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What controls the coarse sediment yield to a Mediterranean delta The case of the Llobregat river (NE Iberian Peninsula)

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Abstract. The human pressure upon an alluvial river in the Mediterranean region has changed its riverine and deltaic landscapes. The river has been channelized in the last 50 years while the delta is being retreating for more than a century. The paper concentrates on the fluvial component, trying to connect it to the delta evolution. It develops a method to compute the actual bed load transport with real data. The paper compares the computation with measurements and bulk volumes of trapped material at a deep river mouth. Sediment availability in the last 30 km of the river channel is deemed responsible for the decrease in the sediment yield to the delta. Moreover, reforestation is deemed responsible for a baseline delta retreat. The sediment trapping efficiency of dams is less important than the flow regulation by dams, in the annual sediment yield. Therefore, it is more effective a step back from channelisation than to pass sediment at dams, to provide sand to the beaches.

1 Introduction

The framework for this research is the mankind pressure upon an alluvial river in the Mediterranean region. The paper aims at showing how and why the riverine and deltaic landscapes have changed. The time frame of the research is the last 50 years, over which the main pressure has been one of channelization, yet some information prior to this period is presented as well. The practice of channelizing a river generally involves increasing channel capacity and so, an erosional response is to be feared, although this is not always the case (Simon and Rinaldi, 2006). Typically, it also involves narrowing of the flood channel by taking a large part of the floodplains out of the hydraulic conveyance system (an encroachment), under the pressure of urban sprawl. This flood width reduction (or contraction) implies a perturbation of the equilibrium (more specifically, a degradation), as demonstrated analytically and experimentally by Vanoni (1975), yet this is only one of the several causes of river bed degradation (Galay, 1983).

As regards the delta, the relative importance of fluvial building and wave and tidal reworking determines the delta morphology and evolution (Bridge, 2003). The relevant maritime factors are reduced to wave action in the case of the Mediterranean sea (no substantial tides). This wave action and its related currents produce a certain longitudinal coastal sediment transport, as well as a loss of sand towards the open sea. The dominance of the fluvial or the maritime factor varies in space and time for a given delta. However, the simple statement made herein is that the greater the river sediment supply rate the more the delta will protrude into the standing water body, to equality of the maritime factor, and vice versa. Literature on delta evolution is abundant (e.g. Orton and Reading, 1993, Syvitski and Saito, 2007) and on river evolution as well (e.g. Rinaldi and Simon, 1998, Martín-Vide et al, 2010), but the connection between the two is almost lacking. It is difficult to find data to evaluate the influence of sediment supply perturbations on delta evolution, except for the Mississippi river (Allison et al, 2012, Viparelli et al, 2015). This connection is attempted in this research.

The paper concentrates on the fluvial component, for which a method is followed to compute the actual sediment transport at different periods, using real data on the long river profile, the grain size of the available sediment and the annual high flows and floods. The focus is on what controls the coarse sediment yield, because the retreat of beaches (close to deltas) is a big concern in the region ('coarse' means sand). What controls the yield into the sea implies, as consequence, which measures are more sensible in order to keep providing enough sand to the beaches.

The beach retreat is presented first, serving as motivation for the river research. Then, the causes of change in river sediment yield are examined one by one, with emphasis on the availability and bed load carrying capacity. A closure with real data allows to draw conclusions on what controls the river sediment yield.

2 River description

Llobregat river is 163 km-long and drains an area of 4925 km^2 of the Northeastern Iberian peninsula, with its headland in the Pyrenees mountain range (fig.1). Archeologists say the river built its delta in the Mediterranean sea since Roman times, up to almost an area of 100 km^2. Geologists say the delta results from the Holocene transgression (6000 years), yet we are more interested in the delta evolution in the last century. The Latin name of the river was Rubricatus, which means dyed in red, in allusion to the color of its waters, probably because of its large fine sediment load. Moreover, Llobregat is a gravel-bed river upstream of its delta, with a high bed load transport capacity. The delta can be classified as sandy mixed load (bed and suspension) with only one distributary (Orton and Reading, 1993).

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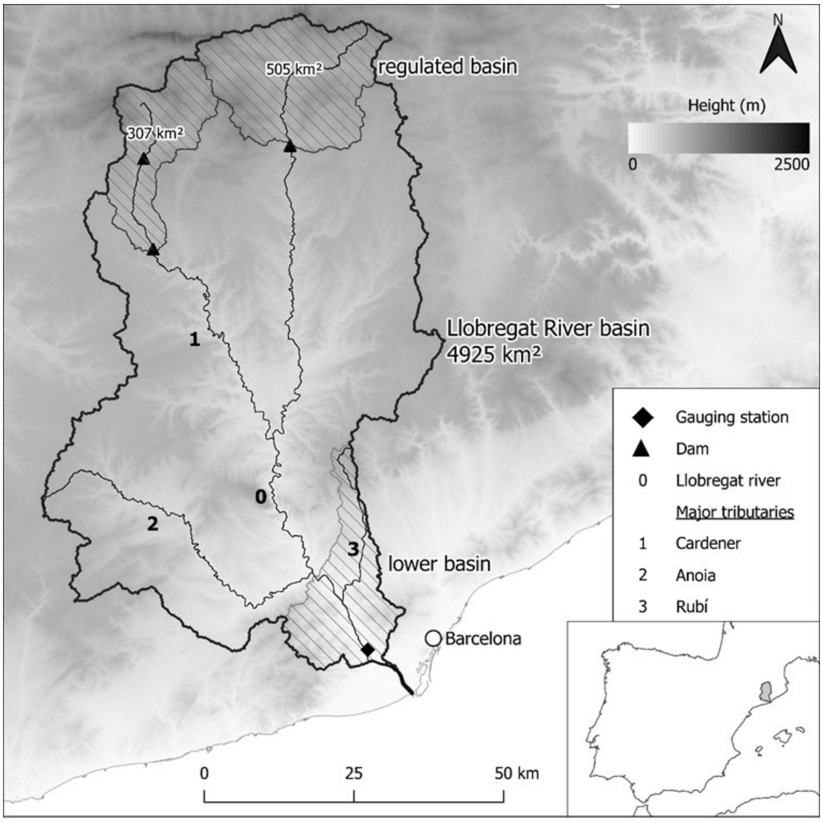

Fig.1. Location map. For lower basin see zoom in fig.4.

3 Beach retreat

Contrary to the delta building up in old times, it is receding in the last century. Fig.2 shows the coastline in the area of the river mouth since 1891 until 1956, with one point data in 1907 and two intermediate aerial photographs in 1926 and 1946. Three more of them, dated 1965, 1974 and 1981 show further receding of the coastline. The coast is a 24 km-long beach, between a northern closed boundary (Barcelona harbor) and a partially open western boundary. The reach is a sedimentary unit throughout the whole period 1891-1981. More recent photographs, such as the 2000 shoreline in fig.2, find this length much intervened by the enlargement of the northern harbor and the construction of dikes and of a second harbor at the western boundary. In addition, dredging for beach nourishment has become normal in recent years. Due to these interventions, the present analysis is limited to the period 1891-1981 and more accurately to 1946-1981. The current situation of the river mouth since 2004 is presented as an epilogue at the end.

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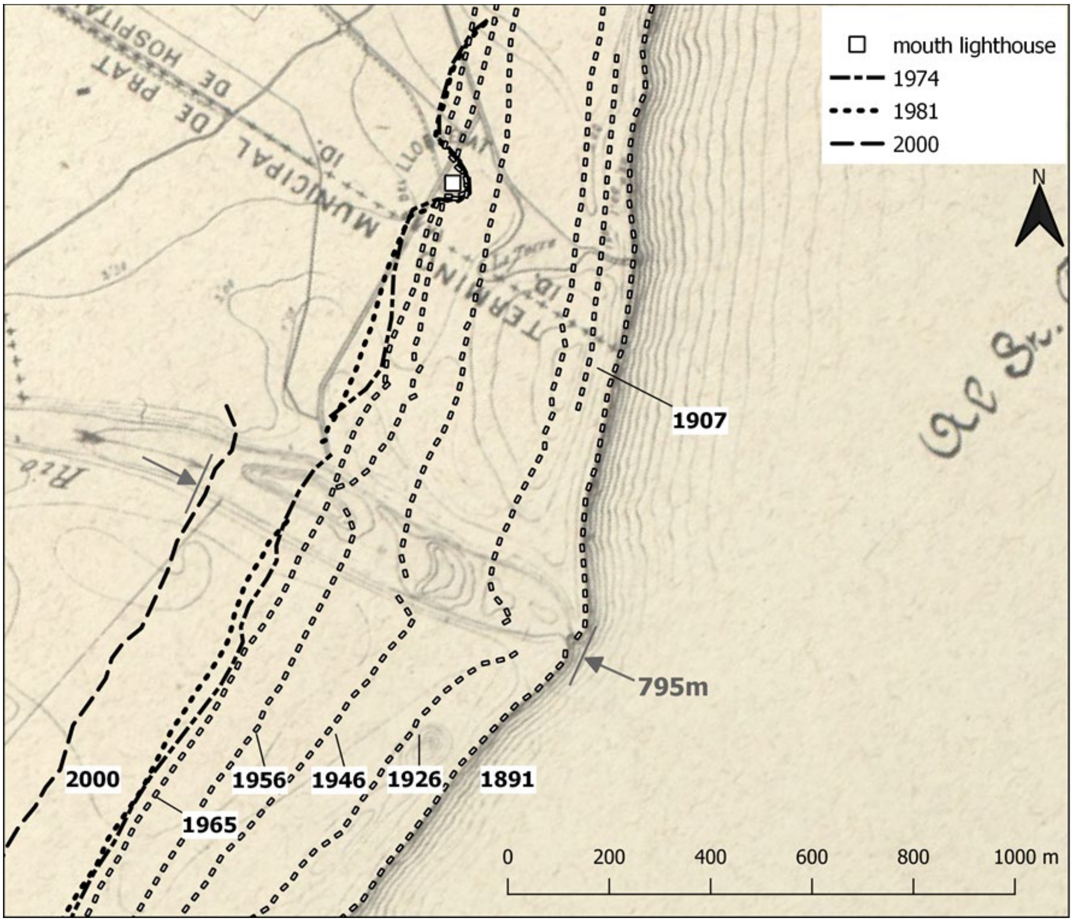

Fig.2. Coastline retreat in the Llobregat delta since 1891. Figure produced by authors using our own and freely available data from Institut Cartogràfic i Geològic de Catalunya (ICGC)

The coastline change, either progradation into the sea or retrogradation inland (retreat), expressed in m, is summarized in fig.3 for the period 1946-1981 when photographs are good and almost complete in area coverage. The total change in these 35 years, discretized in reaches 1 km-long, is plotted against an abscissa x from West (left) to North (right), together with the change in the first and second decades (1946-1956-1965) to show temporal trends and oscillations. An oval contour slightly protruding into the sea, geographically speaking the delta, can be assigned to the length between x=15 and x=24 km, being the river mouth at x=21 km (see plan view in fig.2). In this 9 km-long reach, the delta has been receding in a coherent way, in the sense that the closer to the river mouth, the deeper the receding, suggesting the key role of a decrease in the river sediment yield. This trend is quite common through different decades (fig.3). The beaches between x=0 and x=15 km, on the contrary, are mostly prograding, yet the temporal and spatial fluctuation in this area has been more noticeable.

Fig.3. Above: the 24 km-long sedimentary unit, produced by authors using freely available data from ICGC. Below: Total change in m perpendicular to the coastline in ordinates (progradation +, or retreat –) along the coastline above in the period 1946-1981 and in two decades within it.

The sand grainsize in the long delta beach is around 280 µm (Gracia and Calafat, 2019). A longitudinal sediment transport is going down from North to West, with a transport capacity in the range 10.000—75.000 m^3/yr (CIIRC, 2010). The depth of closure of the beach platform in the delta, i.e. the depth under sea level involved in the sediment transport shaping the beaches, is around 6.35 m. In turn, the berm height above sea level, involved as well, goes from 0.9 to 1.4 m (CIIRC, 2012). Then, every km of beach in the coastline, either prograded or retreated 1 m, means a sand volume of ≈ 3.500 m^3, respectively deposited or eroded (Digital Shoreline An. Sys. by U.S.G.S., Himmelstoss et al, 2018). The computation of sand volumes, by multiplying the change in m (fig.3) by 3.500 m^3/km, produce gross volumes. These are converted into net volumes, by deducting some 35% of voids. The calculation yields a deficit of 57.000 m^3/year in the delta (x=15—24 km) and a surplus of 29.000 m^3/year in the beaches west of it (x=0—15 km). The temporal distribution of these net volumes over the four periods from 1946 until 1981 is (table 1):

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net volume in $10^3 \times m^3$ /year	1946-56	1956-65	1965-74	1974-81	1946-81
surplus, x=0-15 km, beaches	*—5	+32	(1)+21	(1)+32	**+29**
deficit, x=15-24 km, delta	—84	—54	(2)—52	(2)—30	**—57**
balance (surplus vs. deficit)	—89	—22	—31	+2	—28

Table 1. Volumes of change of sand (× 103 m^3 per year), distributed by decades and by region (oval delta and beaches west of it). * it is a deficit, actually, (1) extended over 10 km instead of 15 km, (2) extended over 7 km instead of 9 km.

The deficit is larger than the surplus three times out of four (table 1). The negative balance (loss of sand) can be explained by the partially open western boundary (at x=0). The coastal longitudinal transport capacity cited above (net volume of 10—75×103 m^3/yr) seems capable, by order of magnitude, to take these amounts of sand from North (delta) to West (beaches) and even to push part of it across the western boundary.

One lacking piece in the balance of the coastal system is the sand sediment yield supplied by the Llobregat river, to which the core of this paper is devoted. Our objective is to ascertain to which extent the river sediment yield is important to the delta evolution, as the distribution of beach retreat in fig.3 suggests. Did the river yield decrease over the same period? Do river yield figures compare with the volumes in table 1?, and which hydrological, hydraulic or sedimentary factors control the river yield? Similar to what has been done about the beach retreat, we will primarily use historical information on the river condition. Before that, the causes of decrease in river sediment yield are examined next.

4 Causes of decrease in sediment yield

The decrease of the sediment yield of a river to its delta may be due to different reasons. Here we will consider: a) land use changes including urbanization, b) reservoirs after dam construction, that 1) trap sediment and 2) regulate flow, and c) river engineering works of any kind (mining included) on the channel and floodplains.

Cause a) affects primarily one component of the sediment load, the wash load, i.e. the fine sediment coming from anywhere in the basin. Cause b) affects all components of the sediment load but certainly its coarse fraction, which is more prone to get trapped than wash load in reservoirs. Cause c) in the Llobregat case is mainly the encroachment of the river by infrastructures (roads and railways) and its channelization against flooding with bank erosion measures, in combination with some gravel and sand mining. These engineering works affect sediment load coming from the channel, composed of sand and gravel, not the wash load coming from the basin.

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5 Land uses and urbanization

Land use changes in the Llobregat basin have been analyzed with the best aerial photographs for the past (1956) and a modern land use map (2009). The results are summarized in table 2, with aggregation of land uses in only three main categories: agriculture, forest and urban. The percentages for the whole Llobregat basin show a modest change consisting of a loss of agriculture land for the equitable benefit of towns (urban), on one side, and forest, which grow on the abandoned fields, on the other.

	basin 4925 km^2		lower basin 343 km^2		tributary 3, 124 km^2	
	1956	2009	1956	2009	1956	2009
agriculture	35%	22%	43%	8%	45%	9%
urban	2%	8%	6%	37%	8%	43%
forest	63%	70%	51%	55%	47%	48%

Table 2. Land use change in the whole, lower basin and tributary 3 sub-basin in 1956-2009 (Prats-Puntí, 2018).

For the area surrounding the lower reach of the Llobregat, called here lower basin, amounting to a 7% of the total basin area (fig.1), the loss of agricultural fields is more important and benefits more the urban area than the forest (fig.4). The lower Llobregat channel close to Barcelona is the most intervened reach, so that paragraphs dealing with the river engineering works will focus on it. The case of the most urbanized sub-basin, the tributary 3 catchment (figs.1 and 4, table 2), shows a more marked reversal of shares between fields and urban. There is some channelization in the tributary but not any dam. Therefore, causes a) and c) must have been dominant in the large bed incision reported in it since 1962 (Martín-Vide and Andreatta, 2009).

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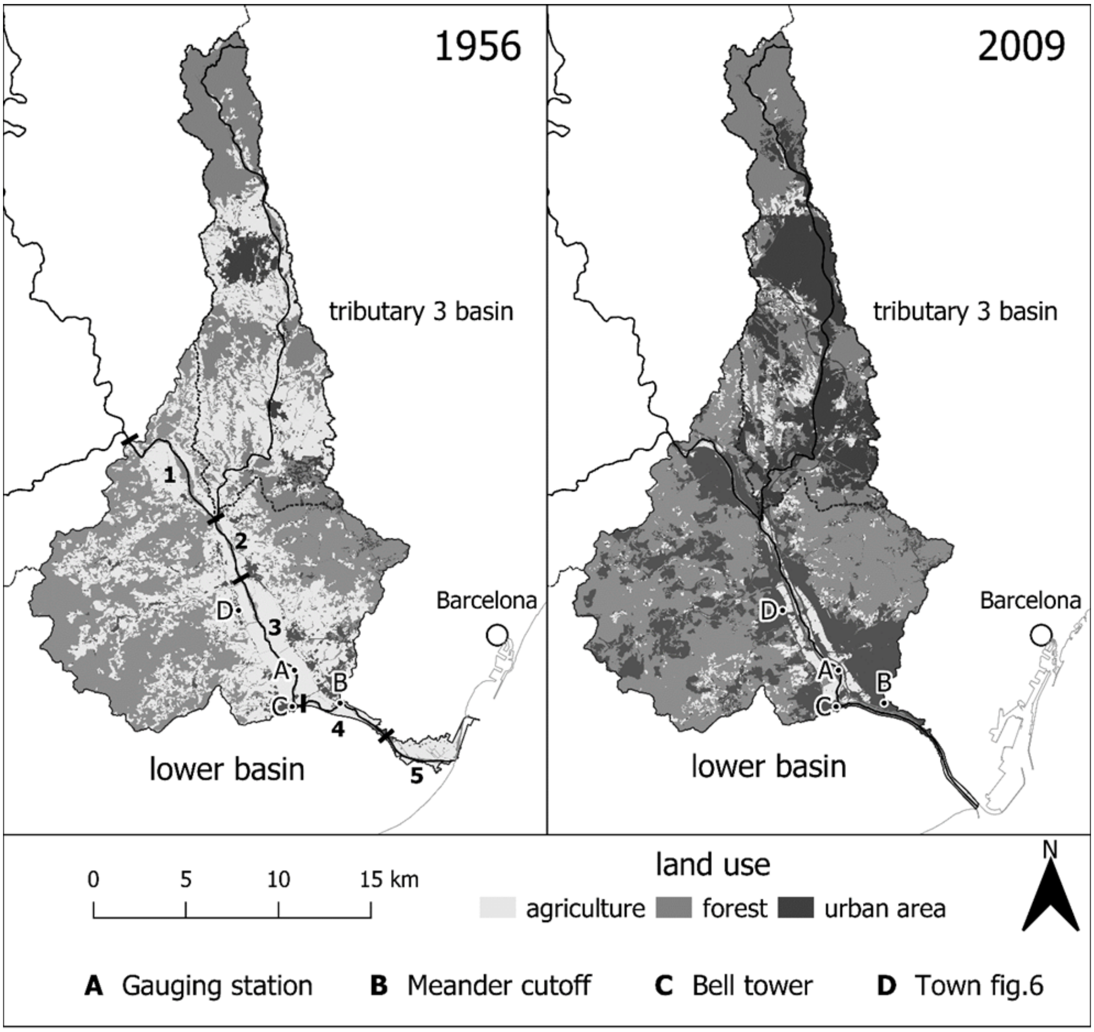

Fig.4. Land use changes in the Llobregat lower basin. Figure produced by authors using our own and freely available data from CREAF public research center. Note the added information on the lower river (reaches nr. 1 to 5 in the analysis and reference points A to D).

6 Reservoirs: sediment trapping

There are two dams in the upper basin (fig.1). One controls a 505 km^2 catchment, with a reservoir of 109 Hm^3, since 1975. The second dam, in tributary 1, controls a 307 km^2 catchment, with a small reservoir of 24 Hm^3 since 1954 (inside this second catchment, another dam with a volume of 80 Hm^3 was built in 1999). Therefore, the area under hydrological control (the regulated basin) amounts to 812 km^2 since 1975, it was 307 km^2 in the years 1954-1975, that is to say a 16.5% and 6.2% respectively of the whole Llobregat basin. None of the three dams has any sediment by-pass device, nor are their bottom outlets able to pass or flush sediment, so far.

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Thus, if soil erodibility is uniform throughout, some 16.5% of the sediment load coming from the basin as wash load will be trapped in the reservoirs since 1975 at the most, and ≈ 6.2% in 1954-75. Whatever the percentage is, the wash load component of the sediment yield, having grainsizes in the clay-silt range (up to 62 µm), is not relevant for the coastline evolution, made of fine sand (280 µm). Regarding the load coming from the channels, ultimately trapped in reservoirs, the alluvial channel bed surface (per unit basin area) is similar or smaller within the regulated basin than downstream of the dams, because of a similar drainage network density and narrower cross-sections up there. Thus, the supply of coarse sediment from channels to the reservoirs is probably similar to a 16.5% of the total load at the river mouth. Sediment supply is resumed in §9.

The previous reasoning involves the flux of coarse sediment along the channel. Dams produce a cut of the coarse sediment supply to the channel downstream, due to their sediment trapping. This deficit travels downstream as a disturbance of incision (Martín-Vide et al, 2010), because supply is cut or reduced while transport capacity remains the same (this argument will be resumed in §9). Liébault et al. (2005) found a propagation velocity of 300-500 m per year for this disturbance (produced by reforestation in their case). In the Mediterranean South Iberian peninsula, Liquete et al (2005) showed that, although damming was active since 1970, leading to a regulation of 42% of the basins, its effect was barely noticeable on the mouths of rivers with lengths in the range 5—150 km. As the distance from dams to river mouth is more than 120 km in our case, it is highly unlikely that this disturbance has reached the lower Llobregat yet. In other words, the trapping of coarse sediment in the reservoirs since 1954 and 1975 must not have been relevant for the delta retreat yet, and neither for the period 1946-1981 of coastal retreat data (§3). In the long term, this trapping will come into picture, but would not probably be a crucial factor because of a decrease less than 16.5 % of the total supply.

7 Reservoirs: flow regulation

Reservoirs produce a second effect on sediment yield, through flow regulation, more precisely through peak flow attenuation. Once a reservoir stores water, the flow duration curve undergoes a reduction in peak flow along with an increase in low flow. These changes affect the sediment load coming from the channels by means of two features of sediment transport: 1) the existence of a threshold for the initiation of transport, so that a reduction in peaks implies fewer days of flow above the threshold and so, more days with no transport, and 2) the non-linearity of bed load equations, in the sense that a certain reduction in flow means a higher reduction in bed load (f.e. 1/2 in flow but 1/4 in bedload, if bedload is proportional to the square of flow).

This effect can be assessed by comparing the flow duration curves with and without reservoirs. The period 2002-2018, after the last dam was built in 1999, is long enough, and so representative of flows and reservoir management, to compute an average flow duration curve with reservoirs. This is done with the hourly data at the downstream-most gauging station (see fig.4). Moreover, this curve together with the contemporary measured daily levels at the reservoirs allow to compute a flow duration curve without reservoirs, a "would-be" curve. This is done by adding or subtracting the reservoirs volume variation in one day to the flow gauged at the station. The travel times of water from reservoirs to the station (22 h through main river and 20 h through tributary 1, fig.1) are the time lags between the volume variation at reservoirs and the discharge to be modified by addition or subtraction at the station.

Then, the comparison of flow duration curves with and without reservoirs assumes that the difference between the two are not much impacted by other hydrological changes, such as: a) water abstractions for irrigation and supply, b) basin runoff, and c) rainfall regime, even under climatic change. It is not meant at all that flows are not impacted by a), b) and c), but only their difference with and without reservoirs are not impacted. In other words, the reservoirs would have produced a similar difference in flow duration curves no matter the rainfall, the runoff and the abstraction had been. Under this assumption, the curve without reservoirs represents the state prior to 1954.

The main results of this computation are: 1) without reservoirs flow is higher than with reservoirs throughout the first 130 days; the opposite happens over the rest of the year, and 2) the representative discharge of the first day in the flow duration curve at the gauging station goes up from 259 m^3/s to 308 m^3/s and a similar, quite constant increase of ≈ 20% extends to the first 100 days. The consequences of these results on sediment carrying capacity are discussed in §10.

8 History and data on the lower alluvial channel

The lower Llobregat river stretches along 30 km from the junction of the last tributary (nr. 2, figs.1 and 4) to the delta mouth into the sea, with the gauging station located half way. It is the most intervened section of the Llobregat channel, luckily with the best archival records. Channel morphology (plan and long profile), grainsizes of the alluvium and the history of floods and engineering works (roads, railways, and flood defenses) are obtained from these archives. Extreme floods in the lower Llobregat occurred in 1907 (≈2900 m^3/s), 1919 (≈1500 m^3/s), 1942, 1943 and 1944 (≈1750 m^3/s), 1962 (≈2100 m^3/s), 1971 (≈3100 m^3/s, the highest peak discharge), 1982 (≈1600 m^3/s) and 2000 (≈1500 m^3/s). The 3-year period ending in 1944 is described in the documents as causing general aggradation.

For the sake of analysis, the 30 km-long channel is divided here in five reaches, 1 to 5, from up- to downstream (fig.4). In the first three (1-3), the channel used to be wandering within its wide valley floor, with incipient braids. In the last two (4-5), the river is rather a single thread, meandering, more stable channel running through the delta plains. Archival documents of different dates confirm this description. The corresponding bed slopes and mean grainsizes from documents are gathered in table 3.

reach	1, valley	2, valley	3, valley	4, delta	5, delta
length (km)	8.5	3	8	6.5	4
slope 1946 ($\times 10^{-3}$)	1.8	1.7$^{(1)}$	1.7	1.0	0.3
slope 1982 ($\times 10^{-3}$)	1.8	1.8	1.6	0.9	0.15$^{(2)}$
D_m (mm)	21	15	17	8	0.7$^{(3)}$

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Table 3. Slope and mean grainsize of the alluvial material for the five reaches of lower Llobregat. (1)is dated 1974 and (2)is dated 2016, actually, (3) additionally D50=0.6 mm, (Prats-Puntí, 2018).

After table 3, the lower Llobregat is a 15-20 mm gravel-bed channel with a slope a little less than 2 per mil in the valley, which turns into a sand-bed river (much finer) with a much milder slope in the delta. This abrupt transition from a gravel-bed to a sand-bed stream typically goes with a sudden change in bed slope and stream morphology (Parker and Cui, 1998) such as wandering to meandering, as happens in our case. The important consequence is that the reach issuing sediment to the coastline is reach 5 with bed grainsize D50 = 600 µm (table 3), similar to the grainsize on the beaches.

Table 3 shows a small slope change in time (1946-1982). On the contrary, width changes during the same period has been extremely large. Table 4 collects the alluvial bed surfaces, strictly considered (excluding areas of early colonizing plants), obtained from the series of aerial photographs (§3). The average width is the alluvial area over the reach length. Note the reduction to roughly half of the alluvial area in the period 1946-1981 (up to one third in reach 3). The current situation (2016) shows the last stage of the dramatic loss of alluvium, so far.

reach	1, valley	2, valley	3, valley	4, delta	5, delta	lower Ll.
length	8.5 km	3 km	8 km	6.5 km	4 km	30 km
alluvial surface (Ha) / *average width* (m)						
1946	148 / *175*	54 / *180*	119 / *150*	57 / *90*	35 / *90*	413 / *138*
1956	86 / *100*	33 / *110*	57 / *70*	42 / *65*	25 / *62*	243 / *81*
1965	106 / *125*	47 / *157*	67 / 84	41 / *63*	28 / *70*	289 / *96*
1974	-	49 / *163*	53 / 66	43 / *66*	30 / *75*	175 / *81*†
1981	-	30 / *100*	41 / 51	54 / *83*	30 / *75*	155 / *72*†
2016	28 / *33*	18 / *60*	29 / *36*	23 / *35*	77 /*190* *	98 / 38††

Table 4. Alluvial surfaces and average widths of the strictly speaking alluvium in the aerial photographs. * this figure have to do with the new mouth (see the epilogue), †these figures extended to and averaged over the lowermost 21.5 km (reaches 2-5), ††idem in the uppermost 26 km (reaches 1-4) (Prats-Puntí, 2018).

This change is conspicuous for any observer of the river. For example, the river landscape prior to 1920 is compared to the present state in fig.5, both photographs taken from the bell tower of town C (see fig.4). The same conclusion is drawn from archival plans and documents. The widest, wandering Llobregat of 1946 seems to be related to the aggradation brought by the 1942-1944 floods.

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Fig.5. Pictures of the Llobregat looking upstream prior to 1920 (left, anonymous in Catalan National Archives) and in 2018 (right, by A.Prats-Puntí) from the same viewpoint on top of the bell tower in town C (fig.4).

These changes have been forced by the infrastructures serving the urban area of Barcelona. Reaches 1-3 make the main corridor of roads and railways across the mountain range towards the plains where the city stands. Dates of opening of the main infrastructures are: 1970 for a highway (a dike) through the middle of the left floodplain; 1979 for a meander cutoff (fig.4); 1998 for the companion highway (another dike) through the middle of the right floodplain, followed by the railway attached to the riverine side of this dike, and 2004 for the new mouth into the sea. According to this calendar, the time frame of our research is the last 50 years. Fig.6 is a close view of a particular section around town D (fig.4). It shows why the highways are also flooding dikes (or levees), which encroach upon the floodplains. This calendar suggests that only the last four rows in table 4, showing a reduction of average alluvial width from 96 m (1965) to 72 m (1981) and ultimately to only 38 m (2016) are attributable to the main infrastructures, which have cut off roughly half of the floodplain widths at least.

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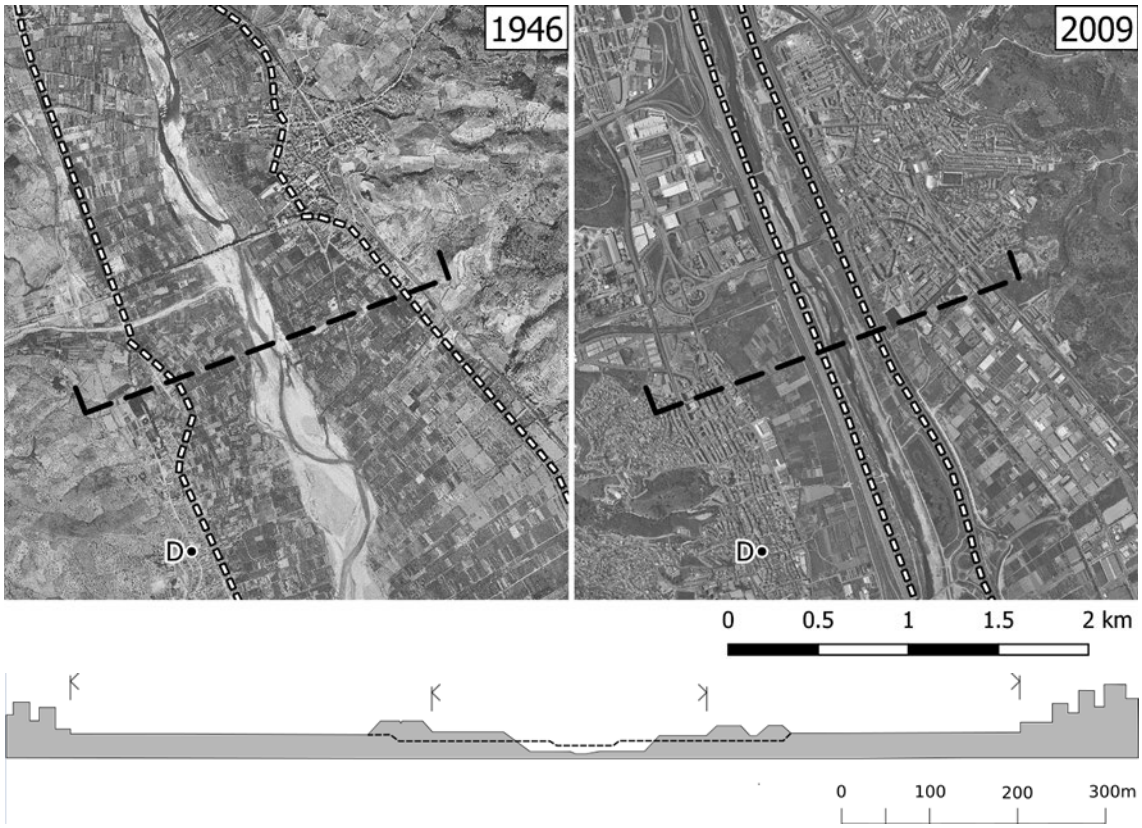

Fig.6. Above: plan view in 1946 (left) and 2009 (right) of the river around town D (see fig.4) in the overlapping of reaches 2 and 3, produced by authors using freely available data from ICGC. Below: cross section in reach 3 taken through the dashed line above.

Some other works are worth mentioning. After the 1944 and 1962 floods, several river training works of lesser scope were executed. Gravel mining operations in the active channel were still minor in 1956, larger in 1965 and their heyday was in 1974, while they were declining again in 1981. Most of the mining pits were located in reaches 2 and 3. Unlike the 1970 left highway, the engineering works for the 1998 highway and railroad included the digging of the channel, from dike to dike, to allow for flow in case of floods.

9 River engineering: supply sources

As presented in §6 for the sediment trapping by dams, the bed material transport of a river reach is the balance between the supply from upstream and the carrying capacity of the reach (Einstein, 1964). Focusing now on supply, table 4 provides metrics to the bed material source of supply. High flows and floods are able to pick particles from the alluvial area, which in this way keeps being alluvial, as seen in the aerial photographs. Thus, table 4 is useful as indicator of the change of supply in time within the lower Llobregat. For example the alluvial bed surface in reach 1 goes down from 148 to 86 Ha in the decade 1946-

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1956 (or from 175 to 100 m in terms of average alluvial width), so that the likely supply to reach 2 from reach 1 is probably reduced in the same proportion.

Unlike the effect of the upland dams, the disturbance of this supply cut is likely able to affect the lower Llobregat, at least the next reach downstream of the one considered, if a disturbance velocity of hundreds of m per year (for ex. 500 m/yr) is reasonable. In one decade then, such as 1946-1956, reach 2 would be affected by the supply cut in reach 1, and so on for the next reaches and decades. Unlike the case of dams as well, this disturbance is not necessarily one of degradation, because each reach downstream suffers a comparable reduction of alluvial bed as the reach upstream. For example, reach 2 goes down from 180 to 110 m in width (table 4) in 1946-1956, at the same time as reach 1 reduces its own from 175 to 100 m. The reduced supply due to a narrower alluvium upstream finds a narrower cross section downstream to carry it further downstream. Whether the difference of supply and carrying capacity is positive or negative, the result will be aggradation or degradation in reach 2 (this argument will be resumed in §10).

Carrying capacities are dealt with next, but the point to be retained now is that the changes of alluvial area in the lower Llobregat are able to control the sediment yield of the river in a period of three to four decades (1946-1981) and even more in the lapse of time until present (1946-2018). Another consequence is that reaches tens of km and farther upstream of the lower basin are not able to affect this sediment yield.

10 River engineering: carrying capacity

The carrying capacity is one of the main topics of river mechanics. A cross-section representative of each date and reach was drawn with the aid of aerial photographs and archival documents. One example is fig. 7 for reach 1 (see also the sketch in fig.6 for a section in the border between reach 2 and 3). Assuming uniform flow and bed shear stress proportional to hydraulics radius and bed slope (table 3), we have applied the bed load Meyer-Peter and Müller (MPM) equation (Wong and Parker, 2006) to each hour of the flow duration curve, with and without reservoirs, to get unit solid discharges, which multiplied by the alluvial widths produce table 5. The mean size Dm (table 3) has also an influence in the result of the MPM equation.

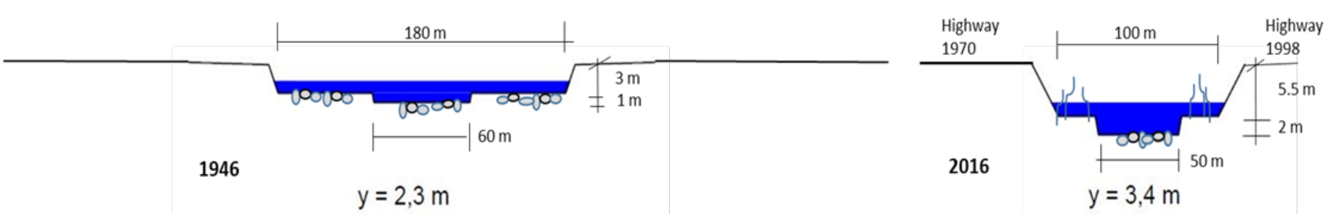

Fig.7. Cross sections of reach 1 for the two extreme dates, 1946 and 2016. Alluvial widths are 175 m and 33 m respectively (table 3). The depth y drawn corresponds to a discharge of 600 m^3/s, within the first day of the flow duration curve.

The ratio of carrying capacity with and without reservoirs is 0.62 for reaches 1-4 and 0.73 for reach 5, on average. In other words, flow regulation by reservoirs is responsible for a reduction of carrying capacity amounting to 38% in most of the lower Llobregat today (reaches 1-4), which is quite more that the reduction of discharge in the flow duration curve of the present flow regime with reservoirs (≈ 20 %, §7).

reach	1, 8.5 km	2, 3 km	3, 8 km	4, 6.5 km	5, 4 km
1946	5.6	12.9	9.6	12.0	12.7
1956	7.5	11.6	8.9	14.2	16.1
1965†	7.5	16.2	9.8	14.1	16.3
1974††	-	7.5 / 4.6	3.8 / 2.3	7.9 / 4.9	13.7 / 10.7
1981	-	8.6 / 5.3	3.0 / 1.8	6.2 / 3.7	13.5 / 10.5
2016	6.3 / 3.9	15.6 / 9.8	8.7 / 5.4	11.4 / 7.9	1.5*/ 0.95*

Table 5. Carrying capacity (× 10^3 m^3/yr) of the five reaches and all years. The underlined figures are the capacity with reservoirs. †computed with none of the reservoirs in operation, ††computed with the three reservoirs in operation, *this figure have to do with the new mouth (see the epilogue) (Prats-Puntí, 2018).

Carrying capacity computed in this way is proportional to the alluvial width. But also, as fig.7 illustrates, it is affected by the depth increase, which implies an increase in shear stress. For high discharges, the unit solid discharge of MPM depends roughly on depth to the 3/2 power. For the example in fig.7, this means a shear stress 1.80 times higher in 2016 than in 1946, which attenuates the large decrease in alluvial width between these two dates (from 175 m to 33 m in average width, table 4).

11 Estimation of the real coarse sediment transport

The balance between supply and carrying capacity states that if the former is larger than the latter, aggradation occurs and the amount conveyed further downstream equals the carrying capacity only, not the supply. If the opposite happens, the amount conveyed is the supply plus material from the bed (and so, degradation occurs), as long as the alluvium is not exhausted but fully available, tending to the carrying capacity at the most. If the two quantities are equal, equilibrium holds.

On the grounds of fig.2, let us assume that the system of river and delta was steadily retreating before 1946, the date of the first quantitative, extensive information, so that supply and capacity changes from 1946 on are disturbances to this state. An attempt to this disturbance analysis is table 6, which combines data of table 4 for supply and table 5 for capacity, in the form of percentages with respect to their 1946 values, either alluvial area (Ha), the surrogate of supply, or computed carrying capacity (m^3/yr). After table 6, in 1956-1965 capacity exceeded supply because it went higher than in 1946 or at least kept quite high, but supply dropped significantly (so, degradation was likely), whereas in 1974-1981 supply exceeded capacity because it was capacity that dropped very much while supply kept still at the previous level (so, aggradation was likely).

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coarse sediment supply > or < bed material carrying capacity (% to 1946)					
reach	1	2	3	4	5
1946	100 = 100	100 = 100	100 = 100	100 = 100	100 = 100
1956	58 < 135	61 < 90	48 < 93	74 < 118	71 < 127
1965	72 < 135	87 < 126	56 < 103	72 < 118	80 < 129
1974	-	91 > 36	45 > 24	75 > 41	86 > 84
1981	-	55 > 41	34 > 19	95 > 31	86 > 83
2016	19 < 70	33 < 76	24 < 56	40 < 66	220 > 7 *

Table 6. Comparison of the amounts of coarse sediment supply and bed material carrying capacity by reaches and years, with reference to a level 100 of both in 1946. The underlined values in table 4 are used; symbols †, †† in table 5 apply here too. Dark grey boxes mean likely aggradation (>), light grey likely degradation (<). *see epilogue.

The main point in table 6 is that the disturbance to the 1946 steadily retreating state observed in 1956 is one of degradation (supply < capacity) for the whole lower river, which probably followed the 1944 flood aggradation (§8). As stated above, the volume dispatched downstream is the capacity if supply > capacity and the capacity at most if supply < capacity. Then, the logical operation < or > in any row of table 6 would allow to transfer amounts in m^3/yr (capacities) to the next period and reach, serving in it as supply (case >) or supply at most (case <), to be compared to capacities in m^3/yr in a consistent way (same unity, m^3/yr). This kind of algorithm is applied to produce table 7 by starting with the 1956 row in table 6 and using the data of table 5. Regarding the "boundary" data, i.e. year 1946 and reach 1, there is no choice but to consider that capacities are dispatched quantities to the next reach and period. This lapse and step of conveyance is justified in §6 and §9 with the velocity of the disturbance created by a cut of supply.

reach	1	2	3	4	5	to coast
1946	5.6	12.9	9.6	12.0	12.7	→ 12.7
1956	7.5	5.6 < 11.6	12.9 > 8.9	9.6 < 14.2	12.0 < 16.1	→<16.1
1965†	7.5	7.5 < 16.2	11.6 > 9.8	8.9 < 14.1	14.2 < 16.3	→<16.3
1974††	-	7.5 > 4.6	16.2 > 2.3	9.8 > 4.9	14.1 > 10.7	→ 10.7
1981	-	5.3	4.6 > 1.8	2.3 < 3.7	4.9 < 10.5	→<10.5
2016	3.9	9.8	5.3 < 5.4	1.8 < 7.9	3.7 > 0.95	→ 0.95

Table 7. Coarse sediment transport (× 10^3 m^3/yr). The quantities at the right-hand side of symbols > or < are capacities from table 5, those at the left-hand side are supplies transferred. Dark and light grey boxes the same meaning as above. Dotted lines with arrows mean transference to the next reach and year, arrows means transference to the coast. The symbols †, †† and * in table 4 apply here too.

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12 Consequences for the coast

Table 7 provides an estimate of the sand sediment yield into the sea in the last column, i.e. ≈ 16×10^3 m^3/yr in the period 1956-1965 but ≈ 10.5×10^3 m^3/yr in 1974-1981. If the river had not been regulated by dams, the yield in 1974-81 would have raised to ≈ 13.5×10^3 m^3/yr (see table 5).

By comparing table 7 with table 1, the river yield in 1946-1981 is lower than both the deficit in the delta (57×10^3 m^3/yr) and the surplus in the beaches (29×10^3 m^3/yr), yet of the same order of magnitude (tens of thousands). Then, the river yield is found to be a substantial factor for the delta evolution, but not the only factor at all. Second, the yield to the delta increased in ≈ 3.0×10^3 m^3/yr from 1946 to 1956 and decreased in ≈ 5.0×10^3 m^3/yr from 1965 to 1974, whereas remained similar in 1956-65 and 1974-81. These features are hardly matched by the temporal distribution of the beach balance in table 1 (only the worsening of the balance in 1965-74 matches our computation, see table 8).

13 Channel incision

Just after the building of the left highway in 1970 (§8), the worst flood of the 20th century (1971) caused a general bed degradation (incision) in reaches 2 and 3. An historical bridge in the middle of fig.6 failed due to the bed lowering (Batalla, 2003).

Similarly, the 2000 flood came just after the construction of the right highway in 1998, which in addition had dug the river channel to fit future floods in. Flows above 1000 m^3/s lasted 12 hours, the receding phase (600 m^3/s on average) lasted 12 more hours. The comparison of the 1998 as-built river long profile and the survey after the flood proved incisions of 0.6 m along 2.5 km of reach 1 (yet locally more than 1.5 m), a minor amount in reach 2 and 0.5 m along 3.0 km of reach 3. Therefore, the volume of alluvium scoured by incision was 70×10^3 m^3 in reach 1 and 55×10^3 m^3 in reach 3.

Two lessons are learnt from these data: i) river bed provides material to the sediment transport, as theory claims, as long as the alluvium does not get exhausted; for example, the 'valley' reaches (1-3) must have issued more than 75 + 50 = 125×10^3 m^3 of bed load to the 'delta' reaches (4-5) in 24 h. Therefore, ii) extreme floods are dominant in the sediment balance, after comparing this figure to those in tables 1 and 7. The carrying capacity computed with hourly data has enough resolution for hydrographs, but the period 2002-2018 of the gauging station data has not caught any extreme flood such as the 2000 flood.

Therefore, the previous estimate of the coarse river yield as 10.5×10^3—16×10^3 m^3/yr may be a large underestimation in years with one extreme flood, since the delta evolution may be mostly driven by the sediment carried during these flood pulses.

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Table 8 gathers, for the four periods of analysis, the sediment deficit at the delta (table 1), the computed change in sediment yield (table 7) and the occurrence of floods, which should push the balance towards less negative figures of deficit at delta.

	1946-56	1956-65	1965-74	1974-81
deficit at delta (x=15-24 km) (10^3×m^3 /yr)	—84	—54	(2)—52	(2)—30
computed change, sediment yield (10^3×m^3 /yr)	< +3.4	≈ 0	> —5.6	≈ 0
any extreme flood in the period ? if so, Q (m^3/s)	NO	2100	3100	1600

Table 8. Comparison of table 1 and the differences in table 7, for the deficit at the delta and the change in sediment yield. Flood discharges come from §8. (2) see table 1.

14 Epilogue about the new mouth and closure with real data

A new mouth of the Llobregat river, moving the channel southwards across the delta to let more room for the port of Barcelona, was opened in 2004 (see fig.4). It is a very wide canal (width from 105 m to 215 m at the end) with a flat bottom excavated at elevation —2 m (below sea level). In other geographical settings, this canal could have functioned as an estuary, but these are rare in the Mediterranean sea. The new width is more than twice the original one (table 4), so that its carrying capacity (table 5) and, then, its sediment transport (table 6) go down one order of magnitude below original figures. The bottom elevation is also much lower than the original one. Therefore, it was prone to silt up.

It was not a surprise, then, that a survey in 2009 disclosed a sedimentation of 700×10^3 m^3 in the new mouth (or 0.5 m of aggradation throughout), i.e. an average of 140×10^3 m^3/yr in 2004-2009. Material trapped in the new mouth is not only sand, of course, but the finer suspended load and part of wash load, as well. Moreover, the concentration of suspended sediment was measured in 1995-2002 in the above mentioned gauging station (see fig.4), resulting a total suspended yield of ≈ 90×10^3 m^3/yr (Liquete et al, 2009, assuming a sediment density of 1.1 t/ m^3 for fresh sediments, Batalla, 2003). These daily measurements failed to monitor in detail the large discharge events, as the 2000 flood. Therefore, the case in hand proves that measurements of concentration in suspension at the station underestimate the actual yield.

15 Discussion and conclusions

The ratio of the bed load computed above (for years with no extreme floods, i.e. 10.5—16×10^3 m^3/yr) and the total sediment load trapped in the new mouth (excluding bed load) is ≈ 10 %. For six Mediterranean rivers: Ebro (Spain), Rhône and Var (France) and Arno, Pescara and Po (Italy) this ratio goes from 2% to 17% with an average of 7%. For the subset of Arno, Pescara and Var, the most similar in size to Llobregat river, the average ratio is 9% (Syvitski and Saito, 2007). This result brings confidence to the computation of this paper, which gets confirmation on the grounds of: i) the total load trapped in the new mouth, and ii) the typical bed to total load ratio in Mediterranean rivers of similar size.

The case-studies of rivers in southeastern France (Liébault and Piegay, 2002) and river Arno (Rinaldi and Simon, 1998) suggest that the Llobregat delta retreat in the first half of the 20th century was the consequence of a reforestation policy, applied to Catalan and Spanish basins as in the French and Italian examples. This factor may have kept being influential in the second half of the 20th century, according to table 2, which shows a decrease of sediment sources (less agriculture and more forest) and an increase of runoff (more urban). The attempt to correlate the channelization of the lower Llobregat since 1970 to the contemporary delta retreat (or any escalation or damping of it) was not satisfactory. The delta kept receding since 1946, more or less steadily, although the retreat was more severe in 1946-1956 and progressively less until 1974-1981. In parallel, the coarse sediment yield decreased steadily after a peak around 1956 (table 8).

The attempt to connect river sediment supply with delta recession has produced an estimate of the annual coarse (sand) sediment yield of Llobregat river. If no extreme floods occur in a year, the computed coarse sediment yield results 10% of the total sediment yield, measured accidentally in the dysfunctional new river mouth. The resulting figure of the order of 13×10^3 m^3/yr is, thus, reliable. One extreme flood, such as several known historical floods (1971, 2000), may exceed this amount by large (one order of magnitude) in just one day. Similarly to the role of sea storms, the role of river floods are also crucial in the actual evolution of the coastline, despite only having recordings in the past separated by decades. The customary assumption of a "steady river" by coastal specialists is equally wrong as the customary assumption of a "steady sea" by river specialists.

The river sediment yield to the delta has not been reduced more heavily so far, i.e. much below 13×10^3 m^3/yr, because alluvial beds have provided much material, at the cost of severe bed degradation in reaches 1 and 3 of the main course, not to say in tributary 3 (Martin-Vide and Andreatta, 2009). However, the sediment supply is hampered since 2004 by the new mouth, which acts as a sediment trap, in such a way that the actual yield is indeed reduced in one order of magnitude to $\approx1\times10^3$ m^3/yr (table 7).

The bed-material sediment yield in the last 50-70 years has been heavily influenced by the channelization works in the lower Llobregat. It is a fact that sources of alluvial bed sediment got reduced in the period, for example to just 29% (2016) in reaches 1-4, out of what they were in 1946, or to just 45% in reaches 2-4 (2016) with respect to 1974 (tables 4 and 6). The channelization reduced also the sediment carrying capacity (tables 5 and 6), for example to 67% in reaches 1-4 (2016) out of what it was in 1946. The channelization is close enough to the sea for the disturbance produced by the works to be felt. The "cut" of supply is not more influential in the sediment yield to the delta because the alluvium is not yet exhausted. However, its likely future exhaustion under a completely channelized river (and the "help" of a sediment trap at the new mouth, specially if this "estuary" is dug out for maintenance) is a future scenario of very severe sediment cut for the delta and its beaches.

In the attempt to connect river and delta it has been demonstrated that the sediment trapping at the dams may not be as influential on the annual sediment yield as the effect of flow regulation due to them. Flow regulation implies a reduction of carrying capacity amounting to 38%. However, some moderate effects of sediment trapping at dams should appear in the long term.

What controls coarse sediment yield in the Llobregat river? It must be concluded that the availability of sediment in the last 30 km has been the key factor in the time frame of the last several decades. Availability of sources in a wide river channel and floodplains would have guaranteed the conservation of a sufficient supply of sediment to the downstream reaches. A reservoir management mimicking real floods would have helped.

A consequence for a management aimed at providing sand to the beaches is that it is more effective a step back from the channelization than the efforts to pass sediment at dams. In a longer time horizon and long-term management aims, the river reaches participating in this policy of guaranteeing supply of sediment would gradually go extending further upstream of the lower Llobregat reach examined in this paper.

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