Water Reuse Project of the Barcelona Metropolitan Area

Water Resources and Water Reuse

Water supply at the Barcelona Metropolitan Area (BMA) is provided by Aigües Ter Llobregat (ATLL), a wholesale Public Water Company of the Catalan Water Agency. The BMA is a supra-municipal organization currently formed by 36 municipalities. The water provided by ATLL to associated water companies within the area varies from 460 hm^3/year to 490 hm^3/year; of those, 180 hm^3/year are transferred from the Ter River, in Northern Catalonia, 120-150 hm^3/year are abstracted from the Llobregat River, that flows through the BMA, and 160 hm^3/year are extracted from several local aquifers within the ATLL territory. The regional water distribution network has been gradually developed over the years, but still has limited facilities to ensure adequate water transfers from the Ter River (entering from the north of the BMA) to the Llobregat River (accessing from the south of the BMA) during the frequent water scarcity episodes affecting the BMA.

The BMA covers 600 km^2 and includes a population slightly above 3.5 million people, just about 50% of the total populations of Catalonia, currently estimated at 7.4 million. It is the first industrial area in Spain and the second in terms of population, work force and income. It has a high mean population density (5,800 people/km^2), with extensive urban areas along the central plains, the coastal stretches and the Llobregat and Besòs Rivers that cover 40% of its total surface area. Natural vegetation areas, mainly the Collserolla natural park in the north and the Garraf natural park in the south cover 38% of its territory. The agricultural sector is located on the Delta and the lower Llobregat valley and covers 16% of its territory.

The intensive exploitation of the Llobregat River as a water source for urban, industrial and agricultural uses, the high population density of the Metropolitan area, and the water quality deterioration of the Llobregat River, due to agricultural runoff and disposal of industrial and urban treated effluents, have resulted in quantitative and qualitative water deficits in most of the areas supplied from the Llobregat River. Two main actions have been implemented to correct the overall water scarcity: 1) construction of a seawater desalination facility (60 hm^3/year), completed in 2009 and 2) operation of the Water Reclamation Plant (WRP) of El Prat de Llobregat to provide 50 hm^3/year of high quality reclaimed water for a diversity of uses: in-stream river flow substitution, natural wetlands restoration, agricultural irrigation and supply to a seawater intrusion barrier at the lower Llobregat Delta.

Since July 2006, the WRP of El Prat de Llobregat has been using biologically treated secondary effluent from El Prat de Llobregat's WWTP to produce reclaimed water. By the end of 2010, it had contributed 67.8 hm^3 of reclaimed water, saving an equivalent volume of surface and groundwater that has been made available for the exclusive use of human consumption (Mujeriego *et al.*, 2008). Since its start-up, the WRP of el Prat de Llobregat has been operated by EMSSA, a BMA's public company responsible for wastewater treatment and water reclamation and reuse.

Water Reuse Project

The water reclamation and reuse project of El Prat de Llobregat is a definite attempt to implement integrated water resources management in the BMA (Mujeriego et al., 2008). It offers a balanced solution to all users affected by surface and groundwater water restrictions so they can have access to alternative water resources for urban, industrial and agricultural uses. The project started in 2002 with the objective of producing 50 hm^3/year of reclaimed water with quality levels suitable for different beneficial uses: 1) in-stream river flow substitution, 2) restoration of natural wetland areas, 3) alternative supply for agricultural irrigation and 4) supply of high quality water for injection into a seawater intrusion barrier. The Project had an initial budget of 102 M€; 85% of that budget was covered by European Union Cohesion Funds, through the Spanish Ministry of the Environment, while the remaining 15% was covered by the Catalan Water Agency. Figure 1 shows the components of the water reclamation and reuse project of the BMA.

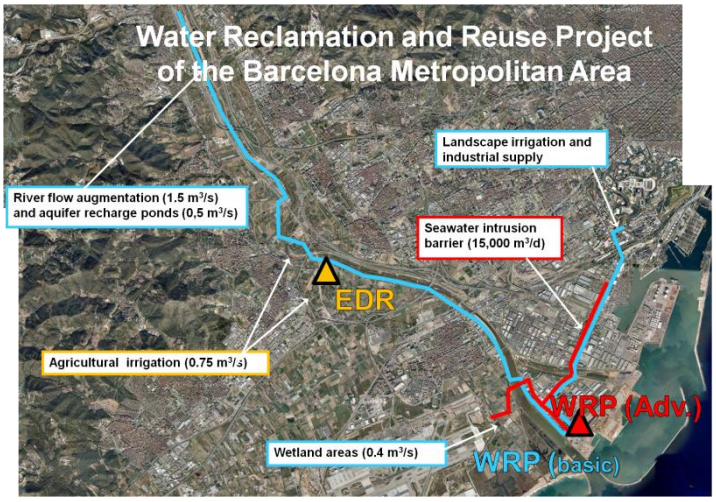

Figure 1. Water reclamation and reuse project of the BMA.

Table 1 summarizes the water flows for the different beneficial uses considered. All water demands are seasonal, but they are satisfied on a regular basis during the summer period, except the seawater intrusion barrier water supply that is satisfied on a permanent basis. The water reuse project was designed to produce three different qualities of reclaimed water, with increasing physico-chemical and microbiological quality levels: 1) water for in-stream river flow substitution and restoration of wetland areas, 2) water for agricultural irrigation and 3) water for supplying the seawater intrusion barrier. The flow of reclaimed water produced during an average hydrological year has been estimated at 50 hm^3/year; however, the basic reclamation processes, the piping system and the pumping stations have been designed for a maximum flow of 110 hm^3/year (3.5 m^3/s). When the facilities will be operated on a permanent basis throughout the year, they will provide a flow of 110 hm^3/year, equivalent to the annual flow of secondary effluent currently produced at El Prat de Llobregat WWTP.

The WWTP of El Prat de Llobregat has been operating since 2004 and has a maximum capacity of 420,000 m^3/day (4.9 m^3/s); it includes an activated sludge treatment process that was upgraded in 2006 to achieve nutrient removal, using biological nitrification-denitrification, plus biological phosphorous removal. The construction cost of the wastewater treatment plant expansion necessary to achieve nutrient removal was 15.6 M€.

Table 1. Reclaimed water allocations for different beneficial uses of the water reclamation and reuse project of the BMA at El Prat de Llobregat, Barcelona, Spain.

Beneficial use	Average flow	
	m^3/day	m^3/s
Substitution of in-stream river flows (seasonal)	130,000	1.50
Artificial recharge of river aquifer, by pond percolation	43,000	0.50
Restoration of wetland areas (seasonal)	35,000	0.40
Substitution of irrigation water (seasonal)	65,000	0.75
Supply to seawater intrusion barrier, 1st phase (permanent)	2,500	0.03
Supply to seawater intrusion barrier, 2nd phase (permanent)(in addition to 1st phase)	12,500	0.15
Street cleansing and occasional irrigation	2,000	0.025
Montjuïc landscape irrigation and industrial use	7,000	0.08

Water Reclamation Processes

Secondary effluent flows into a 2-compartment equalization tank (14,700 m^3 in total) before it is pumped to the WRP, in accordance to water users demands. The WRP has a 300,000 m^3/day (3.5 m^3/s) maximum capacity and includes the following processes (see Fig. 2):

1) Ballasted coagulation-flocculation and lamella settling, using 3 lines of Actiflo process, with addition of coagulant, 130-150 µm sand particles and polyelectrolyte.
2) Filtration through 10 µm pore size micro-screening, using two lines of 5 Hydrotech filters each, operated at a 10-14 m/h filtration rate.
3) Disinfection with UV light, using four parallel channels, each with two banks of 216 lamps, making a total of 864 UV lamps; the disinfection system was designed for an application dose of 55 mJ/cm^2 to a reclaimed water with a SS concentration below 5 mg/l and a UV light transmittance of 60%.
4) Oxygenation: oxygen from a cryogenic tank can be injected into the pipes conveying reclaimed water flows for environmental uses, to ensure that it has enough dissolved oxygen at the discharge point. The facility has not been used so far.

Figure 2. Water reclamation plant (unrestricted irrigation quality) of El Prat de Llobregat.

Reclaimed water for in-stream flow substitution, agricultural irrigation and restoration of natural wetland areas along the Llobregat River is delivered by 2 pumping stations located in a single building. Three submersible pumps are used for supply to natural wetland areas and four submersible pumps are used for the other uses (See Fig. 3.) The largest pumping station, with a capacity of 2.75 m^3/s, provides 0.75 m^3/s for agricultural irrigation and 2.00 m^3/s for in-stream flow substitution; the smallest pumping station with a capacity of 0.40 m^3/s delivers reclaimed water for restoration of natural wetland areas, which are located within a kilometer from the WRP, across the Llobregat River. An additional and separate pumping station has been completed in 2011, to provide reclaimed water for landscape irrigation at the Montjuïc Mountain and for industrial supply to the nearby industrial park. The water distribution network along the Llobregat River has 18.8 km of main pipes, most of them made of steel reinforced concrete and 1,600 mm diameter.

Figure 3. Reclaimed water pumping station for in-stream flow augmentation and agricultural irrigation.

Reclaimed water for agricultural irrigation is further treated to lower its electrical conductivity, using an Electrodialysis Reversal (EDR) plant. Reclaimed water from the pipeline bringing it upstream of Llobregat river is diverted and delivered into an equalization pond of 200 m^3 capacity, from where it flows to the nearby EDR facility for partial demineralization.

The construction cost of the WRP was 28,3 M€. The construction cost of the pumping and distribution network was 26,8 M€ plus 8,1M€ for the Montjuïc project, resulting in a total of 34.9 M€. The construction cost of the EDR plant was 13,8 M€.

Advanced Water Reclamation Process

An advanced water reclamation process was built in 2007, with a capacity of 2,500 m^3/day and subsequently expanded in 2010 with an additional capacity of 12,500 m^3/day, to provide reclaimed water of adequate quality for injection into a nearby seawater intrusion barrier. The treatment processes used at this separate facility are: 1) an ultrafiltration process, 2) a reverse osmosis process and 3) a UV light disinfection process using a close vessel contact chamber. See Figure 4.

Figure 4. Advanced water reclamation plant for supply to seawater intrusion barrier.

The first phase of the project started operation in 2007 and had a production capacity of 2,500 m^3/day of highly treated reclaimed water. The demineralized and disinfected water was subsequently mixed in a 50/50 ratio with drinking water and then injected in a series of 4 deep wells located in strategic zones of the seawater intrusion documented by numerous studies sponsored by the Llobregat Delta Groundwater District (See Fig. 5). During the 2 years of the first phase, the project was able to significantly diminish the intensity and extension of the water intrusion pattern, leading to an extension of the capacity of the plant and the number of injection wells.

Figure 5. Deep injection well of the seawater intrusion barrier at the Llobregat Delta.

The second phase of the project was completed in 2010 to provide an additional capacity of 12,500 m^3/day (15,000 m^3/day total capacity) for the advanced reclamation process; the treatment process adopted were similar to those installed during the first phase: UF, plus RO plus UV light disinfection. A series of 11 deep water injection wells were installed, bringing the total number of injection wells to 15. Since 2010, reclaimed water is directly injected into the deep wells, without any further mixing with drinking water. Follow up studies have clearly shown the real decline in intensity and extension of the seawater intrusion process in the groundwater system.

Spanish Water Reuse Regulations

Water reclamation and reuse regulations are established by Royal Decree (RD) 1620/2007. In summary, reclaimed water quality is defined by four main parameters: parasitic helminth eggs, *E. coli*, suspended solids and turbidity. Other microbiological parameters, like Legionella sp. and physico-chemical parameters are applicable to specific uses of reclaimed water.

Reclaimed water uses are classified according to the expected exposure of workers, the public at large and the irrigated crops to reclaimed water. Quality requirements become increasingly restrictive as the likelihood of human exposure becomes possible, to ensure both public health and environmental protection. Compliance is established according to the 90 percentile (P90) of the series of water quality parameters recorded during the water reuse period.

Although Spain had no official limits for reclaimed water quality in 2003, when the project was initially approved, and in 2006, when the Water Reuse Project began, the Catalan Water Agency had developed quality criteria for reclaimed water suitable to different uses; those criteria covered a range of qualities including the limits established by Title 22 of the California Water Code, the water reuse criteria proposed by the US Environmental Protection Agency in 2004, and the health guidelines recommended by the World Health Organization in 1998.

Since 2007, Spanish regulation RD 1620/2007 defines the quality requirements for reclaimed water suitable for a diversity of uses. Agricultural and environmental uses have to comply with Quality Use 2.1, 2.2 and 2.3, while seawater intrusion barrier has to comply with Quality Use 5.2. Table 2 summarizes the water quality requirements for in-stream flow substitution, restoration of natural wetland areas and agricultural irrigation.

Table 2. Quality requirements for reclaimed water used for in-stream flow substitution, restoration of natural wetland areas, agricultural irrigation and injection into seawater intrusion barrier, according to Spanish regulations for water reuse (RD 1620/2007).

Parameter	Agricultural and environmental (uses 2.1, 2.2, 2.3)	Seawater intrusion barrier (use 5.2)	Additional limit
Parasitic helminth eggs	< 1 U/L	< 1 U/10L	---
Faecal coliforms	<100 CFU/100mL	< 0 CFU/100mL	
Suspended solids, SS	≤ 20 mg/L	≤ 10 mg/L	
Turbidity	≤ 10 NTU	≤ 2 NTU	
Biochemical oxygen demand, BOD_5	---	---	≤ 10 mg/l
Residual chlorine	---	---	≥ 0.6 mg/l (*) optional
Dissolved oxygen, O_2	---	---	≥ 7.5 mg/l (*)
Electrical conductivity	---	---	≤ 1,400 μS/cm (*)

(*) for agricultural irrigation.

Reclaimed Water for Agricultural Irrigation

To promote the use of reclaimed water for agricultural irrigation at the Llobregat's Right Bank Irrigation District, as to reach a 50% substitution rate of surface water allocations from the Llobregat River, it was necessary to diminish its high EC levels, particularly during the summer season when it may reach values close to 3,000 µS/cm. To satisfy the EC limitation posed by farmers, the public agency Depurbaix and the Catalan Water Agency built a water reclamation facility in 2010 which includes a 2-phase Electrodialysis Reversal (EDR) process with a capacity of 55,000 m^3/day. About 85% of the total flow assigned for agricultural irrigation will be demineralized and then mixed with the remaining flow of reclaimed water to produce a reclaimed water for irrigation with an overall EC close to 1,285 µS/cm, suitable for the crops commonly grown at the lower Llobregat Delta. The construction cost for the demineralization plant was 13,8 M€, and the O&M costs are estimated at 0,13 €/m^3.

Reclaimed Water for Environmental Restoration

Reclaimed water for restoration and supply to natural wetland areas, located across the Llobregat river (See Fig. 6), is produced continuously or according to supply needs at the basic water reclamation facility and thus complies with the more stringent water quality limits applicable to unrestricted irrigation of raw eating crops, defined by Quality Use 2.1 (RD 1620/2007).

The Council of the European Communities has declared 900 ha of the wetland areas of the Llobregat Delta as "zones of special protection for birds" (ZEPA) under the control of the NATURA 2000 Network, and from those, close to 500 ha are Partial Natural Reserve. Further details of the landscapes and wild populations of those wetland areas can be obtained at The Llobregat Delta webpage: http://www.deltallobregat.cat/?url=index

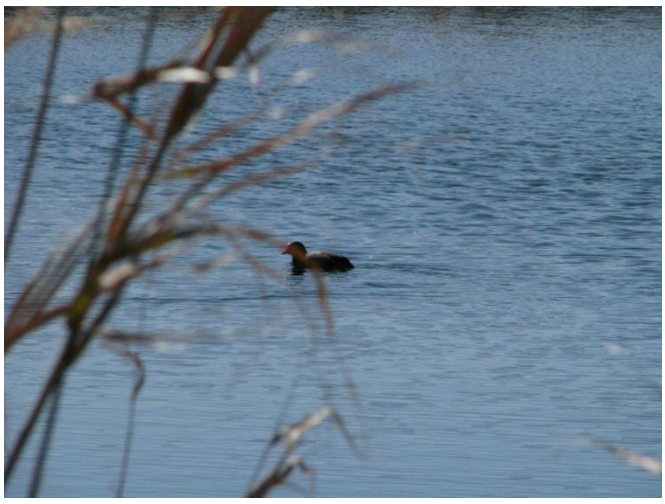

Figure 6. Protected wetland areas of the Llobregat Delta.

Reclaimed Water for In-stream River Flow Substitution

Reclaimed water for in-stream river flow substitution is produced at the basic reclamation process of El Prat de Llobregat WRP and pumped along the left bank of the river up to a point just downstream of the extraction point of the drinking water treatment plant of Sant Joan Despí. This drinking water facility belongs to Agbar Water Company and has a

production capacity of 5,3 m^3/s. Water is conveyed using a pipe of 1.6 m diameter and 8.1 km length, followed by a pipe of 1.4 m diameter and 1.0 km to a discharge point just downstream of the abstraction point of the drinking water treatment plant (See Fig. 7). The second conveyance step uses a pipe of 1.6 m diameter and 1.5 km length followed by two parallel pipes of 1.0 m diameter and 6.8 km length each, to a second discharge point located 6.5 km upstream from the abstraction point of the San Joan Despí drinking water treatment plant. Reclaimed water discharge at this upstream point will mix with stream flows, before it can be abstracted at Sant Joan Despí for drinking water production.

Construction of those facilities was prompted by the severe drought and water shortages experienced by the BMA during 2007 and 2008. Although a definite change in rain pattern started in May 2008, cancelling the fears of water supply interruptions in the BMA, the Catalan Water Agency, the BMA and the Catalan Public Health Service agreed to conduct, that same year, a closely controlled experiment of in-stream river flow augmentation, upstream of the abstraction point for drinking water production at the Sant Joan Despí facility. From 10 October to 23 October 2008, reclaimed water was pumped under controlled quality and flow conditions from the WRP of El Prat de Llobregat to this second discharge point, following a flow increase protocol of 0.50, 0.85, 1.20, 1.5 and 2.00 m^3/s. The natural river flow during those same days varied from 3 m^3/s to 9 m^3/s with a detection limit for this variation of 0.5 m^3/s.

Figure 7. Reclaimed water discharge point at the Llobregat river.

Those discharges of basic reclaimed water resulted in ammonia increases in river water below 2 mg/l and UV absorption increases below 13 UV absorption units, while electrical conductivity always remained below 2,000 µS/cm. The experimental results indicated that the water quality of the river is not significantly affected, as long as reclaimed water represents between 20 and 25% of the natural river flow. Drinking water produced at the Sant Joan Despí WTP was always within the limits specified by the RD 140/2003 relative to drinking water quality control. Ammonia concentration, electrical conductivity and Trihalomethane formation potential are the main sources of concern during this type of in-stream river flow augmentation. The final report concluded in the viability of this type of strategy for providing additional and reliable water sources, particularly during water shortage and drought periods.

Water Treatment Plant of Sant Joan Despí

The water treatment plant (WTP) of Sant Joan Despí started operations in 1955. Since then, it has undergone numerous quantitative and qualitative improvements with the sole aim of adapting drinking water production processes to the new demands of consumers and the progression of water quality standards.

After more than 50 years of experience in producing and distributing drinking water to Barcelona and its surrounding areas, the WTP of Sant Joan Despí has adopted a sophisticated treatment process with a production capacity of 5.3 m^3/s, based on a modern multiple-barrier treatment process, which makes it one of the most complete drinking water treatment plants in Europe.

To comply with current European objectives on organoleptic quality improvements and the more stringent legislation that will applicable in the future, a fraction of the water from the conventional treatment process is further treated using membrane technology: ultrafiltration (UF) and reverse osmosis (RO). This new process requires acidification with sulfuric acid, to maximize retention of residual aluminum during the first UF membrane phase. The submerged UF membranes operate under pressure suction (out-in). Their openings size (0.02 μm) ensures a total elimination of bacteria, but not of viruses, and also of suspended matter up to the level required for the RO membrane process.

The effluent from the UF membrane process undergoes a pretreatment process before it goes into the RO membrane process: 1) ultraviolet (UV) light application (further elimination of bacteria, prevention of bacterial regrowth and virus inactivation), 2) addition of reagents (pH adjustment, dissolved oxygen excavengers, salts precipitation), 3) cartridge filtration (additional protection of RO membrane process) and 4) additional UV light application (control of potential bacterial regrowth).

The RO membrane process offers a total barrier for viruses and bacteria, and also eliminates practically all organic and inorganic compounds in the water, resulting in very low levels of electrical conductivity and total organic carbon. The RO membrane process includes a 2-step membrane sets; the rejection from this phase goes into a third step. The water recovery rate for the 3-step RO membrane process is 90%. The rejection water from this final step is discharged into the brine pipeline that goes along the Llobregat River and into the Mediterranean Sea. Product water from the RO membrane process is remineralized and mixed with the remaining flow from the conventional water treatment process for subsequent distribution through the drinking water distribution system.

Reclaimed Water for Landscape Irrigation in Montjuïc and Industrial Uses

Reclaimed water for landscape irrigation at the Montjuïc mountain (See Fig. 8) and for industrial supply to the El Prat Industrial Park, is produced at the basic WRP and thus complies with the water quality limits applicable to unrestricted irrigation of raw eaten crops, defined by Quality Use 2.1 (RD 1620/2007).

The main construction elements of this recent extension Project are:

1. A new pumping station located next to former pumping stations, provided with 2 submersible pumps of 80 L/s each, plus empty space for 2 additional pumps during a future expansion.
2. A pipe of 5,8 km length and 400 mm diameter, along Street A in Barcelona's Zona Franca.

3. A pipe of 3.4 km length and 200 mm diameter, from the border of Barcelona's Zona Franca to the head storage tank, located at 70 m altitude in Montjuïc.
4. A satellite pumping station that feeds a new hydrant (to supply municipal water tanks) and a pipe of 1.3 km length to bring reclaimed water to the storage tank of Three Pine Nursery.

Figure 8. Mediterranean section of Montjuïc Botanical Garden.

Construction of this additional component of the water reclamation and reuse project of BMA has meant a total investment of 8.1 M€, corresponding to the following items:

1. The pumping station and the conveyor pipe from the WRP to the limits of the Barcelona's Zona Franca represent an investment of 4,1 M€, managed by the BMA and sponsored by the Catalan Water Agency.
2. A section of the conveying pipe across Street A in Barcelona's Zona Franca represents an investment of 2,1 M€, sponsored by the Catalana Water Agency.
3. The remaining conveyor pipe from the Barcelona's Zona Franca to the Montjuïc facilities, including the storage tank and the satellite pumping station, represents an investment of 1,9 M€, sponsored by the City of Barcelona.

A leading demonstration project is being designed with Clariant Ibérica Co. to supply reclaimed water as raw material for their industrial processes. A new municipal ordinance is being prepared to allow drinking water supply companies to manage the distribution of reclaimed water to industrial users. Furthermore, the close collaboration with the research staff of the Montjuïc Botanical Garden will provide in the near future an essential assessment of the benefits and requirements to be considered when approaching the use of reclaimed water for landscape irrigation.

Economic Aspects

Table 3 summarizes the investment costs and the operation and maintenance costs of the different components of the water reclamation and reuse project of the BMA, located in El Prat de Llobregat.

Based on those figures, the following economic indicators can be estimated for the project:

1. Water reclamation (basic treatment):
   Reclaimed water cost (without capital cost): 0.032 €/m^3 annual capacity (2007).

Reclamation investment cost: 0.25 €/m^3 annual capacity (3.5 m^3/s) (2007).

2. Water reclamation for agricultural irrigation (demineralization):
   Reclaimed water cost (without capital cost): 0.13 €/m^3 capacity (estimated).
   Reclamation investment cost: 0.58 €/m^3 annual capacity (2010).
3. Water reuse for in-stream flow, restoration of wetlands and agricultural irrigation:
   Reuse investment cost: 0.24 €/m^3 annual capacity (3.5 m^3/s).
4. Water reclamation and water reuse for seawater intrusion barrier:
   Reclaimed water cost (without capital cost): 0.20 €/m^3 .
   Reclamation and reuse investment cost: 3.38 €/m^3 annual capacity (15,000 m^3/day demineralized).

Table 3. Construction costs and operation and maintenance costs of the water reclamation and reuse facilities of Barcelona Metropolitan Area.

Item	Construction cost, M€	O&M costs, €/m^3
Nutrient removal	15.6	---
Water reclamation plant	28.3	0.032
Water distribution network	26.8	---
Electrodialysis reversal (EDR) plant	13.8	0.13
Seawater intrusion barrier (first phase)	3.70	---
Seawater intrusion barrier (second phase)	14.8	0.20 (both phases)
Montjuïc irrigation and industrial supply	8.1	---

Three main conclusions emerge from this economic evaluation:

1) The investment required for constructing a basic water reclamation plant using a complete physico-chemical process (0.25 €/m^3 annual capacity) and the cost of operating such facility (0.032 €/m^3) are very similar to those reported by similar large scale projects in Spain.
2) A seasonal operation of the facilities (summer season), as it is initially expected in the WRP of El Prat de Llobregat, affects directly the investment cost, as they have to be distributed among the cubic meters of reclaimed water actually produced; the production cost of reclaimed water is affected to a lesser degree by seasonal operation, due to the reduced expenditures in chemicals, energy and labor.
3) Advanced levels of water reclamation, such as demineralization for agricultural irrigation (EDR) and for injection into a seawater intrusion barrier (UF plus RO), result in a significant increase in both the investment cost and the water reclamation costs. Investment costs of water reclamation for agricultural irrigation and for injection into the seawater intrusion barrier are 2 times and 7 times higher than those of a basic physico-chemical reclamation process, per unit of annual capacity; while the corresponding operating costs (without capital costs) are 3 times and 7 times higher than those of the basic water reclamation process, per unit of water produced.

Funding Agencies

Planning, construction and operation and maintenance of the Water Reuse Project of the BMA has been possible thanks to the close collaboration and support, politically,

economically and technically, of the European Union and the three agencies with jurisdiction in the area: 1) the Catalan Water Agency (ACA), as the water resources authority in the Catalana watersheds, interested in promoting new water supply sources, 2) the water resources division of the BMA and its public company EMSSA, responsible for water supply, wastewater treatment and disposal in the metropolitan area and particularly responsible for operating the WRP of El Prat de Llobregat and 3) the city of Barcelona, as one of the final users of this alternative water supply, for what it means as an example of water self-sufficiency, reliability and sustainability when using water resources.

Further Information

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