

# Improving Water Quantity and Quality Supply Security by Managed Artificial Recharge Technologies in the Lower Llobregat Aquifers Integrated into a Conjunctive Surface and Groundwater Management Scheme for Barcelona, Spain

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**Abstract:** The large concentration of human population, industry and services in the Metropolitan Area of Barcelona has to confront scarce water resources, serious seasonal and inter-annual variations and quality deficiencies in the sources. A large fraction of these water resources are in the medium-size Llobregat River basin and the remaining ones correspond to a surface water transfer, seawater desalination and wastewater reclamation. Groundwater dominated water resources availability before 1950. Afterwards, water supply has evolved progressively to integrated water resources management, which includes serious water quality concerns to deal with population density, river pollution, seawater intrusion in the main aquifer, and brine generation in the mid Llobregat basin due to old mining of saline minerals. The role of the alluvial aquifers has progressively evolved from being the main water source to reserve storage to cope with seasonal and drought water resources availability. River-enhanced recharge and artificial recharge are needed to assure enough groundwater storage before surface water becomes scarce and/or suffers a serious temporal loss of quality. Enhanced river recharge started in 1950. Treated river water injection in dual-purpose wells was put into operation in the early 1970s. Basin and pond recharge was added later, as well as a deep well injection barrier along the coast to reduce seawater intrusion and to allow increased groundwater abstraction in moments of water scarcity. There is a progressive evolution from solving water quantity problems to consideration of water quality improvement during recharge, with attention to emergent concern pollutants in river water and in reclaimed water to be considered for artificial recharge. Improvement of artificial recharge operation activities has been introduced and research is being carried out on the difficult behavior to degrade organic pollutants during infiltration and in the terrain. This paper presents the different activities carried out and presents the research activities, and comments on the economic, social and administrative issues involved as well.

**Key words:** Enhanced river recharge, artificial aquifer recharge, integrated water resources management, Llobregat River basin, Barcelona.

## 1. Introduction

Almost all Mediterranean coastal areas have large human concentrations and support activities

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demanding large quantities of fresh water, in dominantly semiarid, and in some cases arid, conditions. Water resources are intensively exploited from both local ones and those coming as allochthonous river flows from inland areas. This means a large stress on water quantity and quality, including river water pollution and seawater intrusion

into the coastal aquifers, and consequently in the environment, which is an important provider of nature services to humans. The existing large urban areas, industrial and services settlements, tourist areas and agricultural and animal rising spaces have to be supplied with good quality water and with sufficient guaranty of availability.

Catalonia, in north-eastern Spain, is one of the most populated and active regions in the Mediterranean area. Its capital, Barcelona, has over 3 million inhabitants in its Metropolitan Area, in which important industrial, services and transportation activities take place, besides some areas devoted to intensive agriculture, green areas and ecologically valuable sites.

In Barcelona, local water resources are scarce, irregular, often of poor quality, and intensively used. There are diverse water sources: local surface and groundwater, water transferred from the Ter River basin, in north-eastern Catalonia, seawater desalination and reclamation of treated urban wastewater. This needs the integrated water resources management of water quantity and quality, and efforts toward sound water governance. Since 1955, the joint use of surface and groundwater has improved water availability. What follows refers to water resources in the medium-size (3,000 km<sup>2</sup>) Llobregat River basin, and specifically to the Low Valley, in the Barcelona's Metropolitan Area (Fig. 1). Here, the alluvial aquifers play a key role that has evolved from being the main water supply source to key seasonal and drought storage. Their integration into the system includes enhanced and artificial recharge, which started in 1950. MAR (Managed Aquifer Recharge) using surface water from the river or reclaimed wastewater, plays currently an important role in the conjunctive management of the diverse water sources and in preventing groundwater quality degradation.

Hereinafter, the aquifer system is introduced with its hydrogeological conceptual model and conditionings, followed by basic data on the MAR

facilities. General operation is commented, from quantity aspects to recent research to improve operation and water quality. Finally, comments on the economic, legal, administrative and management framework are given.

## 2. The Baix Llobregat Aquifer System

Hereinafter, the lower part of the Llobregat River basin is called the Lower Llobregat or Baix Llobregat. In it, the part of the final valley down to Sant Joan Despí is the Low Valley (Vall Baixa) and from here (delta apex) to the coast is the Llobregat Delta.

The alluvial and delta formations contain good aquifers of relative small size. They are well-connected to the Llobregat River. The about 3,000 km<sup>2</sup> river basin yields about 600 hm<sup>3</sup>/year (million m<sup>3</sup> per year), although quite variable and subjected to floods and droughts, which are currently partially tamed by surface dams. The relatively high river-bed slope allows relatively high piezometric gradients under undisturbed conditions, so that most of the delta aquifers were free of the original seawater (see the aquifer genesis below) at the start of the 20th century, except for the intermediate aquitard and at the sides. The aquifer system is an important source of reliable fresh water for the area, but has limited reserves and is prone to seawater intrusion.

The most important aquifers in the Baix Llobregat are the alluvial formations associated to the Llobregat River. They can be broadly grouped into three interlinked units: (1) the Low Valley aquifer, (2) the upper delta aquifer and (3) the deep delta aquifer. The three aquifers merge at the Sant Joan Despí-Cornellà strait, which is the apex of the delta. Aquifers (1) and (3) constitute the main aquifer, as the upper delta aquifer (2) is shallow, low yielding and contains poor water quality. The emerged area of the delta along 12 km of coastline is about 100 km<sup>2</sup>.

The hydrogeology and groundwater hydrology of the area is relatively well known. There are geological and hydrogeological studies since the late 19th



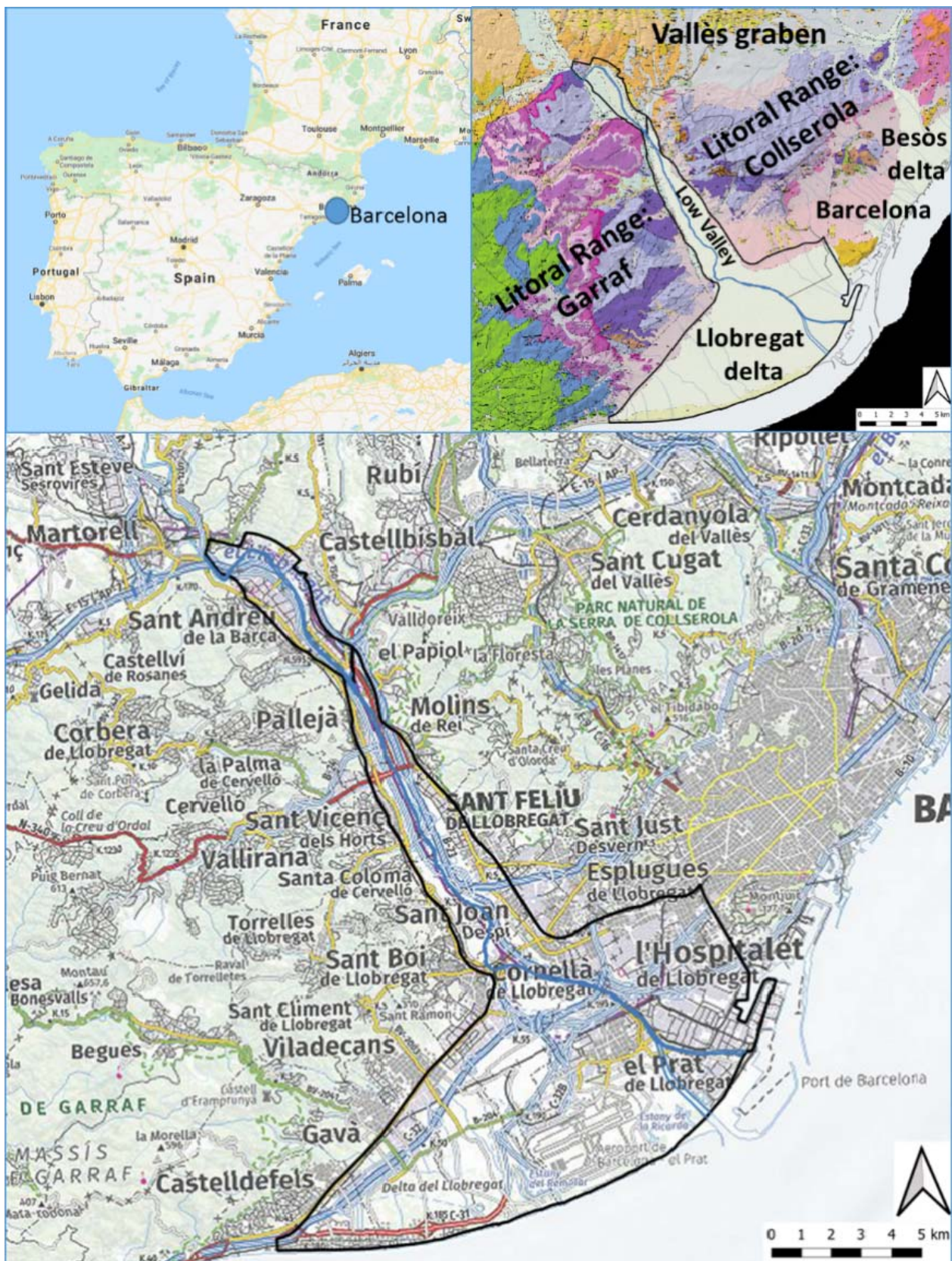


Fig. 1 Location of Barcelona, geological areas of the Metropolitan Area, and the Baix Llobregat [1].

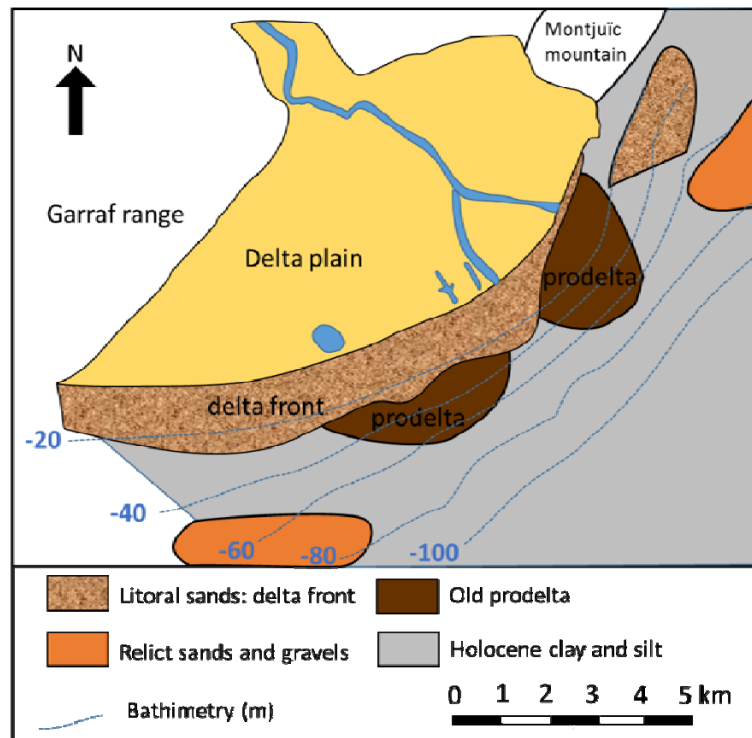
century, although they have no details until the 1960s. A list of the most significant studies can be found in Queralt, et al. [2], Custodio [3] and SASMIE [4].

The aquifers show typical structures of many of the coastal alluvial and littoral formations, mostly related to the effect of Quaternary climate fluctuations in a case of relatively high contribution of coarse material in the sloping Low Valley and the sedimentation in the coastal area since the late Pleistocene, when sea level was about 120 m lower than at present. Therefore, in the delta there is a sequence of (a) radially distributed deep coarse deposits, (b) a fine sand, silt and clay intermediate wedge acting as a low permeability aquitard covering the full area, except at the boundaries, and (c) the variable shallow formations of the current delta.

Macroscopically, the Low Valley alluvial aquifer behaves as unconfined and is formed by diverse fluvial terraces. Downstream, at the delta apex, this aquifer splits in two, separated by a silty-clayish wedge that thickens toward the coast. The shallow

aquifer extends over most of the delta area. The deep aquifer, the most important, is confined below the silt wedge. The deep aquifer is not always continuous, but laterally variable, with a radial layout and total thickness decreasing from about 40 m in Sant Joan Despí-Cornellà to less than 10 m at the coastline and still less offshore. It crops or sub-crops out at the sea bottom at about 4 km and 120 m below current sea level (Fig. 2). Fig. 3 is a simplified longitudinal geological-hydrogeological cross-section.

Intensive groundwater development in the Low Llobregat area started in the late 19th century to supply Barcelona, when large diameter deep wells and steam driven pumps were installed in the lower part of the Low Valley. Also, numerous, small-diameter percussion-driven wells were drilled in the center of the delta, around El Prat de Llobregat. They flowed initially, with heads up to several meters above land surface. Afterwards, many other deep wells to supply factories and other water demands were drilled. Consequently, the existing wells ceased to flow.



**Fig. 2** Bathymetry, thickness of the Holocene sediments in the submarine coastal strip of the Llobregat delta, and sediment type [5], partially modified by Serra Raventós, and Verdaguer Andreu [6].



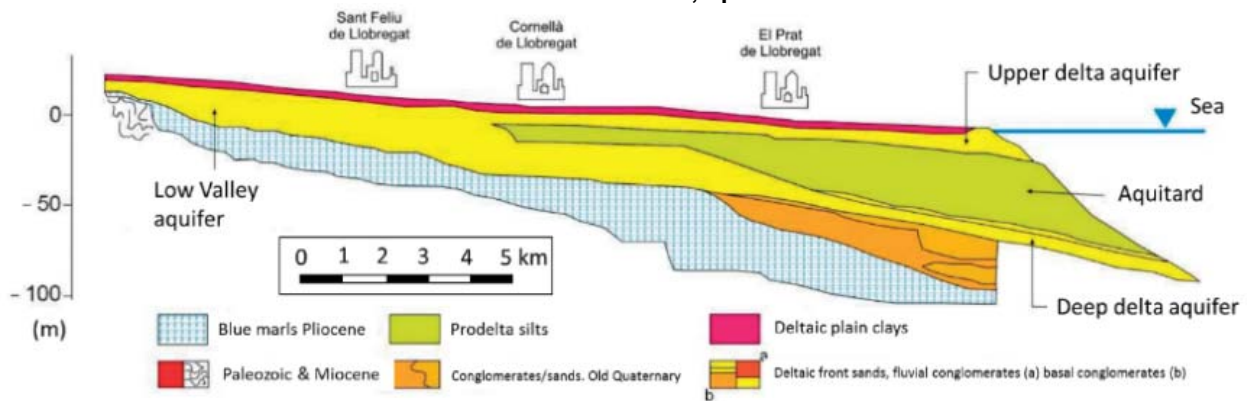


Fig. 3 Simplified longitudinal hydrogeological cross-section of the emerged and submerged delta [7-9].

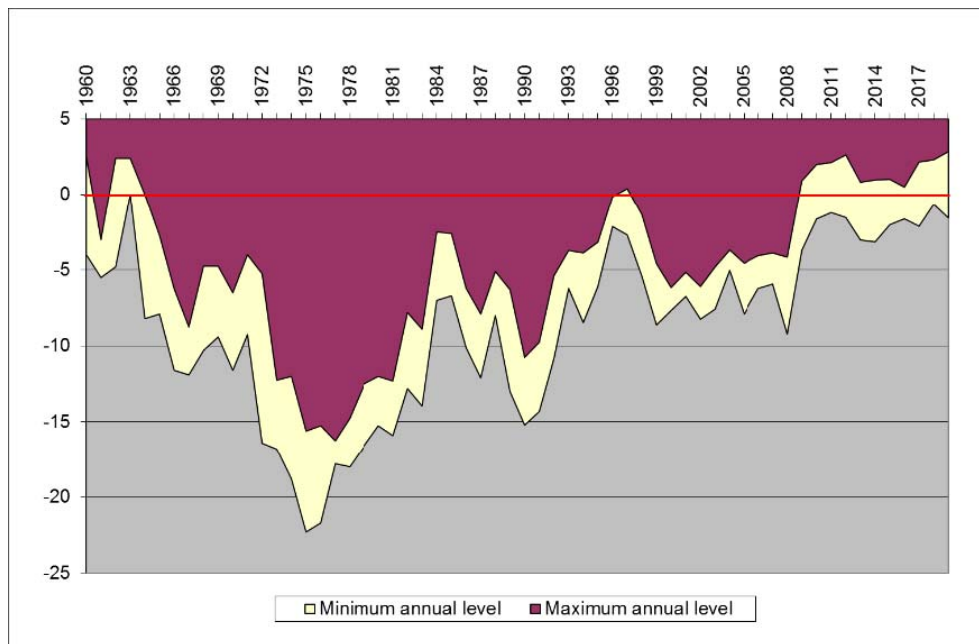


Fig. 4 Piezometric level evolution in the deep delta aquifer in its central area (El Prat de Llobregat). Values in metres relative to sea level.

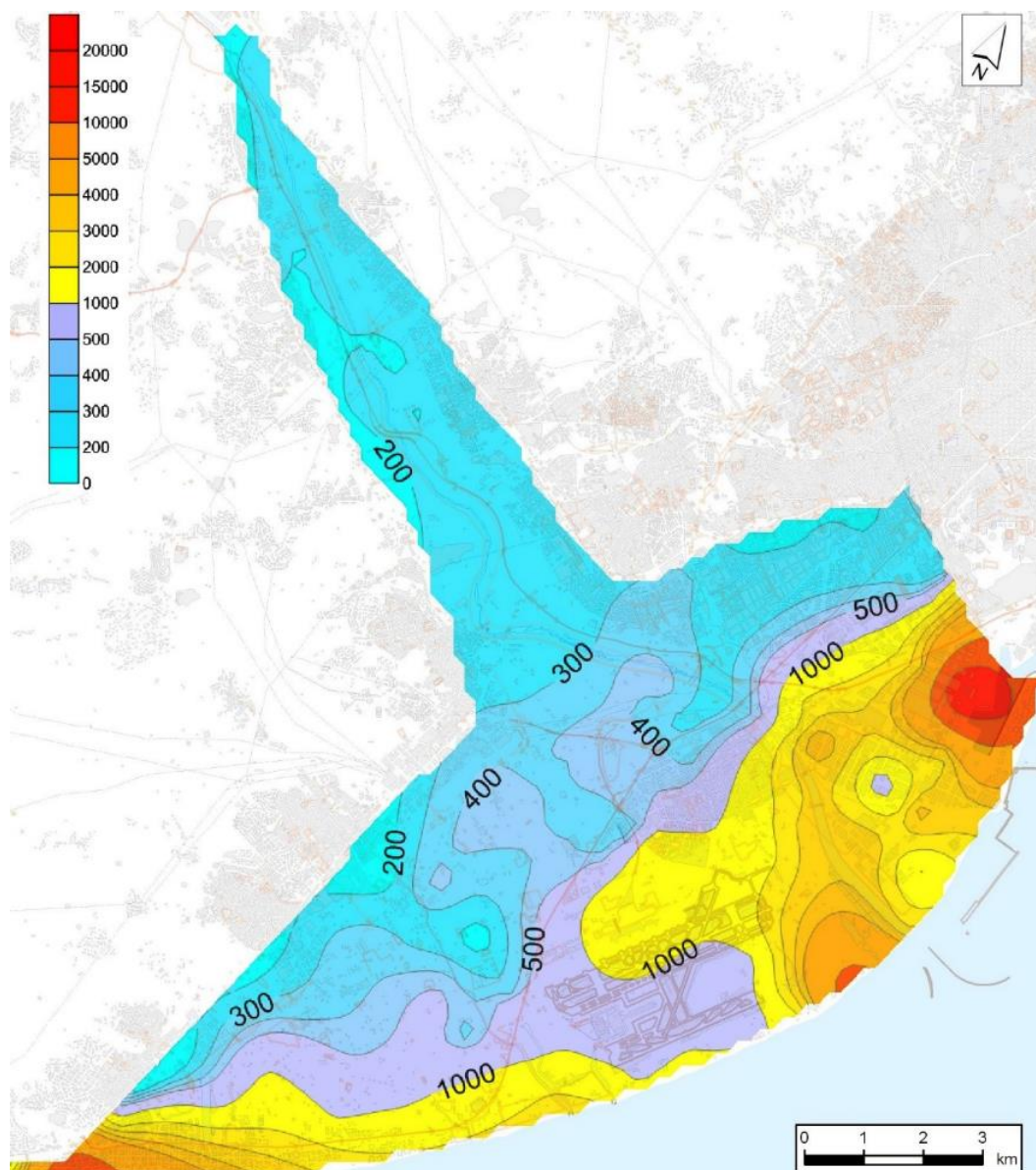
Pumps were installed and groundwater development continued. Exploitation peaked in the 1970s, up to 120 hm<sup>3</sup>/year. Piezometric levels were down to -8 m along the coastline and -22 m in the center of the delta. The water table in the Low Valley was permanently below the river level and even below sea level in some areas. The consequence was reduced groundwater storage in the unconfined areas, with the risk of unsustainable abstraction for water supply in the dry season, seawater intrusion in the central and eastern costal part of the delta, and excessive pumping cost for some of the water-dependent factories [10]. Fig. 4 shows the piezometric level evolution in the deep delta aquifer in

its central area and Fig. 5 contains one of the states of seawater intrusion into the Llobregat Delta deep aquifer. There is a long delay between action and response due to groundwater storage (depletion or/and front displacement). Therefore, direct comparisons may not represent actual functioning and may be quite uncertain. The dynamic behavior has to be accounted for to correctly understand and quantify monitoring data. This includes the previous history of exploitation.

Abstraction for water supply decreased after the construction in 1962 of a river water treatment plant, later enlarged and with the addition of a new large one. New changes appeared in 1976 with the Ter River

water transfer from 80 km to the north, the construction of a seawater desalination plant of 60 hm<sup>3</sup>/year capacity, and plans for treated urban wastewater reclamation, plus the artificial recharge here considered. This was a form of surface and groundwater joint use, which currently is a well-developed case of integrated water resources management. The progressive groundwater abstraction

reduction after the peak in the 1970s and the decrease that has been clearly produced since the late 1990s in the area were partly forced by circumstances, partly due to users' agreements to get a reasonable use and partly due to changes toward an integrated water resources system. Fig. 6 shows the evolution of abstraction per type of water use. Currently the average abstraction is about 40-50 hm<sup>3</sup>/year.



**Fig. 5** Seawater intrusion into the Llobregat delta deep aquifer coming from the off-shore outcrops at the sea bottom. Cl (Chloride) content in 2019, in mg/L Cl.

Source: CUADLL (Llobregat Delta Water users Association).

The figure represents a dynamic situation, resulting from the sequence of groundwater abstraction during the previous one to two decades.

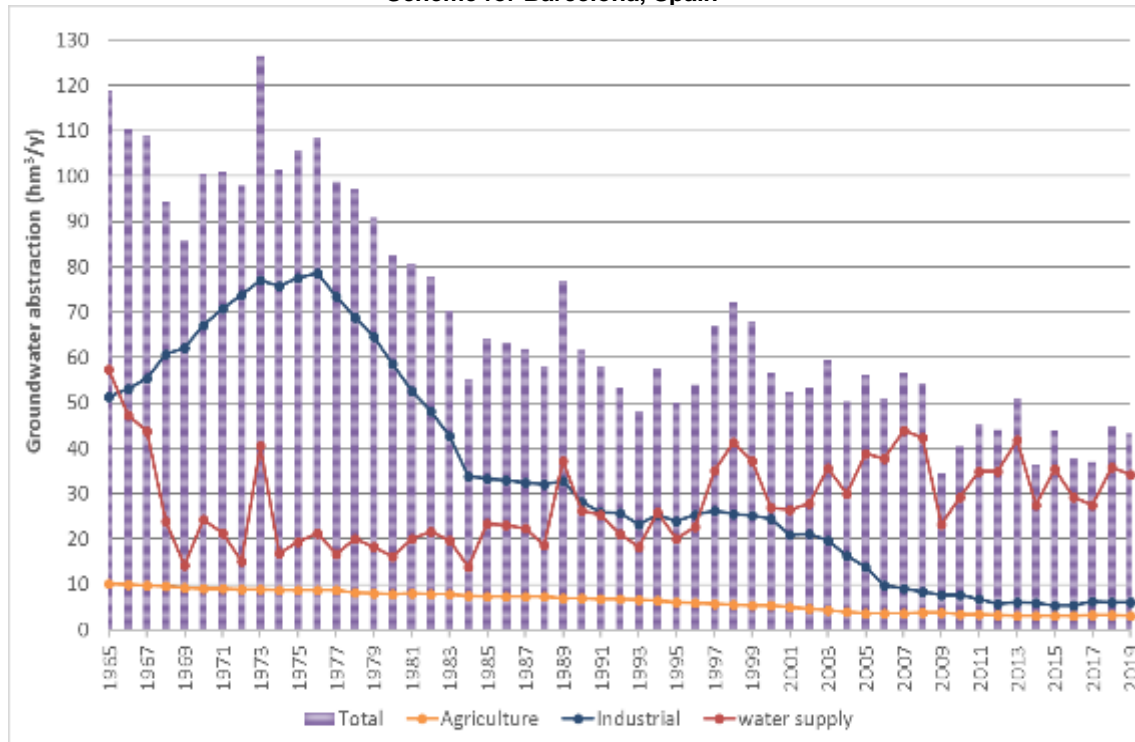


Fig. 6 Evolution of groundwater abstraction in the Low Valley and deep aquifer of the delta.

Groundwater natural recharge to the Low Valley aquifer system under undisturbed conditions was mostly due to contributions from the valley slopes. Groundwater intensive abstraction favored the induced infiltration of river water in its bed, up to a limit depending on bed clogging, river flow and width of the channel. The infiltration of important return irrigation flows in the areas supplied by the surface water canals has to be added. These last two contributions were dominant when exploitation peaked. Currently, local side recharge is again significant but is less than abstraction. This is the reason of considering enhanced and artificial recharge as a permanently needed action, although discontinuous along time, according to water availability, needs and circumstances, and actual groundwater storage.

### 3. Improving Water Security and Aquifer Reserves

The Lower Llobregat aquifer system is a key element for water supply and especially for urban

water supply and to make it more secure and resilient in droughts, emergencies and serious water contamination incidents. It is also important for local self-supplied industrial and services activities, and for the still relevant irrigated agricultural activities sited out of the areas served with surface water canals. The degradation or loss of aquifers will need costly and difficult works to emplace regulation. Using natural infrastructures for storage and distribution is a less expensive and more environmentally friendly solution [11], although it needs operation and management.

The growing complexity of the Lower Llobregat water system, the need of great efficiency in the use of available resources, and the increasing pressure to preserve and improve quality in front of an expanding number of concerning substances, have to be considered with models of processes and numerical models, to help in decision making. Since the early 1970s, there are several quantitative models of the Lower Llobregat aquifer system. They have been very useful tools for understanding groundwater functioning. Currently, available models derive from

the flow and mass transport model developed by the UPC (Polytechnic University of Catalonia) [12-14], for the ACA (Water Agency of Catalonia) and the preceding institutions, with the help of the CUADLL. The model is being operated by the ACA, and the CUADLL uses it as well, with progressive improvements.

Under current environmental, technical, administrative and legal circumstances, from the different modelled scenarios of water resources availability, the sustainable groundwater abstraction is considered to be 40 hm<sup>3</sup>/y. For the current average abstraction of 50 hm<sup>3</sup>/y, recharge has to be increased by 10 hm<sup>3</sup>/y, in the right sites, in order to maximize storage and average transit time, and also to minimize damage by too high water tables in certain urbanized areas with underground spaces. Action is done to improve data and upgrade the models. One objective is increasing the security factor, partly through careful MAR activities.

## **4. Managed Artificial Recharge Experience in the Baix Llobregat Area**

### *4.1 General Considerations and Background*

The managed artificial recharge, MAR, may be defined as controlled operations aimed at transferring water from land surface to underlying aquifers. The managed operation makes the difference with natural recharge. In an MAR facility location, flow rates and quality of the infiltration water are decision variables to be included into the design of the facility and subsequent operation. They can be optimized. There is a long experience in Europe [15].

The great importance of the Lower Llobregat aquifer system was clearly perceived by the Barcelona's water supply company in the 20th century. In the late 1940s, a project was set to increase river recharge in the Low Valley by carefully scarifying a section of the river bed, and in the late 1960s a project to recharge excess water from the river water treatment plant by means of single and dual purpose

injection wells [16, 17]. The different techniques initially applied were synthesized by Custodio [18], including those in the Baix Llobregat and other areas of Barcelona's Metropolitan Area.

There are five MAR technologies used in the Baix Llobregat aquifers. Their location is shown in Fig. 7.

- Scarification of the riverbed in the Low Valley.
- Deep injection in the delta apex.
- Surface ponds in Castellbisbal.
- Surface ponds in Sant Vicenç dels Horts.
- Seawater positive injection barrier in the delta deep aquifer.
- Moreover new projects are in study.

Fig. 8 shows the evolution of yearly recharge water volumes for the several artificial recharge technologies applied in the Lower Llobregat aquifers.

Hereinafter, the most salient features of each activity are given.

### *4.2 Enhanced River Bed Infiltration through Scarification*

In the Low Valley, due to the intensive groundwater abstraction, the water table in the alluvial aquifer is permanently below the riverbed. Since 1950, when conditions are favourable, a tractor with a scrapping tool enters into the river and scars its bed for de-clogging (Fig. 9). This is done in a relatively wide reach of the river that is maintained flat, where sediments are coarse and with low clay and silt content. The scrapped silt and clay move downstream and river water infiltration capacity improves. This is a kind of induced recharge (enhanced recharge) because scrapping favours natural recharge. The only energy consumed is for moving the tractor. The scrapper works downstream ward with a velocity less than that of river water. Fig. 10 shows the sediment deposited in the riverbed before scrapping. The periods of operation depend on river water flow and quality, as well as the need to increase groundwater storage. Table 1 summaries the main parameters that condition the operation.



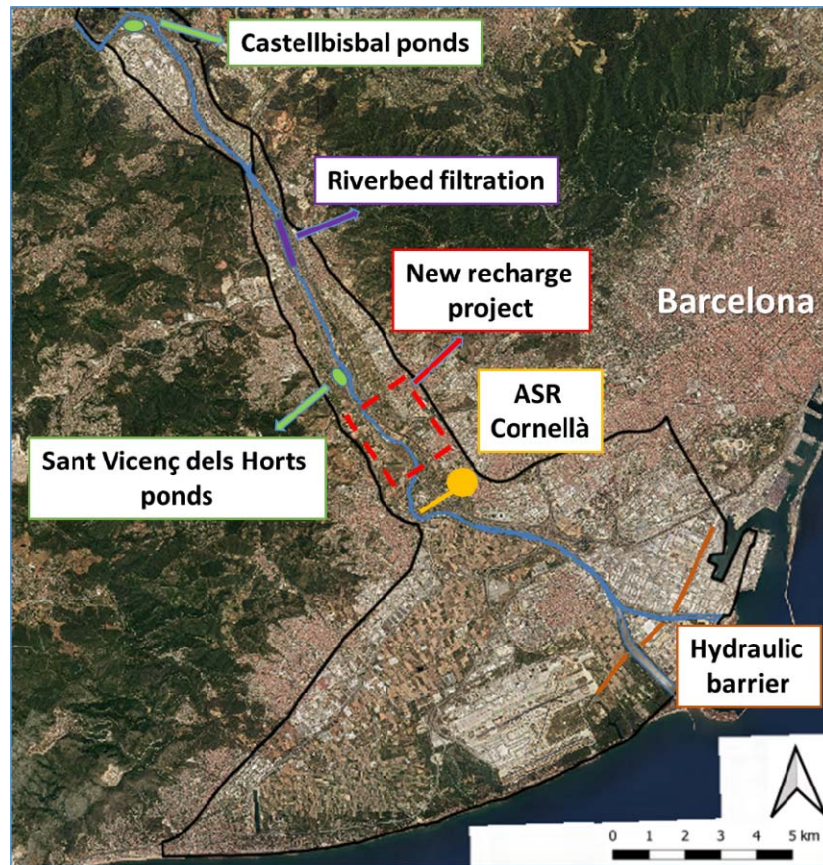


Fig. 7 Location of the 5 enhanced and artificial recharge facilities in the Baix Llobregat.

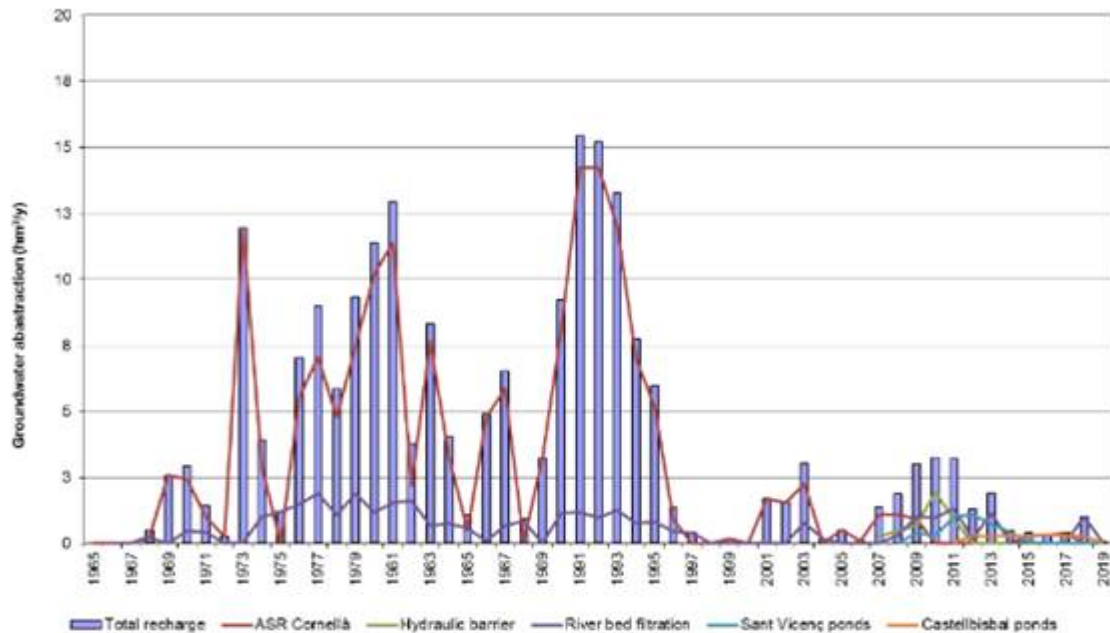


Fig. 8 Evolution of yearly recharge water volumes for the several artificial recharge technologies applied in the Lower Llobregat aquifers.

In the case of Castellbisbal pond there was also recharge between 1980 and 1998, but detailed data are not available. ASR = aquifer storage and recovery.

**Table 1** Parameters that condition riverbed filtration.

Parameter	Daily average daily values	Maximum limit values	Groundwater quality
NTU (Turbidity)	$\leq 100$	150	$<5$
NH <sub>4</sub> (Ammonia), mg/L	$\leq 1$	3	$< 0.25$
Cl, mg/L	$\leq 350$	500	$\leq 300$
Electrical conductivity, $\mu\text{S}/\text{cm}$	$\leq 1,700$	2,500	$\leq 1,700$
Flow, m <sup>3</sup> /s	8-35		--



**Fig. 9** (a) Tractor working in the Llobregat riverbed; (b) detail of tractor nails.



**Fig. 10** Soil below the riverbed before scrapping. From top to bottom: (a) first layer with algae activity, (b) brown clay layer (oxic level), (c) grey clay layer (anoxic level), and (d) bottom high permeability gravels and sands. Below is the top of the aquifer, which receives the water leaking from the soil above.

#### 4.3 Well Injection in the Sant Joan Despí Area

The Sant Joan Despí DWTP (Drinking Water Treatment Plant) uses both river water and groundwater for meeting Barcelona Metropolitan Area water demands, prioritizing river water when its

quantity and quality are acceptable. The plant started in 1956 with sand filtration and chlorination. The current treatment consists of conventional and advanced techniques, which include granular activated carbon, ozonisation and reverse osmosis processes to improve the final water quality. Since the early 1970s,

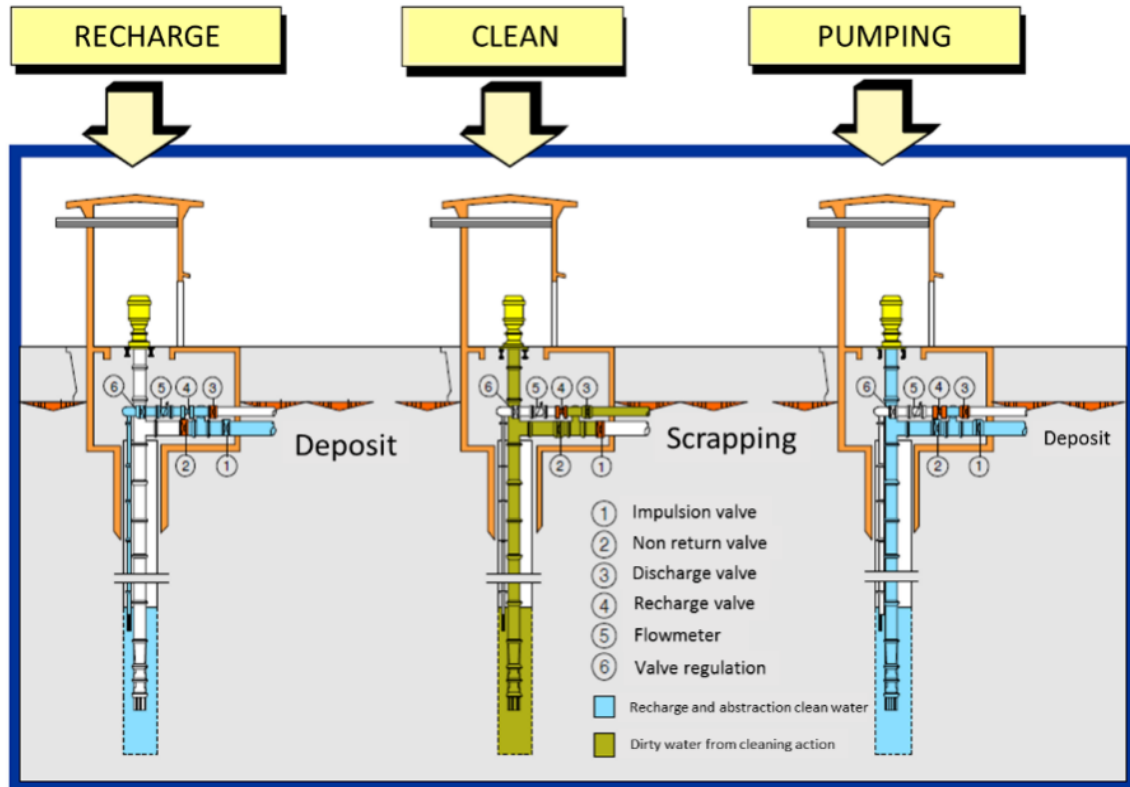
the surpluses of production of the river water plant, with the full treatment given at the corresponding moment, have been injected into the aquifer through 12 dual-purpose wells, with an injection capacity of 75,000 m<sup>3</sup>/d and a much larger abstraction capacity when groundwater reserves are needed. Fig. 11 shows how the wells are operated and Fig. 12 shows the plant layout of the wells. This MAR scheme increases the groundwater storage in case of treated river water availability and provides additional water resources from the aquifer when the quality and the quantity of the river water are not appropriate.

In the 1970s, the injected water was river water after only careful sand filtration. The main concern was how to operate the wells to avoid clogging and the limitations to the treated water to be injected. This situation evolved as more carefully treated water was produced and the existence of micro-contaminants appeared as a rising concern.

Currently, there is no water surplus in the DWTP, as the analysis of the water demand and the increasing

drinking water treatment costs have resulted in the optimization of treated water production. Henceforth, ASR flexible use was identified as one of the main water challenges regarding DWTP functioning and its future feasibility. Consequently, the operation of the injection wells to increase groundwater storage to be used later is a decision instead of deriving a benefit from a surplus. This decision includes testing the possibility of using cheaper water taken at an early stage of treatment, similar to what was done in the early operation times of the facility.

In 2014-2017, the large European FP7 DESSIN project (Demonstrate Ecosystem Services Enabling Innovation in the Water Sector) (<https://dessin-project.eu/>) allowed validating an ASR scheme with pre-potable water (sand-filtered river water) as a recharge source, to be developed in Barcelona [19]. A water injection test of 0.64 hm<sup>3</sup> of pre-potable water took place from July 2015 to July 2016 at the P18 injection well. Fig. 13 shows the transversal cross-section of the valley alluvial and the body of injected water.



**Fig. 11 Operation of the dual-purpose injection and pumping wells (personal communication of J.L. Armenter).**



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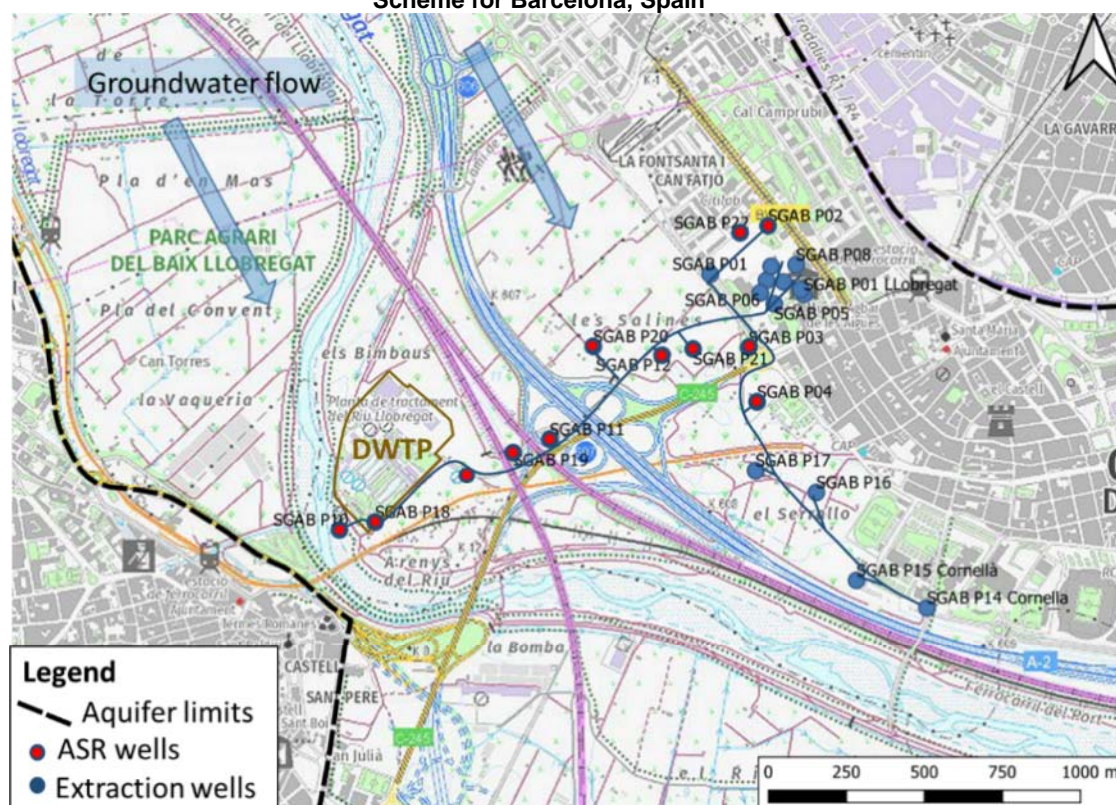


Fig. 12 The Sant Joan Despí DWTP with two sources: river water or groundwater, and the location of the 12 dual-purpose wells extracting or injecting water from/to the aquifer. Other 10 wells only abstract water from aquifer to the DWTP.

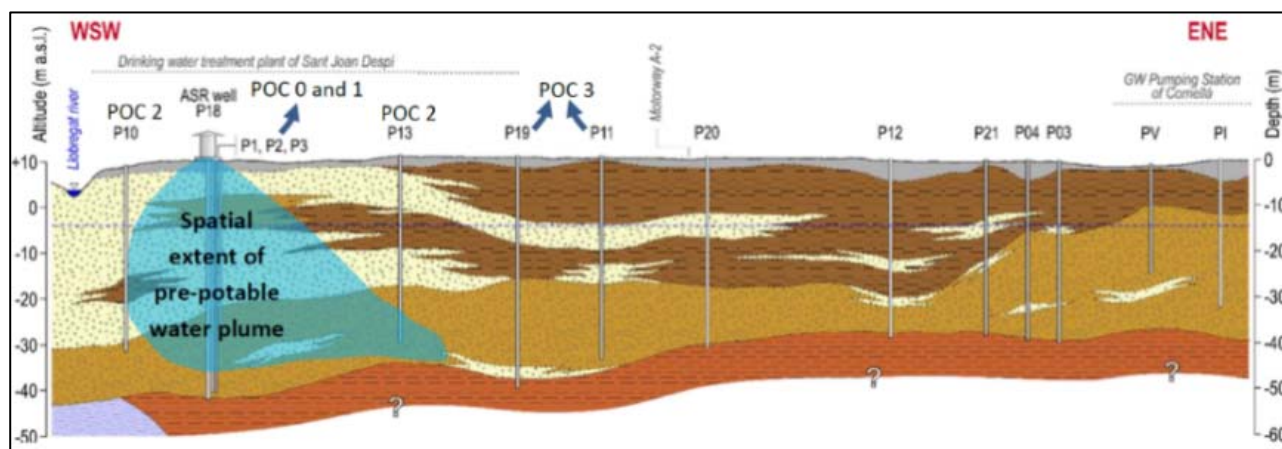


Fig. 13 Transversal cross-section comprising part of the wells at the Sant Joan Despí facility.

The pointed yellow areas correspond to coarse sands and gravels and the brownish ones are the aquitards. The set rests on Pliocene marls and occasionally on Paleozoic schists. It represented the injected water body of the July 2015 to July 2016 injection test at well P18. The suggested Points of Compliance (POCs), as critical control points, are also shown. The POCs are the sites where the results are measured and regularly checked to assure that the operation conditions and aquifer quality conditions are met.

Several techniques of impact assessment, such as time series analysis (water level, electrical conductivity and temperature), groundwater numerical modelling, multivariate statistical analysis and column-type pilot system, among others, have been

applied [20, 21]. The study techniques that have been applied include the study of the behaviour of micro-contaminants of emerging (concerning) interest [22-24] and the remote sense study of the detailed infiltration surface of ponds [25-27].

The risk management approach called “Water Safety Plan” is based on HACCP (Hazard Analysis and Critical Control Points). The results show that it can be applied to MAR projects with pre-potable water in a simple and transparent manner, taking into account all factors involved in risk transfer among different water users. This needs a special focus in determining the organic pollutants to be measured and their monitoring. Their control includes a preliminary assessment on the natural capacity of the aquifer to attenuate and degrade such compounds.

#### 4.4 The Castellbisbal Infiltration Ponds

The water supply to the urban and industrial area of Castellbisbal depends basically on river water infiltrating in the shallow, small alluvial formations in the Sant Andreu de la Barca plain. The ponds have been operated during more than three decades under different circumstances, including temporal infiltration in parts of the riverbed in temporal excavations, which were rebuilt after the flood events. In 2007 and 2018, flood episodes damaged the facility, but it was repaired, as an expectable fact. There are currently 2 ponds in operation (2,000 m<sup>2</sup> and 5,000 m<sup>2</sup>).

The off the river 2,000 m<sup>2</sup> of infiltration surface permanent facility infiltrates 0.3 hm<sup>3</sup>/year. The only source is river water from a weir 1 km upstream and is run only for gravity, with the limitations indicated in Table 2. A wetland and decantation pond store water during 3 days, before entering the infiltration pond. This facility (Fig. 14) was built in 1985.

During the operation of the ponds, the presence and accumulation of dissolved organic matter carried by recharging water create localized reducing

environments in the terrain, in which oxidized Fe and Mn in soil minerals may dissolve. Their behavior is a subject of current research to find operation rules that allow abstracting directly Fe- and Mn-free groundwater.

#### 4.5 The Low Valley Infiltration Ponds

Recharge in the Low Valley is being reduced by decrease of surface area by river channeling and by occupation of the permeable agricultural area by roads and train tracks. This loss needs compensation. Conditions for the construction of these public works have included making available to the ACA economic resources for artificial recharge facilities and their operation. This is the origin of the Sant Vicenç dels Horts ponds, which are active facilities since 2007, with 5,000 m<sup>2</sup> of infiltration surface (Fig. 15) and capacity of 1 hm<sup>3</sup>/year. The facility is currently fed mostly with river water, even though reclaimed water could be an alternative source, but only in case of drought. River water is stored in a decantation pond with 1.5 days average residence time. Water goes to the infiltration pond by gravity. Ponds operability is conditioned by river water quality and flow.

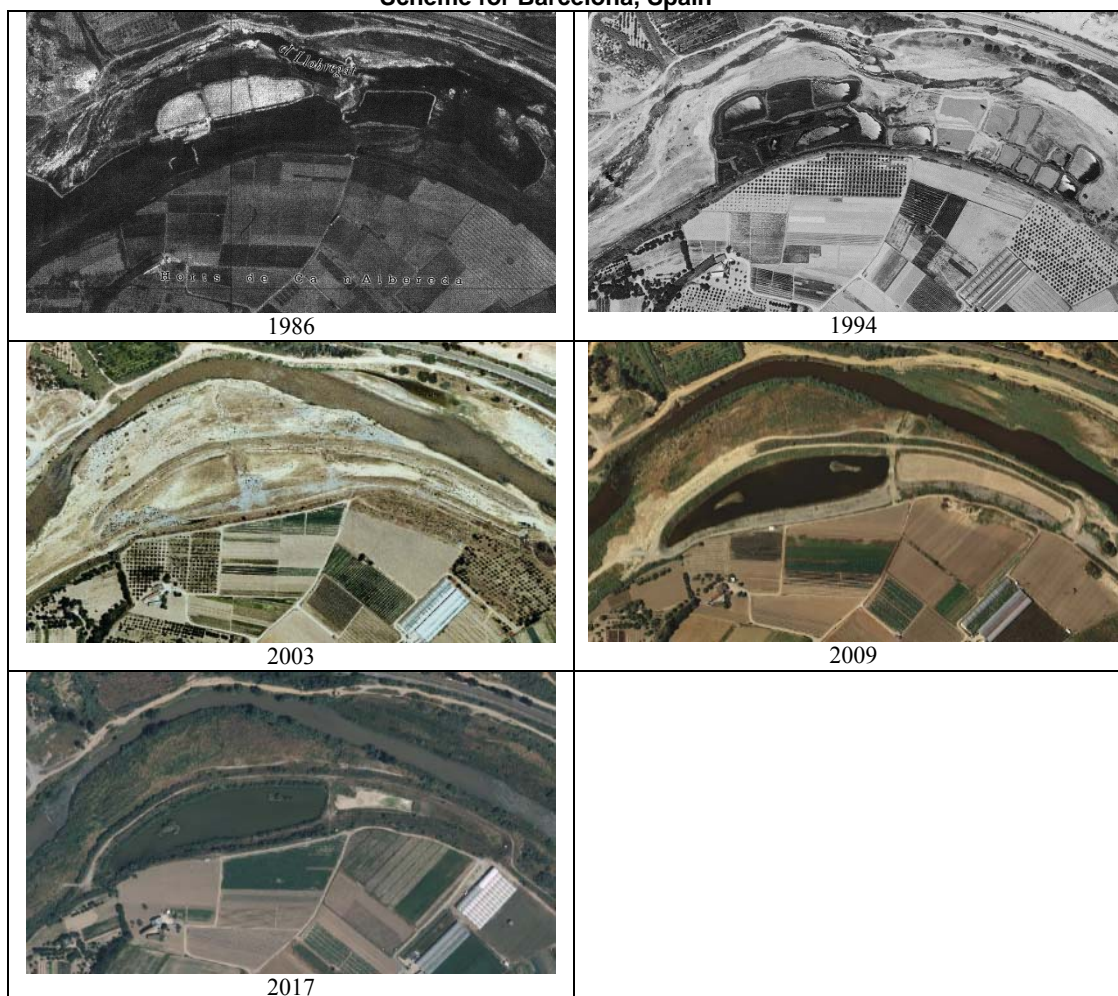
The EU project Life-ENSAT (Enhancement of Soil Aquifer Treatment in Managed Aquifer) (<http://www.life-ensat.eu/>), led by CETAQUA (Technological Centre of Aqua) and three other institutions in Barcelona, was funded between 2010 and 2012. The objective was to demonstrate the application of a well-established technology for aquifer remediation, in an innovative way. This involved SAT (Soil Aquifer Treatment) of infiltrating water during aquifer recharge episodes. This was done by means of a

**Table 2 Parameters which condition riverbed filtration.**

Parameter	Decantation threshold values	Maximum limit values	Groundwater quality
NTU	≤ 150	≤ 25	<5
NH <sub>4</sub> , mg/L	≤ 1	≤ 1	< 0.25
Cl, mg/L	≤ 350	≤ 350	≤ 300
Electrical conductivity, μS/cm	≤ 1,700	≤ 1,700	≤ 1,700

The difference with Table 1 is the values of the maximum limit.





**Fig. 14** Aerial view of Castellbisbal ponds in several years. The morphology of the ponds has changed over the years (photo source: ICGC (Cartographic and Geological Institute of Catalonia), corresponding to 2020).

reactive organic layer placed in the bottom of an infiltration pond, to promote the microbiological activity needed to break down organic pollutants. Specifically, the project aimed to improve the quality of groundwater at the site, develop a modelling hydraulic and hydrochemical tool for predicting the impact of an organic substrate in the basin floor during infiltration, as well as adapt and transfer the tools and methodology developed to other aquifer recharge sites in Europe. The project has demonstrated that physical, chemical and biochemical processes associated with water movement within the subsoil represent a natural and alternative way to reduce the presence of emergent pollutants and their metabolites, with economic and environmental benefits. The project

involved laboratory experiments and an application at real scale in the pond facility. As a result of the tests, a layer of natural vegetal compost was selected, consisting of crushed tree branches, mixed with local soil to maintain infiltration characteristics, and a small fraction of highly adsorbing matter, such as clay and iron oxides. Some pharmaceuticals have been effectively degraded, such as gemfibrozil and carbamazepine epoxide, besides a greater reduction of nitrate content, before reaching the water table [28, 29].

The ENSAT project also included the quantitative evaluation, focused on infiltration rate variation with time, coupled with bioclogging at the surface of the infiltration ponds or wells in the Sant Vicenç dels Horts site. An important aspect is the control and monitoring





Fig. 15 Aerial view of Sant Vicenç dels Horts ponds where monitoring system is shown.

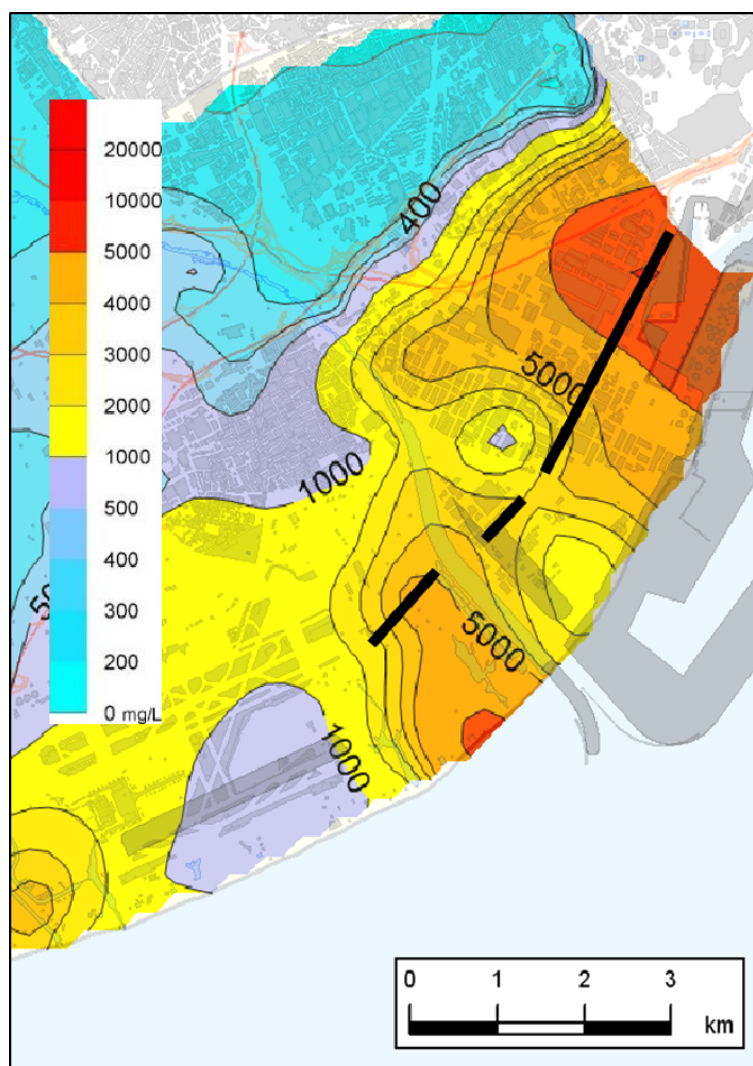
of water quality, including both the variations in water quality during infiltration, focusing in particular on redox zonification and the mixing of the existing groundwater and the recharged water due to hydrodynamic dispersion. Emphasis was given to ways to promote such mixing. The experimental work was done by a combination of batch, column and tank experiments, fieldwork and numerical simulations. As during infiltration a number of biogeochemical processes take place, this needs a multidisciplinary analysis supported by monitoring of oxygen content along a vertical transect and as a function of time. The goal was correlation with an indicator of biological activity diversity, such as the electron transport system activity or the microbial functional diversity, which is a measure of entropy known as the Shannon Index.

#### 4.6 The Llobregat Delta Injection Barrier for Seawater Intrusion Control

As commented above, since the late 1960s the Llobregat delta deep aquifer is affected by a serious

seawater intrusion. The intrusion started at least one decade before it was clearly noticed [30, 31], and affected seriously many factories, a large part of which closed activities and moved to other areas. Groundwater abstraction reduction was introduced and a seawater injection barrier by means of coastal deep wells was devised and constructed by the ACA and the Metropolitan Area Entity, with the support of the Spanish Ministry of the Environment. The initial objective was to stop seawater intrusion and restore part of the salinized deep delta aquifer. However, operative limitations and management experience show that avoiding the trend to saline intrusion but allowing it to increase in drought moments is a more feasible and realistic goal.

There are 14 deep injection wells (13 in operation) close to the coast (Fig. 16), which can infiltrate up to 15,000 m<sup>3</sup>/d of highly treated reclaimed water to control seawater intrusion [32, 33]. They constitute an injection hydraulic barrier of wells, located close to the eastern part of the Llobregat delta coast. The



**Fig. 16** Hydraulic barrier layout in preferential zones of marine intrusion into the deep delta aquifer. The values are Cl concentration in groundwater in 2018, in mg/L Cl.

**Table 3** Injection flow of the hydraulic barrier as a function of the piezometric level of the aquifer.

Piezometric level (masl)	Injection flow (m <sup>3</sup> /d)
+0.5 to -1	2,500
-1 to -4	6,250
< -4	15,000

reclaimed water receives an advanced treatment: ultraviolet irradiation and ultrafiltration for all water, and inverse osmosis salinity reduction applied to 50% of the total flow. The hydraulic barrier has a protocol of operability and the injection rate largely depends on the piezometric level of the deep delta aquifer (Table 3). Piezometric levels will decrease significantly if groundwater exploitation increases.

In 2018, a series of pumping tests were performed on the wells, with the idea of re-launching the hydraulic barrier after a stoppage of 7 years. The object was to evaluate their status by comparing the results with the tests when they were drilled. It results that all wells were in good status, but one of them. In 2019, the barrier was ready again to operate at a capacity of 0.3 hm<sup>3</sup>/year.

**Table 4 Main characteristics of different MAR methodologies implemented in the Lower Llobregat.**

Characteristics	River bed filtration	Castellbisbal & Sant Vicenç ponds	ASR	Hydraulic barrier
Water availability for recharge	15%	>90%	30%	>90%
Chemical impact	Low	Low	Low	High
Annual volume objective, hm <sup>3</sup> /y	2	0.3 & 1	3 (0-14)	5.5
Quantity impact	Medium	Medium	Medium-high	High
CAPEX, M€/hm <sup>3</sup> /year	0.25	0.3-0.9	2.5	5
OPEX, €/m <sup>3</sup>	0.03-0.13	0.10-0.17	0.15-0.25	0.28
Energy	Low (tractor, scrapper)	No (by gravity)	Medium (filtration, decantation, injection and extraction)	High (advanced treatment and injection)
Operator	SGAB	CUACSA & CUADLL	SGAB	SGAB

The cost of water is taken into account. CAPEX = capital expenditures; OPEX = operation expenditures; SGAB = Barcelona water supply company. The value of the euro (€) is that of 2016.

## 5. Cost and Benefit Considerations

The availability of several recharge technologies in the Lower Llobregat allows analysing their environmental and economic costs and benefits in order to apply the most adequate one in each moment. Table 4 gives the main economy-related characteristics of the different MAR methodologies implemented. The hydraulic barrier has the major chemical impact because it controls seawater intrusion. The impact quantity depends on the installed recharge capacity. In this case, the ASR is the best technique. Riverbed filtration is the less expensive. The Sant Vicenç dels Horts and Castellbisbal ponds have the longest time of operation in the last 10 years.

## 6. Administrative Circumstances and Conditions

The water law and the capacity of groundwater users to form organizations to protect their rights and preserve the water sources, evolve toward integrated water resources management, by becoming partners with water authorities and march toward sound water governance. The appropriate legal tools have to be provided. These are crucial points in managed artificial recharge. The existence of five MAR activities in the Lower Llobregat favors analyzing how to optimize action, by combining water quantity with water quality, water supply security and

environmental improvement in the service of citizens.

Before 1985, in Spain groundwater was legally in the private domain, out of the direct responsibility of the water authorities, who were concerned almost exclusively by surface water as a public domain. Most of the Lower Llobregat groundwater development was the initiative of privates. However, in this case, Water and Geological Authority carried out detailed hydrogeological studies that allowed water supply companies to know the seriousness of the water supply system problems. This was the seed leading to a joint effort in 1971, together with the water authority, to create an association to look for solutions. This was the origin of the Groundwater Users Association of the Lower Llobregat, created in 1978, currently the CUADLL. The CUADLL operates from Pallegà to the coast. The upper part, the Sant Andreu de la Barca basin, created a separate association in 1990. The existence of the CUADLL, its effective relationship with the Water Authority and the success in solving problems, in making agreements and in technical realizations, such as MAR, influenced the 1985 Water Act, although the associative figure that was established as an entity publicly recognized was that of the Irrigator's Community. Due to legal conditionings, the Water Act of 1985, even if it considers all water in the public domain, maintained previously existing private rights on groundwater.



This has been blamed as a major handicap for the effective application of the law, although the existence of the CUADLL shows that this is not at all an unsurmountable problem when groundwater users and the water authority have a clear join goal to achieve.

The CUADLL, the ACA, the AMB (Supra-Local Administration) and AGBAR (Barcelona's Water Supply Company) signed an agreement in 2007 for water recharge system operation that includes all technologies of recharge, all requirements of quality, the availability of resources, and the responsibility of each partner.

The transposition of the European WFD (Water Framework Directive) [34] did not change essentially the associational aspects in the Spanish Water Act, but set goals for good groundwater status to be implemented as well as new water quality limits for an extended list of substances. All this affects MAR facilities in the Llobregat area, which currently have different conditions from the initial ones. Using natural infrastructures for integrated water resources management is a less expensive and more environmentally friendly solution.

The RD 1620/2007 is the Spanish quality regulatory framework to be applied when water is reused, as in the hydraulic barrier and in Sant Vicenç dels Horts pond. The ACA and the Health Department of the Generalitat de Catalunya (Regional Government of Catalonia) are the administrations regulating recharge operations in the Lower Llobregat. Ponds and riverbed infiltration, when the source is surface water, are operated under the only control of the ACA. In all cases, operators work according to public permits.

The future of MAR in the Lower Llobregat depends much on these documents. An excess of precautionary restrictions and controls may suffocate the notable advantages and the social benefits.

## **7. Discussion and New Projects**

Small aquifers may play an important role in water supply to population, industry, agriculture and tourism,

while preserving valuable associated ecological functions, if correctly managed, first as a main water source and then integrating then into the whole water resources system. This water resources system may be simple, of only local surface and groundwater, or a complex one that may include water from the upstream part of river basins flowing through the area, imported water, return irrigation flows, necessary drainages, reclamation of waste water and desalination of sea water and local brackish water. In arid areas the initial concern is water quantity scarcity and in coastal areas seawater intrusion.

The evolution in the Lower Llobregat area has followed the above indicated evolution, starting in the late 19th century for groundwater development, introducing artificial recharge to increase aquifer storage and treat poor quality water sources since 1950. The development has been produced progressively, to deal with emerging problems when they are detected.

The success in introducing MAR and in integrating water resources management depends heavily on adequate monitoring and making it available to water agencies, water users and water stakeholders in general, all of whom should be involved in some way in monitoring operations and cost. This is especially important for groundwater, to be able to early detect trends, as the evolution is generally slow, the more the larger the size of the aquifers. Good understanding of aquifer, unsaturated zone and upper soil behaviour may greatly help in improving groundwater quality by taking advantage of enhanced natural processes.

Pending challenges in the Lower Llobregat area are increasing MAR with the technical objective of augmenting water supply security and improving overall available water quality, as well as the administrative objective derived from the transposition of the WFD into the Water Act of Spain of reaching the mandated good status of the groundwater bodies. Additional objectives should be using natural infrastructures while keeping the

ecological functions as much as possible and all this in an economic, resilient and easy to operate form, in a framework tending to sound governance.

Some new solutions are in study:

Changing the location of riverbed filtration downstream of the historical zone. In 2014, a study was conducted on the efficacy of scarification technology after 50 years of experience. The conclusion was that the operated area had lost its filtering capacity. So it did not make sense to continue working with the tractor in the same place. Then, in 2015 the study of other river stretches began with geophysical techniques and geological tests. A new section of 800 m length for recharge was located. However, this operation in this stretch has not been implemented because, even if this technology is the cheapest one, the control of the recharge is worse than in the other technologies.

A new 6 ha infiltration pond in the Low Valley. This project was designed in the period 2005-2008, with a budget of about €8 M. The water source would be river surface water and reclaimed water in the nearby plant.

A new ASTR (Aquifer Storage and Treatment Recharge) project in the Low Valley. In the event that the water transfer from the Ter River stops for repairs and improvements, then the supply of Barcelona will depend largely on the Llobregat. Therefore, the guarantee will have to be improved locally. If there is an additional episode of continuous precipitation (high NTU in the river water) or a drought and the river uptake has to stop, the aquifer should be able to provide a higher flow to the supply system. Therefore, a new injection well line is needed to improve the guarantee of supply in specific situations. This is the right moment to rethink the DWTP's global tuning system and the role of the current line of wells. The ambitious ASTR project is to increase peak flows and to improve water quality because the aquifer does part of the drinking water treatment. However, the new Low Valley project is only to increase reserves

through the Llobregat reclaimed water infiltration. According to Spanish legislation, the reclaimed water has to go always to the environment and never directly to a drinking water plant.

## **8. Conclusions**

In the Llobregat area, different artificial recharges of aquifers are in operation for different purposes, to solve specific quantity and quality problems of water availability and increment of the guarantee. Each one was designed for a given purpose. However, the evolution has been toward the integration of the aquifers into the whole water supply system, including network service and self-supply. The current water system is a complex one, subjected sometimes to strict administrative and legal restrictions. The different five techniques currently in operation allow selecting the most appropriate in a given moment to increase groundwater storage and to improve the water source quality. This allows solving water problems in moments of scarcity, both seasonal and inter-annual if not too long and intense. The cost, operation limitations and management difficulties are different for each technique. Managed artificial recharge is expensive and needs careful operation to assure its sustainability, but is cheaper than most other water storage and treatment techniques and is more environmentally friendly. Research to limit infiltration pond bioclogging and the use of reactive chemical layers in the pond floor to eliminate concerning organics and their metabolites are promising activities to improve MAR schemes. In any case, MAR operation and development have to be based on adequate monitoring, correct interpretation of data and modelling. MAR is part of the framework conducted of sound governance.

Each artificial recharge facility is unique and does not follow general rules, as local circumstances are varying. However, it is possible to distil communalities and modelling guidelines that allow transferring part of the knowledge of a given facility to others when

similitudes can be correctly singled out.

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