RESPONSE TO REVIEW by Carles Ibáñez. Our answers in blue

Very interesting paper that, however, shows some important caveats that need to be solved before a decision of publication can be made. The paper needs a major change in the focus and the specific goals to sort out the weak points that contains right now.

The starting point is the observed secular coastal retreat of the Llobregat Delta. This is an interesting new piece of information that gives value to the manuscript but at the same time shows the limitation of the approach taken. For me it was a surprise to see that the Delta was already retreating quickly by the end of the XIX century and that the retreat kept going all over the time till nowadays. This is very interesting, but in my opinion the possible causes argued in the manuscript to explain it are not convincing. In terms of damming the authors mention two dams built in the last decades in the upper basin, while river channelization is also relatively recent and cannot be the main cause of such a dramatic coastal erosion. The main argued possible cause is reforestation, but again the process is not so widespread from the beginning of the observed retreat and the increase in forest cover along the study period is not so large to explain the most of the deficit in sand delivery to the delta. According to Table 2 forest shifted from a cover of 63% in 1956 to a cover of 70% in 2009 for the whole river basin, and this is the main period of afforestation, mostly driven by the abandonment of traditional farming and public policies during the last decades of the dictatorship regime. At the same time, data also shows that large floods (a major source of sand delivery to the coast) have apparently been occurring all along the study period (a more detailed analysis of the changes in river floods along time could help to understand what's going on).

The reviewer is right. The land use change is now considered a minor factor. The role of the floods has deserved more consideration in the new text.

There must be other causes to explain the sediment deficit in the delta, and the main one that comes to me is the widespread construction of weirs in the Llobregat River and its main tributaries (such as the Cardener) for industrial production (mostly textile) and for hydropower, that was already important in the XIX century. This chain of small reservoirs certainly modified in a dramatic way the hydro-sedimentary dynamics of the Llobregat River and tributaries, and could mostly explain what happened in the Llobregat Delta in terms of erosion. Thus, the paper needs to investigate this point as much as possible, both in terms of data (on the evolution of damming in the basin), mechanisms (how this damming modifies the sedimentary dynamics) and potential effects on sand delivery to the coast.

The reviewer is right. Thanks for the suggestion, which has produced a strong change in the discussion section of the new text. It has been proved the paramount role of these weirs (small dams), standing in the middle reaches of the river, on the sediment dynamics.

In relation to the other analysed mechanisms that could explain in part the changes in river sediment dynamics and delivery to the coast (section 4), I have some other relevant comments:

Land uses and urbanization: as mentioned in the text the change in forest cover is modest, I do not think it can be claimed as the main reason for the sediment deficit in the delta, though it may have some effect (see Ibáñez et al. 2019 and Nienhuis et al. 2020). Besides analysing the changes in land use, is there any possibility to estimate the relative contribution of this phenomenon to the sediment deficit? (the same question applies to the other drivers of change in sediment dynamics in the river).

The effect of changes in land use are rather connected to the wash load component of the sediment transport, which was not the purpose of the paper (it was bed load instead). We could not have improved the estimates done in the references mentioned by the reviewer, which are duly incorporated in the new paper.

Dams (sediment trapping): the authors mention that the percent of sediment retention in the two reservoirs of the upper basin may be proportional to the percent surface area that they close. However, it is well known that most of the erosion worldwide comes from the upper parts of the river basins. See for instance Wilkinson & McElroy (2007): Consideration of the variation in large river sediment loads and the geomorphology of respective river basin catchments suggests that natural erosion is primarily confined to drainage headwaters; ∼83% of the global river sediment flux is derived from the highest 10% of Earth's surface.

Then one should expect a higher proportion of sediment retention due to the two dams, which would be concentrated in the last decades, after dam construction.

The reviewer is right. The paragraph about sediment trap in reservoirs is corrected accordingly.

Dams (hydrological changes): I am not sure it’s a good idea to combine the effect of dam regulation with river engineering to estimate changes in sediment delivery to the coast. In any case, it would be important to have at least an estimate of the change in carrying capacity for the whole river, not only the lower basin.

The combination of dam regulation and river works produced an estimate of the reduction in carrying capacity in the lower Llobregat, as the reviewer says. This was based on careful archival research of historical river cross-sections, bed gradients and so on, which was possible for the very populated lower Llobregat, not anywhere else. However, the same reduction in carrying capacity for the rest of the river is attempted in the discussion just thanks to the new information about the weirs (small dams).

Climate change (rainfall and runoff): this possible driver of change in sediment delivery to the coast has been neglected and could be significant. Sand transport capacity is mostly driven by river flow, so changes in river flow due to changes in rainfall and runoff could play a significant role. This possibility should be analysed (see Xing et al., 2014).

Climate change has not been neglected, actually, but put aside. We think climate change is essential to predict the future of the river and delta, but the purpose of the paper was to explain the past changes, specially in the main period of analysis 1946-1981 (in the discussion it has been extended back to XIX century).

Channelization and flood plain alteration (river engineering): again the analysis of the alteration of the river bed and the alluvial valley focuses only in the lower river basin, but is quite clear that most of the river basin is engineered (including small dams and other works). So, what is the global contribution of river engineering to the reduction of sediment delivery to the delta? Please try to make a global estimate if possible.

The role of river engineering in most of the river is now dealt with in the discussion. It is clear now the paramount role of these weirs (small dams), which sum up almost 400 m of head and many kilometres of influence. The estimate we make now is that 80% of the reduction of sediment delivery to the delta is due to the XIX-century engineering works in the middle reaches (small dams) IN COMBINATION WITH a period of anomalous hydrology in 1830-1870. The remaining 20% is due to the XX century encroachment by infrastructures.

Sand mining: it is mentioned but it would be interesting to have more quantitative information to know the relevance of this activity on the sand deficit to the delta.

Although there are some data about mining, it is not clear to what extent these extractions participate in the bed load dynamics, provided that most of them are located in the floodplains.

Other relevant comments regarding beach retreat (sect ion 3):

It would be interesting to add an extra graph or table to assess the evolution of the coastal erosion in the delta all over the study period, for instance in the river mouth, in order to see if there is any trend along time and also try to see if this trends match with the assessed trends in sediment delivery to the coast.

This is done in table 8, by doing our best with the data. For the river mouth specifically, the graph in fig.3 is what the reviewer is asking for. Note that the comparison between the delta and the sediment delivery is restricted to long periods of roughly one decade, because of the calendar of aerial photographs at those times.

Sediment dynamics in the delta:

"The reach is a sedimentary unit throughout the whole period 1891-1981" (lines 60-61). This is not strictly correct, depends on the interpretation of the sentence. Figure 3 shows two different sedimentary units "erosion-accretion" (quite typical in many deltas). This is likely explained by the existence of an old river mouth around Km 10. So it is a sedimentary unit composed by two sub-units.

The reviewer is right. The text is changed accordingly.

Limits of the Llobregat Delta and sand losses Southwards:

"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" (lines 73-74). "The calculation yields a deficit of 57.000 m3/yr in the delta (x= 15-24 km) and a surplus of 29.000 m3/yr in the beaches west of it (X= 0-15 km)" (lines 93-94).

The two sentences should be modified, since the delta is the whole stretch from km 0 to km 24. All deltas have sections with erosion and the corresponding sections with accretion due to the eroding stretch located "upstream" (in relation to the long-shore transport).

The reviewer is right, also. The text is changed accordingly.

"The negative balance (loss of sand) can be explained by the partially open western boundary (at x=0)" (lines 101-102).

I am no sure that this is the correct explanation. Is there information showing that this volume of sand leaving the delta (quite a lot) is accumulating nearby? Could be the case that there are errors in the calculation of the sediment budget?

The error in the budget, computed on the grounds of aerial photographs and the USGS procedure, must be small, not more than the accuracy of aerial photographs. We could not find information showing this loss of sand, not even in the publications by well-known CIIRC research centre (referred in the paper).

Last but not least I recommend to change the structure and title of the manuscript. I suggest something like: "Changes in coarse sediment delivery to the coast during the last century in the Llobregat River: causes and consequences".

We remained attached to our title. We think that "What controls" stands for "Changes in" in the reviewer's alternative title, ídem "yield" for "delivery", "to a delta" for "to the coast". The time reference "during the last century" in the alternative is misleading in our view, because the centre of attention is only 1946-1981 and secondly because we have had to look back to 1816 (date of the starting of factory construction), that is to say to TWO centuries. But a title "...to the coast during the last TWO centuries…" would also be misleading, in our view.

In terms of structure I would simplify it and present data in a more integrated way, including a table summarizing the estimated contribution of each component to the changes in sediment delivery and what are the data gaps necessary to get a better estimate.

The table summarizing the contribution of each component is well beyond our knowledge and abilities. However, some 80% share by the old engineering works in the middle river, and the remaining 20% by the new encroachment of the lower river, was obtained and is highlighted in the conclusion section.

References

Ibáñez, C., Alcaraz, C., Caiola, N., Prado, P., Trobajo, R., Benito, X., ... & Syvitski, J. P. M. (2019). Basin-scale land use impacts on world deltas: Human vs natural forcings. Global and planetary change, 173, 24-32.

Nienhuis, J. H., Ashton, A. D., Edmonds, D. A., Hoitink, A. J. F., Kettner, A. J., Rowland, J. C., & Törnqvist, T. E. (2020). Global-scale human impact on delta morphology has led to net land area gain. Nature, 577(7791), 514-518.

Wilkinson, B. H., & McElroy, B. J. (2007). The impact of humans on continental erosion and sedimentation. Geological Society of America Bulletin, 119(1-2), 140-156.

Xing, F., Kettner, A. J., Ashton, A., Giosan, L., Ibáñez, C., & Kaplan, J. O. (2014). Fluvial response to climate variations and anthropogenic perturbations for the Ebro River, Spain in the last 4000 years. Science of the total environment, 473, 20-31.

Most the theses references have been mentioned/discussed in the text and added to the reference list.

RESPONSE TO ANONYMOUS REVIEW

The authors thank the reviewer for his/her careful reading of the manuscript and fruitful comments. The paper is indeed, as reviewer says, a historical overview of the interventions and changes in the Llobregat basin and main channel (including some other interventions in the middle reach to be added to the final manuscript to be submitted, thanks to the first reviewer). What is probably a nice but excessive statement by the reviewer is that we have collected "a comprehensive data set", since we just were able, at great pains, to draw one typical cross-section for each of the five reaches of the lower Llobregat, together with one bed slope and one mean grain size, for each of the five dates analysed (from 1946 till 1981). If geometrical data of this kind having more resolution are certainly available for the last date (1981), the need of a fair comparison with the old dates warranted not to involve more detailed information from recent dates in the analysis.

The reviewer is right in the **fourth paragraph** in that it would have been better to use a one-dimensional model coupling Saint-Venant and Exner equations for the estimation of sediment transport and bed changes. Thanks to the comment, we plan to do that in the future. At the moment, however, we have two answers that may nuance the reviewer's assertion (they do nuance it in our view):

1) the very simple geometrical information available, mentioned in the paragraph above, makes less interesting such a numerical model (only five different cross-section, one per reach, along 30 km). It is so because the use of a mass of model results for comparison between different dates would require to average them very much in time (one decade) and space (several km), in a way which is not unequivocal; we wonder if it is not better, in general terms, to average the data before computation that to average the results after computation; in fact, we think that this is a topic of research in itself, to carry on in the future,

2) any model of the type mentioned should use an empirical bedload equation as "closure" of the system of Saint-Venant and Exner equations, that is to say a particular function for the unit bedload rate q_s in Exner eq., no matter this being Meyer-Peter and Müller (as in the paper) or any other else. We think that, in this way, the role of a supply-controlled sediment transport, in the reaches where this is the case, is not captured in the model, which in our view is, therefore, a capacity sediment transport model, strictly speaking.

Nevertheless, we agree with the reviewer that such a model would at least improve the analysis in unsteady flow (although flood hydrographs of past events are rare, let alone any sediment transport rates in floods) and would also overcome the "crude" assumption of propagation of changes between reaches at the time of the available data. Regarding this point, the literature supports the figure used in the paper, 500 m/year in average. Furthermore, the interventions in the middle reach (to be submitted in the proposed final paper) shed more light in the sense that this figure may be reasonable.

We agree with the reviewer's reasoning in the **second paragraph**. This is how the river bed reacts to a local (or not so local) narrowing (for ex. a channelization), no doubt, as has been proved by experiments and by conceptual models of equilibrium, as well. However, again we express some nuances to the application of the reviewer's point of view to our case, without questioning at all the physics in it. Is the narrowing paradigm appropriate to our case?:

1) the floodplain area, made of coarse sediment exposed to entrainment in case of overbank flows, more than the basin area, as reviewer claims, determines the bedload in the lower river, according to the concepts of sediment origin. In fact, in longer time lapses, longer reaches of the alluvial channel, further upstream of the lower Llobregat studied in the paper, would participate in providing coarse sediment for bedload transport to the delta (again, the proposed final paper deals with this).

2) it is never a pure narrowing, i.e. a width change in space, what occurs properly, but a cumbersome spatial-temporal width change, quite general for all reaches (though varied in intensity, it is true), from one date to the following ten years apart. Seen from the neighbour reach downstream, a reduction in the sediment supply has occurred, with one decade of time to have made it feel in its balance. Alternatively, seen from the neighbour reach upstream, a reduction in carrying capacity has occurred in the downstream reach, as well, because the width has reduced after a decade of time for bedload work. Both terms of the balance change. Finally, seen from the reach itself whose width has reduced, questions arise about whether this channel narrowing is externally imposed (as if in a channelization) or results from an upstream reduction in sediment supply or from a upstream-propagating incision process taking place on downstream reaches.

3) the reviewer's physical reasoning leads to a slope change within the narrowed reach in the long term (as the effect of narrowing develops). However, the channels slopes, taken from the archival sources of information, show very little changes in time. This point may make more clear that the physical approach of narrowing (reviewer's approach) and our approach of bed load supply and capacity averaged in long periods of time differ. Reality is only one, different approaches should converge to reality. Moreover, what reviewer points out in **third paragraph** is certainly right. Regarding this, we have not compared the capacities at the two contiguous reaches but one capacity at the reach downstream of the two and one supply from the one upstream of them, which is not necessarily equal to its capacity.

With respect to the rest of the review, we have included the references and details that the reviewer demands in the sixth paragraph. The section called "epilogue" is now section 12 entitled "The new mouth and closure of the computation with real data" (not epilogue any more). This section still stands after the computation, not in the data section, because the paper focus on the period 1946-1981, while the new mouth (2004) was a much later development of a very different nature. However, its role of allowing a check of the previous computation is highlighted with the words "closure… with real data". In table 1, the sign — for deficit and + for surplus, under the headings deficit and surplus, is redundant, but mistakes are avoided, in our view. We are attached to tables instead of bar plots, in spite of being more demanding for the reader. However, the flow duration curve is added to the new version of the paper.

THE REVISED VERSION IN TRACKED CHANGES OPTION FOLLOWS.

ALL CHANGES MADE IN THE REVISED VERSION WITH RESPECT TO THE FIRST ONE ARE VISIBLE IN THIS OPTION.

ANSWERS TO THE REVIEWERS, SPECIALLY WHERE WE HAVE REFERRED TO “new version to be submitted” ARE MORE CLEAR THROUGH THIS OPTION.

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 7~~5~~0 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 limited measurements and bulk volumes of trapped material at a deep river mouth. Sediment availability in the last 30 km of the channelised river~~ channel~~ is deemed responsible for the decrease in the sediment yield to the delta. Moreover, reforestation, power development and flood frequency are~~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 7~~5~~0 years, over which the main pressure has been one of channelization, yet some information prior to this period will be necessary to understand the long term trends~~is presented as well~~. The practice of channelizing a river generally involves increasing channel capacity and so, an erosional response, due to an enhanced sediment carrying capacity, 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 floodplain width reduction (encroachment 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 the degradation of a 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 transfer~~tloss~~ 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 less well known in physical terms, in spite of statistical approaches (Ibañez et al., 2019, Xing et al. 2014)~~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). A~~This~~ connection of this type 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 decades~~periods~~ is followed, by using real data on the long river profile, the grain size of the available alluvium~~sediment~~ and the annual high flows and small floods. The focus is on what controls the coarse sediment yield into the sea, nourishing the beaches with sand.~~, because~~ T~~t~~he retreat of beaches (close to deltas) is a big concern in the Mediterranean region (‘coarse’ means sand herein). What controls the yield into the sea implies, as a consequence, which measures are more sensible in order to keep providing enough sand to the beaches.

~~**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 current delta in the Mediterranean sea since Roman times, up to almost an area of 100 km^2 (Marquès, 1984).~~.~~ Geologists say the delta results from the Holocene transgression (6000 years ago, Ibáñez et al, 2019), yet we are more interested in the delta evolution in the last century (within the so-call Anthropocene). 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, following ~~(~~Orton and Reading, (1993). More river features and flood history will be given opportunely.

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 carrying capacity of bed load. A closure with real data allows to draw conclusions on what controls the river sediment yield.

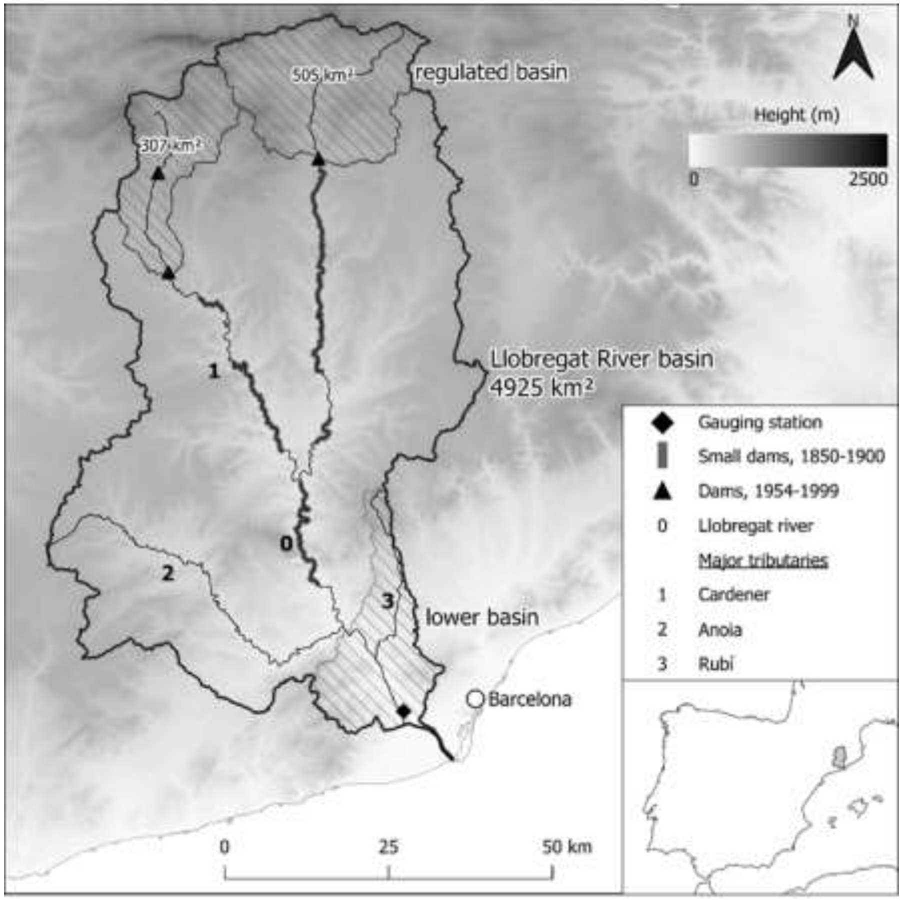

Fig.1. Location map. For lower basin see zoom in fig.4. For small dams see discussion section.

23 Beach retreat

Contrary to the delta building up in old times, it is heavily receding in the last century. Fig.2 shows the coastline in the area of the river mouth since 1891 until 1956, with point data forin 1862 and 1907 (taking advantage of the mouth lighthouse, that was much inland at that time) and two intermediate lines aerial photographs in 1926 from a map and 1946 from an aerial photograph. Three more of them, dated 1965, 1974 and 1981 show further receding of the coastline. The coast is a 24 km-long beach (fig.3), 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 modern interventions, the present analysis is limited to the period 1891-1981 and more accurately to 1946-1981, although we will resort to other facts dated XIX century in the discussion.. The current situation of the river mouth since 2004 is presented as an epilogue at the end of the paper.

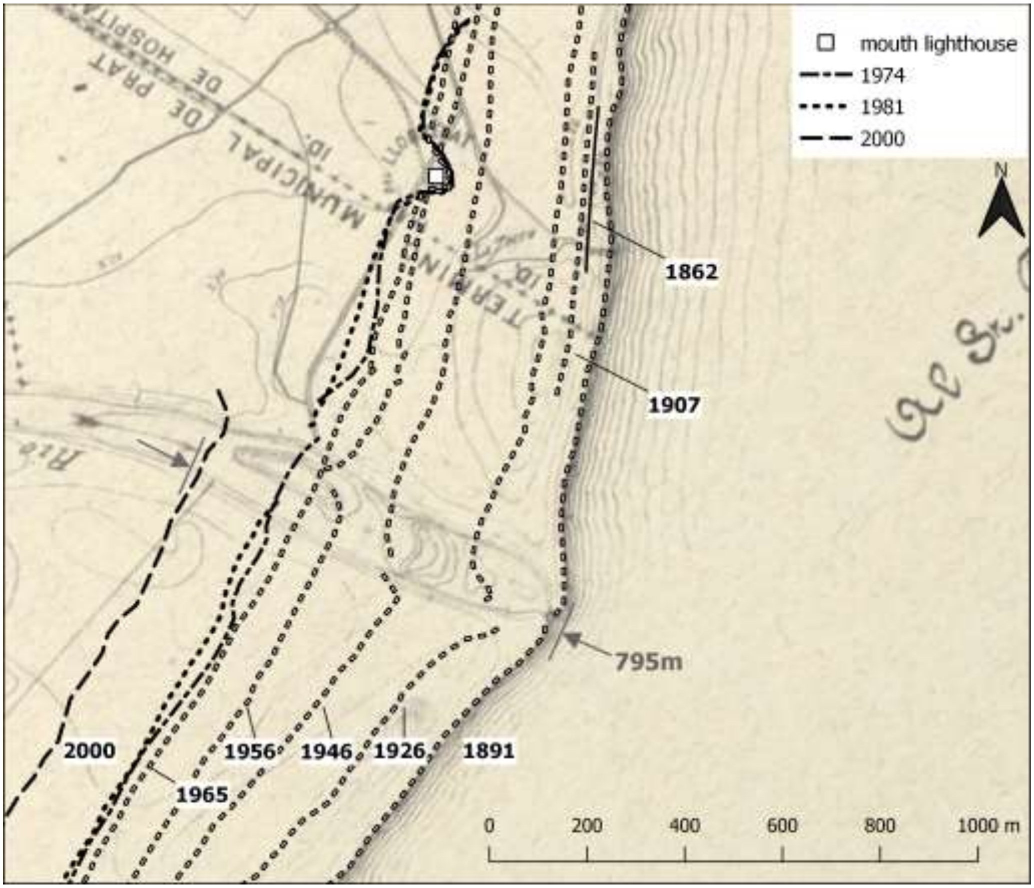

Fig.2. Coastline retreat in the Llobregat delta since 1891 (date of the map in the background, as well). Figure produced by authors using our own and freely available data from Institut Cartogràfic i Geològic de Catalunya (ICGC). The 1862 line comes from Marcos (1995). The lighthouse was built as a watchtower in 1567. Drawings show its location well inland in the XVII century. It was turned into a lighthouse in 1852 to prevent ships to get stuck in the sandbanks of the river mouth.

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 and the coast is not intervened yet. 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. The delta is then composed of two sedimentary subunits. It is even conjecturable an old river mouth around km 10

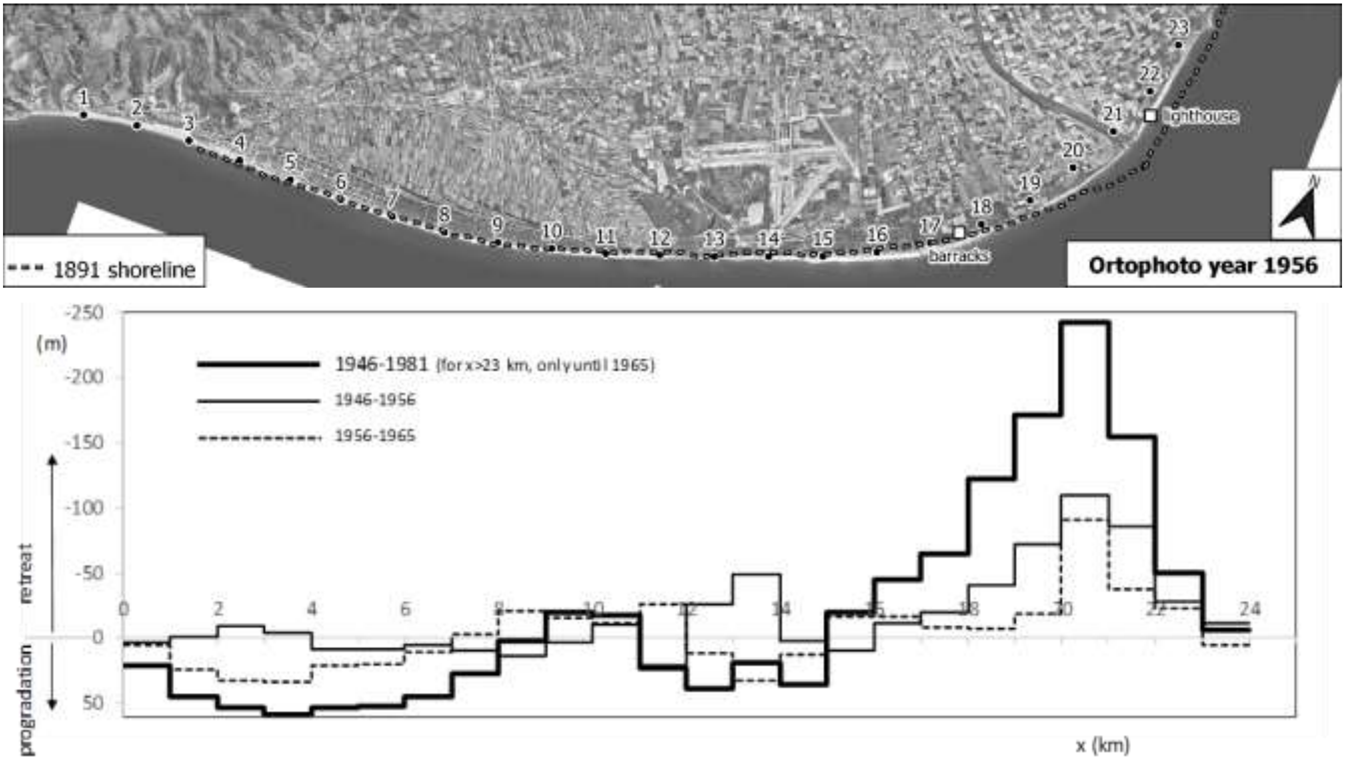

Fig.3. Above: the 24 km-long sedimentary unit (delta), produced by authors using freely available data from ICGC. Below: Total change in m perpendicular to the coastline in ordinates (progradation +, or retreat –) along the coastline above in the period 1946-1981 and in two decades within it. Apart from the lighthouse in fig.2, the history of the barracks at x≈ 17.5 km in 1844 is also known: since that date until 1934 the coastline prograded 179 m (Paladella and Faura, 1935).

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 north~~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):

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

Table 1. Volumes of change of sand (× 10^3 m^3 per year), distributed by decades and by region (oval delta in the north and beaches west of it). * it is a deficit, actually, not a surplus, note the minus sign, (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 in ~~(~~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—75×10^3 m^3/yr) seems capable, by order of magnitude, to take these amounts of sand from North ~~(delta)~~ to West beaches ~~(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 1946-1981? 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 in 1946-1981, although discussion of the results will require to go back to the river condition in the XIX century. Before that, the causes of decrease in river sediment yield are examined next.

3~~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 since 1946 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.

4~~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) (CREAF research center). 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 agricultural fields and urban. There is some channelization in thise 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).

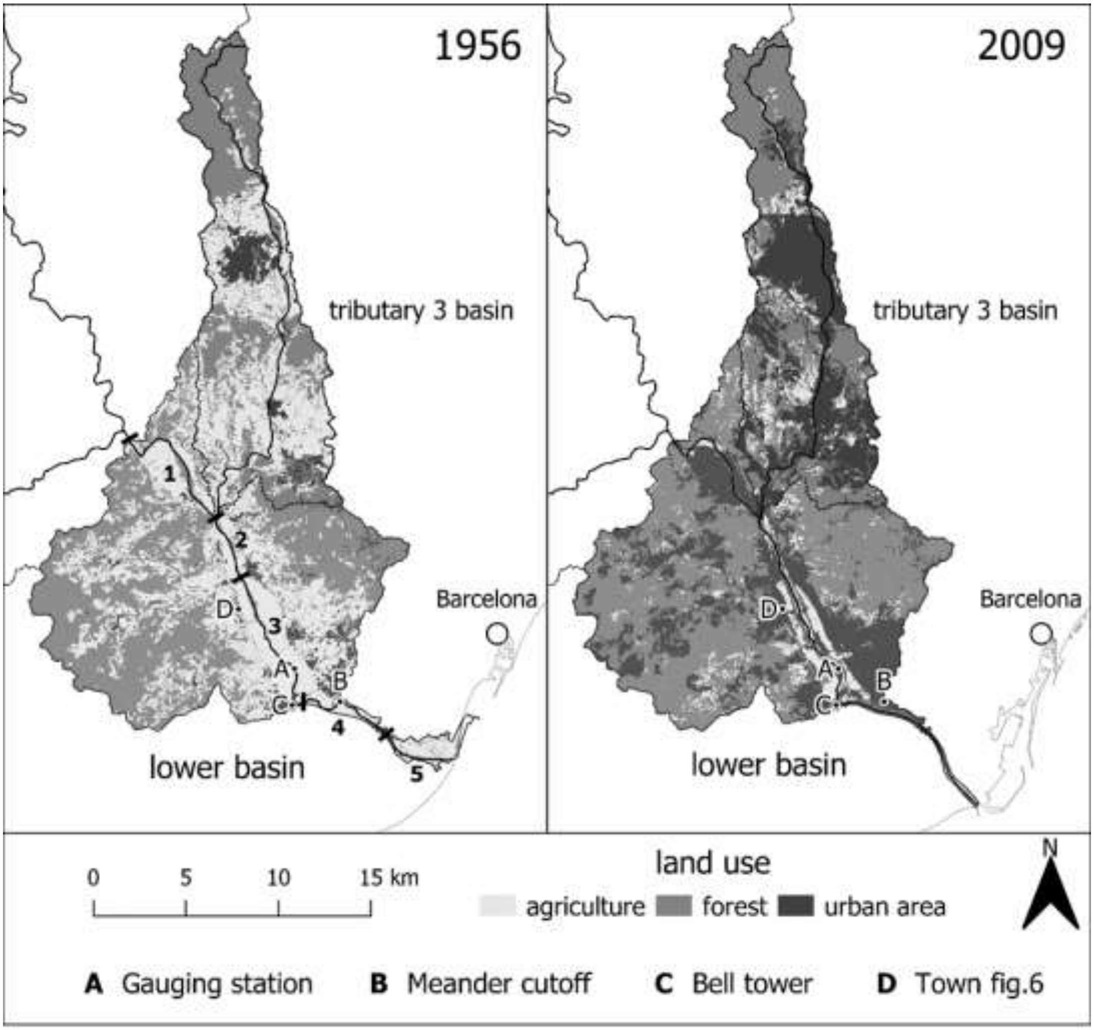

Fig.4. Land use changes in the Llobregat lower basin. Figure produced by authors using our own and freely available data from CREAF public research center. Note the added information on the lower river (reaches nr. 1 to 5 used in the analysis and reference points A to D mentioned in the text).

5~~6~~ Reservoirs: sediment trapping

In the upper basin the~~The~~re are two areas regulated by dams ~~dams in the upper basin~~ (fig.1). One dam controls a 505 km^2 catchment, with a reservoir of 109 ~~H~~hm^3, since 1975. The second dam, in tributary 1, controls a 307 km^2 catchment, with a small reservoir of 24 h~~H~~m^3 since 1954 (inside this second catchment, another dam with a volume of 80 h~~H~~m^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.

~~Thus, if soil erodibility is uniform throughout, some 16.5% of the~~ S~~s~~ediment load coming from the regulated basin as wash load will be mostly trapped in the reservoirs, but ~~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~~ the drainage network density is similar all over the whole basin, but main rivers and tributaries are steeper in the mountainous regulated basins~~and narrower cross-sections up there~~. Thus, the supply of coarse sediment from channels to the reservoirs is probably larger than~~similar to a~~ 16.5% of the same~~total~~ load at the river mouth (Wilkinson and McElroy, 2007). Sediment supply is resumed in §9.

The previous reasoning must be extended to~~involves~~ the flux of coarse sediment along the channel down to the river mouth. 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 basin areas~~s~~, its effect was barely noticeable on the mouths of rivers with lengths in the range 5—150 km by 2005.~~.~~ 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 (§2~~3~~). In the long term, this trapping will come into picture, but would not probably be a crucial factor if the amount trapped is not much larger than~~because of a decrease less than~~ 16.5 % of the total supply.

6~~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 to represent~~, and so representative of~~ flows and reservoir management for~~, to~~ computation of~~e~~ an average flow duration curve with reservoirs. Indeed, it is long enough to handle normal flows and annual floods, but not to take into account large floods, those occurring at return periods larger than, let’s say, 10 years. Since no such large flood occurred in the period 2002-2018, the selected data describe normal flows and annual floods. The~~is~~ flow duration curve is done with the hourly data at the downstream-most gauging station (see fig.1 and 4). Moreover, this curve together with the contemporary measured daily levels at the reservoirs allow to compute a new 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, according to the hydrographs of a real flood, 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 and water resources changes, such as: *a*) water abstractions for irrigation and supply along the river, *b*) basin runoff due to land uses, and *c*) rainfall regime~~, even~~ under the climate~~ic change~~. It is not meant at all that flows are not impacted by *a*), *b*) and *c*), but only that 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 (climate), the runoff (land use) and the abstraction (water use) had been. Under this assumption, the curve without reservoirs represents the state prior to 1954. Note that in this way we have circumvented the lack of any substantial river flow data prior to 1954. Moreover, if these data had existed, their use in comparison with the period 2002-2018 would have brought serious doubts of data homogeneity, just because abstractions, runoff and probably also rainfall regime have changed.

The main result~~s~~ of this computation is~~are: 1) without reservoirs~~ that flow is higher without reservoirs than with them~~reservoirs~~ throughout the first 130 days; the opposite happens over the rest of the year (fig.5). ~~, and 2) t~~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 §9~~10~~.

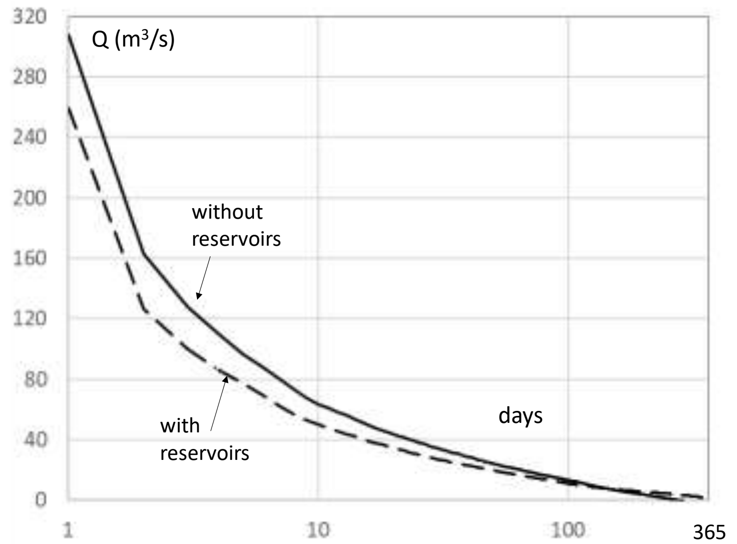

Fig.5. Flow duration curves at the gauging station (see fig.1 for location) with and without reservoirs. Log scale for days.

7~~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 in the XX century, 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 defenc~~s~~es) are obtained from these archives. Large~~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) (Codina, 1971). ~~.~~The 3-year period ending in 1944 is described in the documents as causing general aggradation. Just for reference, 1278 m^3/s has been estimated as the 10-year return period flood and 3050 m^3/s as the 100-year flood (Martín-Vide, 2007). The large floods in the XIX century will be mentioned in the discussion section.

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)]

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 D_{50}=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 D_{50} = 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 have~~s~~ been extremely large. Table 4 collects the alluvial bed surfaces in hectares, strictly considered (excluding areas of early colonizing plants), obtained from the series of aerial photographs (§2~~3~~). The average width in the table is the alluvial area divided by~~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.
l~~L~~ength (km)	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~~ **§12**~~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.6~~5~~, both photographs taken from the bell tower of town C (see fig.4 for location). The same conclusion of a dramatic change 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.

Fig.65. 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 (built as 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.76 is a close view of a particular section around town D (fig.4 for location). 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.

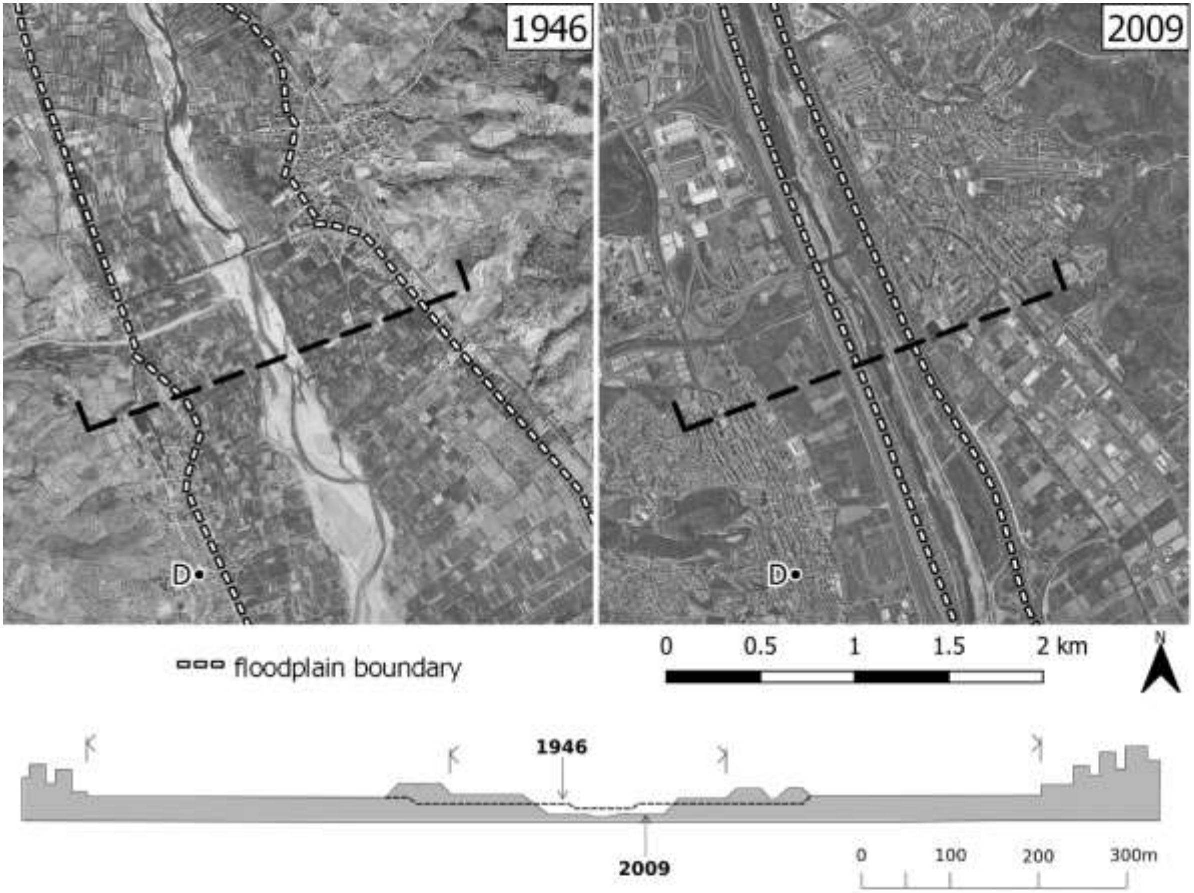

Fig.76. Above: plan view in 1946 (left) and 2009 (right) of the river around town D (see fig.4 for location) in the overlapping of reaches 2 and 3, produced by authors using freely available data from ICGC. The bridge (fig.10) failed in 1971. Below: cross section in reach 3 taken through the dashed line 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.

89 River engineering: supply sources

As presented in §56 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 thoese alluvial sourcesarea, 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 1946-1956 (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. The supply to reach 1 from further upstream is treated in the discussion.

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, Liébault et al, 2005) 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 agains 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 width 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 §910).

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.

910 River engineering: carrying capacity

The carrying capacity is one of the main topics of river mechanics. A cross-section representative of each date and each reach was drawn with the aid of aerial photographs and archival documents. One example is fig. 87 for reach 1 (see also the sketch in fig.76 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.

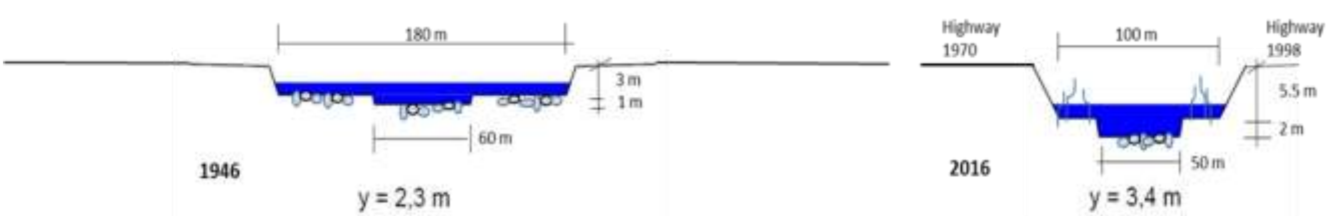

Fig.8~~7~~. Cross sections of reach 1 for the two extreme dates, 1946 (left) and 2016 (right). Alluvial widths are 175 m and 33 m respectively (table 3). The depth y drawn corresponds to a discharge of 600 m^3/s, within the first day of the flow duration curve.

The ratio of carrying capacity with and without reservoirs is 0.62 for reaches 1-4 and 0.73 for reach 5, on average (table 5). 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 %, §6~~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, *these~~his~~ figures have to do with the new mouth (**§12**~~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 in the case of fig.8).~~, which attenuates the large decrease in alluvial width between these two dates (from 175 m to 33 m in average width, table 4).~~

10~~1~~ 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~~ The delta was steadily retreating before 1946 (fig.2), the date of the first quantitative, extensive information (photographs), 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).

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

~~The main~~ One 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 (§7~~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 it ~~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, we assume for the moment that ~~there is no choice but to consider that~~ capacities are dispatched quantities to the next reach and period. This lapse and step of conveyance have been~~is~~ justified in §5~~6~~ and §8~~9~~ with the velocity of the disturbance created by a cut of supply. 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 ≈ 10×10^3 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), i.e. 3.5×10^3 m^3/yr more without dams than with them.

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 decadeyear, arrows means transference to the coast. The symbols †, -†† and * in table 4 apply here too.

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 computed annual river yield in 1946-1981 1 from ≈ 16×10^3 to ≈ 10×10^3 m^3/yr is found to be a substantial factor for the delta evolution. It is of the same order of magnitude but lower than the delta balanceboth the deficit in the delta (57×10^3 m^3/yr) and the surplus in the beaches (29×10^3 m^3/yr), (—28×10^3 m^3/yr)yet of the same order of magnitude (tens of thousands). Its variation of ≈—6×10^3 m^3/yr between 1956 to 1981 due to the river encroachment by infrastructures, which is our main research objective, is less substantial, but it still accounts for ≈ 20% of the balance. The role of the regulation by dams, ≈ —3.5×10^3 m^3/yr, accounts for some 12% of the balance. It must be recalled that the computation is based upon normal flows and annuals floods, not including large floods, whereas the delta evolution (§2) encompasses all phenomena. The role of large floods is explored next.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).

113 Data on large floods —cChannel incision— and role of channelizationn

Just after the building of the left highway in 1970 (§78), the largestworst flood of the XX20th century in (1971) caused a general bed degradation (incision) in reaches 2 and 3. An historical bridge in the middle of fig.6close to town D in fig.76, failed due to the thatbed lowering (Batalla, 2003).

Similarly, the 2000 flood came just after the construction of the right highway in 1998, with a peak of 1500 m^3/s (§7) came just after the construction of the right highway in 1998. which Iin addition to the highway itself, had dug the river channel had been dug to to fit increase hydraulic capacityfuture floods in. Flows above 1000 m^3/s lasted 12 hours, the receding phase (600 m^3/s on average) lasted 12 more hours. Thee comparison of the 1998 “as-built” bedriver long profile has been compared withand athe survey after the flood, resulting proved in 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. A sum of ≈ 125×10^3 m^3, was issued by the valley reaches (1-3) to the delta reaches (4-5) and ultimately to the coast.. It is clear, therefore, after comparing this amount to those in tables 1 and 7, that large floods may be dominant in the sediment yield. For that, the

Two lessons are learnt from these data: *i)* river bed has supplied particlesprovides material to the sediment transport, as theory claims, at the cost of incision. , 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. By inductive reasoning, incision will happen again as long as the alluvium does not get exhausted. 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, thOur e computationprevious estimate of the coarse river yield as 160.5$\times10^3$—106$\times10^3$ m^3/yr misay be a large underestimation in years with large one extreme floods, which can act as pulses driving, since the the delta evolution may be mostly driven by the sediment carried during these flood pulses. It is a challenge to know to what extent this is so, with our data. One can hardly make a count of 9 large floods similar to the 2000 one in the XX century (§7), so that the average amount ‘per year’ of the century would be 11×10^3 m^3/yr. Thus, the total yield in the long term, including large floods, would double our computation for normal flows and annual floods. In this way, the river yield (positive) would roughly match, with opposite sign, the delta balance (negative), both in the range 20—30×10^3 m^3 in absolute value.

-Table 8 shows thegathers more irregular results when considering the same comparison by periods of analysis. , for the four periods of analysis, the sediment Ddeficit at the delta (from table 1), the computed river change in sediment yield (table 7) and flood occurrence (§7) are compared in table 8. Most interesting is the maximum delta retreat in a decade of no floods (1946-1956), after years 1942-1943-1944 of large floods and general aggradation (even causing a positive river change <+3,4×10^3 m^3/yr, afterwards). This suggests that the "normal" river yield is largely insufficient to counteract wave action. On the contrary, the agreement in the last period (1974-81) suggests that floods larger than, but similar to, the 10 year return period (§7) can be sufficient to keep the delta almost at balance. However, the middle decades (1956-65 and 1965-74) contradict the last suggestion, since larger floods, close to the 50 year return period, do not produce delta aggradation, not even a balance. This discrepancy highlights the obvious role of the storms as special events of wave action on the sea side, similar to floods on the river side. Nevertheless, we can extract more information: the difference in the balance between decades with floods (the last three) and without floods (1946-1956), which amounts to ≈ 60—90×10^3 m^3/yr, confirms the order of magnitude of the river yield by one large flood (≈ 100×10^3 m^3/yr), already obtained with data of the 2000 flood. More importantly, note that the largest impact of the encroachment by infrastructures (channelization) in the period 1965-74, depriving the delta of 5.6×10^3 m^3/yr (at most), produces an increase of the delta deficit in a similar amount of 9×10^3 m^3/yr, both with respect to the period 1956-65. Thus, the contribution of channelization to the delta retreat, that seemed absent or hidden, can be evaluated as a portion < 5,6 / 31, i.e. up to18% of the total balance. This confirms the above ≈ 20% by using average figures for the whole period 1946-1981 (§-10).

-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
balancedeficit at delta (x=15-24 km) (10^3×m^3/yr)	—894	—2254	(2)—3152	(2) +2—30
computed river change, sediment yield (10^3×m^3/yr)	< +3.4	≈ 0	> —5.6	≈ 0
any largeextreme flood in the period ? if so, Q (m^3/s)	nNoO	2100	3100	1600

Table 8. Comparison of table 1 and the differences in table 7, for the balancedeficit at the delta and the change in sediment yield. Flood discharges come from §78. (2) see table 1.

124 Epilogue about Tthe new mouth and closure of the computation 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 inland 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, even less in case of small rivers. 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~~alluviation and silting 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. In other terms, it is the sum of bed load, computed so far, and suspended load~~.~~, i.e. a total load. –Moreover, –the suspended load is estimated through~~the~~ measurements of concentration of suspended sediment ~~sediment was measured in 1995-2002 ~~in the above mentioned gauging station (~~see ~~fig.4 for location) in 1995-2002, 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 could not~~failed to~~ monitor in detail ~~the large discharge events, as ~~the 2000 flood. ~~Therefore, ~~T~~t~~he comparison of these figures of suspended and total load proves that the bed load component is not negligible.~~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 load to total load ratio in Mediterranean rivers of similar size.

13 Discussion

~~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 ≈1×10^3 m^3/yr (table 7).~~

The bed-material ~~sediment~~ yield in the last decades~~50-70 years~~ has been ~~heavily~~ influenced by the channelization works in the lower Llobregat, which is close enough to the sea for their disturbance to be felt in the delta. T~~It is a fact t~~he~~at~~ source~~s~~ of alluvial bed sediment got reduced from its 1946 level~~in the period , for example~~ to just 38% of it in 1981 and to just 22~~9~~% in ~~(~~2016~~,)~~ in reaches 1-3~~4 , out of what they were in 1946, or to just 45% in reaches 2-4 (2016) with respect to 1974~~ (table~~s~~ 4 ~~and 6~~). The channelization reduced also the sediment carrying capacity (table~~s~~s 5~~- and~~ 6), for example to 67% in reaches 1-3~~4~~ (2016) with respect to~~out of what it was in~~ 1946. This carrying capacity determines the actual (computed) sediment yield, going from 16×10^3 m^3/yr in 1956 down to 10×10^3 m^3/yr in 1981~~The channelization is close enough to the sea for the disturbance produced by the works to be felt~~. This amount means some 10% of the total sediment yield, measured accidentally in a dysfunctional new river mouth. The agreement with the literature on the subject of bed load to total load ratio confirms the computation. All this is based on normal flows and annual floods, whereas large floods exceed the previous amounts by large (one order of magnitude). An estimate of another 10×10^3 m^3/yr in average over a century, with the discussion on their crucial role in driving the delta balance (either retreat or aggradation) in 1946-1981, is included in §11.

The customary assumption of a "steady river" (no floods) by coastal specialists is equally wrong as the customary assumption of a "steady sea" (no storms) by river specialists. It could even be argued that the equilibrium of a delta is elusive, since the delta either progrades, in case of floods and no storms, or retreats, in case of storms and no floods. The fluvial input to the delta (sediment yield, notably in high flows and floods) is controlled by intrinsic river variables, such as alluvial width and bed gradient, that have nothing to do with intrinsic coastal variables, such as beach profile, that respond to the maritime input to the delta (wave energy, notably in storms).

This sediment yield to the delta has not been reduced more heavily so far, because alluvial beds have provided much material, instead of the alluvial plains excluded from the channelized river, at the cost of incision in several reaches. Since its opening in 2004 the new mouth is further hampering the exit of sand to the coast because it is acting as a sediment trap, in such a way that the current yield is indeed reduced in one order of magnitude to $\approx 1\times10^3$ m^3/yr (table 7). The likely future exhaustion of the bed in the channelized river together with the sediment trap, worsened if it is dug out for maintenance, is a future scenario of more severe sediment cut for the delta and its beaches.

It has been demonstrated that the sediment trapping at the dams may not be as influential on the coarse sediment yield as the effect of flow regulation due to them, which implies a reduction of carrying capacity amounting to 38%. However, some moderate effects of sediment trapping at dams should appear in the long term. 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. This statement points to what controls the coarse sediment yield in the river.

However, despite all the analysis shown so far, the influence of the modern river channelization on the delta evolution is overrun by a much larger long-term trend of the Llobregat delta, which is irreversible as we will see. In fact, the contribution of the channelization to the total retreat in the period of analysis, 1946-1981, has been evaluated above as just 18-20%. The retreating trend was clear in fig.2, updated several times to add new historical data while the effect of channelization was being analyzed. The most advanced delta coastline must have occurred around the turn of the XX century, between the 1891 and 1907 coastlines. The question is why the delta was prograding in the XIX century, at least since 1862, but retreating continuously during the XX century. Is there any explanation for the trend shift around 1900?

Case-studies of rivers in southeastern France (Liébault and Piegay, 2002) suggest that a reforestation policy in the last 150 years, applied to Catalan basins as in the French examples, may be influential in narrowing river channels and so, indirectly, in the retreat of deltas. However, the decrease of sediment sources (less agriculture and more forest) seems very modest in this case (table 2), even more modest in the context of recent research that proves a weak signature of deforestation on delta size, because fine sediments contribute little to delta progradation (Ibáñez et al, 2019).

A second reason stems from a particular hydrological regime in the XIX century. Following documentary research, the period 1830-1870 was marked by a high frequency of floods in the Llobregat and other rivers of Mediterranean Catalonia (Llasat et al, 2005; Barriendos et al, 2019). The most severe floods occurred in 1837, 1842, 1853 and 1866 (Barriendos and Rodrigo, 2006). The XX century has been less active: 6 catastrophic events in the XIX versus only 1 in the XX (Llasat et al, 2005). A natural origin of this anomaly is accepted in the literature on the grounds of its temporary course and the corresponding climatic oscillations between several European regions. It can be assumed that these flood pulses produced an advance of the delta.

A third reason is the development of garment factories on the banks of the Llobregat river to profit from waterpower, in the XIX century (Alayo, 2017). This can be asserted for 91 factories in the middle reaches of the river (see "small dams" sign in fig.1), consisting of a diversion dam with average height of 4,2 m ± 2,9 m (standard deviation). Some 62% of them were built between 1850 and 1900 and most are still in operation as small hydro plants. More specifically, fig.9 is the graph of the cumulated height (m) versus the date of the insertion (calendar years) of small dams in the river. Following the progressive dam insertion, the span in height that keeps free for flow of water and sediment in the river profile is reduced accordingly. Recalling that the bed load carrying capacity is a monotonically increasing function of this free span, fig.9 also serves as a surrogate of the reduction in carrying capacity over the years. These 91 small dams date from 1816 till 1963 and stand from 4 to 100 km away from the upper border of the lower Llobregat reach (fig.1). The delayed effect of the farthest dams, and the quick effect of the closest, in the way to reach this border is taken into account by a disturbance velocity. The graphs for velocities 2 km/year, 1 km/year and 0.5 km/year are plotted in fig.9. Note that the latter has been used in the sediment routing through the five reaches of the lower Llobregat in §10. These graphs express the pace of the decrease in sediment supply at this border due to the space and time dispersion of the factories.

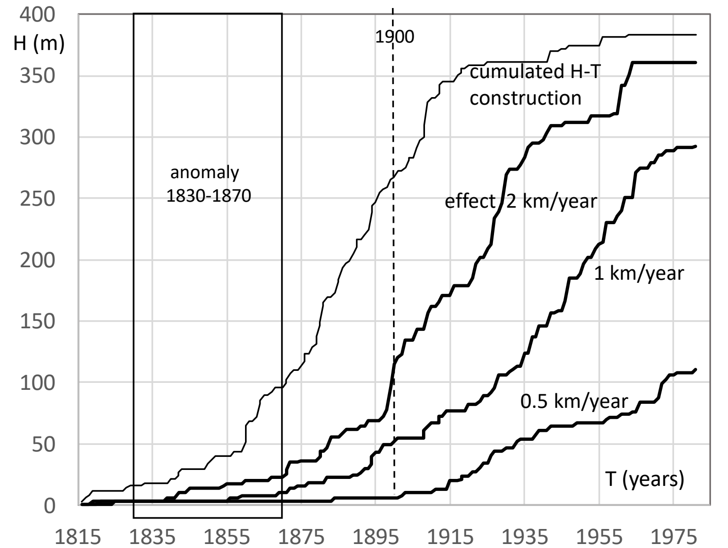

Fig.9. Cumulative height H (m) versus calendar date for the installation of factories in the middle reaches of the river (data in Alayo, 2017), and its effects at the upper border of the lower Llobregat, under three assumptions of disturbance velocity.

Two points are worth of discussion in fig.9: *i*) the hydrological anomaly of 1830-1870 finds the middle reaches of the river before the heyday of the garment factory building; therefore, the severe floods of this period must have brought large amounts of sediment to the lower Llobregat, and *ii*) the increasing effect of factory building on the sediment supply to reach 1 spreads throughout the XIX and XX centuries, including the period 1946-1981 of our main analysis, and even beyond; the turn of the century (1900) may be spotted as the fastest increasing supply cut in case of a 2 km/yr disturbance (or the incipient cut for a 0.5 km/yr disturbance) in order to explain the shift from progradation to retreat in the delta. Obviously, the recovery of free span in height in the middle river by removing small dams would be effective to increase the sediment delivery to the delta, in the long term (Ibisate et al., 2016).

In the event of a more active Llobregat in the middle years of the XIX century, and mostly free of factories in the middle reaches, the alluvial channel in the lower river should have been much wider at that time. Very fortunately, two plans of the lower Llobregat at reach 3, dated 1846 and 1854 just in the years of the hydrological anomaly, do exist in the National Archives to check our hypothesis. They can be scaled by means of landmarks in towns C and D and specially thanks to the historical bridge close to D that failed in 1971 (§11). Moreover, fig.10 is a photograph dated 1866-1867 of this bridge, a very telling picture of the largest alluvial width known and the plenty of sand and gravel there at that time, completely lost today. The average widths within reach 3 from the two plans are 272 m (both 1846 and 1854), with maxima of 447 m (1846) and 579 m (1854) and minima of 155 m (1846) and 123 m (1854). Compare this with an average width of 150 m for reach 3 in 1946 (table 4). This result closes the explanation of the delta retreat in fig.2. The heyday of the sediment yield to the delta was the middle of the XIX century. In 1900 things had started to change.

Fig.10 Bridge close to town D, shot by well-known French photographer Jean Laurent probably in 1866-1867. The only bridge in lower Llobregat at that time had a total length 334,36 metres, with 15 arches, the central 9 of which spanning 19,22 m each. It failed in 1971. Note the extremely wide alluvial area full of sand and gravel.

un final de la discussió que reforci més les troballes dels efectes de les rescloses i de les avingudes del s. XIX. El mateix em passa amb les conclusions, que em semblen que no fan justícia a la feina de posar en comú un munt de dades procedent de fonts d'informació ben diversa.

14 Conclusion

The decrease in coarse sediment yield, causing the continuous retreat of the Llobregat delta throughout the XX century, must be attributed in some 80% to the anomalous hydrology and the small dams built in the XIX century, while the contribution of the land use change is minor. For the first reason (hydrology), the retreat is virtually irreversible. Modern encroachment by infrastructures (from 1970 to day) in combination with flow regulation by large dams (1954 to day) explains the remaining 20%. The future is challenging in view of the new mouth (2004 to day), the depletion of the bed alluvium (by floods under encroahment rather than by mining), the remaining effect of the past small dams and the long-term effect of modern large dams, let alone in view of the climatic change. It is more effective a step back from channelization or a policy of removing small dams than the efforts to pass sediment at large dams, in order to provide sand to the beaches at the delta.

Hydrology, Natural Hazards and Earth Systems research sometimes stress technological innovation in the field of data taking, continuous monitoring and digital communication. However, documentary research (such as Llasat et al., 2005 and others) and archival perusal in search of old maps and photographs should be encouraged as well. The fate of the Llobregat river could not have been disclosed without that kind of work.

~~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.

Acknowledgements

Thanks to National Archives of Catalonia (ANC), Víctor Ténez, and Vicenç Gràcia, Javier Martín-Vide and Carles Ibáñez..

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