

The Llobregat River Basin: A Paradigm of Impaired Rivers Under Climate Change Threats

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Abstract The Llobregat River represents a paradigmatic example of an impaired river subject to emerging global change impacts. This chapter provides an introduction to the main geomorphological, geological, climatic, and biological features of the river basin, as well as an overview on the hydrological alterations and the intense management of water resources in the basin. The Llobregat hydrology has experienced a significant runoff reduction during the last decades. This decrease is related to climatic drift but also to the increasing forest land cover that has promoted a 25% reduction of the streamflow. The chapter also describes the human uses of the Llobregat River waters from a historical perspective, with particular emphasis on the difficulties that an intrinsically unpredictable river like Llobregat posed to the different human uses along history. The historical development makes emphasis on the industrial activities affecting water resources during the twentieth century. The chapter includes a detailed analysis of the present situation on water extractions, discharges, and diversions that define the Llobregat River Basin as a deeply impaired ecosystem, especially in the most downstream reaches.

Keywords Climate, Geology, History, Land use change, Water diversions, Water flow trend, Water treatment

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1 The Llobregat River Basin

The Llobregat River is located in NE Spain, running for 165 km to drain an area of 4,948 km² (Fig. 1). Long-term mean discharge at the mouth is 603 hm³ year⁻¹ or 19 m³ s⁻¹. It has two main tributaries, the Cardener and Anoia Rivers (Fig. 1). The headwaters of the Llobregat and Cardener Rivers lie in the rather pristine Eastern Pyrenees, but soon downstream they are already impacted by sewage treatment plants and industrial effluents (estimated at 137 hm³ year⁻¹ or 4.3 m³ s⁻¹), as well as by potash-mining activities in the Cardener reaches just upstream Manresa. The lower course flows through one of the most densely populated areas of the Mediterranean region (Barcelona Metropolitan Area, over 3 million people), and the waters receive large inputs from industry and urban origin. The case of the Anoia River is somehow different: its headwaters lie in an agricultural area, downstream it flows through an industrialized zone (paper mills, tannery, and textile industries), and near the confluence with the Llobregat River the main land use is vineyard fields (Fig. 2).

Water resources from the Llobregat basin are fundamental for the water supply scheme of the Barcelona Metropolitan Area. In fact, due to the intrinsic variability of the Mediterranean climate, three large dams were built in upstream sections of the Cardener and Llobregat Rivers to ensure water supply during low flow periods (Fig. 1). Presently as much as 30% of the long-term mean annual flow is eventually diverted for human uses, with intakes concentrated in the downstream section of the basin. Aquifer withdrawals are also numerous in the deltaic region and play an important role when water quality or quantity of the Llobregat River is insufficient. A new seawater desalination plant with a capacity of 60 hm³ year⁻¹ started operation recently to help overcoming the threats posed by abnormal, high-frequency water scarcity episodes during the last decade.

Due to the ever increasing human pressure by the end of the 1980s the Llobregat River was one of the most polluted and degraded in Western Europe, and the

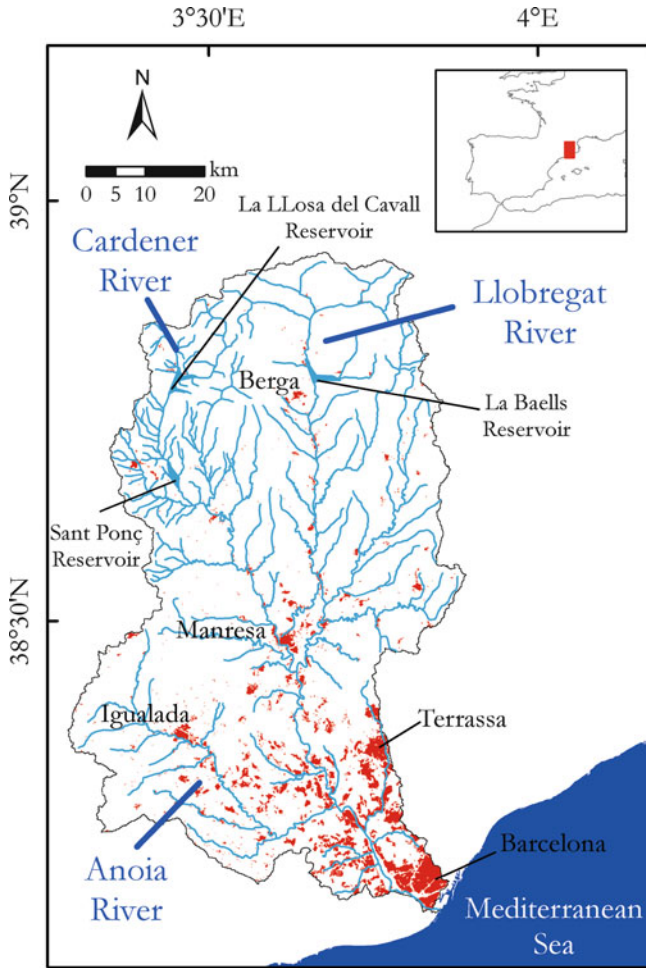


Fig. 1 The Llobregat basin with indication of the main rivercourse and its tributaries, and the location of the three large reservoirs. Urban settlements are also depicted as red areas; only the largest ones are named

overexploitation of the underground water led to salinization of the deltaic aquifer, rendering 30% unusable. Since then, wastewater treatment plants with tertiary facilities have been built along the basin, and the situation has improved dramatically. Nowadays, infrastructures prevent excessive pollution of the river by intercepting specific effluents, such as the channels receiving treated urban wastewater from the Riera de Rubí (near Terrassa) and those collecting brine from the salt-mining sites. Apart from these, there is a major irrigation channel on the right side of the river, the Canal de la Dreta, which provides water for horticulture in the Delta. On the left side of the downstream reaches, the Canal de la Infanta was also built for irrigation purposes, but now its main role is to prevent wastewater from

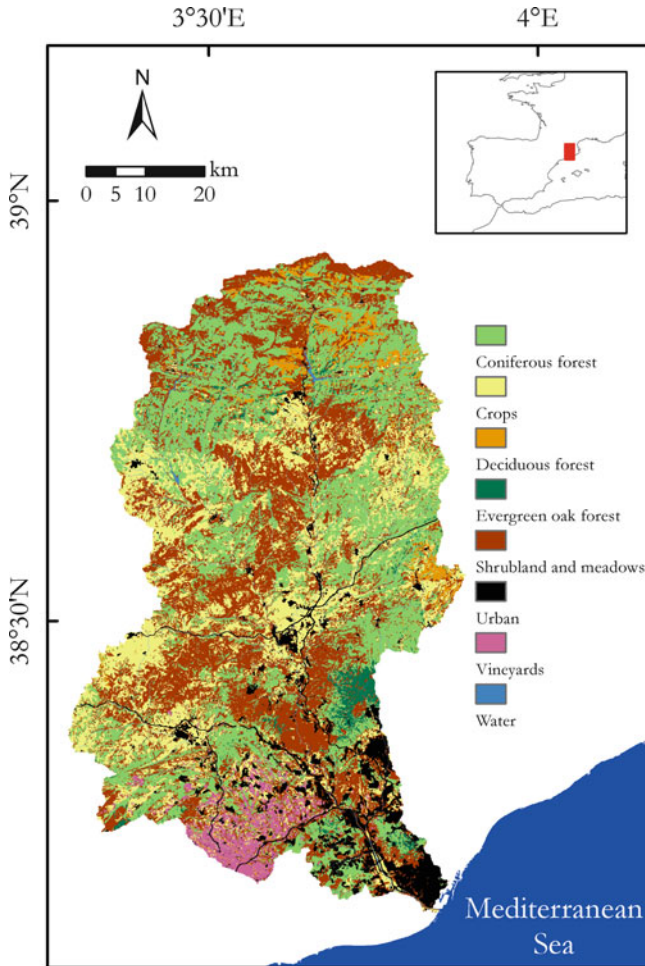


Fig. 2 Land uses distribution in the Llobregat basin. Based on the information gathered by the Thematic Mapper sensor of the Landsat satellite during the year 2002 (30 m grid resolution). Source: Institut Cartogràfic de Catalunya (ICC)

industries and towns reaching the river upstream from main water supply intakes. See Sect. 3 for a comprehensive description of those infrastructures.

The delta of the Llobregat River lies to the south of Barcelona and covers about 100 km² and constitutes a valuable natural habitat close to a big metropolitan area. Its wetlands are part of the RAMSAR network and play a critical role in the wintering of many migratory birds. The delta aquifer is an important freshwater resource for the metropolitan region, with a groundwater capacity around 100 hm³, used by numerous industries, agriculture, and cities. The fertile delta farmland supports intensive agriculture supplying the local market. Since the 1960s, the delta's land has been under constant pressure from Barcelona's urban and industrial

expansion. Most important logistics and transportation facilities in the region (port, airport, motorway network, and railways) were built in this area taking advantage of the flat landscape. The recent port extension even forced a southward movement of the river mouth. Less than 5% of the original wetlands in the area now remain, and in some municipalities half of agricultural land has been lost in the last decade [1].

1.1 Geology

The Llobregat watershed is the product of tectonic movements during the late Mesozoic over 29 million years ago. Upon the rupture of Pangea, the geological plate carrying Iberia drifted separately from Eurasia and Gondwana—prehistoric Africa and South America. The rotation of Gondwana then pushed the Iberian plate against Eurasia causing a collision that raised the Pyrenees Mountains and erected the first contours of the Llobregat watershed. The convergence of the Iberian and Eurasian plates culminated during the Quaternary period over 2 million years ago [2]. The collision of Iberia with Eurasia initially created a bay, and then a salt water lake. Over time the water evaporated, leaving behind layers of salt and other minerals that were pushed up into the Pyrenees Mountains as the two geological plates converged.

The Llobregat River crosses several present geological units (Fig. 3). Headwaters are situated in the Eastern Pyrenees, in an area composed of Upper Paleozoic to Cenozoic sedimentary (mainly limestones and sandstones) and volcanic rocks [3]. In its central part the Llobregat River flows through a Cenozoic Basin composed of a regressive (marine to continental) Eocene-Paleocene age sedimentary sequence. The transition evaporites (gypsumanhydrite, halite, and potash facies) have an Upper Eocene age [3] and there has been salt-mining activity since Neolithic times in the area. Close to the Mediterranean Sea, the Llobregat River crosscuts the Catalanian Coastal Ranges, made up of Hercynian basement and Mesozoic to Cenozoic cover. The Hercynian basement consists of Paleozoic metasedimentary rocks and late Hercynian granites, upon which the Mesozoic sedimentary sequences have been deposited. The delta, consisting of Quaternary sediments, is composed of conglomerates, sands, and marine marls.

Previous work in this area [3] has shown that the chemistry of most of the stream waters in the Llobregat basin is mainly controlled by the weathering of the Tertiary sediments, mainly limestone and marls deposited in upstream regions and middle reaches (Fig. 3). Despite its small extent, the salt deposits have a dramatic effect in the lower Cardener and Llobregat, enhanced by the mining activities. The signature of water is derived from weathering of limestone and marls (Ca^{2+} , Mg^{2+} , HCO_3^- , Sr^{2+} , and Ba^{2+}), gypsum (Ca^{2+} , SO_4^{2-} , Sr^{2+} , and Ba^{2+}), and halite and sylvite (Na^+ , K^+ , Cl^- , Mg^{2+} , Ca^{2+} , and SO_4^{2-}).

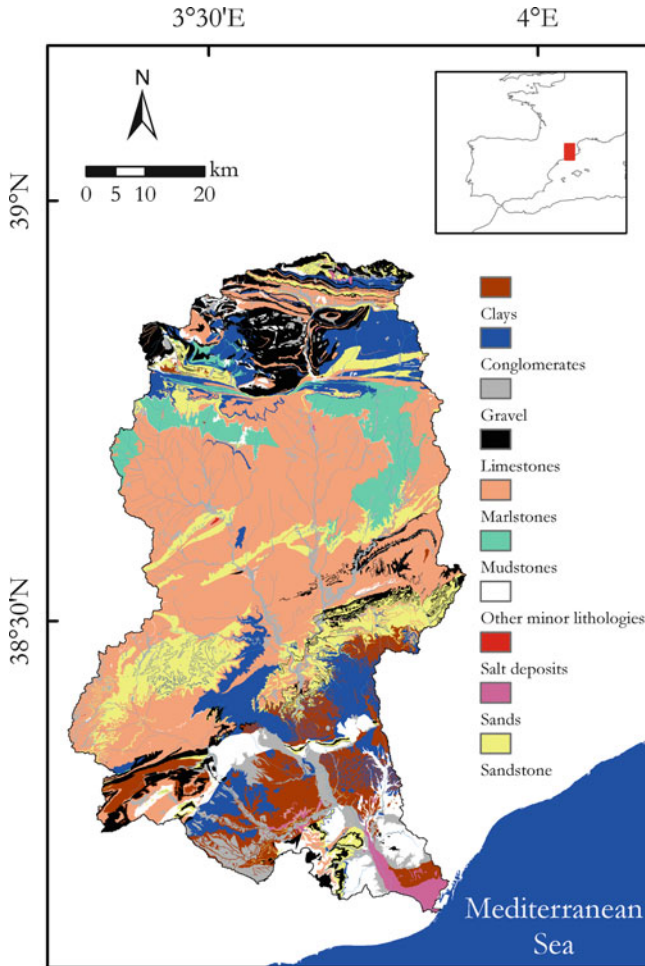


Fig. 3 Main lithology in the Llobregat basin. Source: Institut Cartogràfic de Catalunya (ICC)

1.2 Vegetation

Ice covered the Llobregat watershed during five glacial periods between the Pliocene and Pleistocene. In 8000 BC ice sheets still dominated continental Europe, but with the gradual rise in global temperatures, the ice retreated and temperate forests migrated north. By 2000 BC the composition of tree and shrub species in the Iberian Peninsula began to resemble the native vegetation cover we are familiar with today [4]. Before the massive clearing for agriculture, the Llobregat was covered in oak forests (*Quercus humilis*, *Quercus ilex*) mixed in with Mediterranean white pine (*Pinus halepensis*) and shrubs (*Rhamnus alaternus*, *Phyllirea latifolia*, and *Smilax aspera*).

The lithological variety, climate, and topography of the Llobregat basin encompass the great variety of vegetation formations (Fig. 2). The agricultural areas predominate in the plain areas around Manresa and upstream regions of the Anoia and Cardener Rivers, while native forest patches are abundant in the headwaters of the Llobregat and Cardener. Vineyards dominate the landscape in the southernmost region of the Anoia basin. In general terms, the Llobregat basin is highly influenced by both Mediterranean and Boreoalpine forest species.

The vegetation characteristic of the Boreoalpine region appears in the mountainous Pyrenees, particularly well-developed in the northern slopes. The region has no continuity beyond the Pyrenees, as it develops above 1,600 m. Coniferous forest (*Pinus sylvestris*, *Pinus nigra*) dominate between 1,600 and 2,300 m a.s.l., with some Atlantic deciduous species in the most humid places. Subalpine scrubs and alpine meadows are restricted to the highest ranges.

The Mediterranean region encompasses most of the basin. It is constituted by xerophytes formations typical of Mediterranean climate, highly degraded by centuries of human exploitation and forest fires. In fact, human management switched the dominant vegetation toward white pine forest (*Pinus halepensis*). Holm oak forest (*Quercus ilex*) is the theoretical climax in the area, now limited to small patches and areas of the Catalanian Coastal Ranges (Fig. 2). Human management and fires also favored the extension of woody, thorny, and aromatic, evergreen species of shrubs that occupy vast extensions (among others juniper, thyme, and rockrose).

Riparian forest is in general highly degraded along river corridors. One can now find white poplars (*Populus alba*), black poplars (*Populus nigra*), narrow leafed ash (*Fraxinus angustifolia*), or white willows (*Salix alba*) [5]. In the case of main channels of the three main tributaries, only reaches crossing canyon valleys with stepped topography preserve well-developed riparian areas, even in the Pyrenees. Low-order tributaries maintain most of the good shaped riparian strips. Nonetheless, the most downstream reaches of the Llobregat River are highly degraded, frequently channelized (Fig. 4).

1.3 Climate

The Llobregat River spans from the Pyrenees to the Mediterranean Sea, including an altitudinal gradient with profound impact on the basin climate. The Llobregat River headwaters, well rooted in the Pyrenees, show a perhumid climate (following the classification by Thornwhaite), which rapidly transforms in a dry subhumid climate as we approach the middle reaches (Fig. 5). This shift roughly coincides with the distribution of mean annual temperature and precipitation. The amplitude in mean annual temperature in the basin reaches 11°C, with a remarkable increase as we approach the sea, and the difference between maximum and minimum annual precipitation is as high as ~550 mm (Fig. 5). Most precipitation occurs far from the regions where water is most intensively used, and the highly heterogeneous



Fig. 4 Two aerial pictures of the Llobregat River near the mouth. On the left, the main channel after the water supply intake at Sant Joan Despí (squared blue patch and upper left-hand side). Note the highly degraded channel, the brown color of the water, and the total absence of riparian strip. On the right, the present mouth of the river, pointing southeast. Note the ancient mouth pointing toward the East, now desiccated. The huge infrastructure occupying most of the Deltaic region and coastal wetlands is El Prat International Airport. The reach on the left is just upstream from that on the right picture

distribution of precipitation and temperature explains the location of the three main reservoirs in the basin. In general vegetation growth is more difficult in the most downstream sections and some central reaches in the middle Llobregat (see hydric deficit; Fig. 5).

However, spatial climate variability hides a strong seasonal variability, especially in the dry areas. Here, there is a strong arid period during summer (Fig. 6), when vegetal communities face a long period of hydric stress that lasts the whole summer. The dominance of xeric Mediterranean species in these areas is an outcome of this climatic challenge. However, the situation in the headwaters is much milder (Fig. 6), with a gentle deficit period in summer and a long lasting saturation period during winter and spring. In fact, deciduous species belonging to the Atlantic climatic region are restricted to areas with hydric deficit below 100 mm (Figs. 2 and 5). This seasonal variability is reflected in the long-term behavior of the Llobregat River at the mouth (Fig. 7). The median seasonal flow shows a marked seasonal pattern, with a clear peak during May, most probably reflecting runoff generated in the Pyrenees by snow melting. It is remarkable that the typical Mediterranean autumn storms do not have a translation in the long-term hydrograph, probably reflecting the erratic nature of these events, and also probably the increased storage capacity of upstream reservoirs after the summer. Note that minimum flows (Fig. 7) are quite similar along the year, showing that drought periods may extend during the whole year. The temporal evolution of the daily streamflow shows the erratic water flow in a Mediterranean river like the Llobregat, defining very long periods below $5 \text{ m}^3 \text{ s}^{-1}$, and abrupt transitions to wetter periods that can increase the water flow by a factor of 50 ($\sim 300 \text{ m}^3 \text{ s}^{-1}$) in a single day (Fig. 8).

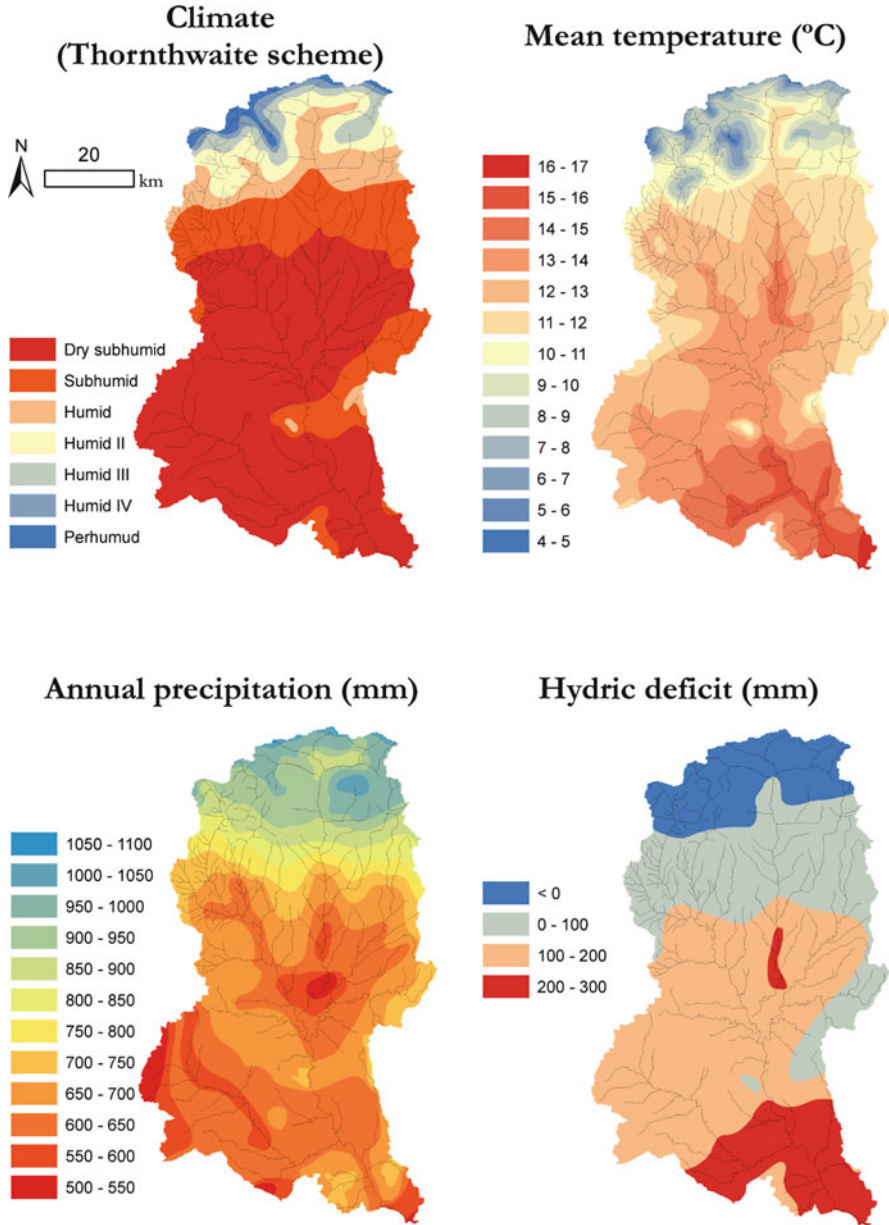


Fig. 5 Spatial distribution of climate descriptors of the Llobregat basin

Interannual variability is also a characteristic trait of the climate in the Llobregat basin, best reflected in the interannual variability of runoff. Figure 9 shows mean annual streamflow for the period 1945–1998, which shows a strong interannual

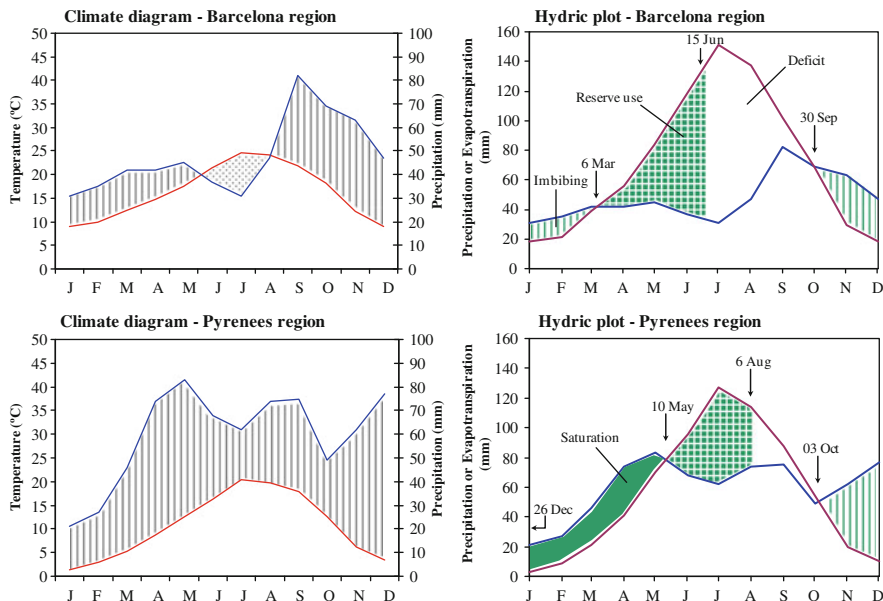


Fig. 6 Climate diagrams and hydric plots for two distinct areas in the Llobregat basin. Data for Barcelona derive from the meteorological station in Sant Boi de Llobregat. Data for the Pyrenees region are from the Sorribes meteorological station. In the climate diagrams, precipitation is the blue trace, and temperature the red one. Arid and wet periods are depicted as a pointed and vertical strip pattern, respectively. In the hydric plots, potential evapotranspiration is the brown line, and precipitation the blue one. Imbibing periods are depicted as green vertical strip pattern, periods of reserve use as green squared pattern, deficit periods as white areas, and saturation as a plain green area. Key dates were added for reference. All data from the Worldwide Bioclimatic Classification System, 1996–2009, <http://www.globalbioclimatics.org>

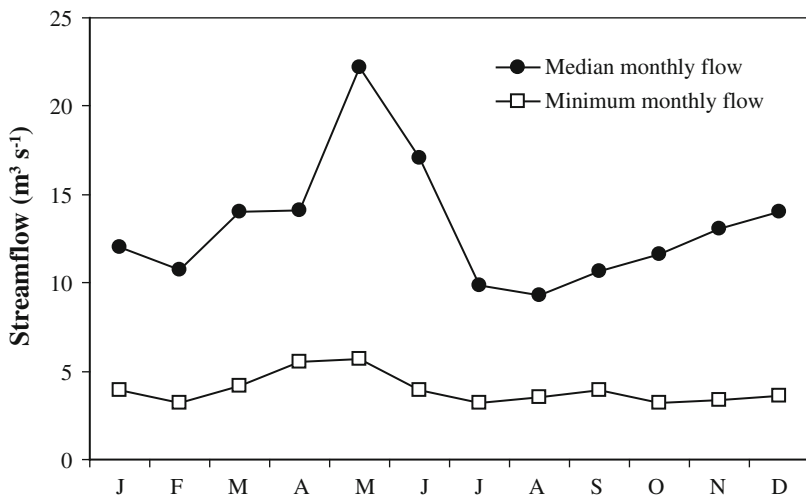


Fig. 7 Median and minimum monthly flow in the Llobregat River near the mouth (Martorell). Data are from the period 1945–1998, provided by the Catalan Water Agency (ACA)

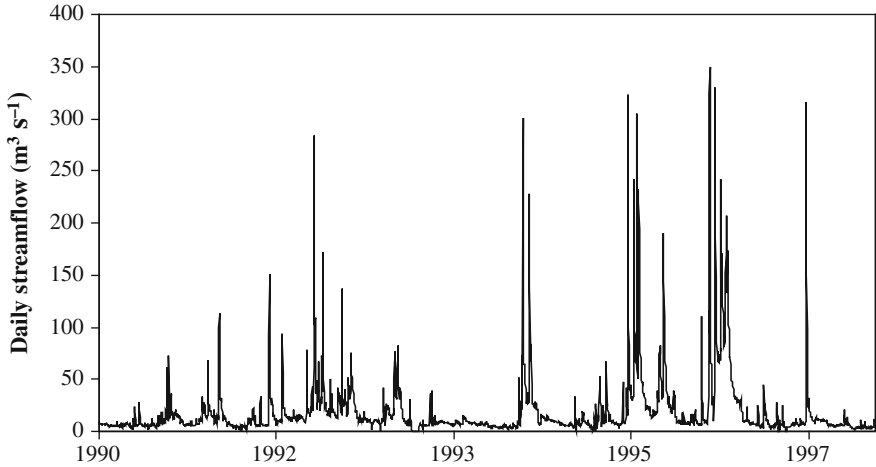


Fig. 8 Daily mean flow in the Llobregat River near the mouth (Martorell). Data are from the period 1990–1998, provided by the Catalan Water Agency (ACA)

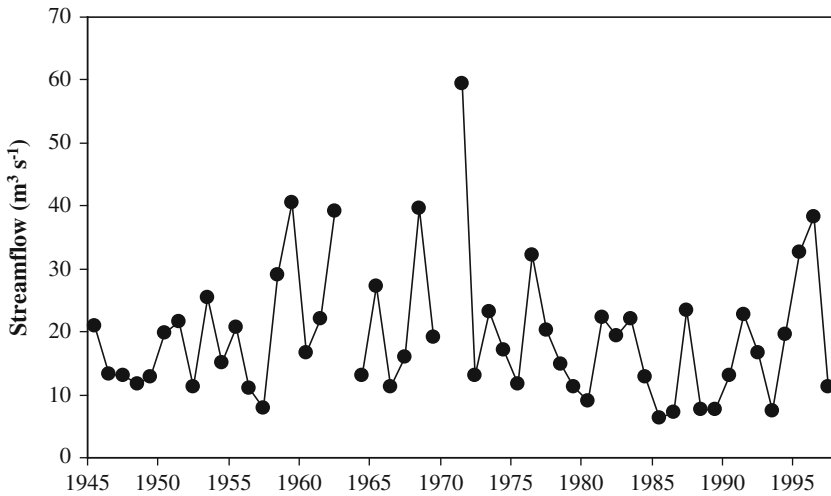


Fig. 9 Mean annual flow in the Llobregat River near the mouth (Martorell). Data are from the period 1945–1998, provided by the Catalan Water Agency (ACA)

variability, with mean flows between 6 and 40 $\text{m}^3 \text{s}^{-1}$. This is noteworthy considering that the magnitude of wastewater effluents in the whole basin is $\sim 4 \text{ m}^3 \text{ s}^{-1}$. Therefore, the impact of human activities during dry years is severe.

1.4 *Hydrological Alterations due to Global Change*

Many studies have anticipated future threats related to shifting availability in water resources in Mediterranean countries [6]. Future climatic trends point toward the aggravation of water scarcity that will add to an already precarious situation in many Mediterranean regions [7]. Results in experimental basins throughout the world show that changes in land cover from grassed to forested areas are associated with a reduction in runoff [8, 9]. Northeastern Spain experienced a demographic growth during the late nineteenth and the first half of the twentieth centuries that resulted in the expansion of agriculture, the decrease in forested areas and overgrazing of steppes and natural vegetation [10]. Conversely, social and economic changes in recent decades have reversed this trend and resulted in the abandonment of most old marginal agricultural fields and the decrease of human pressure on forests and pastures [11].

The historical flow records of nearly all of the streams on the southern flank of the Pyrenees show decreasing annual trends at least during the last 60 years [12]. This alarming trend is attributed to three causes of dissimilar weight depending on the watershed: climate shift, increasing irrigation, and the encroachment of forest cover in the headwaters [12, 13].

In the Llobregat River Basin the amount of water currently used for irrigation ($\sim 44 \text{ hm}^3$) is a small fraction of the total water load at the mouth ($\sim 600 \text{ hm}^3$), and at the annual time scale this value should be regarded as a gross estimation, since an unknown but probably significant volume of the withdrawn water eventually returns to the river. Moreover, most of the irrigation diversions occur in the deltaic region near the mouth ($\sim 34 \text{ hm}^3$), and the single significant diversion for irrigation located upstream (the Sèquia at Manresa) dates from the Middle Ages. Thus, we can discard irrigation as a fundamental driver of any streamflow trend detected in the headwaters of the Llobregat basins during the last decades.

Indeed, water flow in the Llobregat and Anoia Rivers showed significant decreasing trends between 1945 and 2005 [12]. The reduction in runoff was particularly conspicuous during the spring months, probably reflecting alterations in snowcover at the Pyrenees. Conversely, no significant trends have been detected during summer. At the annual time step [12], Lorenzo-Lacruz et al. estimated a decreasing trend between 1% and 3% per year.

To unravel the role of climatic drifts and land use changes in the generation of those observed trends Gallart and coworkers [14] applied two complementary methodologies to independently estimate the amount of streamflow trend explained by climate and land use changes in the headwaters of the Llobregat Basin. First, the authors estimated the changes in forested cover in two locations in the basin between 1957 and 1993. Then they applied the Zhang equation [15] as a simple model to translate the differences of land cover types into differences of annual evapotranspiration (see [14] for further details). Under the assumptions of this methodology, forest regrowth in a given basin increases evapotranspiration and, as a result, decreases streamflow in its river courses. Gallart et al. [14] found that the

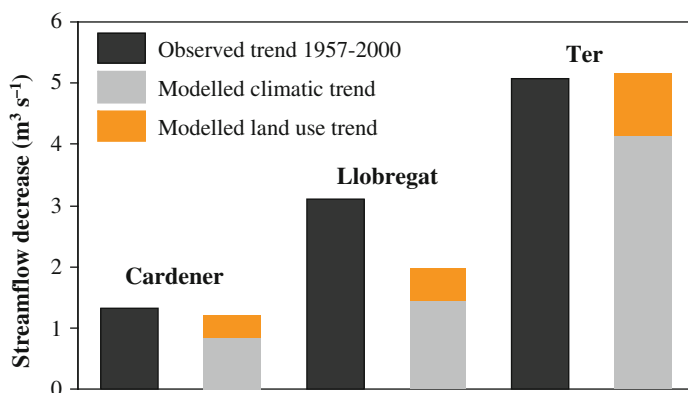


Fig. 10 Magnitude of the observed streamflow decreasing trend in two gauging stations from the Llobregat Basin (Cardener at Olius and Llobregat at La Baells), and in the Ter River at Sau (this last example included for comparison). *Black bars* denote the trend calculated with observed data, and *grey* and *orange bars* correspond to the trends calculated with the SACRAMENTO model and the land use changes (Zhang approach), respectively. If the hydrological model and the Zhang water balance results are fundamentally correct, the result of pooling both trends should resemble the observed trend in each gauging station. Results are adapted from [14] and [16]

most conservative estimate of the streamflow trend promoted by forest expansion was a reduction between 0.36 and 0.55 $\text{m}^3 \text{s}^{-1}$ of the mean annual water flow. Independently, Gallart et al. [14] estimated the streamflow trend promoted by climatic drift during the same period applying the hydrologic model SACRAMENTO, which only takes into account climate variability, but not land uses changes. The result was that climate explained a streamflow trend that amounted between 0.84 and 1.43 $\text{m}^3 \text{s}^{-1}$, depending on the site.

The question remains on whether or not the sum of the two streamflow trends estimated with the two independent methodologies (climatic trend + land uses trend) reasonably match with the streamflow trend observed in the two gauging stations from the Llobregat Basin considered in those studies (Fig. 10). Considering the uncertainties associated to the estimation of the two hydrologic trends, the good correspondence between observed and estimated trends when the two drivers (climate and land uses changes) are pooled is impressive. In the case of the Llobregat at La Baells (Fig. 10), the lack of fit may be explained by the short record available to properly calibrate the SACRAMENTO model (see [14]). In any case, all results converge to a significant streamflow trend in the watercourses of the Llobregat Basin during the last decades, mainly promoted by a climatic shift, probably related to an increase in the mean air temperature [14]. Land uses changes have a moderate role in this change, account for the 17%–27% of the observed trend. These estimations broadly coincide with results obtained by [16] for the nearby Ter Watershed using an independent approach.

2 A Historical Perspective on Human Exploitation of the River

2.1 *Early Uses: The Feared River*

Neolithic societies benefited from the rising temperatures and colonized the Iberian Peninsula, first as hunter-gatherers, and eventually as rudimentary farmers. These primitive societies drank water from streams in the watershed, just as other mammals would, but there is scarce evidence that they succeeded in managing water resources for irrigation or other uses. The Neolithic peoples employed very basic agricultural techniques, and while it has been suggested that irrigation predates Roman conquest elsewhere in the Iberian Peninsula [17] this is disputed when considering the Neolithic peoples that lived in Catalonia [18]. There is agreement however that the Phoenicians, Greeks, and Romans had already developed irrigation systems long before the native peoples of Iberia, and they brought this knowledge with them when they traded or settled on the peninsula.

Unlike the societies in Mesopotamia or Egypt, the first settlers in the Llobregat watershed shunned the river, preferring to live at higher elevations instead. Living near a Mediterranean river must have been an inconvenience and danger rather than an asset. Maps of prehistoric settlements show that Neolithic peoples avoided major water ways in the watershed, preferring to live in mountain caves instead. Archeologists have found Neolithic remnants perched far above the Llobregat River, in the caves of Collbató, or in the mountains of present day Sant Feliu de Llobregat and Begues [19, 20]. These original peoples have left us with little material evidence of their society, but their names endure, such as the Palladianus from Pallejà or the Apararia from Abrera [19].

Even if Neolithic tribes knew that irrigation could increase crop production, it is still difficult to imagine that irrigation alone would bring them closer to the water's edge. River banks must have been dangerous and inhospitable for the establishment of permanent settlement due the erratic and flushing nature of Mediterranean rivers. Smaller streams and tributaries were surely preferable sites for habitation. Historians have suggested that the first river dwelling people may have been outcasts, excluded from the secure caves or strategic mountain tops [21]. When forced to migrate to lower elevations, the refugees were more vulnerable to attack from wildlife or rival tribes, and without the technical or social skills to protect themselves from floods, fires, or other threats lurking in the valleys.

We might wish to believe that rivers played a critical role in determining the location of human settlements. As far back as 1476, it has been asserted that rivers played a fundamental role in the development of Catalonia: "Human society has always begun along rivers, because there are three things that lead to growth in this world, water, land and human industry" [22]. And yet in the case of the Llobregat watershed, rivers appear to be largely shunned, more feared than revered.

If Neolithic tribes avoided living near Catalonia's large rivers, the Romans hardly paid any more attention to them. The site for Tarraco, the Roman capital of Hispania Ulterior, was chosen because of the depth of its port, not its meager

stream. Roman Barcelona, or Barcino, was founded on the top of a hill, Mount Tàber (16.9 m), flanked by two small streams, the Merdança and Caganell, each named after the human waste they carried [23]. The Roman's were not attracted to Barcino's location between the Llobregat and Besós Rivers, but rather they found the enclave conveniently located midway between Tarraco and Emporiae which provided a useful resting point for marching legions. And when Barcelona grew to become the political and administrative capital of Old Catalonia, neither of the larger rivers played any commercial role in the city's development.

In fact, when Roman soldiers rested in Barcino on their way to Emporiae, the Llobregat Delta was entirely underwater. Two thousand years ago the Llobregat River met the Mediterranean Sea 3 km inland from its current point today, probably near Sant Boi de Llobregat [19]. In the centuries that have passed since then, the rains have eroded the mountains, the sediment has tumbled down the watershed, and pushed back the Mediterranean to create the delta we see today.

The Romans called the Llobregat Rubricatus of Hispania Tarraconensis. Rubricatus translates from Latin as red or purple, although it is unclear if the color refers to the river itself or the dark red soils colored by iron oxide that flank the river between Barcino and the major river crossing in Ad Fines (Martorell). The early Roman geographer Pomponius Mela refers to the Llobregat as Rubricatum majus, suggesting that the river branched out into smaller channels as it passed through the delta and reached the Mediterranean [24]. Rubricatus was not a unique name; since the Romans also spoke of another Rubricatus River in northern Africa, located in modern day Libya [25].

Before humans used the Llobregat River to irrigate their crops, propel their mills, or transport their waste, the river was a source of problems: a threat and a nuisance; an obstacle and a barrier. First and foremost, the river's floods threatened to wash away life and property. The frequent and dangerous floods led the river to be referred to as *flumen terribile et periculosum* [24]. We do not have direct reports on the Llobregat's floods during first millennium after Christ, perhaps in part because there were so few structures to destroy or people to write about them. However, Thorndycraft et al. [35] after the analysis of paleoflood deposits in the Llobregat River described that floods higher than $2,300 \text{ m}^3 \text{ s}^{-1}$ were exceeded in five occasions during the last 2,700 years, reaching discharges of $3,700\text{--}4,300 \text{ m}^3 \text{ s}^{-1}$. The first written report of a flood in the Llobregat dates back to 1143, that flood washing away the original Roman bridge at Martorell. In the next 850 years, up until 1900, historians have counted 129 more major floods along the Llobregat, although certainly there must have been more [24]. As human settlements began to develop closer to the river, residents complained that their proximity to its water made it an unpleasant place to live. In 1807 municipal officials from El Prat lamented that the river's frequent floods were the primary cause of its "misery" [24]. And indeed, some of the floods were of biblical proportions. One flood transformed the Llobregat Delta into an inland sea, covering the entire area with water from Montjuic to Castelldefels [24].

2.2 *Bridging the River*

The Llobregat might have inspired more sympathy had it at least been navigable; but alas, not even that. The Llobregat's shallow and irregular discharge made its waters unforgiving to floating vessels. The river was large enough to obstruct travel and communication, but not large enough to be useful for transport. This was not unusual for this part of the world. Of all of the rivers in northeastern Spain, only the Ebro River (Hiberus Flumen) to the South has any evidence of useful commercial transport. Thus, towns near the river were largely cutting off from communicating with those on the other side, and crossing the river was a major inconvenience for locals and travelers trekking along the Mediterranean rim. The Roman bridge at Ad Fines (Martorell) must have been the first permanent crossings of the Rubricatus. The bridge was a critical piece of the Roman's via Augusta, a protected transportation artery which connected Imperial Rome with the Tarraco, and further south, the silver mines in Carthago Nova, and the aristocratic city of Gades (Cadiz) in Baetica [23]. The bridge crossing at Martorell was a full day's journey from Barcelona.

But the inconvenience of the Llobregat River also provided strategic military defense. For over 300 years, between 801 and 1148, the Llobregat and Cardener Rivers marked the divisionary lines of the Christian and Islamic worlds [23]. The rivers served as a natural moat, albeit sometimes an ineffective one, that protected Catalunya Vella (Old Catalonia) from southern invasions. The threat of southern invasion prompted the Catalan peasantry living near these rivers to move north, inland, or to higher elevations. Once again, just like the Neolithic peoples before them, safety could be secured far from the river, perched in the high lands.

2.3 *Approaching the River: Mills and Irrigation*

When the North Africans were finally pushed beyond the Ebro River in the twelfth century, the Catalan peasantry slowly began to come down from the mountains and populate the lower Llobregat and Cardener valleys. In 1188 the Catalan king gave the first known water concession over the Llobregat to build a flour mill at Molins the Rei. In 1317 a second permanent crossing of the Llobregat was built at Monistrol, giving the church and pilgrims access to the monastery of Monserrat. A few years later another medieval bridge was built in Castellbisbal [19, 22].

By the middle ages, small scale irrigation along the river's banks was widespread, especially in the upper reaches of the Pyrenees. The medieval period also saw a boom in flour mills as the peasantry became more skilled in harnessing the rivers energy. In the Merlès stream alone, historians have documented 32 medieval flour mills [26]. Many medieval mills have also been found in Capellades along the Anoia River [27]. This tradition of harnessing hydropower along the Anoia would eventually develop into other river related industries such as a paper mills, textiles, and leather tanning.

2.4 *River Industries*

The Llobregat and Cardener Rivers played a central role in the industrialization of Catalonia. As elsewhere, industrialization began with the production of fabrics and textiles. Spaniards in the eighteenth century produced fabrics by hand; manually separating the seeds from cotton fibers, carding the fibers, spinning the thread, and weaving the fabric. Starting in the early nineteenth century industrialists began to import new technologies from northern Europe in an effort to modernize textile production. One of the first imported technologies was the water frame, which substituted the manual spinning of cotton for a mechanized process with wooden and metallic cylinders. The first water frame appeared in the Llobregat watershed in 1801, and by 1804, these devices spread throughout the Cardener and Llobregat valleys [28].

The mechanization of fabric production was largely driven by hydraulic energy, and this brought entrepreneurs to set up production near rivers. The first company town along the Llobregat was Can Prat, built in the town of at Puig-Reig in 1810. However, hydraulic energy alone was insufficient to massively produce fabrics. It was not until the development of the steam engine in 1833 that industrialists obtained the efficiency necessary to make textile production highly profitable. A few decades later, in the 1860s, the innovation of the modern turbine allowed for the more efficient and widespread use of hydropower [26].

To exploit these technological innovations, entrepreneurs descended upon the Cardener and Llobregat to set up production along the river in the second half of the nineteenth century. The amount of energy produced depended on two critical factors: total river discharge and vertical drop. The more discharge and higher the vertical drop, the more energy produced. The problem with setting up industry next to the river was that they were far from existing towns and infrastructure (in addition of course to the threat of flooding). This led industrialists to build company towns: complete with housing for workers and their families, schools for their children, a church, a theater, and a local store.

The largest and most profitable company towns in the Llobregat were built in the 1870s: Colònia Burés (1873), Vilodomi Nou (1874), Ametlla de Merola (1874), Colònia Pons (1875), and Colònia Borrás (1876). Hydropower was a major source of energy, but it was always complimentary to the steam engine. By 1888 the best spots in the Llobregat were occupied, and industry migrated east to the Ter watershed [27].

With the development of the industrial colonies, one after another, the Llobregat River became to be called the “most exploited river in the world” [27]. Only in retrospect is it easier to appreciate this navel glaring. But the reputation of the Llobregat as a hard working river, producing much with little, stuck in the minds of the Catalans. A “Llobregat mentality” entered the Catalan lexicon as a way of describing someone able to maximize the exploitation of resources, no matter how small, for the maximum advantage.

Industrial activity along the Llobregat peaked in the early twentieth century. At the height of production, between 1900 and 1910, the Sedó company town employed over 2,000 workers [27]. The last industrial colonies were built at the turn of the twentieth century, at which point, electrification gave industrialists the freedom to start production on higher ground, far away from the unpleasant Mediterranean rivers.

2.5 Dams

For centuries, floods from the Llobregat had threatened to wash away crops, boats, and bridges. The first efforts to contain the river's waters date back to the fourteenth century when the residents of Sant Boi de Llobregat built levies along the river's edge in the hopes that the structures would protect them from rising waters. But these levies were repeatedly washed away, despite diligent efforts to test building materials and designs that gave the river a generous floodplain [24].

In the 1880s, engineers drafted the first dam project in the Llobregat watershed at a site near Cabrianes [29]. The goal was to mitigate flood damage and provide water for crop irrigation. But the proposal met opposition from the forester Rafael Puig Valls, who advocated for managing forests in the upper segments of the watershed and recognized the natural variability of Mediterranean streams, but emphasized that floods could be mitigated with savvy ecosystem management [29, 30]. The Cabrianes dam project was eventually discarded, but would repeatedly come up again in the various water management plans in the twentieth century.

A plan in 1902 projected five dams in the Llobregat basin: two on the main stem of the Llobregat, one below Montserrat at La Puda, and another at the town of El Pont de Vilomara. The third dam was to be erected along the Cardener River, above Clarianes, the fourth near the confluence of the Anoia with the Montbui, and a fifth on the Anoia between Vallbona and Cabrera. The hydraulic plan of 1902 included similar ambitions and aspirations throughout Catalonia and the rest of Spain, but most of these projects never broke ground [27].

In 1933 engineers drafted another ambitious hydrological plan with the primary objective of increasing hectares under irrigation. Energy and drinking water were secondary objectives. In the plan of 1933, the Cabrianes dam project resurfaced again, as did the proposal to build a dam along the Cardener at Sant Ponç. In 1935, the Catalan Government revised this proposal, and in addition to Sant Ponç, planned for dams at Malagarriga, Sorba, Vilomara, and Boades [26]. However, these plans were interrupted by the Spanish Civil War (1936–1939).

Of all the dam proposals in the Llobregat watershed, the first to be built was at Sant Ponç. Construction began in 1949 and the project was completed 1954. When complete, the reservoir held a capacity of 12 hm³ [27]. It was the first human made reservoir in the watershed, and later followed by the Baells in 1979 and the Llosa del Cavall in 1997.

2.6 *Water Pollution and Salinity Conflict*

The first momentous conflict over water pollution concerned salinity concentrations in the Cardener and Llobregat Rivers. Starting in 1926, the owner of a textile mill along the Cardener, Antonia Burés Borràs, noticed that her metallic turbines were corroding. She suspected that this chemical reaction was produced by the unusually high concentrations of salts flowing into the Cardener River from the mining industry upstream. Burés soon initiated legal proceedings against the mining company in order to halt their “impurification” of the Cardener’s waters. The Spanish Government began two investigations to study effluent flowing out of Súria, but it was not until the third investigation began in 1931, that the Commission for the Study of the Salinity of the Waters of the Llobregat River (CESALL) was established to study the issue in detail [31]. The CESALL commission used the latest science and technology in order to clarify the fundamental chemistry and hydrogeology, in an attempt to create new rules that would reconcile their water uses among competing interests. The extensive deliberations of the CESALL commission were arguably the first watershed planning process in the Llobregat basin [32]. By the time the CESALL Commission had begun meeting regularly in 1931, Sociedad General Aguas de Barcelona had also raised concerns that the salts flowing into the river from the mines were percolating into the Llobregat aquifer, and as a result, polluting Barcelona’s main source of drinking water. The company wells at Cornellà had registered rapid increases in salinity values since mining operations began in 1926. The Municipal Laboratory of Barcelona also became concerned that the mining activity would permanently contaminate Barcelona’s primary source of drinking water. The CESALL released their conclusions in 1932 and recommended that salinity effluents be limited to 250 mg/l in Pallejà. The commission also advocated for the building of a brine collector that would transport the mining waste directly to the Mediterranean, and a dam that would regulate flows and dilute salinity concentrations during summer months. The legal limits on salinity in the watershed were debated in the Catalan Parliament and approved by the Catalan Generalitat in 1933 [33], however the structural solutions took several decades before the projects materialized. While the dam at Sant Ponç was completed in 1954, the brine collector was not completed until 1983.

In the first half of the twentieth century, Barcelona drank from the Llobregat but only indirectly, since its waters were pumped up from the aquifer below the Llobregat delta. But starting in 1955, Sociedad General de Aguas de Barcelona began to withdraw surface water from the Llobregat River at a new drinking water facility constructed at the mouth of the watershed in Sant Joan Despí (see Fig. 4). From a water quality perspective, the facility’s downstream location could hardly have been worse, but the selection was related to the existing water rights for irrigation or industrial production upstream [32]. With rise of industrial activity along the Llobregat in the 1960s and 1970s, water managers began to detect a cocktail of contaminants flowing down the Llobregat River. According to one former employee, the laboratories at Sant Joan Despí have detected “every possible

element in the periodic table.” Efforts to protect the source quality of the Llobregat River have been a combination of stop-gap measures. In the 1960s, water managers captured two highly polluted tributaries, the Rubí and Anoia, piped them into a channel, diverting them away from the main stem, and then dumped them back into the river just a few meters below the water treatment facility (see next section). This diversion remains today, in addition to other diversions, such as the water collector of the freeway, which also dumps below the water treatment facility. At the same time, it must be recognized that the water quality of the Llobregat River has largely improved due to the construction of municipal waste water treatment facilities.

3 The Llobregat as an Overexploited River: Interconnectivity in the Llobregat Basin and the Urban Loop

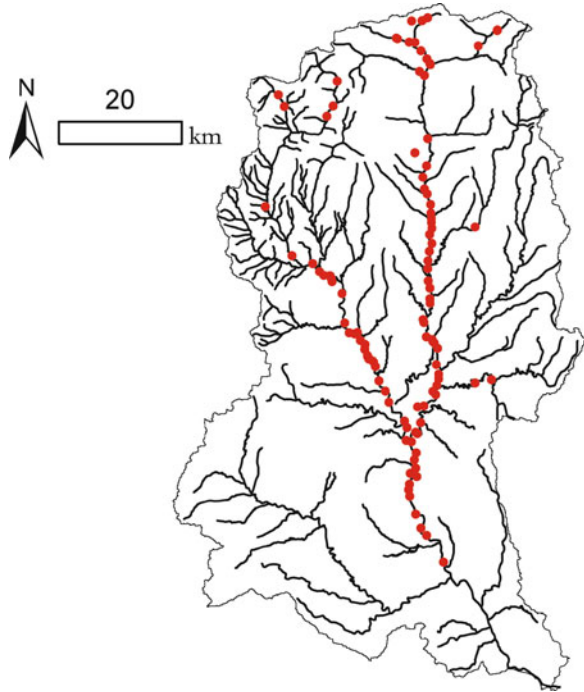
In terms of human exploitation of the river, reservoirs are the most conspicuous in the Llobregat. The Llobregat has three main reservoirs. One is located in the Llobregat itself (La Baells; 109 hm³ capacity) and other two in the Cardener (Llosa del Cavall, 79 hm³, and Sant Ponç, 24 hm³). Their waters are mostly used for irrigation and hydroelectric power, but not so much for local drinking purposes. However, their regulation capacity is fundamental to maintain a sufficient amount of baseflow in the downstream reaches to sustain water supply for Barcelona during the summer months.

Apart from big dams, a total of 101 weirs are located in the basin (Fig. 11), mostly to profit the water for small hydroelectric power stations. As stated above, most of these weirs were built to support local industry during the boom of textile and mining activities. Nowadays many of these small dams still are in use, although their role on the power budget of the region is irrelevant. In some sections of the river network the occurrence of weirs challenges the very definition of the Llobregat as a river: in the middle section the main channel is dammed by weirs once every ~2 km, for a total amount of 45 weirs (Fig. 11).

Further to these medium and large infrastructures, the hydrological complexity of the Llobregat cannot be understood without considering the multiple connections, derivations, withdrawals, and returns that are scattered all over the basin. These connections are implemented since long ago and have received new incorporations to make compatible the multiple uses with the preservation of water quality.

In the Llobregat headwaters, the Berga Industrial Channel derives water mainly for hydropower that will be later returned to the river downstream of La Baells dam. It has a maximum capacity of 2.5 m³ s⁻¹ (Fig. 12), and only a minor amount is used for water supply in Berga. Also in the headwaters, but in the Cardener River, some resources are derived from a small tributary of the nearby Segre River (located to the West). Most of this supply is used in the city of Solsona and returns to the Negre and Cardener Rivers in the form of WWTP outflows. A water channel built in medieval times (Sèquia de Manresa) supplies water to Manresa directly from the

Fig. 11 Location of weirs in the Llobregat River network.
 Source: Catalan Water Agency (ACA)



Llobregat. It was aimed to provide drinking water as well as water for irrigation in the plains surrounding the city, and later was also used to feed several small hydroelectric plants. Nowadays is the first link of a complex urban schema including natural wetlands, treatment plants, wastewater facilities, and a complex network of pipes (Fig. 12).

As noted above, mining activities enhanced the impact of salt leachates that originate in several areas of the middle section of the river (at the urban nuclei of Balsareny, Sallent, and Súria), causing waters to show conductivity far beyond the quality standards. Therefore, in the 1980s, a salt brine collector was built to directly bypass these salty waters to the sea, avoiding them to enter into the Llobregat waters. The water volume is not so high, but the leachate concentrations are sometimes fivefold the marine concentration. Other industrial salt brine residues are also incorporated in the collector as it develops downstream.

Downstream the city of Manresa and up to the city of Abrera, water is obtained primarily from groundwater sources some of them closely connected to the alluvial aquifers. The aquifer Carmen–Capellades is used to feed the needs of Igualada and some neighboring towns; a large fraction of these waters return later to the river through WWTP effluents. In the Abrera area is placed the second largest Drinking Water Treatment Plant (DWTP Abrera) in the Llobregat. It treats waters from the middle-lower part of the river, and serves a large area including Barcelona. Another

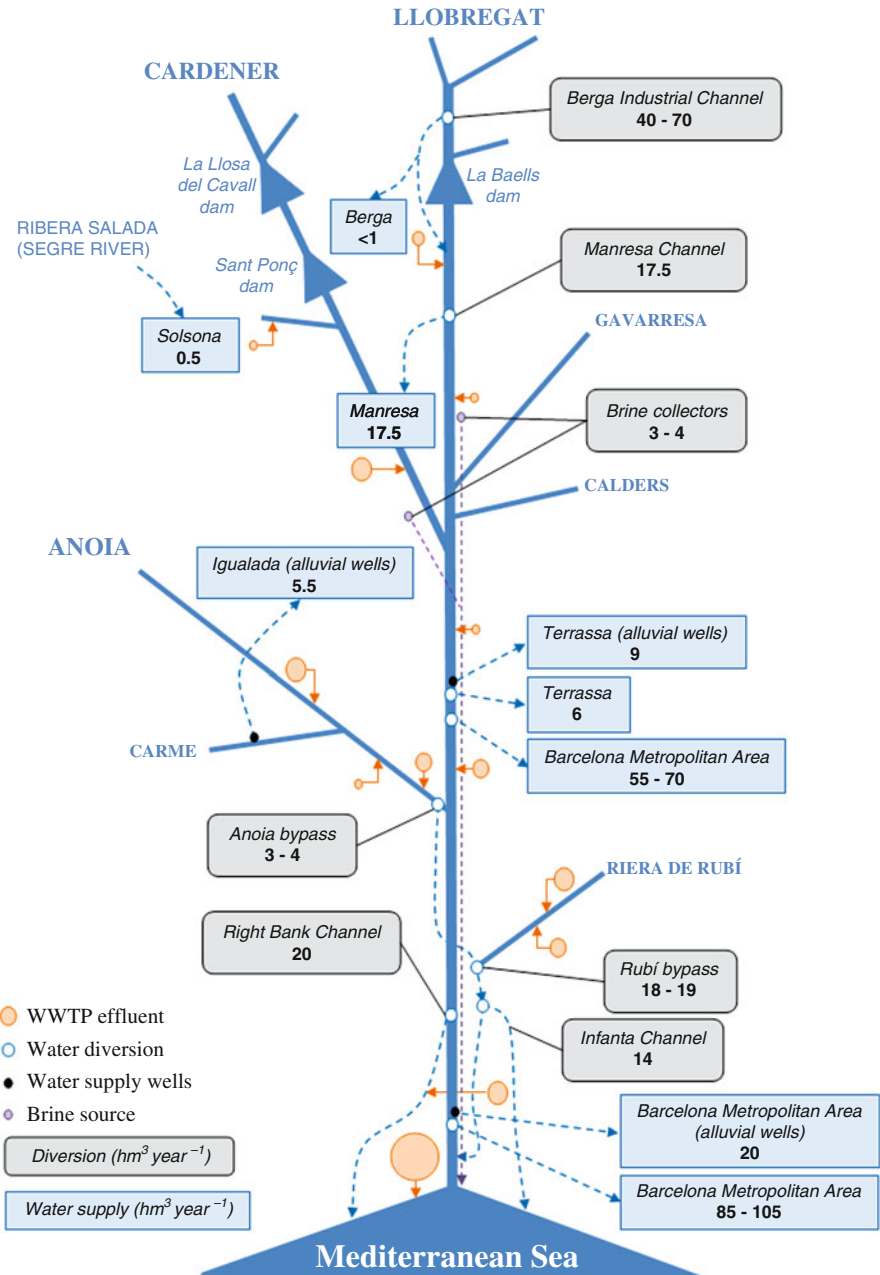


Fig. 12 Scheme of the main withdrawals, diversions, and wastewater effluents in the Llobregat River Basin. Water diversions are denoted by *dashed blue arrows* and named from the origin with a *grey box*. When withdrawals are devoted to urban water supply the *blue arrow* points to a *blue box* indicating the supplied area. Numbers in *grey and blue boxes* are $\text{hm}^3 \text{ year}^{-1}$. When the water supply depends on alluvial wells the origin of the intake is denoted by a *black dot*. For WWTP effluents (*orange circles*), the size of the symbol is approximately proportional to the volume of the effluent

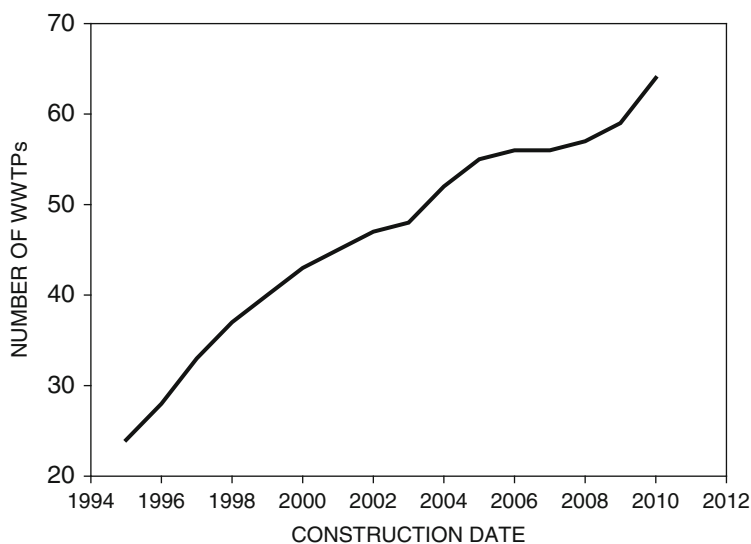


Fig. 13 Evolution in the number of EDARs in operation in the Llobregat River Basin for the last 15 years

and smaller one is the DWTP at Terrassa that treats a lower but significant water volume, from the Llobregat as well as from groundwater alluvial sources.

The last big withdrawal of superficial waters from the Llobregat River is at the DWTP of Sant Joan Despi, located at a short distance from the city of Barcelona near the river mouth. The uptake of this water leaves the river nearly exhausted downstream. When the superficial resources are scarce (summer) or difficult to capture, resources from underground wells (at Cornellà and Sant Feliu de Llobregat) are also used.

The treatment of sewage waters in the Llobregat was nearly none before 1981. In 1984 and 1985 the WWTPs of Martorell and Manresa were placed in operation, but it was only in 1995 that the Catalan Parliament approved the Sanitation Plan for the inner watersheds. This Plan defined the fast construction and operation of up to 64 WWTP in the Llobregat watershed (Fig. 13), which presently include a total collector network of 516 km and 113 bombing stations. The present overall treatment capacity of these facilities amounts to 850,929 m³ per day, and serve more than 2 million people.

The first WWTPs installed at the Llobregat watershed mostly used physico-chemical treatment. However, presently most of the WWTPs in the Llobregat include biological treatment, and in ca. 20% of them there is a biological treatment with capacity to eliminate phosphorus and nitrogen. Three of the WWTPs have a facility for water regeneration (tertiary treatment: Prat de Llobregat, Sant Feliu, Piera). In other two the treatment is based on the use of macrophytes or in water infiltration-percolation (Sant Martí de Sesgueioles and Hostalets de Pierola).

This network of WWTPs is complemented by other infrastructures to help on the sanitation in lower areas of the river. Mostly to avoid further pollution inputs to the superficial waters in the lower part of the river prior to their uptake for drinking purposes, most of the streamflow of the main tributary Anoia is diverted at its mouth to the Infanta Channel, which in part returns to the Llobregat downstream from the intake of the DWTP at Sant Joan Despi. The Anoia waters add to those of the Riera de Rubi and its WWTPs (water volume ca. $0.5 \text{ m}^3/\text{s}$), and the waters remain available for irrigation in the Llobregat lowlands. The share in recent years between the two inputs is of $3\text{--}4 \text{ hm}^3 \text{ year}^{-1}$ from the Anoia and $18\text{--}19 \text{ hm}^3 \text{ year}^{-1}$ from Riera de Rubi. About $8\text{--}14 \text{ hm}^3 \text{ year}^{-1}$ of the total are used for irrigation, and the remaining volume is derived through another channel to the Llobregat downstream the DWTP of Sant Joan Despi, and finally reaches the Mediterranean Sea. The Right Bank Channel in the Lower Llobregat derives about $16\text{--}22 \text{ hm}^3 \text{ year}^{-1}$ which is also used for irrigation.

Superficial waters in this final section are also allocated in recharge ponds to increase the aquifer reserves of the Delta, which are used as a strategic reserve for drinking water to Barcelona. Some other projects to improve the water quality as well as the volume of the water resources are under planning or execution. The WWTP of El Prat is planned to pump water upstream to maintain environmental flows in the final stretch of the river. Finally, a large desalination plant using reverse osmosis was recently put into operation and is able to produce a maximum yield of 60 hm^3 per year. The plant was defined to allow avoiding critical episodes of water shortages as well as to alleviate the existing pressure on the Llobregat and Ter Rivers, the two main sources for drinking water for the Barcelona metropolitan area.

A significant volume of the water withdrawn from the Llobregat River has already been treated by WWTPs and returned to the river itself, defining a major urban loop in the fate of the water as it travels along the basin. The average volume of water treated and delivered to the river accounts for $205 \text{ hm}^3 \text{ year}^{-1}$ (remember that total streamflow near the mouth is $\sim 600 \text{ hm}^3 \text{ year}^{-1}$). It is estimated that from this huge volume $23 \text{ hm}^3 \text{ year}^{-1}$ are reused at the DWTP in Abrera and $40 \text{ hm}^3 \text{ year}^{-1}$ at the DWTP in Sant Joan Despi. This contribution therefore reaches ca. 8% of the total water volume from the Llobregat supplied to Barcelona Metropolitan Area, but may account ca. 30% under drought situations.

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