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Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "What controls the coarse sediment yield to a Mediterranean delta The case of the Llobregat river (NE Iberian Peninsula)" *by* Juan P. Martín-Vide et al.

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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 qs 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 reviewer may be interested to know the other interventions in the middle reach of the river that are mentioned several times in this response. That is why the corresponding text is reproduced here:

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 $\pm$ 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.8 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.8 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.8. 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.

here first figure with caption: 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.8: 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.9 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.

here second figure, with caption: 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.

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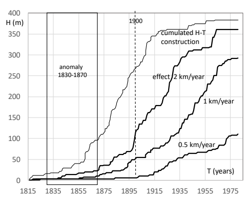

Fig. 1.

Fig. 2.