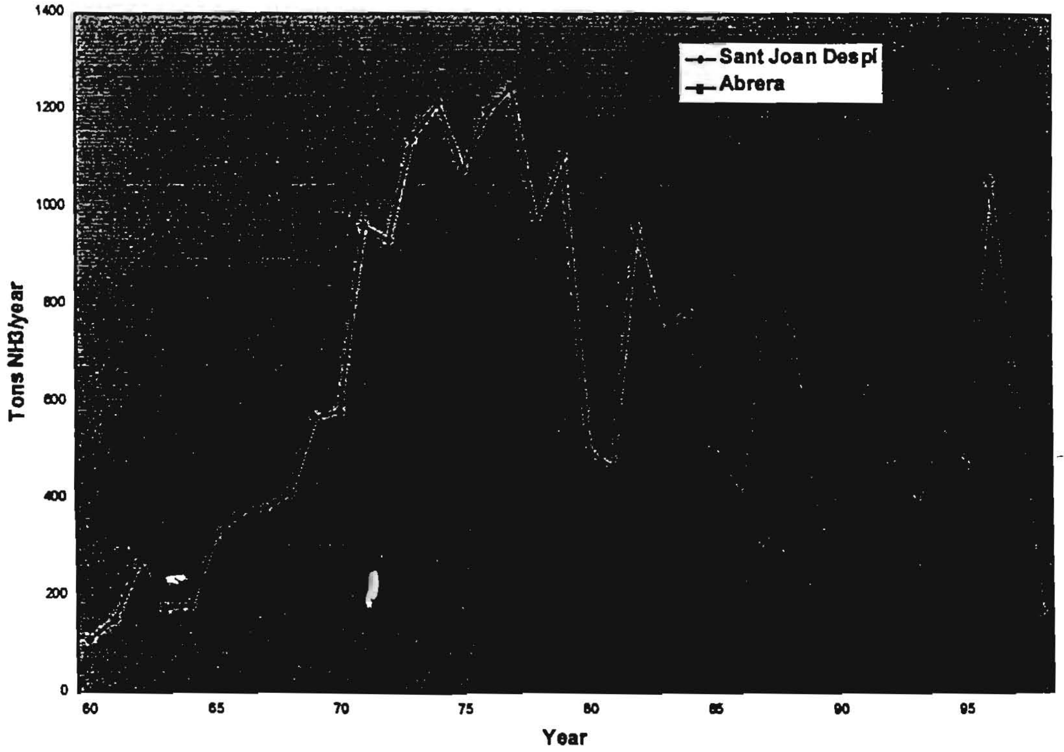

Figure 8 - Nitrogen ammonia carried by Llobregat River in Sant Joan Despí.

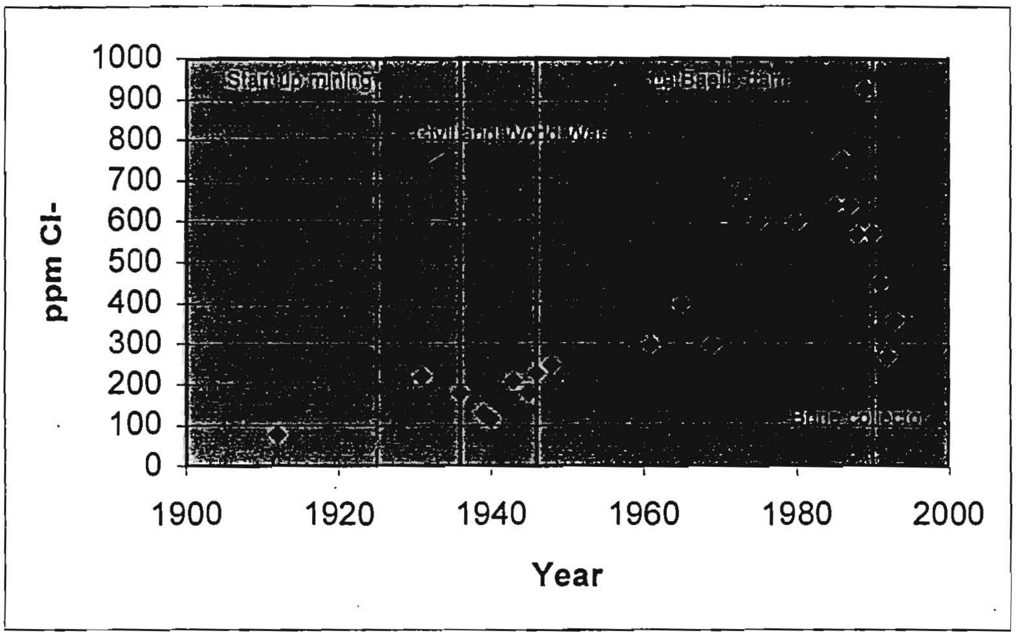

Figure 9 - Time evolution average chloride content.

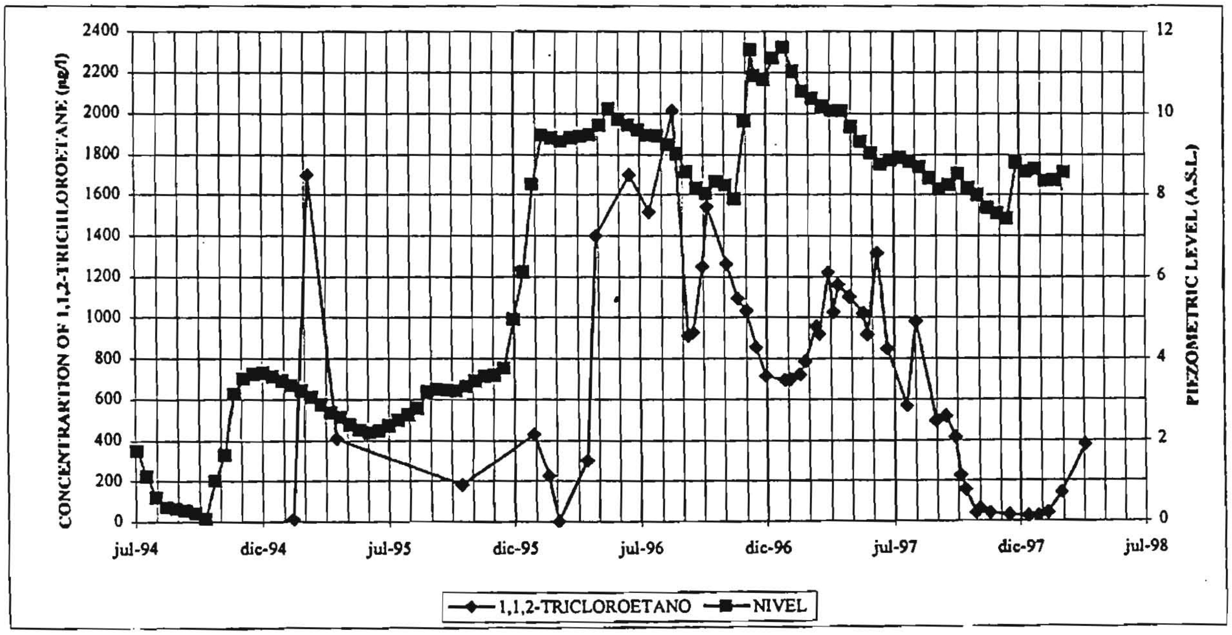

Figure 10 - Evolution of the piezometric level and the 1,1,2-trichloroetane concentration in the Estrella 4 well water.

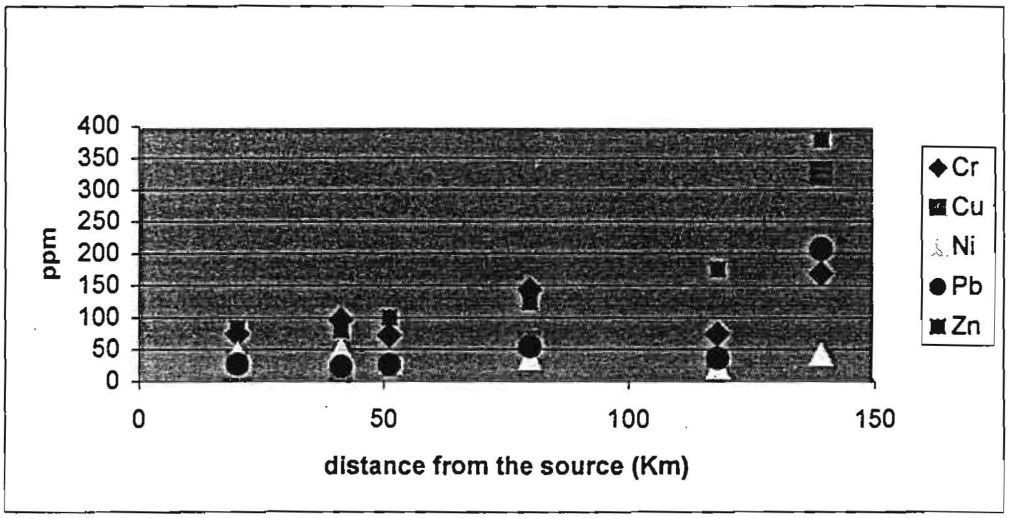

Figure 11 - Evolution heavy metals in Llobregat sediments.

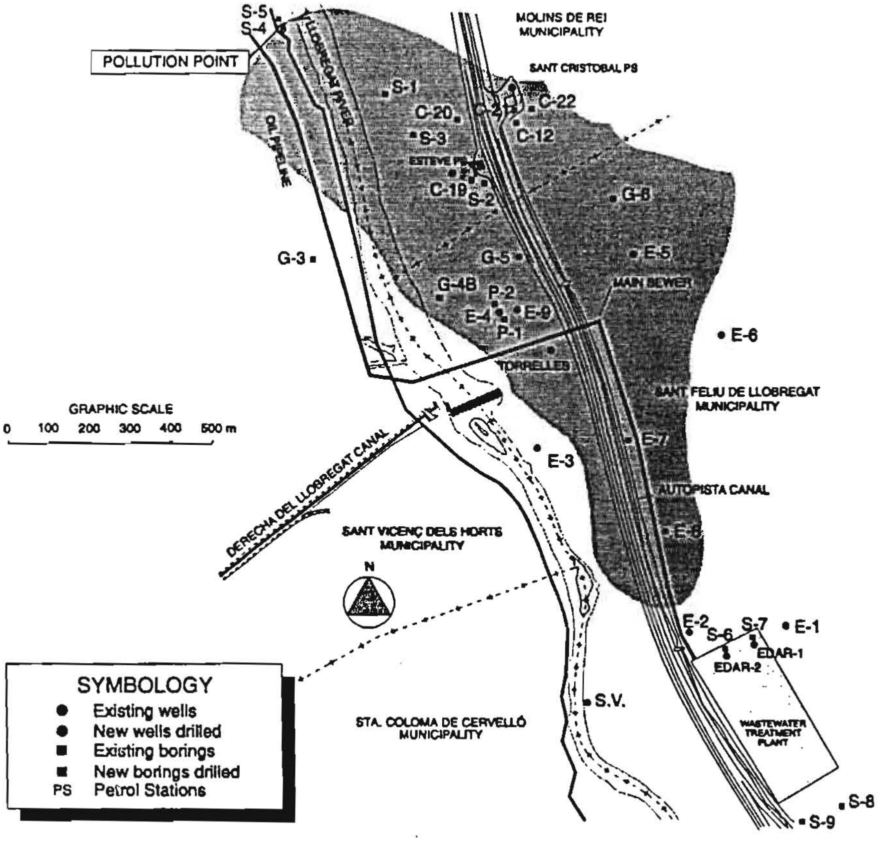

Figure 12 - Affected area by petrol pollution in the Delta Llobregat aquifer (Sant Feliu Municipality).

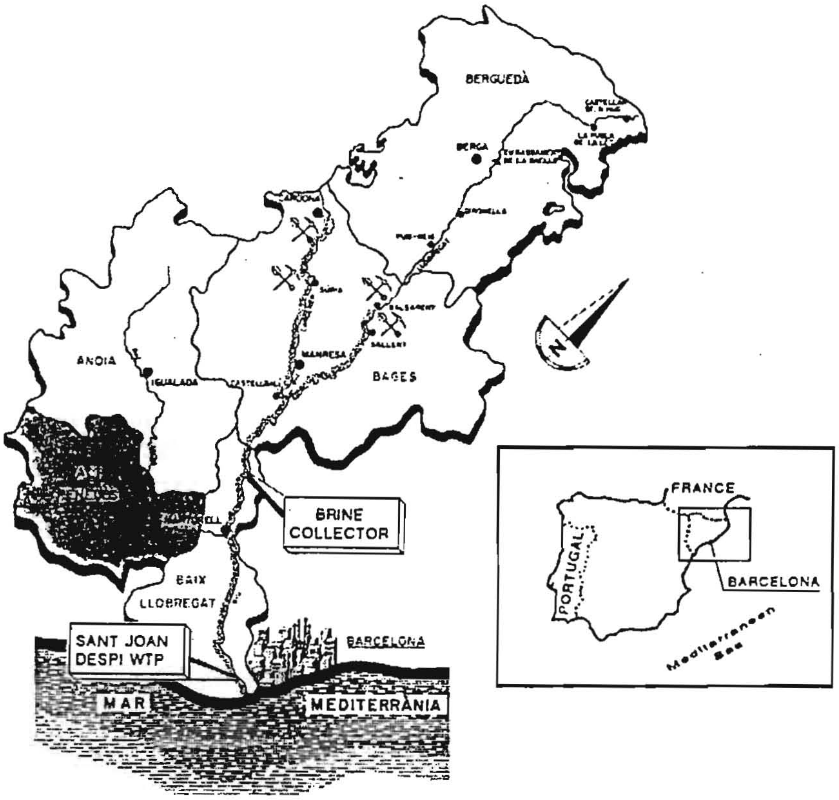

Figure 13 - Geographical situation of Brine Collector of the Llobregat Bassin.

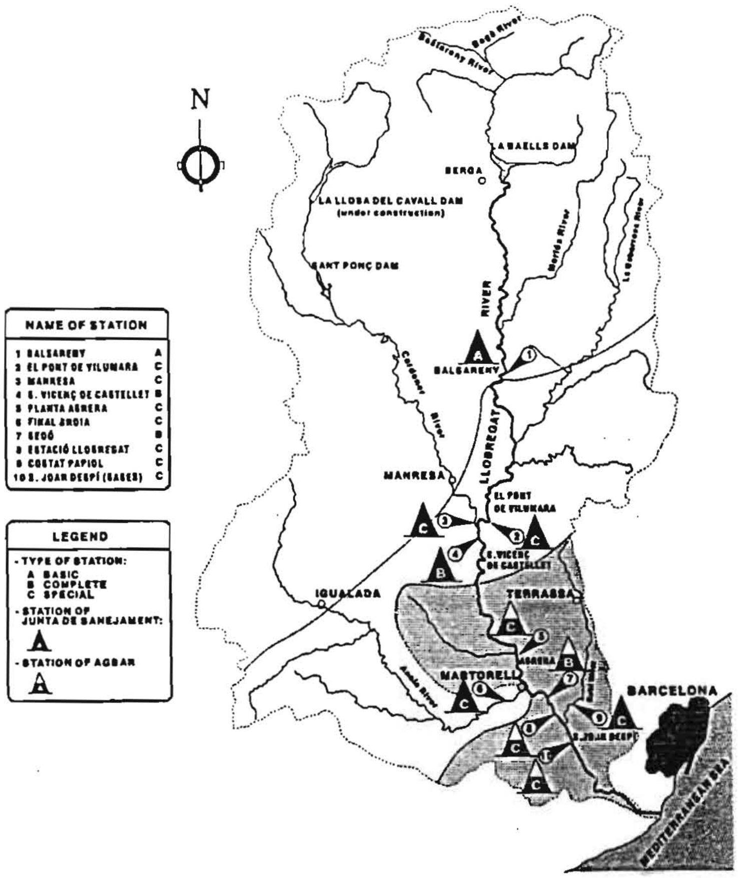

Figure 14 - Map of automatic control stations in the Llobregat Bassin.

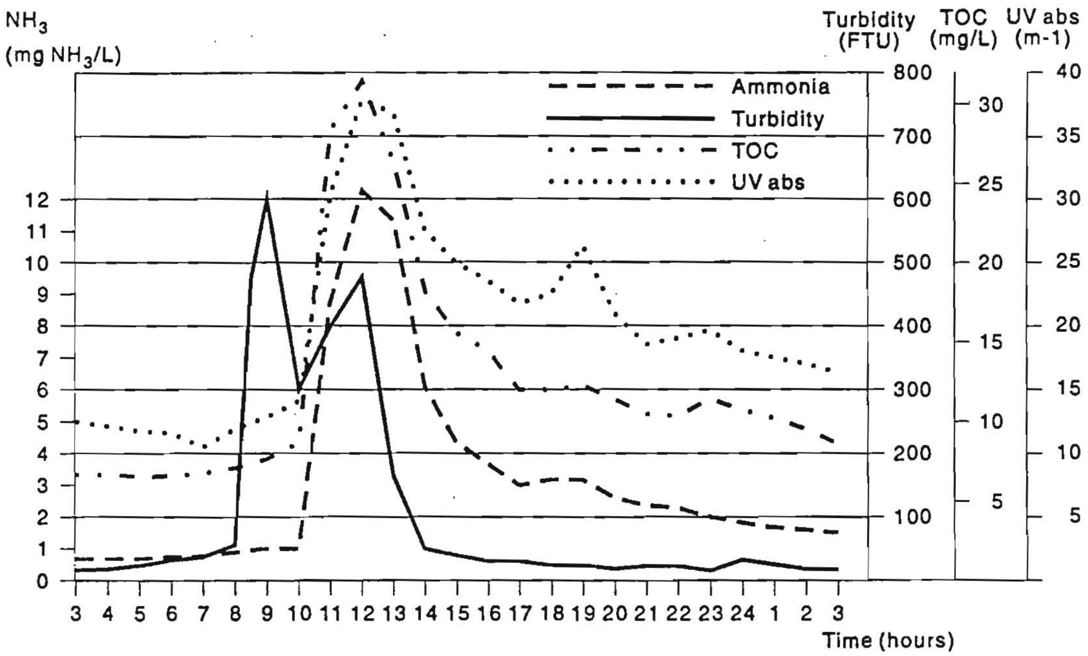

Figura 15 - Pollution episode in the Llobregat River : raw water in the Sant Joan Despí Water Treatment Plant.

USE OF WATER IN AGRICULTURE

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1. Introduction: The Challenge of Producing Sufficient Food.

The most remarkable and most ignored fact of world population growth in recent decades is the concomitant increase in food production that has made such growth possible. United Nations population studies (UN, 1996) indicate that by the year 2020, world population, currently at six billion, will be approaching eight billion. Will there be sufficient food for all?. The challenge that we are facing is enormous, too often ignored in the affluent societies.

To evaluate the prospects for meeting this challenge, it is instructive to study how the last doubling of world population – from three to six billion in just three decades – has been fed. Increasing agricultural production requires more planted area and/or improvement in production per unit area. Since the 1960's the area devoted to crop production worldwide has hardly changed from a figure of about 1.5 billion cultivated ha. The spectacular growth in food production of recent decades has been brought about almost exclusively by improvements in agricultural productivity. Science and technology developed new varieties that could take full advantage of improved management methods, particularly of increased soil fertilization with nitrogen. Crop yield increases of the major staples have been truly remarkable both, at the potential (theoretical maximum for a given location) and actual (average) levels. Today, potential yields of wheat or rice vary between 10-15 t/ha while that of maize may approach 20 t/ha. While increases in yield potential have been important, closing the gap between actual and potential yield has had even more influence in the improvement of agricultural productivity. In areas of favorable soils and climate and with access to capital (human and economic) to acquire news technologies, the gap between actual and potential yield has shrank to the point that record yields obtained by some farmers in recent years are essentially at potential levels. On the contrary, the gap between actual and potential yield in areas less endowed for agricultural production (physically and socially) continues to be substantial.

Among the environmental factors adversely contributing to the reduction in crop yield, insufficient water is probably the most important worldwide. Water-limited crop production are often a small fraction of what can be produced in the absence of water deficits. It is therefore not surprising that since the very beginning of agriculture, man has attempted to remove the water deficit constraint by applying water to crops, a practice known as irrigation. However, even though irrigation was practiced since ancient times, it has been during the last four decades when it has really contributed to feeding the world. Presently, the 260 million ha of irrigated land which represent a mere 17% of the cropped world area, contribute nearly 40% of world food production. Thus, irrigation has contributed significantly to the intensification of agricultural production that has been so important in matching the population expansion of recent decades.

Looking at food production in the future, it appears that irrigation will have to play even a more important role than it does today. Several studies have analyzed forecasted world food supply and demand 20 to 25 years from now. If we choose the 2020 vision of IFPRI (IFPRI, 1998) as an example of a predictive analysis, it appears that demand for cereals would increase by 40 percent and possibly more in improvements in the diet quality take place. To meet such demand, IFPRI predicts that there would have to be a modest increase in cultivated area (about 6% increase over present) but a substantial increase in productivity. The same analysis predicts that either irrigated areas must increase by about 40 million ha (over the present 250 million) or that areas currently irrigated increase their present productivity by over 20% in 20 years. Given that most of the expansion in irrigated lands would have to take place in the developing countries (IFPRI, 1998) and considering the physical and economic limitation to irrigation expansion, and the losses caused by the urbanization and salinization processes, it slams that the only avenue open for meeting the increased food demand in the future will be the continuous improvement of productivity in irrigated agriculture. There are severe constraints for further productivity gains in many world irrigated areas, however, a discussed below. The large productivity gains increases observed in the 60's and 70's have given way to more modest increases in the 80's and 90's to the point that many authors speculate with the possibility that world crop yields are approaching a plateau (References).

Table 1. Annual growth in cereal crop area, production and yield. 1967-1994. (percent per year)

	Peak Green Revolution 1967-1982			Post Green revolution 1982-1994		
All Cereals	**Area**	**Production**	**Yield**	**Area**	**Production**	**Yield**
Developed Countries	0.23	1.92	1.69	-1.27	0.01	1.30
Developing Countries	0.48	3.36	2.87	0.46	2.34	1.87
World	0.37	2.61	2.24	-0.24	1.27	1.51

Source: Rosegrant, Leach, and Gerpacio, 1998

There are a number of reasons for the slowdown in productivity growth but dramatic changes from present trends are improbable in the short run, despite the promises made by the biotechnology advocates (see below).

In conclusion, there seems to be significant uncertainty in meeting future world food demand for the next two decades and there is even more uncertainty in achieving the goal of eradicating or reducing the hunger that presently affects more than 800 million people. It is in light of these uncertainties that the use of water in agriculture becomes of primary importance. But food production is only one of the uses that water has in irrigated areas. Irrigation is a multifaceted, complex activity with deep cultural roots and with many ramifications in rural societies.

The objectives of this paper are first, to present a balanced view of the process involved in the use of water by agriculture and second, to evaluate the opportunities and constraints that exist to conserve water in irrigated agriculture and its complications for irrigation in the future.

2. The Process of Irrigation: Nature and Constraints

Irrigation is by far the biggest consumer of fresh water on a global basis. Seckler et al (1998) estimate that irrigated agriculture uses 72 percent of per capita water diversions while industry and urban diversions amount to 19 and since percent of average per capita diversions, respectively. Such a high level of water use by agriculture of ten raises two key questions: Why does irrigation demand so much water? and, could irrigation demand be reduced? Much of what is discussed in this paper focus on answering these two questions.

The analysis of the process involved in determining irrigation water use is broken down there in two parts; first considered are the processes starting at the level of the crop up to the individual farm to be followed by an integrative analysis at the district and watershed levels.

2.1. Irrigation: from the crop to the farm.

Crop plants require a continuous supply of water to their aerial organs to meet the evaporative demand. Such demand arises simply because internal plant surfaces are nearly saturated with water and are exposed to a drier atmospheric environment. To sustain the water flow needed to prevent tissue dehydration, plants have evolved an elaborate water gathering and transport system. Water flows from the soil into the root system and is transported via the xylem vessels to the leaves where it replaces water that evaporated to the atmosphere. Thus, from a purely physical viewpoint, plants are water transport systems from a source, the soil, to a sink, the atmosphere. Such systems are capable of transporting large amounts of water, equivalent, in a typical summer day, to several times their own weight. However, a small imbalance in the transport process -that is hardly detectable- may occur in Reponses to alterations in water supply or demand, thus creating a plant water deficit. Such very mild water deficits are often detrimental to yield even though large amounts of water are being transported by the plants at the same time (Hsiao et al., 1976).

Transpiration and Crop Yield

The evaporation losses from crop and soil surfaces over a season are quite large relative to the amount of yield produced. It is not uncommon to require from 100 to more than 1000 kg of water per kg of harvested crop yield. As good conditions for high productivity (high solar radiation and favorable temperatures) are also conducive to high rates of evaporation, high yields and high water consumption are unavoidably linked. Generally, evaporation and biomass or dry matter production are linearly related and, within a certain range, the yield of many crops and total evaporation are linearly related as well. This fact has led to the development and use of water production function (Vaux and Pruitt, 1983) to predict yield as a function of water use. The empirical nature of these relationships, however, have limited their transferability even though they are often treated if they were universal truths. There is little awareness among most engineers and economists that use water production functions, of their limitations and of the processes that determine water-limited crop productivity under field conditions.

The Water Balance of a Field

The crop water demand is met in many would agricultural areas by rainfall. Irrigation is Applied in areas where natural rainfall is insufficient to meet the crop water requirements during the growing season. As a farmer applies water to a field , the fate of that application needs to be determined. Figure 1 shows the disposition of water over an irrigated field during and after irrigation. Water is lost from an irrigated field in four ways: (1) Direct evaporation of water from the soil surface, (2) evaporation of water from plant surfaces, (transpiration), (3) surface run-off, and (4) deep percolation below the crop root zone.

A water balance equation may be derived from Figure 1 stating that the water entering an irrigated field either changes the root zone water content or must leave the field

Figura

Mathematically,

$$AW + P + ET + RO + DP + AW = 0$$

were

AW = applied water

P = precipitation

ET = evaporation + transpiration

RO = run-off

DP = Deep percolation (may be negative if capillary rise occurs)

AW = Changes in soil water content in the crop root zone

Equation 1 states the water balance of a field from an hydrologic point of view. From the farmer's viewpoint, the irrigation water requirements (IRW) are defined as:

$$IWR = ET - E + ISL \qquad (2)$$

ER is effective precipitation and ISL, irrigation system losses are the run of RO and DP combined as part of the unavoidable losses resulting from the application of water to the land. Effective precipitation is defined as the fraction of the seasonal rainfall that contributes to the crop water requirements. Implicit in Equation 2 is the concept that some deep percolation is needed to maintain the salt balance of the root zone. All irrigation waters contain salts. Evaporation from the soil and plant uptake remove pure water and leave the salts behind. These salts must be leached out of the root zone if crop productivity under irrigated conditions is to be sustained. The fraction of deep percolation needed to displace the salts below the root zone is called the leaching requirements and must be considered part of the irrigation water requirements. The need for salinity control is of particular importance in areas where annual rainfall in insufficient to accomplish the leaching of the soil profile, thus achieving salt balance.

Irrigation system losses at the field scale do not include surface fun-off and deep percolation but also spray evaporation losses in the case of sprinkler irrigation. Contrary to a popular belief, spray evaporation losses are a small fraction of a sprinkler irrigation application and can be neglected under most conditions.

Irrigation Efficiency and Uniformity.

When considering the partitioning of irrigation water applied to a field into the various forms indicated in Figure 1, it is important to quantify the proportion of irrigation water that is consumptively used and the proportion that is nonconsumptive use. For example, water used in evaporation and transpiration is considered consumed while runoff is part of the nonconsumptive use.

Irrigationists have been concerned with the beneficial use of irrigation water since long ago and have used for that purpose the term irrigation efficiency originally defined as the fraction of applied water that is consumed by the crop. An additional concern relates to the spatial distribution of the applied water within the field. High uniformity of distribution in considered derivable to avoid underirrigation of some parts of the minimun depth and the average depth of application of water over the field. Confusion has frequently arisen over the terminology and definitions of irrigation efficiency and uniformity leading to recent efforts that attemped to clarify the processes and the terminology (Clemmens et al., 1995; Jensen, 1996). The current definition of irrigation efficiency is (Clemmens et al., 1995):

$$\text{IE}= \frac{\text{Volume of irrigation beneficially used}}{\text{Volume of irrigation water applied} - \text{A storage}} \text{ X } 100\% \qquad (3)$$

Where A storage is the change in stored water in the root zone of the field considered, and water beneficially use refers to that used in processes that contribute to the objectives pursued under good management.

Jensen (1996) has proposed to clarify the differences between efficiency factors (output/input ratios) and the fraction of water delivered that is actually consumed. Figure 2 taken from Clemmens et al., (1995) shows that there are be differences between the water fractions that are beneficially and/or consumptively used in a field or a farm. The other parameter indicative of the quality of irrigation is the distribution uniformity (DU). The usual definition of DU is:

$$DU = \frac{\text{Average depth in the quarter with lowest depth}}{\text{Average depth of water}}$$

Another measure of DU has been the Christiansen Uniformity Coefficient (CUC) used in sprinkler irrigation.

FIGURE 2.

Figure 2. The division between consumptive and nonconsumptive uses is distintc from the division between beneficial and non-beneficial uses. (IE = Irrigation Efficiency; IUCU = Irrigation Consumptive Use Coefficient).

Relations between Irrigation and crop Yield.

We have seen that there is often a linear relation between transpiration and crop yield. However, the relation between applied irrigation water and crop yield is usually curvilinear as the magnitude of deep percolation losses tend to increase as the irrigation depth increases. The example shown in figure 4 illustrates the relations between applied irrigation, distribution uniformity and yield.

FIGURA GRAFICO

The two curves showed the relations between applied irrigation water and yield of maize for two levels of distribution uniformity (quantified as 70 and 90% CUC) for a typical situation in a semi-acid area where 40% of crop ET is supplied by rainfall or soil water storage (Fereres et al., 1993). In the case of the 70% CUC, the depth of irrigation required to achieve maximun yield is about twice the net irrigation requirements, thus leading to a very low irrigation efficiency (about 0.4). The curvilinear nature of these relationships allows for an economic analysis and for the quantification of an economic optimun irrigation depth, and require simulation models which must be validated to provide realistic estimates of optimun irrigation (Fereres et al., 1993)

From the Farm to the Watershed.

First, strategies for improving the efficiency of water use in irrigation must focus first on the nature of the potential water savings. Measures reducing irrecoverable water losses represent a net reduction in consumptive use in the basin. On the contrary, techniques applied to decrease recoverable losses will not result in reducing the basin water demands and may even alter the water supply of downstream users. To understand the importance of these differences suffice hereto describe the results of a study on irrigation water use in the Western United States (Interagency Task Force Report, 1979).

A number of water conservation measures on and off the farm were evaluated in terms of the potential reduction in irrigation water demands. While the estimated reduction in irrigation diversions exceeded 30 million acre-feet, the net water savings were estimated to be between two and five million acre-feet only.

It is surprising that, even thought the idea of water reuse has been around for some time, it is not always accounted for in the estimates of water supply at the watershed or regional levels. Often it is assumed that once water is withdrawn, it is lost to further use to evaluate sectorial water use on the basis of water diversions could be very misleading in many cases. For instance, the estimated figure of 72 percent of per capita diversion for irrigation (Seckler, 1993) probably overestimates irrigation water use as much water diverted for irrigation endsup being reused for other purposes within a basin.

Seckler et al. (1998) has called the attention that most international data sets on the water supply of countries ignore the water recycling effects. In one case, figure of 20 percent of diversions is used as the average reuse for the whole country (Libro Blanco del Agua, 1998). It is true that tracing and quantifying recoverable water losses within and between basins is a difficult task and that the quantity and quality of hydrologic data in most cases is not adequate for that purpose. Therefore, renewed, efforts must be launched to obtain the reliable information needed to quantify the importance of reuse in irrigation at the basin and regional levels.

Recycling Irrigation Water: Impacts on the Environment

The positive aspects of water reuse must be balanced against the deterioration of water quality and the effects that such degradation caused by reuse, have on the environment. Figure 5 (insertar la última) shows the same water balance of Figure 1 with the addition of the processes which contribute to water quality degradation of return flows from irrigated lands. Sediments, nitrate pollution, pesticide etc...are all detrimental to other users and threaten the sustainability of irrigated agriculture. The control of water pollution is of paramount importance to extend the use of a given water diversion as much as possible.

Conservation efforts to increase the efficiency of water use in irrigation must pay attention to non-point source pollution as well as to the distinction between conserving recoverable and now-recoverable water losses in irrigation.

The Situation in irrigation in the Developing Countries.

It is very difficult to discuss issues related to agricultural water usewithout defining at the outset the context where irrigation is taking place. About two thirds of irrigated lands are located in the developing countries where 85 percent of the world population lives. Even though there are substantial variation among and countries in the status of irrigation, there are a number of common features that are important to highlight:

- High fraction of irrigation system losses, on-farm and at district levels.
- Lack of payment of water charges.
- Loss of irrigated land due to salinization and water logging.
- Limited participation of water users in the management and institutional aspects of irrigation.
-

One major concern among those above, normally of little importance in the developed world is the impact of irrigation on health. Irrigation networks may contribute to increase the sister of transmission of water-borne diseases, water-based infections and water-related vector-borne diseases. More than 30 diseases have been linked to irrigation, the major ones being schistosomiasis, malaria and onchocerciasis (Hespanhol, 1996). The situation varies vastly among continents but is showly improving although it remains a health issue of great concern in the developing world. Solutions to the problems above are often advocated favoring rapid modernization with the inclusion of most modern technologies (Plusquellec et al., 1994). There have been a large number of failures by introducing the latest technological developments in areas where adequate education is lacking and the culture is vastly different. For that reason, others (Kirpich et al., 1999) prefer to emphasize working on improving management and institutions. Without adequate understanding of the nature of the problem, no technologies can provide permanent solutions to problem.

In addition to the problems above, one feature of irrigation in developing countries is the multiple uses that irrigation water usually have, much more so than in the developed countries.

A recent case study in Sri Lanka (Bakker et al., 1999) provides a good contrast with the traditional role of irrigation in the developed countries nowadays. The paper argues that to ensure efficient, equitable and sustainable water use, all usesand users of water must be taken into account. Bakker et al. (1999) list the following uses of water in a Sri Lankan irrigation system: irrigation of crops; home gardens; natural vegetation (through raised water tables; domestic water; brickmaking; livestock supply; fisheries in ponds and fuel (wood) production.

Such a variety of uses requires detailed accounting to assess, within an order of magnitude, the value of water for the different productive uses. Information is required before "improvements" are introduced that might negatively in the productivity or equity of water use in the basin.

There is little doulot that irrigation is esential fot the development of rural communities in the developing countries and that it must be viewed from a different perspective than the commercial irrigated agriculture of the developed world.

Reducing agricultural water use: Myths and Realities.

Irrigated agriculture is the largest user of water, looking at the future, it is important to assess the potential that exists for reducing irrigation water demand worldwide.

If the primary goal of irrigation is food production, increasing crop yield per unit irrigation water would be an important objective. To increase the productivity of irrigation water it would be necessary to:

a) increase biomass production per unit water transpired

b) increase harvestable yields per unit water transpired

c) reduce evaporation from soil

d) reduce deep percolation and run-off losses to sinks

We now consider briefly the potential that each of the four options have for increase by combining advances, not only from science and technology but from the improvement of water management and from institutional reforms as well.

- **Improving the of water productivity of crops. The potential of biotechnology.**

Since the beginning of this century, data has been collected on the amount of biomass produced per unit of water transpired transpiration efficiency, (TE). All scientific evidence points out that for a given crop species, TE depends primarily on the evaporative demand of the location where the crop is grown (Tanner and Sinclair, 1983). There are differences in TE among species; those with a C-4 photosynthetic pathway (such as maize) having higher TE values than wheat or rice which have C-3 pathways. Until now, attempts to alter the photosynthetic pathways of crop plants have failed, including recent attempts using genetic engineering.

The one factor that can be modified is the evaporative demand (ET_0) by growing the crops at times when ETo is low (i.e., winter). Under low Eto, biomass production per unit water loss increases relative to he sifrations of high ETo. There have been some gains in TE already by shifting summer crops to spring or fall. There is a limit to improving TE by changing the growing season as in many climates, low ETo is associated with low solar radiation and low temperatures which slow down or can even prevent the growth of summer crops . Breeding for tolerance to low temperature is therefore an important objective for the improvement of TE.

1.- Growing off-season crops can increase TE by at least two-fold in some cases. A comparison of estimated WUE of tomatoes grown outdoors in the summer of the

Central Vally of California versus winter tomatoes grown in greenhouses at a similar latitude in Almeria, Spain would give estimated WUE ranging from 14 Kg/m^3 in the summer to about 45 Kg/m^3 for the greenhouse crop. This is a large improvement in WUE, achieved by displacing the season and by the use of plastic, unheated greenhouses. Obviously, there are economic and marketing constraints limiting greenhouse expansion in irrigated agriculture.

While TE is a conservative attribute of a crop, the amount of harvestable yield per unit water transpired (WUE) could be increased. Indeed WUE has been raised dramatically by plant breeding during the Green Revolution. Is it possible to raise WUE it much further? That would require increasing the harvest indices proportion of biomass that is harvested of major crops, which are approaching theoretical limits in the improved varieties, at present..

In spite of the promises from biotechnology, it is unlikely that drastic improvements are realized in potential yield or in harvest index of the major crops in the next 10 to 20 years. This is because such crop features depend on many genes and on their interactions with the environment. At present, biotechnology has addressed successfully defect modifications or resistance to pests or diseases, which depend on one or a few genes. Breeding for drought resistance using whichever technologies become available, will produce no more than limited, incremental improvements of yield under limited water supply in the next one or two decades.

Reducing Evaporation from the Soil.

One of the perceived benefits of drip irrigation is the reduction in soil evaporation relative to other methods that wet the whole ground surface. It is true that important water savings via reduced E can be accomplished using drip irrigation in young orchards but the method is not feasible for irrigation of the major staples. Even if it, would be economical to use drip, E savings would be small be cause, when the crop fully shades the ground, E is a small fraction (10-15%) of the total ET. A recent assessment of the potential E savings by using subsurface drip in an olive orchard gave an estimate of less than 7 percent of the seasonal depth of irrigation (Bonachela et al., 2000).

Evaporation losses from the soil are largely unavoidable; they are most important in the early stages of crop growth and in the sparse canopies of rainfed agriculture. Drip irrigation reduces E in tree crops and vines but such reduction would be negligible for most of irrigated agriculture (Pruitt et al., 1984).

Reduction of Irrigation System Losses.

Science and technology have provided over the years with a wide range of irrigation method and techniques that can improve irrigation methods and techniques that can improve irrigation effectiveness and reduce runoff and deep percolation losses. Recent developments on surface irrigation optimization are providing guidelines to design surface systems where system losses are kept to a minimum. If soil variability and for topography prevents the use of surface systems, a variety of sprinkler and drip systems are available to offer high **potential** efficiency and uniformity. Thus there are no limitations to identify a technical solution no more irrigation problems in the field. Then; are irrigation system losses being reduced?.

The problems are of a different nature. To optimize the design and operation of existing surface irrigation systems may require changing the water delivery procedures and flows, land consolidation and changes in the design and operation delivery networks. Such changes not only require capital investments but agreements amony different users as well. The introduction of pressurized systems (sprinkler and drip) in collective irrigation networks also require other changes in physical infrastructure. Thus, there must be at least, economic incentives and access to capital in order to effect the changes in irrigation systems needed to increase the potential efficiency and uniformity.

Before introducing measures to reduce irrigation system losses, knowledge of the potential net water savings is required. Here, there have been important scientific and technological limitations to the quantification of water sources and sinless at the district and basin levels. New technological developments based on the use of modeling and GIS is allowing the assessment of irrigation return flows and the impacts of various off-farm conservation measures on the net water savings at the basin level (Mateos et al., 2000).

The role of Management and of Institution.

We have seen that technologies are available to potentially increase irrigation effectiveness. To realice that potential, both improved water management and institutional reforms are required.

On farm water management optimization may be achieved by using irrigation scheduling (IS) techniques that determine the data ans amount of irrigation (Fereres, 1996). For the most part, IS techniques have already been developed, although new refinements are possible (Goldhamen et al., 1999; Fereres et al., 1999). Such techniques have not been widely adopted by farmers in the developed countries due to lack of economic incentives and/or appropriate regulations. There are indications that increased adoption of IS technologies in the more advanced irrigated areas is taking place (Fereres, 1996). In the developing countries, however, where irrigation networks have often been designed to meet only a fraction of the crop demand, the proposal of using IS techniques is not realistic at all. The starting point there could be to develop basic soil and climatic data that can be used to establish seasonal requirements for planning purposes at the district or watershed levels.

5a.- Institutional reforms are advocated for more effective management of water resources in agriculture, including the introduction of market forces to deal with water as an economic good (e.g., Briscoe, 1997).

In mani world areas, there are two prerequisites before treating water as an economic good and allowing market forces to determine the allocation of water to agriculture, one is the quarantine of water deliveries to farmers and the other is quarantined and defined water rights. Both conditions are often lacking in developing countries where irrigation entitlements are often nuclear. However, in the developed countries, the introduction of market forces in the management of water in irrigated agriculture is a derivable development to increase irrigation effectiveness, particularly in situations of water scarcity.

Seckler et al., (1998) have analyzed world irrigation demand for the year 2025. Although the study is only a rough approximation to the real world, as the quality of the data used is questionable at best, it is a refreshing attempt at obtaining a global view of this important problem. One conclusion is that about half of the projected increase in demand from 1990 to 2025 could be provided by increased irrigation effectiveness via conservation.

Conservation of irrigation water is the most important new source of water for agriculture now and in the future. As we have seen in this paper, technologies 6 already exist to conserve irrigation water; what limit their adoption?

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Seckler et al (1998)

Hsiao et al., (1976).

(Vaux and Pruitt, 1983)

(Clemmens et al., 1995; Jensen, 1996)

Fereres et al., 1993

Interagency Task Force Report, 1979

(Seckler, 1993)

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