(Author responses in italics)

J. Guillen (Referee)

General comment: This is a “bold” manuscript exploring how the evaluation of the sediment budget in a coastal system during long-term periods (thousands of years) is suitable for the interpretation of past sedimentary processes, their timing and their morphological evolution (and presumably be applied to future projections). I like this aspect of the work. However, I suspect that the necessary assumptions required to simplify natural processes in the model make the results merely conjectures without firm evidence and that different test proposed by authors are just a sensitivity analysis of considered parameters. In fact, the application of this methodology to the Ebro delta evolution during the late Holocene mainly adjusts model results to previously known data (or interpretations derived from it). This provides the opportunity to authors to discuss several issues of the Ebro delta recent evolution that are interesting but quite speculative.

We thank Jorge Guillen for his thoughtful review. We are aware that many aspects of the fluvial and coastal model are sensitive to the considered parameters. However, we would like to also stress that in this study we are looking for the simplest possible scenario that would mimic the Ebro’s modern observed morphology. Therefore an important conclusion that we draw from this study is that we ARE able to reproduce the general Ebro Delta morphological history even when applying simplified models. Such results do not indicate the absence of any complicating factors; rather, they suggest that one does not necessarily have to appeal to such factors to explain the large scale morphology of the Ebro delta.

We now highlight this important point in the abstract, introduction and conclusion.

Specific comments: Sometimes I’m a little confusing with the use of the term “delta” in the manuscript. The Ebro delta (understood as delta plain, prodelta and associated fluvial and lagoon environments) developed during the Holocene (Díaz et al., 1996), but previous “delta” deposits are recognized before since the Messinian (Farrán and Maldonado, 1990; Urgelés et al., 2011). Sentences as “the delta was already formed -6000 years BP” (p. 4, l 10) or ”. . .the effect of fluvial sediment supply on Ebro delta morphology. . .” (p. 12, l15) suggest that delta and delta plain are used indistinctly along the text. In fact, a question what comes to my mind is if we can properly reconstruct the Holocene sedimentary history of a deltaic area and their fluvial inputs just using the shoreline variations and almost ignoring the submerged delta (the presentday delta plain area is about 325 km2 and the prodelta area is one order of magnitude larger, about 2300 km2). I realize that the 1-D model of shoreline evolution assume that shoreline variability is proportional to the shoreface translation considering a constant shape of the profile (and the shallowest submerged delta is included in this way). However, previous studies show that the depth of closure varies along the delta and, probably, there were important changes in the littoral profile during progradational and erosional periods of the shoreface. This is corroborated by the distinct morphology and sediment distribution on previously abandoned deltaic lobes areas (Guillén and Palanques, 1997). I am afraid that values obtained from these approximations are very close to the error range of the method because these uncertainties. For instance, it sounds reasonable to expect values of subsidence in the Ebro delta area of a few mm per year. During 2000 years this implies changes of several meters in the level of emerged and submerged delta. Apparently this should be a significant parameter for long-term evolution that probably change the sediment budgets inferred from shoreline data but which is ignored in the manuscript.

> *First, we agree that in many instances we used the word delta when delta plain would be more appropriate and we did so in the revised version.*
>
> *We also agree that an important simplification in our model approach is the 1-line shoreline assumption. Unfortunately, even though 2 or n-line shoreline models exist, we argue that the application of more complicated models would lead to an increase in uncertainties because of the lack of proper data constraints. Our modeling approach does account for growth of the delta into a deeper basin and subsequent erosion that is limited by the depth of closure. We state this more clearly in the revised version.*
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> *Even though subsidence on the delta plain is significant on millennial timescales, we argue that subsidence mostly affects the finer-grained and organic delta topset. We now include a cautionary note concerning the potential uncertainty arising from long-term subsidence of the delta plain.*

Regarding the reconstruction of the Holocene sedimentary volume based on the reviewer's delta plain area (325 km^2), the shoreface depth we have used (10 m), and the 70 kgs^{-1} sediment flux we have estimated from the shoreline model:

$$\text{Delta age} = \frac{DeltaArea(m^2)\cdot ShorefaceDepth(m)}{SedimentLoad(m^3 yr^{-1})} = \frac{325\cdot 10^6 m^2 \cdot 10m}{70kgs^{-1}\frac{1}{1600kgm^{-3}}} = 2355yr$$

This number is remarkably similar to our model estimate of 2100 years. This first-order calculation does not include the wave dominated delta area older than 2100 years, which we suggest was formed before an increase in fluvial sediment flux. We now include a short section regarding this simple mass balance in the text.

Estimation of sedimentary fluvial inputs and fluvial model: Here there is a mesh of data from different sources. To choose a grain size of 0.2 mm for the fluvial profile model seems unrealistic. This sediment grain size characterizes deltaic beaches but the sediment in the river (including in the delta plain) is coarser. Upstream of the deltaic area most of fluvial bed sediment is gravel. The assumption that this sediment (0.2 mm grain size) is mostly transported during floods of 900 m3/s is also inaccurate. Batalla et al (2004) refers this value for bedload of gravel beds upstream of delta plain. The bedload transport in the river at the delta plain (which determines the sediment supplied to the coastal zone) begins with water discharges of about 400 m3/s and progressively increases with water discharge (flow velocity). There is an inflection point in this relation with water discharges around of 800-900 m3/s. This means that the potential bedload transport is "most effective" with that water discharges, but total bedload transport depends of the duration of flow conditions. Finally, the estimated sediment supply of 70 Kg/s-1 during Riet Vell formation and used in model simulations, which is equivalent to the pre-dam bedload flux (71 kg s-1) by Syvitski and Saito (2007), should be considered as a feasible number that could give an order of magnitude of sedimentary inputs but whose variation would significantly change the results of the model.

We use 900 m^{3}s^{-1} as a formative flood at which most of the bed material load is transported. We then adjust the duration (intermittency) of the flow such that the annual bed material load is consistent with the bed material load under the full flow-exceedance *frequency curves of Batalla et al (2004) and Vericat and Batalla (2006). We now include a more thorough description of the fluvial profile model parameters in the methods section.*

We recognize that the sand designation is inconsistent with the bed material of the Ebro River channel, and we changed bed material in the fluvial profile model to the most transported bedload grain size of 10 mm (Vericat and Batalla, 2006). Because we simultaneously change the channel bed roughness set to reflect a gravel bedded channel (3x D50 of bed material), the resulting fluvial profile timescales and sediment fluxes are similar to the original calculations for a sand bedded river.

We are aware of the simplification of using one fluvial sediment flux to represent an "average" for the last ~2000 years of the Ebro Delta. Variability in this sediment flux would greatly affect the morphologic development of the Ebro Delta. However, we are not aware of any data constraining the fluvial sediment flux history over the previous millenia. An important conclusion of our study is that we are able to reproduce certain elements of the Ebro morphology with the simplest possible assumption: a steady sediment flux.

I found the analysis of section 4.3 about wave climate change during the Holocene really weak. The evaluation of storminess during the Holocene is a complex issue and the approximation carried out in this section is too simplistic to prove any trend.

We agree that paleo wave climate of the Ebro Delta is a complex issue that needs to be investigated and therefore we provide a start for that in our paper. However, based on the most complete NAO reconstruction (Olsen et al., 2012) and the longest wave climate record available for the Ebro Delta (Sotillo et al., 2005) our conclusion is that there appears to be no clear evidence to expect significant wave climate changes, particularly in comparison to previously inferred fluvial sediment flux changes of the Ebro delta and other Mediterranean deltas (Anthony et al., 2014; Giosan et al., 2012; Maselli and Trincardi, 2013). The assumptions underlying our analysis are clearly laid out, including correlations between measured and paleorecords. The lack of strong evidence from our one analysis does not prove that wave climate changes did not occur. However, it does *show that more evidence would need to be presented do demonstrate a secular change in wave climate, as has been suggested by others. Also, our results indicate that one does not necessarily have to (or should) appeal to wave climate changes to explain large scale morphologic features of the Ebro delta.*

E. Viparelli (Referee)

This manuscript describes an interesting application of two reduced complexity models to quantitatively characterize the long term impact of changes in flow rate and sediment loads on the progradation of the Ebro delta over the last ~2000 years. The application of the two models, a coastline evolution model and a river morphodynamic model, is novel in the sense that the output parameters of the river model are used to update the input conditions of the coastline evolution model. Although the models were not fully coupled because the input parameters of the coastal evolution model do not seem to change in time during a simulation, the results of this exercise are useful to determine what could have caused an the increased delta progradation rates that occurred about ~2000 years ago. I consider the level of model simplification appropriate for the spatial and temporal scales of interest. I like the choice of not modeling autogenic river avulsions and backwater effects and to impose the orientation of the channels based on field observation. The model is well written and I have some general comments on the manuscript and I list them below.

Comment 1

The detailed description of recent changes in flow regime and sediment supply to the delta (section 2.4) is relevant to characterize the present Ebro delta, however this information does not seem to be used in the model application and in the discussion sections of the manuscript. Is the Ebro delta suffering of land losses or shoreline retreat? How are these changes (if they have been documented) related to the dam construction based on the four model scenarios considered in the manuscript?

> *We thank Enrica Viparelli for her thoughtful review of our manuscript. Our main answer to this question is that the question is one of scale and objective. Our main objective is to investigate fluvial sediment flux increases that have been hypothesized to have caused the Ebro land gain over the last 2000 years. We do use the recent changes to the Ebro delta shoreline as a test case for the applicability of the coastline modeling, finding that there appears to be little fluvial sediment reaching the modern shoreline. However, our fluvial model scenarios focuses on delta formation. We are hesitant to use the shoreline model or the fluvial profile model to project future changes over the coming century to the Ebro delta because, for one, this has been done previously (e.g., Sánchez-Arcilla, et al, 2008)*

using a model approach more directly tuned to the historical changes of the delta shoreline. Second, as we now also state, our modeling approach does not account for sea-level rise; projections for the coming century suggest rates that are unprecedented compared to the previous 2,000 year period we investigate. We now state the objective of our research and suggest some potential methods for investigations of future change in the conclusion section of the manuscript.

Comment 2

It is not very clear how the effects of changes in flow regime and sediment supply to the Ebro delta were studied. One of the output parameters of the fluvial model can be the mean annual sediment load (I do not remember if the original model has it as output parameter or if the code needs to be slightly modified to print it). Are the authors imposing a variable sediment supply or its equilibrium value, i.e. the value at the end of the numerical simulation when the system reaches a new equilibrium state? I understand that equilibrium values of sediment supply were used in the simulations. I am not asking to do more simulations, but it can be nice to fully couple the two models in the near future and see how the coastline evolution changes in case of sediment supply that changes in time.

We impose its final equilibrium value at the upstream boundary condition, which we now state clearly in the methods and the results section. We impose a constant fluvial sediment supply to the Ebro delta for the coastline model. We chose not to couple the two models directly because they are exploratory and there is no feedback (i.e., the coastal model does not affect the fluvial model). An example of a coupling of fluvial and coastal models is described in: Ashton et al., Comp. and Geosc. 2013. We agree that modeling wave-affected delta evolution with a gradually time-varying sediment influx remains an interesting problem. Here, we use the fluvial models to investigate how a sudden and sustained increase in fluvial sediment input to the shoreline could have affected the evolution of the Ebro delta.

Comment 3

The description of the fluvial model can be improved and refined. I would clarify that since the authors are using a channel model, they consider the bed material only and do not model washload. In line 37-38 the description of equilibrium is not very clear and should probably be improved by saying that in the absence of subsidence/ uplift and sea level rise, if the flow regime and the sediment supply are constant in time rivers tend to reach a mobile bed equilibrium in which the channel bed elevation does not change in time. If streamwise changes in flow discharge and sediment load are not modeled, at equilibrium the bed slope does not change in space and time and the bed material transport capacity is equal to the mean annual supply of bed material everywhere in the modeled reach (Parker, 2004 and 2008).

We realize that the description of equilibrium was less clear and we adjusted the wording following the reviewer's recommendations.

On page 7, lines 4-15, the normal flow assumption appears and it is not linked to the rest of the text and this part needs some re-writing. I would reference to De Vries (1965) and/or Parker (2004 – chapter 13) to say that when the time scales of changes in channel bed elevation are long compared to the time scales of the changes in flow characteristics, the flow can be approximated as steady, i.e. the time derivatives of the Saint Venant equations are dropped. This is the quasi-steady approximation, which is at the base of the vast majority of the morphodynamic models. When it is further assumed that the flow is locally uniform, the quasi-steady approximation becomes a quasi-normal approximation and the flow characteristics are computed with the formulation that is implemented in the fluvial model used in this study. Thus, on line 9 the normal flow assumption breaks down when the flow is sufficiently non-uniform, i.e. the spatial changes of the flow have to be considered (not non-steady because steady refers to time and when this is the case you cannot drop the time dependence in the flow equations, as happens for e.g. tidal morphodynamics). There is a huge number of river and delta morphodynamic models that use the quasi-normal approximation for the flow (see e.g. Parker et al., 2008 and Paola et al. 2011 for references) and they have been used to approach the study of a large variety of problems. The choice of the quasi-steady or of the quasi-normal approximation depends on the problem of interest, on the available field data and on how the downstream boundary has to be modeled. I honestly do not think that the use of a quasi-normal approximation is a problem for this particular study.

We thank the reviewer for her recommendations. We have improved the description of the normal flow assumption.

Page 10 line 25, the authors are using a bedload transport relation for 0.2 mm sand. This requires some justification. Why not to use an Engelund and Hansen formulation (Parker, 2004 bulk load relation chapter) for total (bedload plus suspended) bed material load? The model should allow for it. Further, the change in reference Shields number in equation (3) from 0.047 to 0.0495 suggests that the authors are using the Mayer Peter and Muller bedload relation corrected by Wong (Parker, 2004), but they are not changing the coefficient of the load relation. This is perfectly fine with me, since the authors are obtaining reasonable results, but they should mention it in the text.

> *In the original formulation of the 0.2 mm sediment bed we agree that the Engelund and Hansen formulation would have been more appropriate. However, see also our response to reviewer #3, we changed the sediment bed grain size to 10 mm to more accurately reflect incision and aggradation of the Ebro River. We use the MPM formulation to predict river profile changes with a 10 mm bed median grain size (Vericat and Batalla, 2006).*

Comment 4

It is hard to understand how the intermittency factor was estimated.

> *Data (Vericat and Batalla 2006) show that the 900 m^3s^{-1} flow transports most of the sand and is exceeded ~15% of the time (pre-dam). However, this does not mean that 15% intermittency is a good indicator of annual sediment transport, stronger flows will carry relatively more sediment. An appropriate intermittency is therefore likely higher than 15%.*

> *We use the sediment (which roughly scales with Q^2) -exceedance frequency table from Batalla et al (2004) and Vericat and Batalla (2006) to fit a relationship between exceedance frequency and Q2 (the trend is approximately ~ $x^{-½}$). We then integrate this relationship between 0 and the exceedance frequency of a 700 m^3s^{-1} flow (the minimum to transport bed material) to obtain a sum with units $(m^3s^{-1})^2$ days/year. This sum divided by the discharge^2 we use in the model (900^2) is about 100 days/year (~30% intermittency). Because we scale the intermittency to the discharge we choose in the model, the results are not very sensitive to an exact flood discharge (e.g. a 1200 m^3s^{-1} flood discharge in the*

model would correspond to a ~20% intermittency and results in a similar annual sediment flux).

We agree that this was insufficiently clear in the previous text (also pointed out by reviewer #1) and explain this more thoroughly in the methods section of the revised version.

Comment 5

Figure 6, does the figure become clearer if the temporal changes in bed elevation (eta – eta_initial) are plotted? Do the authors have one or two field data to add to the figure to show that the model is able to reasonably reproduce the field case?

We have added a bed level difference plot to this figure, which is indeed more illustrative. We are unfortunately not aware of any channel bed degradation studies of the Ebro River downstream of the dams, aside from the cited studies of Vericat and Batalla (2006)

Comment 6

This is a very personal request, can the authors express the sediment fluxes in million tons per year? It is very hard for me to understand how much sediment is delivered to the cost when the fluxes are given in kilograms per second.

We included the MT/yr conversion in every first instance in every section. We omitted it in some instances of high repetition.

Comment 7

Is there any evidence for a change in flow regime and sediment supply to the fluvial reach and to the delta between 6000 and 3000 years ago? It would be nice to have this information to justify the results of the modeling exercise.

Thorndycraft & Benito 2006 QSR discuss changes in fluvial flooding in Spain before 3000 years BP. We now discuss their findings in more detail in the background section of the manuscript.

Comment 8

A table with the values and the justification of the model parameters will greatly help.

We now include a table providing river profile model and coastal model parameters (new Table 1).

E. Anthony (Referee)

General comment: This is a fine effort that attempts to combine shoreline processes and fluvial water and sediment discharge to account for the evolution of the Ebro River delta based on reduced complexity models. This combination is a novel approach that needs to be encouraged but it is based on many simplified assumptions that can be called into question. The authors have been quite exhaustive in integrating into their model as many parameters and aspects as possible, but one ends up with the impression that the output has been geared to fit input parameters that are not always well determined. This can be expected given the complexity of delta morphogenesis, interactions between fluvial sediment supply and wave climate, and uncertainties regarding long-term large-scale environmental changes involved in such morphogenesis. These weaknesses should not, however, detract from the utility of the combined simple modeling approach proposed by the authors in this paper.

> *We thank E. Anthony for the thoughtful review. We agree with the essence of these comments, that although we explore many parameters in our study, we cannot exhaustively investigate the full breadth of parameter space, in particular the potential for all fluctuations. We hope that we are clear in our assumptions, and emphasize that we do explore a rather large variation in several model parameters that are difficult to constrain (Figure 7). We now more clearly stress the variability and the objectives of the paper in the abstract, introduction, and discussion sections.*

Specific comments:

1. The evidence on the inception and growth of the Ebro delta is altogether rather scanty to be used as a justification for the stages in delta growth replicated by the combined model, especially for the earlier stages of evolution. The use of the presence of beach ridges as a criterion for affirming that the delta was already extant 6000 years ago seems, in this regard, rather dubious as these forms could simply reflect shoreline reworking by waves.

> *We agree that beach ridges are not necessarily evidence of delta existence. However, the preserved beach ridges on the Ebro delta plain older than 2000 years are updrift of the mouth curving toward the mouth, in a region where the coast is otherwise cliffed (i.e. no outside sediment sources). This essentially rules out any other possibility but a delta. We*

rephrased this section and provide a better summary of the findings presented by Canicio and Ibanez (1997) and Cearreta et al. (2016)

2. The sediment input and grain-size parameters also need to be reconsidered. The construction phases of the delta are based on the supply of sand-sized sediment to the shore. What justifies the choice of a grain size of 0.2 mm in the river channel, given the much larger size range and the dominance of coarser bedload in the channel?

We realize we did not provide sufficient clarification for the 0.2 mm fluvial sediment size. Reviewers #1 and #2 also requested more clarification. We initially used this grain size because it is approximately the grain size of the littoral zone and therefore most likely makes up for most of the delta between the depth of closure and the surface.

However, in response to all reviewers, we now calculate the river profile changes with a 10 mm grain size, the median bed-load grain size (Vericat and Batalla, 2006). We have adjusted the methods section. Because of the likely higher bed roughness (~3x D_{50} *of the median bed material for no bedforms, see Parker 2004) of the gravel bed, the actual sediment transport magnitude is similar to our original results.*

3. The assumption that the wave climate and storminess in this part of the Mediterranean did not change significantly in the course of the evolution of the Ebro is doubtful. More cautious wording should be used regarding this aspect.

We state this claim more carefully, also following similar concerns of reviewer #1. However, we used the best data available to us and found no indication that wave climate change would have a strong effect, as significant as changes in the fluvial sediment flux found for the Ebro delta and other Mediterranean deltas (Anthony et al., 2014; Giosan et al., 2012; Maselli and Trincardi, 2013). This of course does not prove that wave climate changes did not occur; rather, it shows that one does not necessarily have to (or should) appeal to wave climate changes to explain some morphologic features of the Ebro delta. We stress this distinction more clearly in the revised manuscript.

4. The changes in delta plan-shape associated with the successive lobes are based on the fluvial dominance ratio but the input data justifying this ratio are rather poorly constrained, and the

authors do not seem to consider morphodynamic feedback between lobe plan shape, wave approach direction and alongshore sediment fluxes, except for the current spits.

The fluvial dominance ratio as we use it in the study purely serves as a diagnostic tool for our model simulations. The simulations themselves include feedbacks between shoreline shape, wave approach angle, and fluvial sediment fluxes. We rephrased our explanation of the fluvial dominance ratio and its use in our analysis in the background and results sections.

5. How do recent post-dam changes in water and sediment discharge fit in with the evolution of the modern delta and with the evolution of the two spits flanking the present channel mouth?

While it is tempting to run the shoreline evolution model into the future we chose not to do so. See also our response to reviewer #2, Enrica Viparelli. There are more appropriate models and methods (e.g. Jimenez 1997) available to predict future delta shape that can take into account a more constrained set of boundary conditions such as (perhaps importantly) sea level rise. A modern Ebro delta model would also probably use the Ebro's present shape as initial condition rather than our assumed shape (a straight coastline) 2000 years ago. We mention this now in the conclusion. However, our analysis of predicted alongshore sediment transport trends and scenario-based models both suggest river damming effects on the shoreline should be noticeable only close to the modern river mouth itself.

Jose Jimenez (Referee)

General comment

This manuscript is a very interesting attempt to reconstruct (explore) the long-term evolution of the Ebro river-delta system by using (relative) simple models. The adopted approach based on using wave and river sediment supply scenarios permits to analyse the potential influence of each factor on delta development and, thus, to reconstruct dominant conditions controlling the Ebro delta development. This gives a great flexibility to the analysis since it permits to practically test any combination of forcings controlling deltaic formation and reduction processes. Although this is a great advantage, it also opens the question on how confident authors are on used (selected) conditions. In addition to this, the proper selection of models' parameters will control obtained results (delta configuration). This may cause that different combinations of both factors (forcing conditions and parameters' selection) will produce a given response.

> *We thank Jose Jimenez for his thoughtful review of our manuscript. The two model outcomes are indeed sensitive to many less well constrained variables including the factor k in the shoreline evolution model and the location of the upstream fluvial model boundary. Where possible, we used site-calibrated constants and test model outcomes to recent Ebro river and delta changes. Rather than proving a particular depositional history of the Ebro, we state that our models have provided us with the "best estimate" outcome. Given that this "best estimate" outcome is similar to outcomes from other Ebro delta studies, we can suggest that perhaps our simple models and boundary conditions are sufficient to explain general aspects of Ebro delta morphology that can advance our interpretation on geological timescales. That does not mean that they should substitute for detailed models on shorter timescales.*
>
> *Other reviewers have brought up similar concerns and we now more thoroughly discuss the sensitivities of the models to specific model parameters. We also more clearly describe the implication of our model results.*
>
> *Specific comments and responses are discussed below.*

Specific comments:

[1] Authors use many times the term "delta" and in other places "delta plain". It will be great to clearly specify which is the target (that apparently it is the deltaic plain).

Reviewer #1 shared similar concerns. We now more carefully distinguish between the terms delta plain and delta.

[2] When describing the suitability of the used models, authors mention that they were validated by comparing predictions of observed changes observed during the last century [page 3, lines 21-23]. However, it is not clear how a model "validated" for a period of few decades (for coastal changes) can be used to predict changes in a time frame of millennia.

We agree that perhaps another terminology than the term "validated" is more appropriate. In lines 21-23 of the original manuscript we did not use this specific term, instead stating: "we compare the model predictions to observed deltaic and fluvial change over the last century". However, beyond word definitions, we sought to develop the best possible parameterization, in particular for the alongshore transport coefficient k, and thus used changes over the last century as a calibration. The physics of our model, however, are not dependent on this specific calibration (although this comparison shows that many changes can be explained through alongshore transport gradients). Temporal scale mismatch is not unique to the model we use here; for example, small-scale laboratory experiments are used to calibrate sediment transport parameters used in Delft3D which are often applied over large space and time scales. We believe that several decades represents a reasonable timeframe for testing our model, annual to inter-annual changes would certainly be inappropriate in this regard. We also do not intend to present our results as an exact replication of the formation of the Ebro Delta.

[3] In different parts of the paper, authors mention the potential effects of deforestation on river sediment fluxes. However, it is not clear/justified in the text which is the magnitude of the deforestation or land-use changes in the river basin required to produce such increase in sediment load. Moreover, it is not justified if population and land use at the required time (1000 years BP) was enough to produce such deforestation.

The sediment flux response to deforestation and land-use changes is an area of active research even in the case of modern changes. We are unaware of detailed studies of the *relationship between historical land-use changes and sediment loads for the Ebro River. Studies such as ours could potentially inform these relationships.*

A global compilation of recently modified deltaic systems indicates that increases in the sediment load due to deforestation and land-use changes could amount to a factor of two or larger (Syvitski and Milliman 2007, p 12-13). Xing et al (2014) estimated a 40% increase in the fluvial suspended sediment flux for the Ebro River. We now include a discussion of their results to justify the potential increase of the Ebro river sediment load in response to deforestation.

[4] Authors make reference to a threshold of 860 m3/s to produce bedload transport in the river [page 5, lines 10-11]. However, previous estimations done in the area for 0.2 mm sediment give a threshold value of 400 m3/s. Is this affecting scenario development?

See also our response to other reviewers; as we have changed the median grain size of the bed-material load to 10 mm to more accurately reflect the gravel bed nature of the Ebro River. We now more thoroughly describe how the exact flood discharge of the Ebro is not critically important, as we adjust the flood intermittency to capture the full hydrograph from Batalla et al (2006). We have adjusted the methods section to more clearly describe this procedure.

[5] When presenting the delta evolution model, authors mention that they propagate waves to breaking but the presented alongshore sediment transport formula is given as a function of deep water waves.

We thank Jose Jimenez for pointing out this potential source of confusion. Deep-water wave relationships are used for visualization and analysis of wave climate data (Ashton and Murray 2006 pt. 2). The description of wave breaking is applicable to the numerical 1-line model (Ashton and Murray pt. 1).

[6] The calibrated K value of Jiménez & S-Arcilla (1993) used by authors was obtained by comparing computed sediment transport rates with inferred ones from shoreline changes. To do this, several hypotheses were done, being the depth of closure one of them (to be about 7 m) to convert shoreline to volume changes. Formally, this K value should be strictly valid to be used

under the same conditions. Thus, if it is used with a different depth of closure (e.g. 10 m), same wave action should induce a smaller shoreline change.

We agree with the reviewer's assessment and now add that for the direct comparison between the different wave climates and the shoreline analysis of Jimenez et al. (Fig. 4) we use 7 m as the shoreface depth. The actual model simulations run over much longer timescales, and therefore we use a deeper shoreface depth (10 m). We now include this distinction in our methods section. We refer to our response to detailed comment #7 below for further explanation.

[7] It is questionable to use a depth of closure of 10 m for very long-term runs (centennial or millennia time scales). This concept was designed to be used at yearly scales and, when time scale increases, it has been observed that it usually increases (e.g. Hinton & Nicholls, 1998). In the study area, non-published data show that beach profiles along the northern part of the Ebro delta taken 20 years later than the work of Jiménez and Sánchez-Arcilla (1993) presented significant bottom changes at locations deeper than 10 m. Moreover, if authors used the inner shelf bathymetry to identify the extension of ancient lobes (following Canicio and Ibañez, 1999), changes are observed down to 20 m water depth. If depth of closure is increased, deltaic plain growth rates will be smaller for given sediment supply and wave scenarios.

We realize the shortcomings of a 1-line shoreline model applied over ~1000 year timescales, see also our response to reviewer #1. The increase of the shoreface depth over time becomes intertwined with the simultaneous translation (erosion and progradation) of the shoreline such that an accurate measure of the depth of closure across the entire shoreface and throughout all 2000 years would be practically impossible to constrain. Although we cannot model all scenarios, we have added discussion of closure depth, including the time component, to the manuscript.

Our model uses a shelf-slope such that the Ebro progrades into deeper waters over time. Erosion actually only occurs up to a shoreface depth (see also Ashton and Murray, 2006, part 1). We now state this more clearly.

[8] How well wave conditions are correlated with NAO? Authors only mention how transport rates change with NAO positive and negative phases but not how significant (in statistical sense) variations are. This is important to support the hypothesis of no significant change in wave conditions during the period of simulation.

We are not sure we fully understand the reviewer's question. However, to make our analysis more straightforward, we have altered the presentation of the data in Fig. 9b. It now shows more clearly the modern potential littoral transport across all wave angles (a function of only wave height, wave period, and wave directions) as a function of the modern NAO index, without the binning.

Additionally, we do not wish to imply the NAO does not affect the wave climate, but we state that we do not find evidence of a significant effect of the NAO on the annual average potential sediment transport Qs,max. We now make this point more clear in section 4.3.

Large-scale coastal and fluvial models constrain the late Holocene evolution of the Ebro D~~d~~elta~~, Spain~~

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Abstract. The distinctive plan-view shape of the Ebro d~~D~~elta~~'s~~ coast ~~plain,~~ ~~Spain,~~ reveals a rich morphologic history. The degree to which the form and depositional history of the Ebro and ~~many~~ other deltas represent autogenic (internal) dynamics or allogenic (external) forcing remains a prominent challenge for paleo-environmental reconstructions. Here we use simple coastal and fluvial morphodynamic models to quantify paleo-environmental changes ~~that~~ affecting~~ed~~ the Ebro d~~d~~elta over the late Holocene. ~~We find that~~Our first finding is that our simple models are able to broadly reproduce the Ebro delta~~'s~~ morphology, even with ~~highly simplifiedless detailedconstant or slowly varying~~simple fluvial and wave climate histories. Based on numerical model experiments and the preserved and modern Ebro d~~d~~elta plain shape, we estimate that a phase of rapid shoreline progradation began approximately 2100 years BP, requiring a large increase (doubling) in coarse-grained fluvial sediment supply to the delta. ~~We do not find evidence that changes in wave climate aided this delta expansion.~~ River profile model simulations suggest that such an instantaneous and sustained increase in coarse-grained sediment to the delta would require a combination of flood discharge increase and ~~increased~~ augmented sediment input into the river channel from upstream drainage basin erosion. The persistence of rapid delta progradation throughout the last 2100 years suggests an anthropogenic ~~signal~~ control on~~f~~ sediment supply and flood~~ing~~ intensity. Using proxy records of the North Atlantic Oscillation, we do not find evidence that changes in wave climate aided this delta expansion. Our findings highlight how scenario-based investigations of deltaic systems using simple models can assist first-order quantitative paleo-environmental reconstructions, elucidating the effects of past human influence and climate change and allowing a better understanding of the future of deltaic landforms.

1 Introduction

The Ebro ~~D~~delta, Spain, with its distinctive plan-view shape, has experienced significant morphologic changes over the last millennia caused by the growth and reworking of different delta lobes (Fig. 1) (Canicio and Ibáñez, 1999). While autogenic ~~delta~~ processes might have caused some of these morphological changes, others aspects could be attributable to past climate changes or anthropogenic activities within the drainage basin. Many different scenarios leading to the modern morphology have been proposed, including high-frequency (centennial scale) sea-level fluctuations (Somoza et al., 1998), human-induced sediment load changes in the Ebro River (Guillén and Palanques, 1997a), and climate fluctuations affecting river discharge (Xing et al., 2014).

Many deltas around the world have experienced substantial morphologic changes over the last millennia due to anthropogenic factors such as river damming, land-use change, and climate change (Anthony et al., 2014; Giosan et al., 2012; Maselli and Trincardi, 2013; Syvitski and Saito, 2007). The Ebro d~~d~~elta lends itself particularly well to quantitative reconstructions because it is morphologically constrained (Nelson, 1990),~~;~~ it displays a distinctive plan-view shape (Fig. 1),~~;~~ and its environment is relatively well-studied (Cearreta et al., 2016; Maldonado, 1975). Here, we use a coastline evolution model and a river profile evolution model to quantitatively constrain the style, timing, and rate of ~~Ebro dDelta~~ morphologic change and the associated fluvial transport ~~conditions towards~~ to the Ebro d~~d~~elta during the Holocene.

Our goal in this paper is to investigate the general evolution of ~~the Ebro~~ a wave-influenced delta-river system using "scenario-based" and quantitative model experiments. We do not attempt to capture the precise morphology or geochronology of any one segment of the Ebro d~~d~~elta, but rather approximate delta paleo-morphodynamics to assess the potential physical mechanisms that could have formed this delta plain. Our scenario-based approach has two objectives:~~;~~ (i) to investigate whether we can reproduce the broad morphology of the Ebro delta plain with simple models and ~~simple~~available data on fluvial and wave climate histories, and, if ~~we are able to,~~possible, then (ii) ~~to~~ use simple models to quantify first-order sediment fluxes and timescales. ~~The ability of simple models to reproduce the morphology of the Ebro Delta can serve as a test of some of thefor existing hypotheses of environmental changes. allows~~

~~us to test existing hypotheses of environmental changes that may have affected the Ebro delta's development, and to quantify first-order sediment fluxes and timescales.~~ As a test of the suitability of the delta and the river models, we compare the model predictions to observed deltaic (Jiménez and Sánchez-Arcilla, 1993) and fluvial change (Vericat and Batalla, 2006) over the last century. Overall, our approach allows us to test existing hypotheses of environmental changes that may have influenced the development of the Ebro d~~D~~elta.

2 Background

2.1 Ebro River

The Ebro River reached the Mediterranean Sea, after an endorheic phase, sometime between 13 and 5 million years ago (Babault et al., 2006; Garcia-Castellanos et al., 2003). Its modern drainage basin extends over 85,530 km^2, covering a large portion of the Pyrenees, the Cantabrian mountains, and the Iberian massif (Mikeš, 2010). The average channel width in the lower course of the river is ~150 m, with a bankfull flow depth of ~5 m (Guillén and Palanques, 1997a). Average (pre-dam) discharge has been estimated at about 500 m^{3}s^{-1} (Batalla et al., 2004). The fluvial sediment flux during the Holocene highstand, based on radiometric dating of Ebro continental shelf deposits, is estimated to be ca. 200 kg s^{-1} (6.3 MT yr^{-1}) (Nelson, 1990). The suspended load consists mostly of clay and silt (Muñoz and Prat, 1989), while the bedload is predominantly sand and gravel (Vericat and Batalla, 2006).

2.2~~1~~ Ebro d~~D~~elta

At the Ebro River outlet to the Mediterranean Sea, fluvial sediment deposition over the course of millions of years has expanded the Ebro continental shelf and constructed successive deltas (Babault et al., 2006; Nelson, 1990). During the Holocene, strong waves and limited coarse-grained sediment input have shaped the Ebro coast towards a wave-dominated deltaic morphology ~~-~~with a smooth shoreline and single thread distributary network (Jiménez et al., 1997). The Ebro nearshore zone consists mostly of sand-size sediment (Maldonado, 1975; Somoza et al., 1998) to a depth of ~12 m, transitioning into muds farther offshore (Guillén and Palanques, 1997b). Two distinctive features on the Ebro d~~d~~elta plain are the spits to the north (El Fangar) and south (La Banya) of the current river mouth, considered to be formed by wave reworking of abandoned delta lobes (Fig. 1) (Maldonado, 1975).

2.3 Ebro d~~D~~elta Holocene evolution

Similar to many other deltas around the world, Holocene sea level rise led to the transgression of the ~~last~~ previous Pleistocene ~~Ebro dDe~~delta deposit (Maldonado, 1975). The maximum flooding surface of the Ebro d~~d~~elta is dated to about 6900 years BP, with its landward extent near the town of Amposta (Lario et al., 1995; Somoza et al., 1998). Several studies have interpreted historical references to suggest that the Ebro was still an estuary ~2000 years ago (Guillén and Palanques, 1997a; Maselli and Trincardi, 2013); however, radiocarbon dating of relict, arcuate, beach ridges on the delta plain (Canicio and Ibáñez, 1999) and recently dated sandy beach shells from boreholes (Cearreta et al., 2016) indicate that the delta was already formed by ~6000 years BP ~~(Cearreta et al., 2016)~~.

~~These d~~Dated beach ridges show that the Ebro d~~d~~elta ~~pplain~~coast was small, cuspate, and wave-dominated at least until 3000 years BP (Canicio and Ibáñez, 1999). The same study suggested that sometime between 1400 and 1000 years BP the Riet Vell lobe had grown~~had grewgrown~~ rapidly and extended approximately 20 km into the Mediterranean Sea, although no confirming dates are currently available. This increase in progradation rate, at least 2 to 3 times faster than previous and initiating sometime after 3000 but before 1400 years BP, is commonly ascribed to ~~land use changes and/or climatic variability increasing~~ an increase in fluvial sediment supply (Canicio and Ibáñez, 1999).

What could have caused this increase in fluvial sediment supply? Thorndycraft and Benito (2006) ~~Benito et al. (2008)discuss~~examining periods of fluvial flooding in Spain suggest, ~~n. A~~although with limited ~~by~~ data, ~~-availability, their study suggest~~ that extensive fluvial flooding occurred prior to 9000 years BP and after 3000 years BP, ~~and~~with ~~that~~ most records from the period in between ~9000 and ~3000 years BP pointing~~ed~~ to floodplain forestation and low-~~-~~energy floodplain deposition. Floodplain alluviation of Spanish rivers after 3000 years BP ~~, dating floodplain alluviation of Spanish rivers,~~ suggests~~ed~~ three periods of intense flooding ~~over the last three millennia~~: 2710-2320 years BP, 2000-1830 years BP, and 910-500 years BP (Benito et al., 2008). The first of these three periods has been associated with large-scale climate variability causing increased flooding. The last period of floodplain aggradation however is not in phase with palaeoflood records, which Benito et al. (2008) therefore attributed to anthropogenic modifications such as deforestation that increased the Ebro River sediment load. Other deltas around the Mediterranean and the Black Sea, whose hinterlands have comparable observed land-use change histories, also show periods of increased progradation in response to human activities (Anthony et al., 2014; Giosan et al., 2012; Maselli and Trincardi, 2013).

Xing et al. (2014) used the long-term fluvial discharge and sediment supply model HydroTrend (Kettner and Syvitski, 2008) to quantify the effects of anthropogenic and climate change on fluvial suspended sediment supply to the Ebro ~~d~~delta. HydroTrend uses empirical relations between, among others, basin area, land-cover, drainage basin relief, temperature, and precipitation and is calibrated using modern sediment transport records to simulate river sediment load. The model results of Xing et al. (2014) suggest that discharge variation was mostly a result of climatic variability, whereas forest clearing likely contributed to changes in suspended sediment load. Their study estimated a 40% increase in the fluvial suspended sediment load in response to deforestation. Other studies, such as Nelson (1990) and Guillén and Palanques (1997a), who reconstructed a sediment budget from delta plain and shelf aggradation rates, have estimated a greater fluvial sediment flux increase of 350%.

The i~~TheI~~ increase in the Ebro delta plain progradation ~~initially~~first ~~led to the~~ formed~~ation~~ of the Riet Vell lobe (Fig. 1) (Canicio and Ibáñez, 1999).
From ~~R~~relict channel deposits on the delta plain (Maldonado, 1975)~~ combined with~~ , published maps, and historical evidence, Canicio and Ibáñez ~~-~~(1999) and Somoza and Rodriguez-Santalla (2014) suggest that the progradation of the Riet Vell lobe stopped after 1000 years BP but prior to 600 years BP, when the avulsion of the main channel started the new Sol de Riu lobe to the north (Fig. 1), which also prograded rapidly. Subsequently, the Riet Vell lobe was reworked into the La Banya spit to the south. After a second river avulsion about 300 years ago to the Mitjorn-Buda lobe in between the previous active channels, the Sol de Riu lobe was also abandoned and reworked into the northern El Fangar spit (Fig. 1).

2.4 Recent changes

Starting in the 20th century, over 187 dams have been built in the Ebro that have highly regulated its discharge and currently impound 57% of the mean annual runoff (Batalla et al., 2004). The average fluvial water discharge based on hydrographic records before dam construction was approximately 500 $m^3\ s^{-1}$, while post-dam discharge has averaged about 340 $m^3\ s^{-1}$ (Batalla et al., 2004).

Prior to the construction of the major dams in the Ebro, peak discharge was about 50% higher than ~~current~~ modern flows ~~values~~ (Batalla et al., 2004). As a consequence, while bedload-transporting river flows (~~>~~ ~ ~~860~~ 900 $m^3\ s^{-1}$) were previously exceeded 15% of the time, dams reduced the exceedance frequency of these floods to just 4% of the year and thereby lowered the bedload sediment flux at the delta outlet (Vericat and Batalla, 2006). Additionally, reservoirs behind dams trap about 90% of the upstream suspended sediment load and 100% of the upstream bedload (Vericat and Batalla, 2006).

Accurate measures of pre-dam fluvial sediment flux are challenging, but from early 20th century sediment concentration and discharge measurements, Guillén and Palanques (1992) obtained an annual average suspended load estimate of ~600 kg s^{-1} (20 MT yr^{-1}). Syvitski and Saito (2007) used Bagnold's (1966) equation to estimate a pre-dam bedload flux of 71 kg s^{-1} (2.2 MT yr^{-1}).

Post-dam measurements taken 50 km upstream of the delta (25 km downstream of the Flix dam, the last major dam in the main river channel) estimate a modern total sediment load of about 28 kg s^{-1} (0.9 MT yr^{-1}), of which 40% is transported as bedload (Vericat and Batalla, 2006). Using predictive sediment transport formulae from van Rijn (1984) combined with discharge measurements, Jiménez (1990) estimated the modern sand (bedload) transport at the mouth of the delta at 1.6 kg s^{-1} (0.05 MT yr^{-1}).

A comparison of estimates of pre-dam to post-dam bedload transport to the delta suggests a reduction of about ~ 95%. Evidence of this sediment deficit include scours of the lower course of the channel bed and the formation of armored layers. Immediately downstream of the Flix dam, the channel bed surface consists of coarse gravel (D_{50} = 38mm) while the subsurface consists of mixed sand and gravel (D_{50} = 17mm) (Vericat et al., 2006).

The 20th century fluvial sediment flux reduction has also led to morphologic changes of the delta at the coast. While for much of the last millennia, the Ebro d~~d~~elta mouth likely exhibited~~was probably~~, at least periodically, close to a river-dominated morphology, the sediment supply reduction has led to a more wave-dominated form of the modern Mitjorn-Buda lobe (Jiménez et al., 1997). River damming may not be the only cause for large-scale coastal changes in the future. A bath~~-~~tub-style estimate projected that subsidence and sea level rise may submerge about 40% of the delta ~~surface~~ plain by 2100 (Ibáñez et al., 1997). However, the projected effects of sea-level rise on coastal change up to 2050 are negligible compared to ongoing change resulting from alongshore sediment transport gradients (Sánchez-Arcilla et al., 2008). These gradients have caused retreat rates of 50 m yr^{-1} near the river mouth, and have resulted in spit accretion at rates of approximately 10 m yr^{-1} between 1957 and 1992 (Jiménez and Sánchez-Arcilla, 1993).

2.5 Modeling wave-influenced deltas

Many numerical models have been developed over the last decades to quantitatively reproduce, predict, and understand the dynamics of deltaic systems. Complex 'simulation models' such as Delft3D typically are used to reproduce a particular well-constrained natural environment (e.g., van der Wegen et al., 2011) or to parameterize poorly understood physical processes (e.g., Nienhuis et al., 2016a). Simple 'exploratory models' of 'reduced complexity,' on the other hand, are designed to capture the essential feedbacks leading to an observed phenomenon (Murray, 2003). Because, ~~on~~ in the long ~~-~~term, the millennial- to centennial-scale development of the Ebro d~~d~~elta is poorly constrained, ~~here,~~ we apply exploratory models of wave-influenced delta dynamics to capture the essential physical mechanisms affecting the evolving morphology of the Ebro ~~d~~delta using scenario-based approaches.

The plan-view shape of the Ebro d~~d~~elta, like other wave-dominated deltas, is governed by wave-driven alongshore sediment transport (Bakker and Edelman, 1964; Bhattacharya and Giosan, 2003; Jiménez and Sánchez-Arcilla, 1993). Modeling of wave-dominated delta shape is therefore usually performed with coastline models (e.g., Ashton and Giosan, 2011; Bakker and Edelman, 1964). By assuming the cross-shore profile maintains a constant shape, gradients in alongshore transport can be linearly related to accretion or erosion any one contour line, typically the coastline. Such one-contour-line models calculate alongshore sediment transport based on surf-zone averaged equations such as the CERC formula (Komar, 1971), which relate the relative wave angle and height to a sediment transport flux. The cuspate coastline shape typical of wave-influenced deltas arises when adding a point-source of (fluvial) sediment to an otherwise straight sandy coast (Grijm, 1960).

By comparing fluvial and wave-driven sediment fluxes, Nienhuis et al. (2015) quantified when deltas would be expected to attain a wave-dominated versus a river-dominated shape. If the fluvial sediment supply is larger than the maximum potential alongshore sediment transport away from both delta flanks, waves cannot transport fluvial sediment delivered at the river mouth alongshore and a delta would be expected to be river-dominated. Their study defined a river dominance ratio R as the fluvial sediment flux (Q_r) divided by the maximum alongshore sediment transport flux away from the river in both directions ($Q_{s,max}$). For $R > 1$, the delta is river-dominated. If $R < 1$, there is an equilibrium plan view delta flank orientation such that the fluvial sediment flux (Q_r) equals the wave-driven sediment flux (Q_s) away from the river mouth along both flanks. The amount of shoreline deflection at the river mouth of a wave-dominated delta is therefore an indicator of its wave dominance, with flatter coasts more wave-dominated.

Ashton and Giosan (2011) showed that for very obliquely approaching waves, wave-dominated deltas can become asymmetrical and develop downdrift migrating sand waves and spits on the downdrift flank. These shoreline instabilities can form on growing deltas in which case they are oriented roughly parallel to the delta flank. Nienhuis et al. (2013) later showed that prominent recurved spits can develop from the reworking of delta lobes. These recurved spits develop after a reduction in fluvial sediment supply to a delta lobe (e.g. due to avulsion or dam construction) only if one or both flanks of the delta grew past the maximum in alongshore sediment transport. These recurved spits are generally not oriented parallel to the delta coastline. Rather, the orientation of free spits is controlled by the wave climate and the rate of delta lobe retreat (Ashton et al., 2016; Nienhuis et al., 2013).

2.6 Modeling fluvial sediment supply

The sand-sized sediment feeding the Ebro d~~d~~elta is supplied as bedload and suspended load through the ~~Ebro river~~Ebro River, interacting with the alluvial river bed (Jiménez et al., 1990). In alluvial rivers, channel-bed interaction sets up an equilibrium between the along-stream slope, river discharge, and sediment supply (Lane, 1955). One of the first attempts to numerically model fluvial sediment transport was by Hirano (1971), who combined the depth-averaged, one-dimensional Saint-Venant equations for fluid flow with a simple formulation for sediment transport. Their model resulted in a typical concave up longitudinal river profile for a scenario of gradually increasing water discharge downstream (Hirano, 1971; Snow and Slingerland, 1987).

If one assumes that changes in bed elevation ~~changes~~ are ~~slow~~less pronounced compared to changes in flow characteristics, the flow can be approximated as steady (de Vries, 1965). If it is further ~~is~~ assumed that the flow is locally uniform (spatial changes are small compared to the flow), thean the steady flow becomes quasi-normal and ~~we can formulate~~ an ~~For normal flow conditions, the Saint-Venant equations can be simplified substantially by formulating an~~ alongstream momentum balance relates ~~that~~ to ~~relates~~ bed shear stress to water depth and bed slope. ~~River profile models are usually c~~Combined with an Exner equation for sediment conservation and a Chezy or Manning coefficient for form drag, the Saint-Venant equations for fluvial flow can then be reduced to~~. For normal flow conditions this combination results in~~ a simple analytical expression for longitudinal river profile shape and equilibrium sediment transport rates (Parker, 1978).

~~The normal flow assumption breaks down if the flow is sufficiently non-steady, such as in backwater zones in the vicinity of a river delta (Hotchkiss and Parker, 1991). In that case, sediment is deposited in the backwater zone upstream of the river mouth but also in the delta foreset downstream of the river mouth. Even though the normal flow assumption is no longer valid in the backwater zone, generally sediment deposition during low flow nearly balances erosion during fluvial floods (Chatanantavet et al., 2012) such that the foreset can be considered the dominant location of bedload sediment deposition. In our simplified~~ r~~Ebro delta river profile model, we therefore assume that all bedload sediment transported to the apex of the Ebro delta is deposited near the river mouth as delta foreset.~~

3 Methods

3.1 ~~Delta evolution model~~Coastline Evolution Model

We study the morphologic evolution of the Ebro d~~d~~elta plain using the Coastline Evolution Model (CEM), an exploratory, process-based one-contour-line model (for a full description see Ashton and Murray, 2006). In this model, the plan-view coastal zone is discretized into 50 m square cells that are either filled (land), empty (water), or partially filled (coastline), the latter allowing for a smooth, continuous shoreline. Incoming deep-water waves are refracted and shoaled across parallel contours from the toe of the shoreface up to the breaking wave depth, where their characteristics are used to compute alongshore sediment transport (Q_s, kg s^{-1}) with the CERC formula (Komar, 1971)~~ assuming parallel shoreline contours~~. ~~We calculate alongshore sediment transport Q_s (kg s^{-1}) with the CERC formula (Komar, 1971), using the wave height and the relative wave approach angle to determine the sediment flux across different shoreline cells:~~

~~$Q_s = K_1 \cdot \rho_s \cdot (1-p) \cdot H_s^{12/5} T^{1/5} \cos^{6/5}(\phi_0 - \phi_s)\sin(\phi_0 - \phi_s)$, (1)~~

~~where H_s is the offshore deep-water significant wave height (m), T is the wave period (s), ϕ_0 is the deep-water wave approach angle (which equals γ - θ in a regional setting, Fig. 3a), and ϕ_s is the local shoreline orientation (Ashton and Murray, 2006; Nienhuis et al., 2015). The density of sediment is ρ_s (kg m^{-3}) and p is the dry mass void fraction. From Ebro delta calibration studies of Jiménez and Sánchez-Arcilla (1993), we use a littoral transport coefficient K_1 of 0.035 m$^{3/5}$ s$^{-6/5}$ compared to the typical coefficient of 0.06 m$^{3/5}$ s$^{-6/5}$ (Komar, 1998).~~

Following the one-contour-line approach, the divergence of alongshore sediment transport ~~-~~is related to shoreline accretion or erosion up to the shoreface depth using the shoreline Exner equation,

$$\frac{d\eta}{dt} = -\frac{1}{D_{sf}} \frac{1}{(1-p)\cdot\rho_s} \frac{dQ_s}{dx}, \qquad (~~2~~1)$$

where $d\eta/dt$ is erosion or progradation of the shoreline (m s^{-1}), D_{sf} is the shoreface depth (m), and dQ_s/dx is the alongshore gradient in alongshore sediment transport (kg s^{-1} m^{-1}). The density of sediment is ρ_s (kg m^{-3}) and p is the dry mass void fraction. Based on calibration studies of Jiménez and Sánchez-Arcilla (1993) we use an adjusted CERC constant of 0.12 m$^{1/2}$ s^{-1} compared to a more typical 0.~~18~~2 m$^{1/2}$ s^{-1} (Komar, 1998).

As equation (1) shows, the shoreface depth D_{sf} ~~is~~represents an important scaling parameter for coastline change rates. In a study of short-term (decadal) coastal change of the Ebro delta, Jiménez and Sánchez-Arcilla (1993) suggest a 7 m ~~depth of closure~~shoreface depth based on cross-shore profile variability. Research suggests however that ~~for~~across longer timescales~~ studies~~, the shoreface depth ~~should be ~~increase~~s~~d as a result of ~~to take into account the occurrence of ~~lower frequency (storm) events (Hands, 1983). As ~~an~~potential -indicator~~ion of this~~, Guillén and Palanques (1997b) found that the sand-mud transition of the Ebro delta is located at approximately 12 m water depth based on bed-surface samples. In our centennial time-scale modeling of the Ebro delta we take advantage of a recent quantitative analysis of shoreface ~~depths~~evolution (Ortiz and Ashton, 2016), which suggests morphological response rates may set the effective shoreface closure depth. ~~ that f~~For 1 m wave heights, a 100-yr depth of closure is approximately 40% deeper than a 10-yr timescale depth of closure. In our model, we therefore choose a shoreface depth of 10 m.

~~Based on calibration studies of Jiménez and Sánchez-Arcilla (1993) we use an adjusted CERC constant of 0.12 m$^{1/2}$ s^{-1} compared to a more typical 0.18 m$^{1/2}$ s^{-1} (Komar, 1998).~~ The characteristic shoreface slope (0.01) and shelf slope (0.002) are set based on the geometry offshore of the ~~of the~~ Ebro ~~Delta~~ (Guillén and Jiménez, 1995; Jiménez and Sánchez-Arcilla, 1993). The inclusion of a shelf slope in CEM makes the delta plain prograde slower as it builds out into deeper water further from the coast (Ashton and Murray, 2006). ~~Delta~~Shoreline retreat maintains a minimum shoreface depth of 10 m. This approach results in a more realistic mass balance, yet does not fully ~~While this behavior is obviously a simplification of the na~~capture potential long-term shoreface ~~tural~~ dynamics; the latter would be difficult without ~~of the Ebro Delta, the absence of~~ appropriate ~~data to further constrain~~ centennial--scale measurements of shoreface dynamics~~shoreline change would make the application of more detailed models ineffectivedubious~~.

An advantage of the CEM is its ability to produce arbitrarily sinuous shoreline shapes such as spits. When shoreline erosion causes a neck of a spit to reach a critical width, overwash occurs and sediment is transported from the shoreface to the backbarrier to maintain a minimum width (Jiménez and Sánchez-Arcilla, 2004). Overwash allows spits and barriers to retreat without disconnecting from the rest of the coastline (Ashton and Murray, 2006). Following observations of Jiménez and Sánchez-Arcilla (2004) of the La Banya spit, we set the critical barrier width to 250 m. The overwash depth is determined geometrically assuming a shoreface slope (0.01) and an overwash volume. Even though this is obviously a simplification that could result in overwash depths that are unrealistically deep, it avoids the need for a complicated assessment of backbarrier elevations coastwide.

~~From bed-surface samples of the Ebro delta coastline, Guillén and Palanques (1997b) found that the sand-mud transition is located at approximately 12 m water depth. In a study of short-term (decadal) coastal change, Jiménez and Sánchez-Arcilla (1993) suggest a 7 m depth of closure based on cross-shore profile variability. In our model, we choose an intermediate shoreface depth of 10 m. The characteristic shoreface slope (0.01) and shelf slope (0.002) are set based on the geometry of the Ebro Delta (Guillén and Jiménez, 1995; Jiménez and Sánchez-Arcilla, 1993).~~

~~In~~ the ~~CEM, the river channel is highly simplified and is only represented as the location alongshore where the littoral-grade portion of the fluvial sediment is deposited. By modeling the mass balance this way, we assume that fine-grained fluvial sediment is winnowed by waves and eventually deposited largely offshore beyond the shoreface (Guillén and Palanques, 1997b). As the delta either progrades or retreats, the channel location follows a predefined trajectory from the river apex based on observed Ebro delta (paleo) channel trajectories of the Riet Vell, Sol de Riu, and Mitjorn-Buda lobes (Fig. 2).~~ CEM does not have the ability to incorporate base-level changes in its shoreline change estimates. Surface elevation tables on delta topset deposits indicate~~s~~ a relatively high relative sea level rise rate of about ~3 mm yr^{-1} (Ibáñez et al., 1997). Although relative sea level rise rates in the sandy delta foreset deposits were likely significantly lower, we cannot rule out their potential effects on Ebro delta change.

3.2 Application to the Ebro d~~D~~elta

We have adapted the CEM to model growth and reworking of the different Ebro d~~d~~elta lobes. Rather than growing perpendicularly to the initial coastline, we force individual channels to grow along channel paths that we choose based upon the paleo and modern channels of the Ebro d~~d~~elta (Fig. 2, Maldonado, 1975). The first lobe builds out at 5º from shore normal and represents the growth of the Riet Vell ~~lobe~~. The second (Sol de Riu) lobe grows -45º from shore normal, and the modern Mitjorn-Buda lobe is oriented at -20°. For all these lobes, the river channel is highly simplified and only represented as the location alongshore where the littoral-grade portion of the fluvial sediment is deposited. By modeling the mass balance this way, we assume that fine-grained fluvial sediment is winnowed by waves and eventually deposited largely offshore beyond the shoreface (Guillén and Palanques, 1997b). As a second modification to the original model, we disable alongshore sediment transport out of a cell that is part of the initial coastline. This modification accounts for the fact that the Ebro d~~D~~elta juts out of the rocky coastline of Mediterranean Spain, and is not connected to an updrift littoral sediment source (Fig. 2).

Even though the Ebro d~~d~~elta channel orientations are likely in part determined by wave climate, fluvial sediment supply, and alongshore sediment bypassing of the river mouth (Nienhuis et al., 2016b), we choose to impose channel orientations directly to constrain model variability. Similarly, ~~delta~~ channel avulsion has been suggested to be controlled by backwater length and channel filling time scales (Chatanantavet et al., 2012). To limit model sensitivity we do not allow autogenic river avulsions in our model, instead we model avulsions at their ~~historically~~ geologically inferred locations (Maldonado, 1975) at which we impose avulsion times directly.

It is important to note that we are not explicitly simulating the history of the Ebro ~~River d~~delta plain; rather we use simple models to constrain fluvial sediment fluxes and delta growth in a broadly representative wave-dominated environment. Because both fluvial and coastal models are exploratory and there is no feedback, we do not couple the two models directly. We run scenarios of different fluvial sediment supply rates to investigate ~~its~~ the effect on delta~~Ebro Ddelta~~ morphology, including the ~~characteristic~~ growth of spits. We also run scenarios of different channel avulsion timings and match the resulting modeled delta shape to the modern Ebro d~~d~~elta plain shape to constrain Ebro d~~d~~elta ~~geo~~chronology. See T~~t~~able 1 for an overview of the model parameters.

3.3 Wave climate

Wave height and the directional distribution of incoming waves exert a first-order control on wave-influenced delta evolution (Ashton and Giosan, 2011). We compared five different wave climatology sources from nearby the Ebro ~~d~~delta and investigated their effect on modeled alongshore sediment transport. Wave climates are extracted from two directional wave buoys and three hind-casted wave models (Fig. 3 and Table 2~~1~~). All sources are located in sufficiently deep water for the waves to be treated as deep-water waves (depth > ¼ πT_p^2), and all sources show peaks of wave intensity from the East and from the South that affect Ebro d~~d~~elta alongshore transport. The different wave sources differ particularly in the relative strength of the waves approaching from the south. This could be because the southerly (summer) waves are generated more locally (Jiménez et al., 1997) and therefore their magnitude may be sensitive to buoy location or hind~~-~~cast methodology.

3.4 Testing the alongshore sediment transport model assumptions

Jiménez and Sánchez-Arcilla (1993) used aerial photographs from 1957 to 1989 and beach profile measurements between 1988 and 1992 to calculate Ebro coastline change. Their study found sustained multi-decadal rates of erosion of up to 50 m yr^{-1} close to the river mouth, and progradation of about 10 m yr^{-1} along the spits (Jiménez and Sánchez-Arcilla, 1993). These measured recent shoreline changes allow us to test the one-line shoreline assumptions underlying the delta evolution model. We use the back-refracted CERC formula (Ashton and Murray, 2006) to calculate alongshore sediment transport (Q_s, kg s^{-1}) from deep-water wave characteristics,

$$Q_s = K_1 \cdot \rho_s \cdot (1-p) \cdot H_s^{12/5} T^{1/5} \cos^{6/5}(\phi_0 - \phi_s)\sin(\phi_0 - \phi_s), \qquad (2)$$

where H_s is the offshore deep-water significant wave height (m), T is the wave period (s), ϕ_0 is the deep-water wave approach angle (which equals $\gamma - \theta$ in a regional setting, Fig. 3a), and ϕ_s is the local shoreline orientation (Ashton and Murray, 2006). From Ebro delta calibration studies of Jiménez and Sánchez-Arcilla (1993), we use a littoral transport coefficient K_1 of 0.035 $m^{3/5}\ s^{-6/5}$ compared to the typical coefficient of 0.06 $m^{3/5}\ s^{-6/5}$ (Komar, 1998; Nienhuis et al., 2015). For five different wave sources (Table 2 and Fig. 3), we computed net alongshore sediment transport along the modern Ebro delta shoreline, extracted from the NOAA shoreline database (NOAA, 2015).~~With the CERC formula (eq. 1, Komar, 1971), and using the 5 wave sources (Table 1 and Fig. 3)~~ We correct for shadowing of certain wave approach angles by other portions of the delta coastline. ~~, we computed net alongshore sediment transport along the modern Ebro delta shoreline extracted from the NOAA shoreline database (NOAA, 2015), taking into account~~ correcting for ~~shadowing of certain wave approach angles by other portions of the delta coastline.~~

The calculated littoral sediment transport trends along the ~~Ebro delta~~Ebro delta coastline are similar between the five wave climates (Fig. 4), showing sediment transport is greatest along both spits and close to the modern river mouth. The computed sediment transport magnitude however between the wave climate sources differs by almost a factor of 3. All wave climates except for the MedAtlas have similar correlation coefficients when compared to sediment transport patterns estimated based on observed beach change (Fig. 4b, black markers) (Jiménez and Sánchez-Arcilla, 1993). We choose to use the Cap Tortosa buoy data (described in Bolanos et al., 2009) in the delta evolution model because its 21 year record is sufficiently long, it is located close to the mouth of the modern ~~Ebro river~~Ebro River, and its ~~its~~ wave height and wave period are bound by the ~~average compared to the~~ other 4 wave sources.

From the computed alongshore sediment transport gradients from the Cap Tortosa data, we predict shoreline accretion and erosion using the one-contour-line approach (eq. 1)~~and the same shoreface depth and littoral transport constant as the delta evolution model~~. For this comparison we use a decadal timescale shoreface depth of 7 m (Jiménez and Sánchez-Arcilla, 1993). In general, the rate of shoreline change is well predicted ($R^2 = 0.84$) by the one-contour-line model and the wave climate from the Cap Tortosa buoy (Fig. 4c).

Aside from testing our model, we can draw two observations from the measurements of Jiménez and Sánchez-Arcilla (1993) about the ongoing coastal changes of the ~~Ebro delta~~Ebro delta. First, around the river mouth there is rapid coastal retreat to the south, and deposition further to the north. The field measurements align with the one-contour-line predictions close to the river mouth—these predictions do not ~~without~~ includ~~e~~ing a a fluvial sediment contribution, and are therefore ~~which provides further evidence of the~~consistent with other studies suggesting negligible modern fluvial sediment supply to the coast (Jiménez and Sánchez-Arcilla, 1993).

Secondly, the sediment transport patterns along the spits can be cast in the framework proposed by Ashton et al. (2016). Along the barrier sections of the ~~Ebro Delta~~Ebro delta spits, the computed alongshore sediment transport gradients are nearly zero, whereas measured shoreline retreat is approximately 10 m yr^{-1} (Fig. 4c). This suggests that in these regions overwash is driving coastline retreat without gradients in alongshore sediment transport. The barrier section (the "neck") is fed by a sediment source upcoast and is generally erosional up to a fulcrum point, where alongshore sediment transport is maximized and erosion transitions into deposition (Ashton et al., 2016). The measured and predicted shoreline change indicate that the northern and the southern spit are indeed depositional and are prograding at approximately 10 m yr^{-1} (Fig. 4c).

3.5 River Profile Model~~modeling~~

We investigate the response timescales of the river basin to climate and land-use changes using an exploratory 1-D river profile model (Parker, 2004). In this model, sediment is not merely a passive tracer, but interacts with the bed elevation to reach a longitudinal profile in morphodynamic equilibrium (Carling and Cao, 2002). The interaction between flow and topography creates a dynamic model – rivers are not treated as static pipes – which allows us to use the computed longitudinal profiles together with the observed modern longitudinal profile to investigate potential past and present sediment transport conditions. Additionally, by focusing on the interaction of the flow with the channel bed, we can model the bed material load – the sediment that makes up most of the delta shoreface (Maldonado, 1975) – while we ignore the finer grained ~~material~~ washload that is mostly deposited farther offshore. In the absence of subsidence or sea level changes, and if the bed material load and the flow discharge are in equilibrium, the bed slope does not change and the capacity is equal to the supply.

The channel bed in the model is freely erodible and our approach is therefore strictly applicable to alluvial, transport-limited systems (Parker, 2004). A similar 1-D river profile model was recently applied to study timescales of sediment supply decreases in the Mississippi River (Nittrouer and Viparelli, 2014). Their study suggested a long (O 100 yr) delay between dam construction ~1000 km upstream and sand load changes near the coast.

The 1-D river profile model assumes normal flow conditions, such that a width-averaged momentum balance connects bed slope and flow depth to bed shear stress. Flow depth in the channel is determined using a Manning-Strickler formulation for the flow resistance (Parker, 2004). ~~The model uses~~Because of the gravel bed of the Ebro River (Vericat and Batalla, 2006) we use the Meyer-Peter and Muller (1948) equation to calculate fluvial bed-material load~~sediment transport~~ (kg s^{-1}),

$$Q_r = I \rho_s B \sqrt{RgD} D \alpha_t \left\{ \left(\frac{Q^2 k_c^{1/3}}{\alpha_r{}^2 g B^2} \right)^{3/10} \frac{S^{7/10}}{RD} - \tau_c^* \right\}^{2.5} , \tag{3}$$

where R is the submerged specific gravity of the sediment (1.65); g is gravity (m s^{-2}); D is the median grain size (m) ~~which we choose to be the littoral grain size of 0.2 mm (Jiménez and Sánchez-Arcilla, 1993)~~; α_t and α_r, ~~α_r, and n_t~~ are flow and sediment transport coefficients; $Q_{~~flood~~}$ is ~~the flood~~ a representative flood discharge (m^3 s^{-1}); k_c is the bed roughness (m); S is the channel bed slope; I is the flood discharge intermittency; ρ_s is the sediment density (kg m^{-3}); B is the channel width (m); τ_c* is a critical Shields stress for sediment motion ~~; and τ_c is the non-dimensional critical bed shear stress for sediment motion (0.0495)~~ (Parker, 2004). See table 1 for an overview of the model parameters.

From equation (3) we can observe that the intermittency I, the flood discharge Q, and the grain size D are sensitive parameters for the fluvial sediment load estimates. The flood intermittency factor I characterizes fraction of time (generally a year) the river is in flood. Frequently, this~~The first two are flooding characteristics. Often, the flood intermittency~~ factor ~~I~~ is rescaled with a particular flood discharge to match an observed annual fluvial sediment flux Q_r (Wright and Parker, 2005). However, the pre-dam fluvial sediment flux of the Ebro River is poorly constrained, so here instead we estimate the flood intermittency I directly from flow records from Batalla et al. (2004) to generate an~~, but this~~. ~~does not result in an~~ independent estimate of the fluvial sediment flux.

To estimate flood intermittency, we first fit a function to the ~~Because of the poorly constrained pre-dam fluvial sediment flux of the Ebro River, here instead we choose to estimate the pre-dam intermittency using the~~ flow-exceedance frequency ~~tables~~statistics of Batalla et al. (2004)~~,~~. ~~The first two are flooding characteristics. Often, the flood intermittency factor *I* is rescaled to match an observed fluvial sediment flux Q_r (Wright and Parker, 2005). A discharge of approximately about 900 m^{3}s^{-1} represents the critical flood discharge to move bedload, (Vericat and Batalla, 2006)which occurredoftenpre-dam Commonly, the flood intermittency factor *I* is selected to match an observed fluvial sediment flux Q_r (Wright and Parker, 2005). To convert flow-exceedance to flood-intermittency, we first fit a trend to the flow-exceedance frequency data,~~

$$Q(e) = 550 \cdot e^{-0.25}, \qquad (4)$$

where Q is Ebro River discharge (m^3 s^{-1}) and e is the pre-dam exceedance frequency (i.e., e = 0.1 indicates a discharge that is exceeded 36.5 days each year). From equation (4), a representative flood intermittency for an annual bed-material load Q_r can be estimated by ~~Because all the flow above a threshold for motion contributes to the annual bed-material load Q_r, a representative flood intermittency should~~ takinge into account all the ~~exceedance frequencies~~floods from an extreme flood (e = 0) to a critical exceedance frequency for bed-material-load motion (700 m^3 s^{-1}, or $e_{crit} \approx 0.25$) (Vericat and Batalla, 2006). ~~Furthermore~~Because~~,~~ sediment transport is non-linearly related to flow~~, so~~ we do not integrate equation (4) directly, but rather we convert it to a sediment flux proxy based on discharge (Q^2). Formalized, the flood intermittency of a particular flood magnitude can be described as,~~)~~

$$I(e) = \frac{1}{Q(e)^2} \int_0^{e_{crit}} Q(\varepsilon)^2 \, d\varepsilon \,. \qquad (5)$$

In the river profile model we choose a flood discharge of 900 m^{3}s^{-1} which occurred relatively often with a pre-dam exceedance frequency e of 0.15~~%~~ (Vericat and Batalla, 2006). For a 900 m^{3}s^{-1} flood, equation (5) evaluates to an intermittency I of approximately 0.3. In other words, the instantaneous bed-material load of a 900 m^3 s^{-1} flow roughly corresponds to an annual ~~average~~ fluvial bed-material load if we use a 30% *intermittency* factor ~~flow~~, which we therefore use in the model.

The ~~thirdfinal~~third sensitive ~~The normal flow assumption is invalid in the backwater zone near the delta, where the channel aggrades and progrades (Hotchkiss and Parker, 1991). Technically therefore, the apex of the delta should be considered the downstream boundary of the fluvial profile model. However, as Chatanantavet et al. (2012) recently showed, annual flooding cycles in the backwater zone often create a condition where aggradation during low flow is nearly balanced by erosion during high flow. This (near) balance suggests that in terms of bedload volumes, delta progradation is significantly larger than channel aggradation and, therefore, that the absence of a backwater zone in our normal flow model only results in a limited underestimation of the fluvial sediment supply to the river mouth when considering centennial timescales.~~parameter affecting ~~in~~ the fluvial profile model is the grain size. The Ebro River is a gravel-bed river (most mobile D_{50} is ~ 10 mm) (Vericat and Batalla, 2006), so aggradation and erosion due to divergences in the bed-material load should be modeled using gravel size sediments. However, the median sediment size of the Ebro shoreface is sand (~0.2 mm) (Jiménez and Sánchez-Arcilla, 1993). In the coupled fluvial-delta system we should therefore consider the sand load as the representative bed material load volume at the river mouth. To retain the simplicity of a unimodal fluvial profile model we choose a 10 mm median bed-material load grain size to compute the timescales of profile incision and aggradation. ~~Furthermore, g~~ Given the relatively constant slope of the Ebro River (S = 5.8$\cdot$10^{-4}~~F~~, Fig. 5), we assume that the bed material load at the Ebro delta should be roughly similar to the bed-material load further upstream despite the change in the median grain size.

Applying the model based on the pre-dam fluvial and discharge conditions, the median bed-material ~~transport~~load grain size, and the observed slope ~~up to 450 km upstream of the delta,~~ (D_{50} = 10 mm, Q_{flood} = 900 m^3 s^{-1}, I = 30%, S = 5.8·10^{-4}) we find an annual average bed-material load transport rate Q_r of 70 kg s^{-1} (2.2 MT yr^{-1}). This estimate however is sensitive to the bed roughness (k_c)~~).~~ which we estimate at 100 mm, ~3 times the bed material D_{50} (Vericat et al., 2006).

~~to~~We model the Ebro drainage basin as a single channel representing an average of its tributaries.

~~Following Jiménez and Sánchez-Arcilla (1993), we choose a grain size of 0.2 mm for the fluvial profile model. This grain size is mostly transported during floods of 900 m³ s⁻¹ or larger; flows which during pre-dam conditions were exceeded 15% of the time (Batalla et al., 2004). The fluvial profile model uses one flood magnitude with an intermittency factor rather than an exceedance frequency. We have estimated an intermittency factor by fitting and integrating a logarithmic trend to the flood frequency analysis data of Batalla et al. (2004). This integration shows that the sediment load of a 900 m³ s⁻¹, 15% *exceedance* frequency flow roughly corresponds to a 900 m³ s⁻¹, 30% *intermittency* factor flow, which we therefore use in the model.~~

~~We can compare the predictions from the model to the observed modern river profile and see how close the modern profile is to equilibrium. The modern Ebro River profile (Fig. 5) shows an approximately constant slope up to the confluence with the Arga River, 450 km upstream. Applying the model based on the pre-dam fluvial and discharge conditions (D~~$_{50}$ ~~= 0.2 mm,~~ Q_{flood} ~~= 900 m~~^{3} ~~s~~$^{-1}$~~, I = 30%,~~ Q_r ~~= 70 kg s~~$^{-1}$~~), we find that the equilibrium slope is estimated surprisingly well (5.8·10~~$^{-4}$~~, Fig. 5b). Note that the observed channel slope remains constant upstream of the confluence with Cinca River even though the flood discharge decreases significantly. This could be due to different channel bed grain sizes between the Cinca River and the Ebro River upstream of this confluence. We model the Ebro drainage basin as a single channel representing an average of its tributaries. A spatially explicit model of the Ebro basin would be a significant departure from our exploratory model approach.~~

Th~~is~~e 1-D river profile model requires the choice of an upstream boundary, representing the average location of the fluvial discharge and sediment supply into ~~in~~ the drainage basin. The choice of an upstream boundary is important because it acts as a first-order control on fluvial sediment transport timescales from the drainage basin to the delta. To find an appropriate upstream boundary, we calculated the pre-dam morphologic (2-year) flood discharge along the ~~Ebro river~~Ebro River relative to the discharge at the delta from existing hydrologic records (Batalla et al., 2004). We set the upstream boundary condition at 450 km upstream of the delta, where the ~~Ebro river~~Ebro River pre-dam morphologic (2-year) flood discharge is 50% of its final discharge at the delta and a clear discontinuity in the longitudinal profile occurs (Fig. 5). Note that the observed channel slope remains constant upstream of the confluence with the Cinca River even though the flood discharge decreases significantly, a sign of fluvial or sedimentological heterogeneity within the drainage basin. However, a spatially explicit model of the Ebro basin taking into account these heterogeneities would be a significant departure from our exploratory model approach. ~~Applying the model based on the pre-dam fluvial and discharge conditions and the observed slope up to 450 km upstream of the delta, (~~D_{50} ~~= 10 mm,~~ Q_{flood} ~~= 900 m~~^{3} ~~s~~$^{-1}$~~, I = 30%, S = 5.8·10~~$^{-4}$~~) we find an annual average bed-material load transport rate~~ Q_r ~~of 70 kg s~~$^{-1}$ ~~(2.2 MT yr~~$^{-1}$~~).~~

The apex of the delta should be considered the downstream boundary of the fluvial profile model, ~~B~~because the normal flow assumption is invalid in the backwater zone near the ~~delta~~river mouth, where the channel aggrades and progrades and the flow is non-uniform (Hotchkiss and Parker, 1991)~~, the apex of the delta should be considered the downstream boundary of the fluvial profile model~~. However, as Chatanantavet et al. (2012) recently ~~showed~~demonstrated, annual flooding cycles in the backwater zone often create a condition where aggradation during low flow is nearly balanced by erosion during high flow. This (near) balance suggests that in terms of bedload volumes and neglecting subsidence and sea level rise, delta progradation is significantly larger than channel aggradation and, therefore, that the absence of a backwater zone in our normal flow model only results in a limited underestimation of the fluvial sediment supply to the river mouth when considering centennial timescales. In our simplified river profile model, we therefore assume that all bedload sediment transported to the apex of the Ebro delta is deposited near the river mouth as delta foreset. Additionally, this prevents the need~~As such, there is no need~~ to ~~We do not~~ couple the coastal and fluvial models directly. Rather, we treat both models as exploratory and inform timescales and sediment fluxes of coastal and fluvial change based on outcomes from each model.

3.6 Testing the fluvial profile model

To test the applicability of the river profile model to the Ebro drainage basin, we compare model estimates to recent measured bed elevation and sediment transport changes 25 km downstream of the lowermost Flix Dam for 55 years after its construction in 1948 (Fig. 6) (Vericat and Batalla, 2006). Between 2002 and 2004, Vericat and Batalla (2006) observed an average bedload transport rate of 12 kg s^{-1} (0.4 MT yr-1), ~~-~~down from pre-dam estimates of around 70 kg s^{-1} (2.2 MT yr-1). They also observed downstream scour at a rate of about 0.03 m yr^{-1} in Mora d'Ebre, although with much variability ~~(Fig. 6b)~~. To model river profile response to dam construction, we applied a 100% reduction in sediment supply immediately downstream of the Flix Dam. Concomitantly, following analysis of Vericat and Batalla (2006), we impose a fourfold decrease in the occurrence of bedload transporting floods of 900 $m^3 s^{-1}$ (from a 15% to a 4% exceedance probability, or a 30% to an 8% intermittency factor).

Even though the model does not capture processes such as bed armouring and downstream fining, results show reasonable agreement with the field measurements, estimating about ~~1~~ 1.5 m of bed degradation at Mora d'Ebre 5~~0~~5 years after dam construction, an incision rate of ~~about~~approximately 0.03 m yr^{-1}, ~~(0.02 m yr^{-1}),~~ and a local sediment ~~bedload~~ bed-material load of 12~~6~~ kg s^{-1} (0.4 MT yr^{-1}). ~~Furthermore, the modeled bed response to dam construction has not yet reached the Ebro delta.~~ At Mora d'Ebre, the measurement location of Vericat and Batalla (2006), equation (3) predicts that the change in flooding frequency decreased the coarse grained sediment flux from 70 kg s^{-1} (2.2 MT yr^{-1}) to 17~~19~~ kg s^{-1} (0.5 MT yr^{-1}). The sediment capture in the reservoirs and the subsequent channel bed slope adjustment decreased the coarse grained sediment flux further from 17~~19~~ kg s^{-1} to 1~~6~~2 kg s^{-1}. Furthermore, model results suggest ~~we find that the modeled~~that the bed response to dam construction has not yet reached the Ebro delta. At the delta, the model predicts a bed-material load of 16.5 kg s^{-1} 55 years after dam construction, compared to a predicted 17 kg s^{-1} immediately after dam construction due to the change in flooding frequency. O~~Therefore, o~~f the total reduction in bed-material load to the delta, the model therefore predicts that ~~the model predicts that~~ about 9~~5~~9% is due to changes in the flooding frequency, whereas only 1~~5~~% is due to a capturing of the sediment in the reservoirs and a resulting change in the channel bed slope. The model prediction for the Ebro delta is higher than the estimate of 1.6 kg s^{-1} (0.05 MT yr^{-1}) of Jiménez ~~and Sánchez-Arcilla~~ (1990) based on the formulae from van Rijn (1984)

4 Results

4.1 Delta response to increased fluvial sediment supply

We investigated ~~if~~ whether changes in fluvial sediment supply could explain the rapid growth of the Riet Vell lobe, which ~~that is thought to have~~potentially occurred~~ed~~ sometime between 3000 and 1100 years BP (Canicio and Ibáñez, 1999). Cast in terms of the fluvial dominance ratio R~~, which equals Q_r / $Q_{s,max}$~~ (Nienhuis et al., 2015), the transition from a slowly growing cuspate delta to a rapidly growing pointy (not cuspate) delta ~~occurs~~ should be expected to occur when $R > 1$ (or Q_r ~ 50 kg s^{-1} for the Cap Tortosa wave data,~~,~~ see Table 2~~1~~). At a pre-dam estimate of 70 kg s^{-1} (2.2 MT yr-1) (Syvitski and Saito, 2007), this means that during the period of rapid growth, a single thread channel ~~the Ebro delta~~~~Ebro Delta~~of the Ebro should have been river-dominated or close to a transition to river dominance, with a fluvial dominance ratio R of 1.4.

We also investigated the effect of fluvial sediment supply on plan-view Ebro d~~D~~elta morphology with the ~~delta evolution model~~CEM. After 750 model years, for bedload sediment fluxes up to about 35 kg s^{-1} (1 MT yr^{-1}), the modeled delta plain exhibits a smooth cuspate morphology (Fig. 7a) while prograding at about 6 m yr^{-1} (5 km in 800 years, Fig. 7c). A delta supplied double this ~~with a~~ sand load (~~of~~ 70 kg s^{-1}~~,~~; (2 MT yr^{-1}), however, progrades five times more rapidly (~~at~~ ~30 m yr^{-1}~~-~~) developing~~and forms~~ shoreline instabilities along the updrift and downdrift flanks.

From the same set of model experiments, we can also study the effect of fluvial sediment supply on post-avulsion abandonment and wave reworking. For low pre-abandonment fluvial sediment supply (< 40 kg s^{-1}~~,)~~; (1.2 MT yr-1), because the delta remains wave-dominated during growth ($R < 1$) and ~~, bec~~with cuspate and continuous ~~ause the~~ pre-abandonment morphology, ~~is cuspate and continuous,~~ no spit forms after abandonment (Fig. 7b) (Nienhuis et al., 2013). For high fluvial sediment supply during growth ($Q_r > 50$ kg s^{-1}, $R > 1$), because the delta ~~plain~~coast grows with ~~develops~~ a pointy shape, ~~and~~ a spit forms after abandonment (Fig. 7b).

~~Therefore, w~~We therefore estimate that the early cuspate morphology (around 3000 years BP, Canicio and Ibáñez, 1999; Cearreta et al., 2016) was formed with a fluvial sediment supply of at most 35 kg s^{-1}. The latter, more rapidly growing Riet Vell lobe that was reworked into a spit, was formed with a significantly larger fluvial sediment supply~~, of~~ such that R > 1 (likely more than 50 kg s^{-1}~~.~~). Extending the progradation trajectory of the Riet Vell lobe (Fig. 7c) and keeping in mind that the modern bathymetry suggests a maximum Riet Vell lobe extent of ~20 km (Canicio and Ibáñez, 1999), we estimate a Riet Vell fluvial sediment supply of ~70 kg s^{-1}. Note that these flux estimates ~~model outcomes~~ are sensitive to model parameters such as the effective shoreface depth, the littoral CERC formula constant, and the wave height ~~(Ashton and Giosan, 2011)~~, which were ~~calibrated~~ estimated based on modern Ebro delta change as described in section 3.1.

4.2 Timescales of change on the delta plain

~~The~~ Aside from linking fluvial sediment fluxes to Ebro delta morphology, we can also use the ~~delta evolution model~~Coastline Evolution Model ~~not only allows us to estimate sediment fluxes and the morphology of wave-influenced deltas, but also allows us~~ to assess the timescales Ebro Delta morphologic change. To investigate the timescales, we have simulated the growth and reworking of all three lobes. In 42 different simulations we use the estimated fluvial sediment supply of 70 kg s^{-1} and we vary the growth times of the different lobes. For example, in one simulation we grew the Riet Vell lobe for 800 years, then the Sol de Riu lobe for 400 years, and finally the Mitjorn lobe for 300 years. In another simulation, we used growth times of respectively 500, 500, and 500 years.

To assess which one of all the 42 simulations best represents the actual history of the Ebro d~~D~~elta, we measured the radial lengths of the modeled lobes through time. Then, we measured the radial lengths of the lobes on the modern Ebro d~~D~~elta from the avulsion apex. Both the paleo channels of the Riet Vell and the Sol de Riu lobe currently extend approximately 10 km from the avulsion apex. The modern active lobe, the Mitjorn, extends about 15 km from the avulsion apex (Fig. 2). We select ~~T~~the best matched model simulation as ~~is~~ the one where the three lobes reach the currently observed lengths of the modern Ebro d~~D~~elta at the same time. This "reverse engineering" approach yields an estimate of how long each lobe was active and therefore also of the start of Ebro d~~D~~elta plain's rapid growth. These estimates are made independently of published field studies, using the modern delta plain morphology.

For example, in one simulation the Riet Vell lobe grows for 800 years, the Sol de Riu for 400 years, and the Mitjorn for 300 years (dashed lines in Fig. 8). We find that for these growth times the radial extent of the Riet Vell and the Sol de Riu are never 10 km when the Mitjorn is 15 km (the current observed channels lengths) because both the simulated Riet Vell and the Sol de Riu shores ~~have~~ erode~~d~~ past the modern shore following~~too much since their~~ avulsion.

The best matched model scenario of the consecutive growth of the three delta lobes has growth times of 1200, 600 and 300 years, respectively (solid lines in Fig. 8), ~~before~~ when the modeled Riet Vell and Sol de Riu have eroded back to ~~it reaches~~ the modern observed lengths of 10 km, ~~for the Riet Vell and Sol de Riu~~ and the Mitjorn has prograded to 15 km ~~for the Mitjorn~~. We estimate therefore, based on this best matched model scenario, that the period of rapid growth of the ~~Ebro delta~~Ebro delta plain lasted approximately 1200+600+300 = 2100 years, placing the time at which rapid ~~Ebro delta~~~~Ebro Delta~~delta growth started approximately 2100 years BP (Fig. 8). These growth times would suggest that the second avulsion occurred 300 years BP, and the first avulsion occurred 900 years BP. Note however that these avulsion times estimates are sensitive to the fluvial sediment supply to the delta (here kept at 70 kg s^{-1}) and its variability through time. We keep the fluvial sediment supply constant during the simulations to limit the number of model variables ~~and keep this strictly a scenario-based approach~~.

The best matched model estimates for the start of rapid delta growth, made purely based on physical constraints set by alongshore sediment transport and fluvial sediment supply, roughly coincides with a simple volumetric ~~back-of-the-envelope calculation~~estimate based on our ~~estimated~~assumed shoreface depth (~10 m) and coarse-grained sediment supply (~70 kg s^{-1}, 2.2 MT yr^{-1}), and the modern delta plain area beyond the dated beach-ridges of Canicio and Ibáñez (1999) (~280 km^2),

$$T_s = \frac{A \cdot D_{sf}}{\rho_s \cdot (1-p) \cdot Q_r} \approx 2030\,yr, \qquad (6)$$

where T_s is the time since the start of ~~Ebro Delta's~~ rapid growth and A is the ~~Ebro D~~delta plain area (m^2). Our best matched model also agrees with observations suggesting increased flood plain deposition in the drainage basin (~2000-1800 years BP, Thorndycraft and Benito, 2006).

The model-estimated avulsion times ~~also~~ compare closely with scant historical evidence (Canicio and Ibáñez, 1999; Somoza and Rodriguez-Santalla, 2014), at least for the avulsion of the Sol de Riu at ~300 years BP. Other model predictions, such as ~~We also find that~~ the maximum extent of the modeled Riet Vell Lobe (~20 km, Fig. 8), approximate~~s~~ earlier ~~indications~~ estimations of its extent made from ~~Ebro Delta~~ bathymetry (Canicio and Ibáñez, 1999). Even though the history of the Ebro delta was likely more complex than our model simulations, t~~T~~he qualitative agreement between the model scenario and the growth, reworking, and spit formation observed on the ~~Ebro delta~~Ebro delta, suggests the possibility that the gross morphology of the delta plain can develop without significant ~~significant~~ sea level or fluvial sediment supply fluctuations.

~~Importantly, m~~Model simulations show the development of spits during both lobe growth and lobe abandonment. However, ~~these~~ spits growing during growth and reworking have markedly ~~at~~ different orientations (Fig. 8). Ashton et al. (2016) suggest that spit orientation is strongly affected by the updrift shoreline change rate. We speculate that, based upon their more river parallel orientations, the lagoons in the southern region of the modern ~~Ebro delta~~Ebro delta plain (e.g. the Encanyissada, Clot, and Tancada lagoons, Fig. 2) formed as they were enclosed by spits created while the delta was growing. On the other hand, the active southern La Banya spit has a different orientation because it was formed as the updrift shoreline retreated during reworking of the Riet Vell lobe.

4.3 Wave climate change as a potential cause of delta growth

Investigating the effect of changes in sediment supply on the ~~Ebro delta~~Ebro delta, we assumed the wave climate was constant. However, previous studies (Goy et al., 2003; Sabatier et al., 2012) focusing on the western Mediterranean over the last millennia suggest evidence exists of significant changes in wave climate ~~as well~~. Goy et al. (2003), studying the cuspate coast of the Gulf of Almeria in southern Spain, correlated beach ridge progradation to periods of negative North Atlantic Oscillation (NAO) because of stronger winds from the southwest that would increase littoral drift to the coast.

To investigate the potential effect of a change in the NAO index on the fluvial dominance ratio *R*, we correlated the monthly NAO index (Jones et al., 1997) with the Hipocas record (Sotillo et al., 2005), the longest wave climate hind-cast record available, spanning 44 years (Table 2~~1~~). ~~We use a littoral K_1 constant of 0.024 compared to the 0.035 used in the delta evolution model (eq. 1) to correct the alongshore sediment transport predictions of the Hipocas record compared to the Cap Tortosa record (Table 1).~~

Over this 44 year timespan, there were higher waves from the south during periods of negative NAO (Fig. 9a). For more positive NAO values, average wave height is lower, particularly from the south. Calculating the monthly $Q_{s,max}$, and comparing it to the NAO index, we find a weak trend from ~~100~~ 60 kg s^{-1} ~~(3.2 MT yr^{-1})~~ for strongly negative NAO (-4), to ~~40~~ 35 kg s^{-1} ~~(1.2 MT yr^{-1})~~ for periods of strongly positive NAO (+4) (Fig. 9b). ~~We use this obtained trend to assess late Holocene changes in $Q_{s,max}$ based on a NAO index proxy record from the last 2000 years.~~

Climate reconstructions suggest that the NAO index since the mid Holocene can be divided into three distinct periods. Prior to 2000 years BP the ~~NOA~~ NAO index was mostly negative, afterwards up to about 600 years BP it changed to become mostly positive. Over the past 600 years, the NAO index has been fluctuating with short but strongly negative periods (Jones et al., 1997; Olsen et al., 2012).

To obtain approximations of $Q_{s,max}$ ~~for each of the three periods~~ of the last 3000 years, we determined ~~representative~~ distributions of NAO indices from ~~NAO paleoclimate records~~Olsen et al (2012) and Jones et al (1997) for each of the three periods (Fig. 9b). We find that extreme NAO indices are rare and that the distributions of NOA indices, even though distinct, also overlap considerably. Therefore, although $Q_{s,max}$ can vary with changes in the NAO, particularly on a year-to-year basis (Fig. 9b), ~~geologic~~ proxy-record constructions based on the~~of~~ NAO do not suggest significant sustained differences across the previous two millennia

(Fig. 9c), also in ~~-~~comparison to suggested increases in the fluvial sediment supply to the Ebro delta that range from 40% to 350% (Guillén and Palanques, 1997a; Xing et al., 2014)~~. While this analysis of course does not prove that~~ Large-scale ~~(significant)~~ wave climate changes may have occurred over the past 2,000 years; such changes, however, do not jump out of our analysis of NAO cycles, ~~did not occur, it does~~ suggesting that one does not necessarily have to appeal to wave climate changes to explain ~~some of the hypothesized changes of~~the evolution of the Ebro delta. ~~This suggests that changes in the fluvial sediment load have likely been a more important driver to the morphodynamic change of the Ebro delta than wave climate changes.~~

4.4 Timescales of environmental change in the fluvial catchment

Results from the ~~delta evolution model~~CEM in concert with previous records indicative of hydrologic change (Thorndycraft and Benito, 2006), place the start of ~~Ebro delta~~Ebro delta plain's rapid growth at approximately 2100 years BP. Additionally, CEM model experiments indicate that roughly a sustained doubling in the sediment flux (from 35 kg s^{-1} (1 MT yr^{-1}) to 70 kg s^{-1} (2 MT yr^{-1})) over this period of time could create the observed morphologic changes in growing delta morphology. We have run four different scenarios in the river profile model to estimate the types and timing of drainage basin changes that could explain this increased fluvial sediment supply to the delta from 35 kg s^{-1} to 70 kg s^{-1} starting 2100 years BP and lasting up to the 20th century. The four scenarios are: (1) an increase in fluvial sediment supply, (2) an increase in fluvial flood discharge, (3) an increase in fluvial flood discharge and fluvial sediment supply, and (4) an increase in fluvial flood discharge and a 500 year lag in an increase in fluvial sediment supply (Table 3).

In scenario one we change the fluvial sediment supply 450 km upstream from the ~~Ebro delta~~Ebro delta from ~~about~~ 35 kg s^{-1} to 70 kg s^{-1}, with the flood discharge and its intermittency remaining constant ~~(Table 2)~~. Such a scenario could arise from land clearing that increased sediment supply without altering the discharge. The model experiment shows that the channel bed slowly aggrades to the new sediment supply and that the change in supply signal takes ~~about~~ approximately 5,~~4~~000 years to significantly affect the ~~Ebro delta~~Ebro delta (Fig. 10). This increase is associated with upstream aggradation of about 80~~130~~ m. While there are numerous field studies that show large alluvial deposits throughout the Ebro drainage basin that date between 6000 years BP up to 2000 years BP (e.g. Benito et al., 2008; Constante-Orrios et al., 2009; Constante et al., 2010; Constante and Peña-Monné, 2009; González-Sampériz and Sopena Vicién, 2002; Gutiérrez-Elorza and Peña-Monné, 1998; Soriano, 1989), the majority of these deposits are on the order of ~10 m thick. The unrealistic magnitude of the predicted aggradation is in part caused by the assumption that floodplain width remains constant, although the likely formation of a wider floodplain would not greatly affect the sediment supply to the delta. More importantly, the lack of any observed 80~~130~~ m thick Holocene deposit makes it unlikely that exclusively a fluvial bedload sediment supply increase occurred in the Ebro drainage basin. Even though subsequent erosion of some deposits is likely, a sustained increase in sediment supply should have been accompanied by a sustained high slope and preserved upstream alluviation (Fig. 10b).

In contrast to an increase in fluvial sediment supply, any change in hydrology (flood magnitude and/or flood duration) affects sediment supply to the delta instantaneously. A ~~doubling~~ 50% increase in the flood magnitude results in a doubling of the fluvial sediment flux delivered to the delta, but would simultaneously cause the channel to start incising upstream (Fig. 10a). Over time, this discharge-driven incision gradually lowers the fluvial sediment flux at the river mouth, returning to the previous value after approximately ~~8~~5,000 years (Fig. 10c). A concave-down river profile would be diagnostic of an ongoing upstream adjustment to a large increase in discharge over the past several thousand years. However, as a concave-down river profile is not observed (Fig.

5b), we find it unlikely that an increase in flood discharge and/or duration is the sole cause of increased ~~Ebro delta~~Ebro delta growth.

In a third scenario, we investigated a simultaneous doubling of upstream sediment supply and a 50% increase in the flood discharge. A combined change in sediment supply and discharge instantly doubles the sediment supply at the delta (Fig. 10a). Over time, incision due to discharge increases is compensated by the aggradation caused by increased fluvial sediment supply (Fig. 10d).

Lastly, the fourth scenario we tested is also a doubling of the upstream sediment supply and a 50% increase in the flood discharge, but now we included a 500 yr lag on the sediment flux. Such a scenario could be result of deforestation, where an instantaneous hydrologic signal is followed by a delayed secondary channel slope signal reaching the main stem of the Ebro River. We find that this fourth scenario has a ~~double peaked~~ nearly similar effect on~~in~~ deltaic sediment supply as the simultaneous discharge and sediment supply change (scenario 3).~~ The first (discharge-driven) peak is instantaneous, and the second (sediment-supply-driven) peak is delayed by ~4000 years (Fig. 10a).~~ A delay in the fluvial sediment flux ~~Combined, such a delay~~ has a small and temporary but measurable (~5~~5~~ m) effect on the fluvial longitudinal profile (Fig. 10e).

Because floodplain aggradation is dependent on the elevation of the channel and water surface with respect to the surrounding floodplain (Heller and Paola, 1996; Schumm and Lichty, 1963), each of the tested scenarios would leave a distinct record in the floodplain deposits. ~~We investigated~~Looking at modeled vertical profile changes 200 km upstream of the Ebro delta, approximately the location of some of the floodplain records from Benito et al (2008)~~. Our~~ , t~~T~~he forth scenario of increased floods (leading to channel incision) and a delayed increase in sediment flux (leading to channel aggradation) shows a~~has not only a double peaked response on the delta, but is also~~is ~~expected to have a~~ double peaked response in floodplain aggradation. Our fluvial profile model suggests that an increase in flood discharge would reflect an initial period of floodplain aggradation that ~~, and~~ would decrease gradually as the channel starts to incise (Fig. 10i). The second period of floodplain aggradation would ~~be related to the aggradation~~ result~~ing~~ from the increase in fluvial sediment supply. Radiocarbon dating of floodplain aggradation across the entire Iberian Peninsula similarly shows two periods of increased aggradation in the last 2000 years, one between 2000 and 1830 years BP, and one between 910-500 years BP (Benito et al., 2008).

In general, the river profile model experiments suggest an increase in either sediment or discharge alone are not responsible for the rapid and sustained growth of the ~~Ebro Delta~~Ebro delta plain. Instead, a combination of increased flood discharge and increased fluvial sediment supply generates a response that best agrees with our understanding and previous findings of changes on the ~~Ebro delta~~Ebro delta plain. The observed channel bed slope appears to be in a long-term equilibrium, with no evidence of thick Holocene floodplain deposits. These model results here show that changing flooding and sediment discharge can ~~by the same amount mostly~~ cancel each other out, resulting in a sustained signal that can be felt instantaneously at the river delta. Both climate change and human impacts on landscapes such as deforestation can increase both the fluvial flood discharge and the fluvial upstream sediment flux (Syvitski and Milliman, 2007; Xing et al., 2014). Our fluvial profile model is therefore not able to ~~(Cosandey et al., 2005; Ferrier et al., 2013), which makes it difficult to use our model results to~~ quantify the individual response of either climate or land-use changes. However, the application of this fluvial profile model does highlight that care should be taken when assuming that any change in the basin can result in an instantaneous and sustained change in sediment delivery to the delta (see also Nittrouer and Viparelli, 2014).

5 Discussion and conclusions

In this study we used two reduced-complexity models to temporally and physically constrain the late Holocene evolution of the ~~Ebro delta~~Ebro delta plain. Where possible, we assumed the simplest possible scenario of environmental change, focusing on the first-order effects on the ~~Ebro R~~river and its delta. The CEM~~delta model~~ is able to broadly reproduce the size and shape of the Ebro delta plain using only simple fluvial and wave climate histories. However, ~~B~~both the delta model and the fluvial profile model are sensitive to a number of ~~poorly~~less well constrained parameters, such as the shoreface depth and the fluvial grain size. Therefore, the general agreement of our model outcomes with earlier studies of the Ebro delta change (e.g., Canicio and Ibáñez, 1999) should not be implied to indicate the absence of complicating factors; rather, it suggests that one does not necessarily have to appeal to complicating factors to explain the large scale morphology of the Ebro delta.

Using best estimate model parameters, ~~model experiments~~we find ~~show~~ that an increase in ~~the~~ coarse fluvial sediment supply to the delta approximately 2100 years BP is the most likely driver of growth of the modern ~~Ebro delta~~Ebro delta plain, whereby the delta prograded approximately 2-3 times faster than before (Cearreta et al., 2016). Additionally, model experiments with the delta evolution model show that ~~Ebro delta~~Ebro delta avulsions, where reworking of the abandoned lobes resulted in development of the modern La Banya and El Fangar spits, likely occurred around 900 years BP and 300 years BP, respectively, consistent with previous studies (Canicio and Ibáñez, 1999).

~~Given that we do not find evidence of significant long-term changes in the wave climate, model experiments show that an increase in the coarse fluvial sediment supply to the delta approximately 2100 years BP is the most likely driver of growth of the modern Ebro delta plain, whereby the delta prograded approximately 2-3 times faster than before (Cearreta et al., 2016). Additionally, model experiments with the delta evolution model show that Ebro delta avulsions, where reworking of the abandoned lobes resulted in development of the modern La Banya and El Fangar spits, likely occurred around 900 years BP and 300 years BP, respectively, consistent with previous studies (Canicio and Ibáñez, 1999).~~

Aside from physically constraining ~~Ebro delta~~Ebro delta change, our models also highlight the physical mechanisms responsible for the generation of observed morphology. Simulations ~~also~~ point to the formation of spits during delta growth, potentially responsible for delineating the Clot, Encanyissada and Tancada lagoons, with orientations distinct from large recurved La Banya and El Fangar spits that formed from reworking of abandoned lobes. The suggested changes to the ~~Ebro delta~~Ebro delta leading to the formation of the observed spits is possible under a constant sea level and sediment supply, caused by river avulsions.

Using constraints from the delta evolution model together with a river profile model, we find that a combination of increased fluvial flood discharge and fluvial sediment supply that started approximately 2100 years BP is the most likely cause of a rapid and sustained period of deltaic growth over the last 2100 years. The rapid growth of the ~~Ebro delta~~Ebro delta plain is likely not solely caused by an increase in fluvial flood discharge because that would greatly increase fluvial incision. Instead, a combined change in discharge and sediment supply can be felt instantaneously at the river delta while persisting for millennia without a significant channel profile change. A combined change in discharge and sediment supply can also, depending on their respective timing, generate two periods of floodplain aggradation (Fig. 10i).

In this study we have highlighted a few factors that particularly influence the sensitivity of our ~~the~~ results ~~presented here~~. Fluvial sediment supply, wave climate characteristics, and the littoral sediment transport constant all have a first-order effect on gross delta plain shape~~, as abstracted in~~reflected by the fluvial dominance ratio *R*. Shoreface characteristics such as the depth of closure and the basin depth determine how the delta plain responds to sediment flux changes. Timescales of the river profile model are particularly sensitive to the median channel bed grain size and the upstream boundary location: the average distance between the delta and environmental change in the drainage basin. In all of the simulations presented here, we have chosen average, representative model parameters frequently mentioned in literature, with model results showing the broad first-order agreement with other studies of Ebro Holocene evolution.

As the Ebro delta moves into the 21st century, the effects of sea-level rise and river damming will increasingly manifest themselves in the delta morphology (Sánchez-Arcilla et al., 2008). Even though it is tempting to run our delta model into the 21st century, we emphasize that future delta shoreline ~~forecasts~~ predictions should be ~~based on historically observed changes and~~ should ~~likely more directly~~ include the effects of sea-level rise (e.g., Sánchez-Arcilla et al., 2008). However, ~~B~~by quantifying potential effects of historical land-use and climate change on historical delta evolution, simple models such as the one discussed here might ~~also~~ be able to simulate long term future deltaic change and help guide management decisions (Giosan et al., 2014).

Acknowledgements

This study was supported by NSF grant EAR-0952146. This article greatly benefitted from constructive reviews form Jorge Guillen, Enrica Viparelli, Edward Anthony, and Jose Jimenez.

Competing interests

The authors declare that they have no conflict of interest.

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Tables and Figures

Table 1. Overview of the model parameters chosen for the fluvial and the coastal model

Name	value	Units	Note
			~~coastal model~~**CEM** (Ashton and Murray, 2006)
K_1	0.035	$m^{3/5}\,s^{-6/5}$	deep-water alongshore sediment transport coefficient
ρ_s	2650	kg m^{-3}	sediment density
p	0.4		dry mass void fraction
H_s	0.8	m	significant wave height, from the Cap Tortosa wave buoy (Bolanos et al., 2009)
T_p	4.1	s	peak wave period, from the Cap Tortosa wave buoy (Bolanos et al., 2009)
D_{sf}	10	m	shoreface depth
shoreface slope	0.01		
shelfslope	0.002		
critical barrier width	250	m	width below which storm overwash occurs
cell width	50	m	
timestep	1	day	coastal model time step
			~~f~~F~~luvial~~River Profile ~~m~~Model (Parker, 2004)
D	10	mm	D_{50} of transported bed material (Vericat et al., 2006)
B	150	m	channel width
S	$5.8 \cdot 10^{-4}$		modern profile gradient
I	0.3		flow intermittency
k_c	100	mm	bed roughness, 3x bed material D_{50} (Vericat et al., 2006)
profile length	450	km	along channel distance of the upstream boundary condition
time step	0.2	yr	fluvial model time step
α_r	8.1		dimensionally homogenous Manning-Strickler coefficient (Parker, 2004)
α_t	8		sediment transport coefficient (Parker, 2004)
n_t	1.5		sediment transport exponent
τ_c*	0.045		critical Shields stress for sediment motion
ϕ	1		skin friction fraction

Table ~~1~~2. Overview of five different sources of wave climate data close to the ~~Ebro delta~~Ebro delta. See Figure 3 for an overview of locations and the angular distribution of alongshore sediment transport potential. Wave height is the effective, yearly averaged wave height weighted by its ability to move sediment alongshore, i.e. $(\Sigma\, Hs^{2.4})^{1/2.4}$. The R^2 value is the coefficient of determination of the alongshore sediment transport calculated from the wave data versus the measurements of Jiménez and Sánchez-Arcilla (1993)**.**

Name	**Type**	**Lat ˚N**	**Lon ˚E**	**Water depth (m)**	**Wave height (m)**	**Wave period (s)**	**Qs,max (kg s^{-1})**	**R^2**	**Data period (yr)**	**Reference**
Cap Tortosa	buoy	40.7	1.0	60	0.8	4.1	47.9	0.89	1990-2011	Bolanos et al., 2009
Tarragona	buoy	41.0	1.2	24	1.0	5.5	72.4	0.86	2004-2011	Puertos del Estado, 2015
MedAtlas	model	40.0	1.0	222	0.7	4.0	48.3	0.76	1992-2002	Gaillard et al., 2004
Hipocas	model	40.8	1.0	68	1.1	4.9	71.1	0.87	1958-2001	Sotillo et al., 2005
Wavewatch III®	model	40.8	0.8	63	0.7	4.9	31.1	0.86	1979-2009	Chawla et al., 2013

Table 3~~2~~. Overview of the four river profile model experiments and their final equilibrium slope and bed level change. *Q* is the fluvial flood discharge, Q_r is the upstream fluvial sediment supply, *i* is the initial antecedent fluvial environment, and *f* is the final fluvial environment.

Description	**Q_i (m^{3}s^{-1})**	**Q_f (m^{3}s^{-1})**	**$Q_{r,i}$ (kg s^{-1})**	**$Q_{r,f}$ (kg s^{-1})**	**Slope (i) (·10^{-4})**	**Slope (f) (·10^{-4})**	**Upstream bed level change (m)**
Sediment x2	900	900	35	70	~~2.9~~4.0	5.8	80~~130~~
Discharge x~~2~~1.5	600~~420~~	900	35	35	5.8	~~2.9~~4.0	~~-130~~80
Discharge x1.5 ~~and~~& sediment x2	~~420~~600	900	35	70	5.8	5.8	0
Discharge x1.5 &~~and~~ sediment x2 w/ delay	~~420~~600	900	35	70	5.8	5.8	0

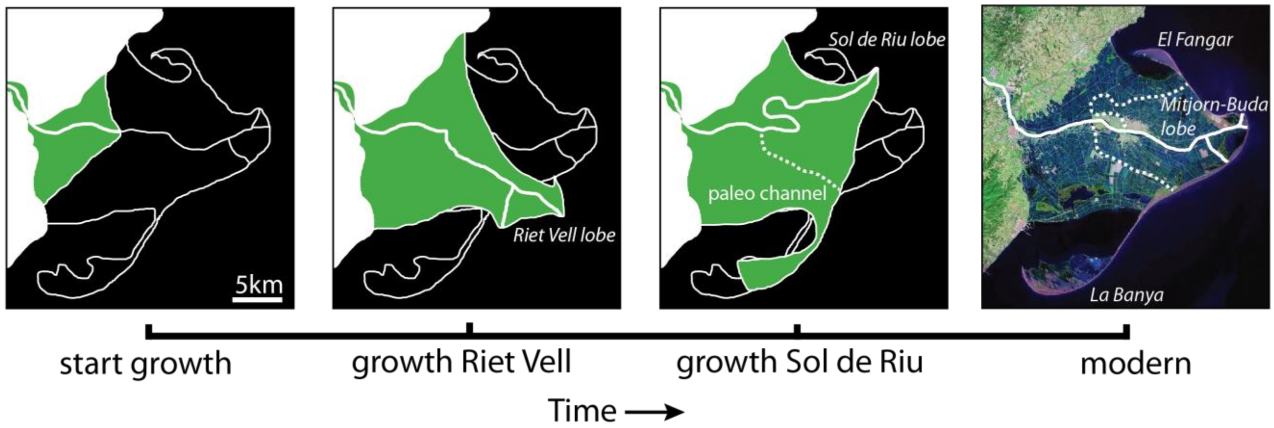

Figure 1: Reconstructed morphologic development of the ~~Ebro delta~~Ebro delta, modified from Canicio and Ibáñez (1999)**.**

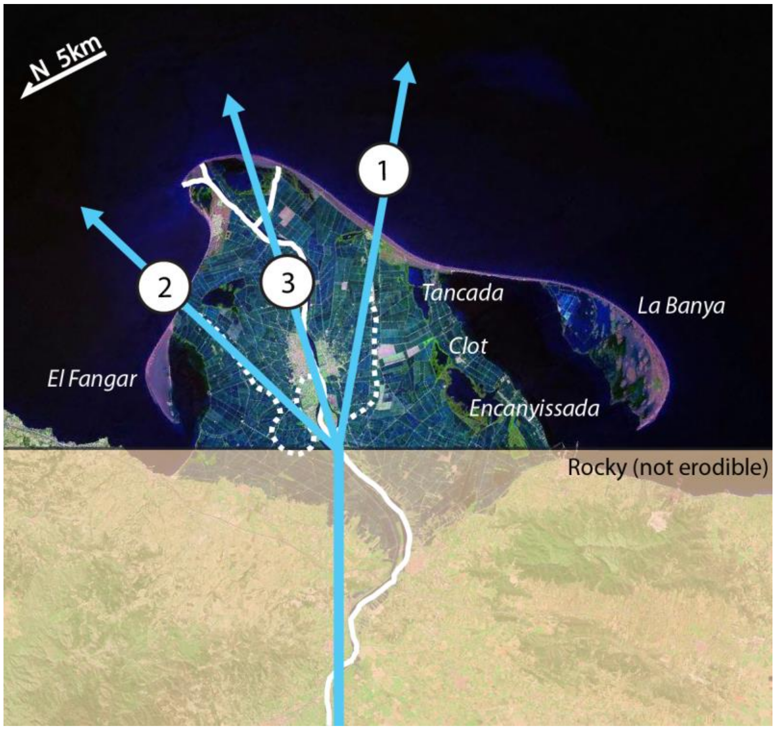

Figure 2. Schematic of modeling scenario, highlighting the succession and orientation of ~~Ebro delta~~Ebro delta lobes, shown on top of the modern ~~Ebro delta~~~~Ebro Delta~~ morphology (NASA Landsat image) and the inferred paleo channels (dotted lines, from Maldonado, 1975)**. In the model, the straight reference coastline is assumed to be non-erodible. Names refer to the spits and the lagoons on the ~~Ebro delta~~Ebro delta. Numbers refer to the (1) Riet Vell, (2) Sol de Riu, and the (3) Mitjorn-Buda lobes.**

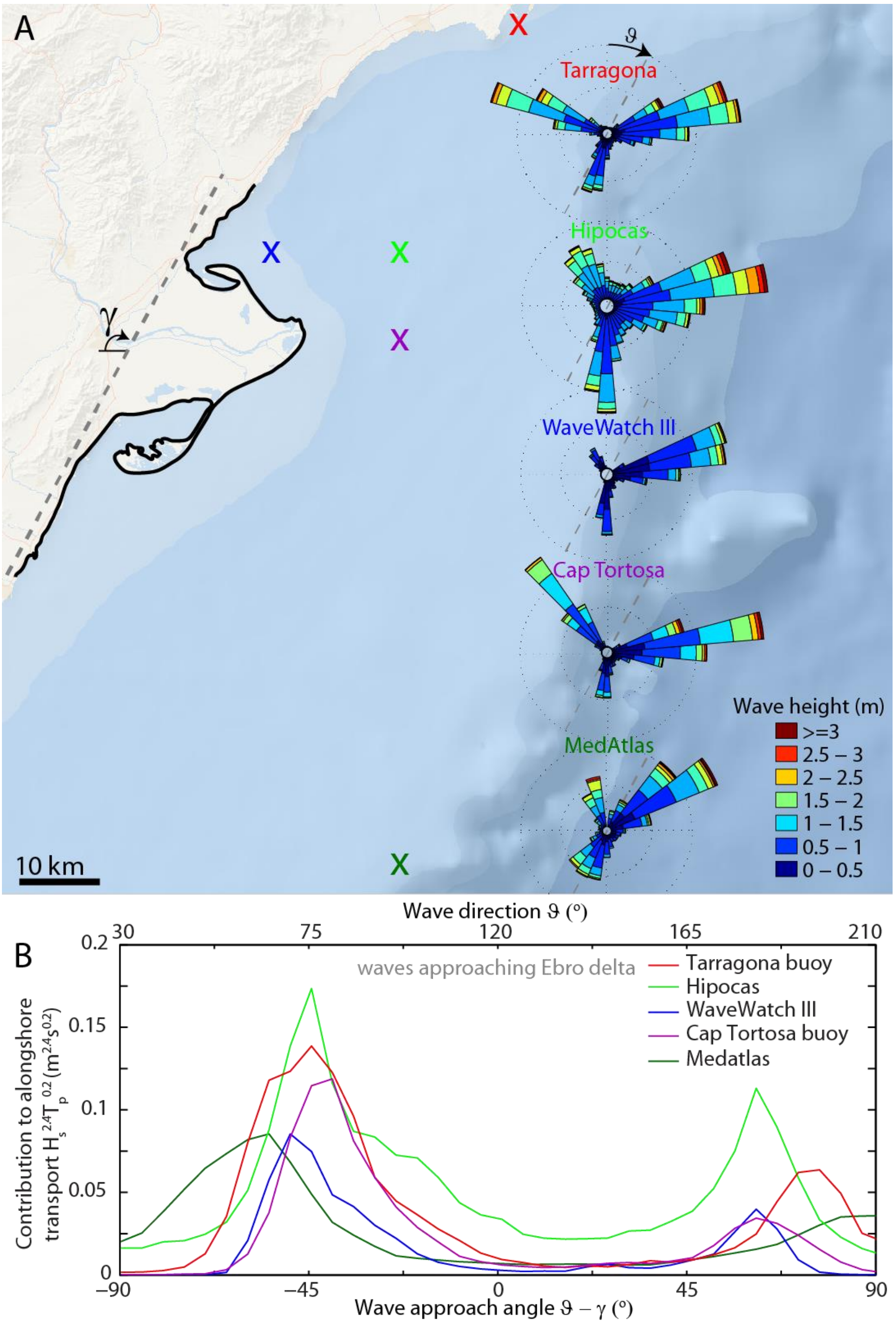

Figure 3: (A) Comparison of the five different wave roses and their location on a map from NOAA (2015)**. See table ~~1~~2 for an overview of the sources. (B) Angular distribution of alongshore sediment transport potential for the five different sources.**

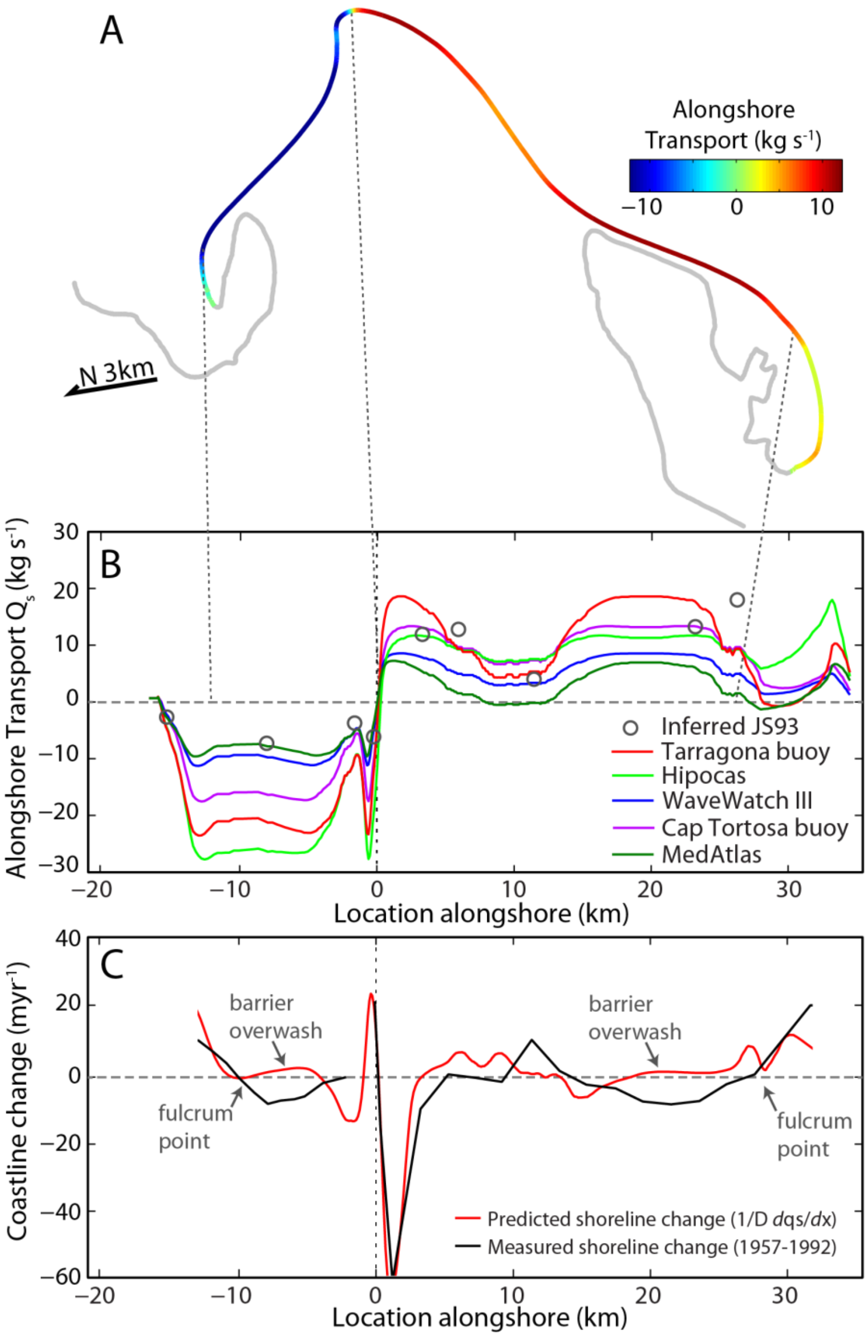

Figure 4. (A) The ~~Ebro delta~~Ebro delta coastline, colored by the simulated alongshore sediment transport flux from the Cap Tortosa data. (B) Alongshore sediment transport along the ~~Ebro delta~~Ebro delta coastline from all five wave climate sources (and assuming no sediment was supplied by the Ebro River). Alongshore transport is positive to the right when looking offshore. Black markers indicate alongshore sediment transport estimates from Jiménez and Sánchez-Arcilla (1993)**. (C) The Cap Tortosa buoy data recast into shoreline change rates using the one-contour-line approach (eq. 2) compared to the measured shoreline change rates from Jiménez and Sánchez-Arcilla** (1993)**.**

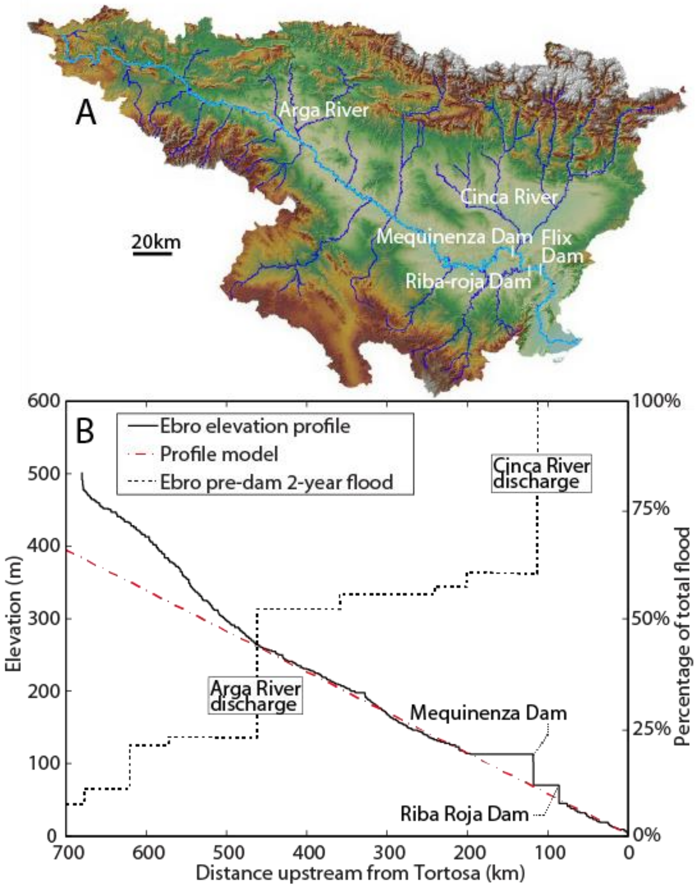

Figure 5. (A) The ~~Ebro river~~Ebro River basin showing the main river channel in light blue and larger tributaries in darker blue, colored by elevation. (B) The elevation profile of the ~~Ebro River~~Ebro River, with the equilibrium profile model prediction in red dashed line. The black dashed line shows the cumulative fraction of the Ebro pre-dam discharge from Batalla (2004)**.**

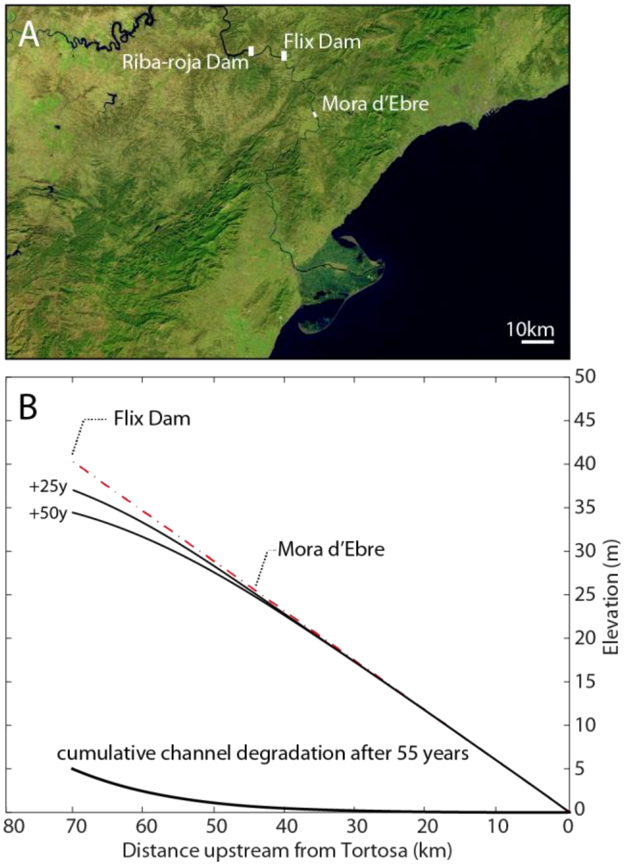

Figure 6. (A) A close-up of the Ebro drainage basin close to the delta ~~(data from Google Earth, 2015)~~(image Landsat). (B) Modeled response of the Ebro River downstream of the lowermost modern dam, the Flix dam. ~~The bed degradation measurements from Vericat and Batalla~~ (2006)**~~, are taken 25 km downstream of the Flix Dam, in Mora d'Ebre.~~**

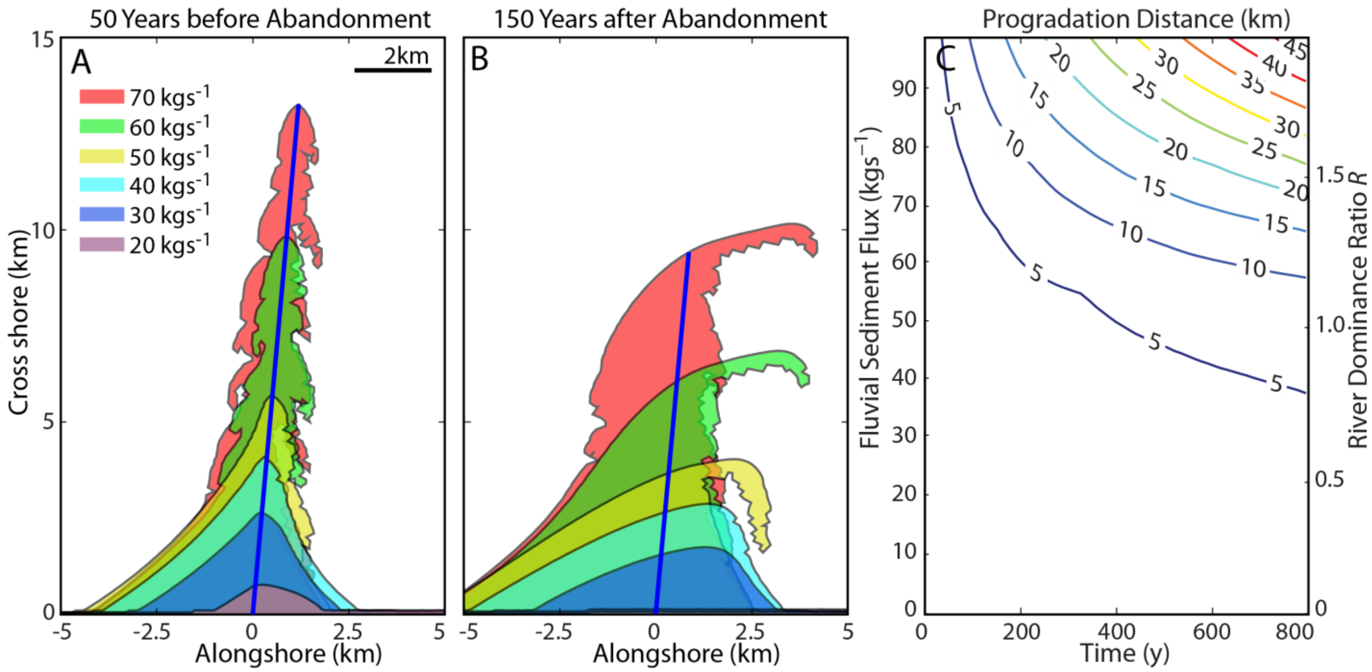

Figure 7. A modelled delta lobe (A) after 750 years of growth and (B) after 150 years of reworking (950 years of total model time). (C) Contour diagram of the progradation distance versus time as a function of the fluvial sediment flux Q_r, or the river dominance ratio R.

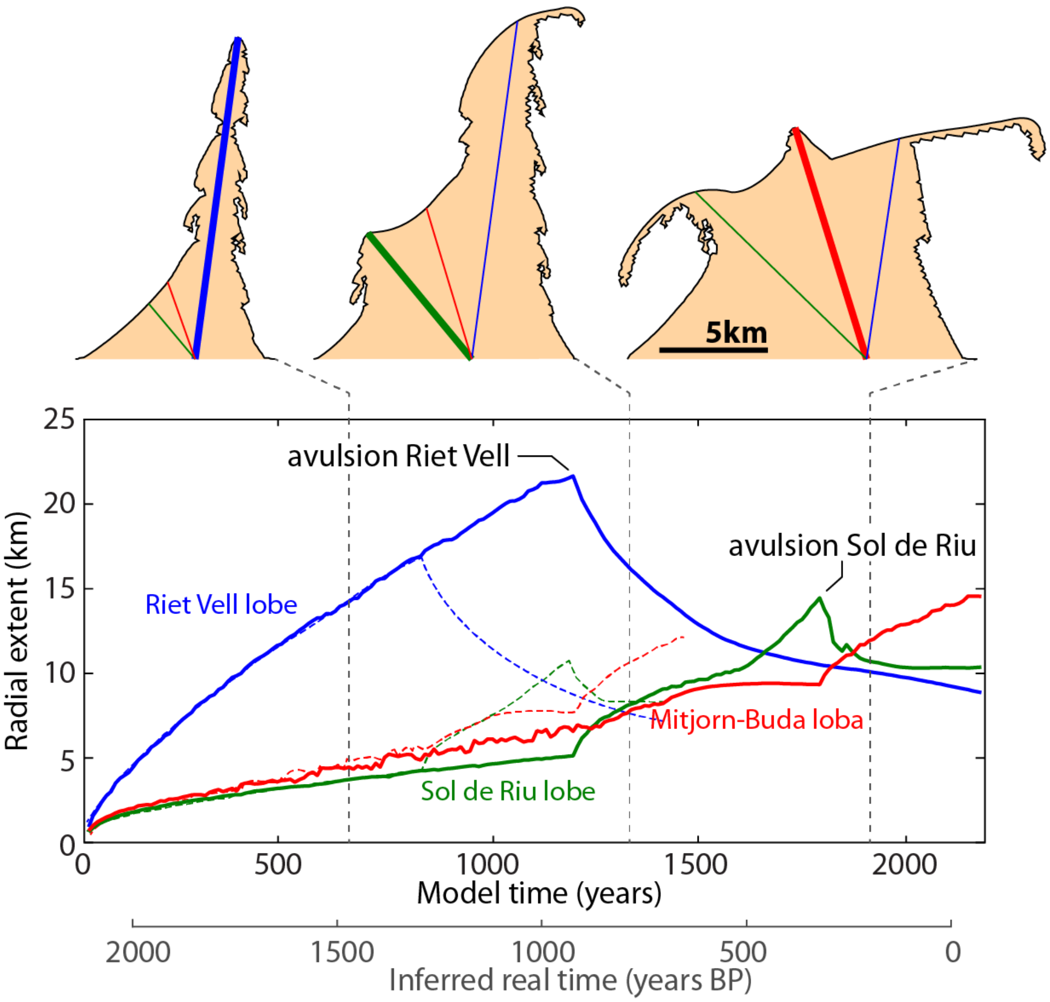

Figure 8. Simulated radial extent of the three different ~~Ebro delta~~Ebro delta lobes for a sediment supply of 70 kg s^{-1} and forced avulsions after 1200 and 1800 model years (solid lines) and after 800 and 1200 model years (dashed lines). Note that the radial extent can increase without the lobe being active because of littoral sediment transported from adjacent lobes. Three inset deltas show the solid line model run after 700, 1350 and 1900 years. The gray 2nd horizontal axis indicates the real time inferred from the solid line model run and the modern ~~Ebro delta~~Ebro delta morphology, where at the year 2015, lobes 1 and 2 are approximately 10 km long, and the active lobe is 15 km long, measured from the apex (Fig. 2).

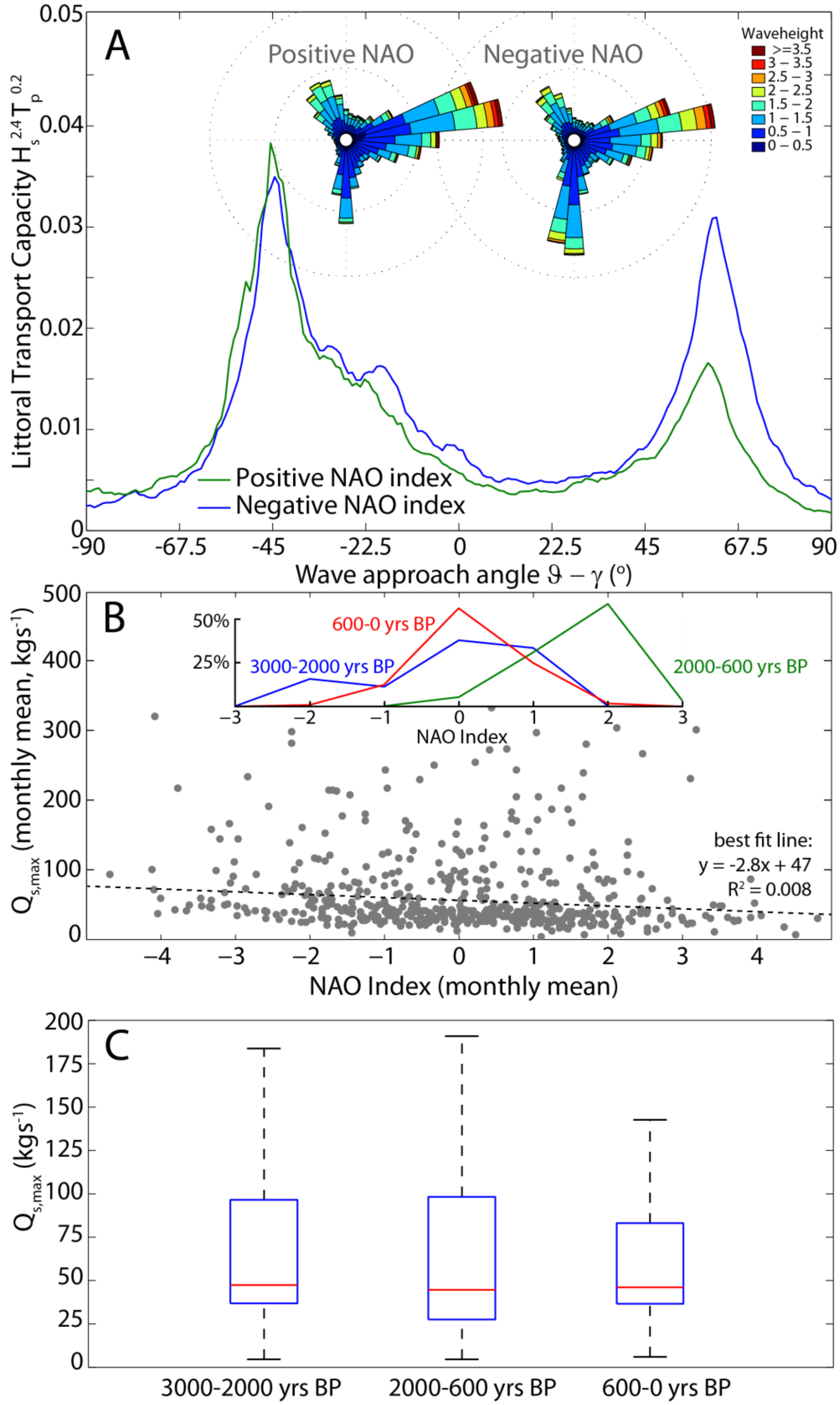

Figure 9. (A) The angular distribution of alongshore sediment transport potential from Hipocas hind-cast data (Sotillo et al., 2005)**, separated into periods of negative and positive monthly North Atlantic Oscillation (NAO) index** (Jones et al., 1997)**. Insets show wave roses weighted by alongshore sediment transport potential for positive and negative NAO. (B) The ~~effect of the~~ monthly NAO versus~~on~~ the monthly maximum potential alongshore sediment transport $Q_{s,max}$. Dotted line shows the least-squares best fit line. Inset shows the NAO index distribution for 3000-2000 years BP, 2000-600 years BP, and 600-0 years BP** (Jones et al., 1997; Olsen et al., 2012)**. (C) Computed distribution of Q_{smax} for different time periods.**

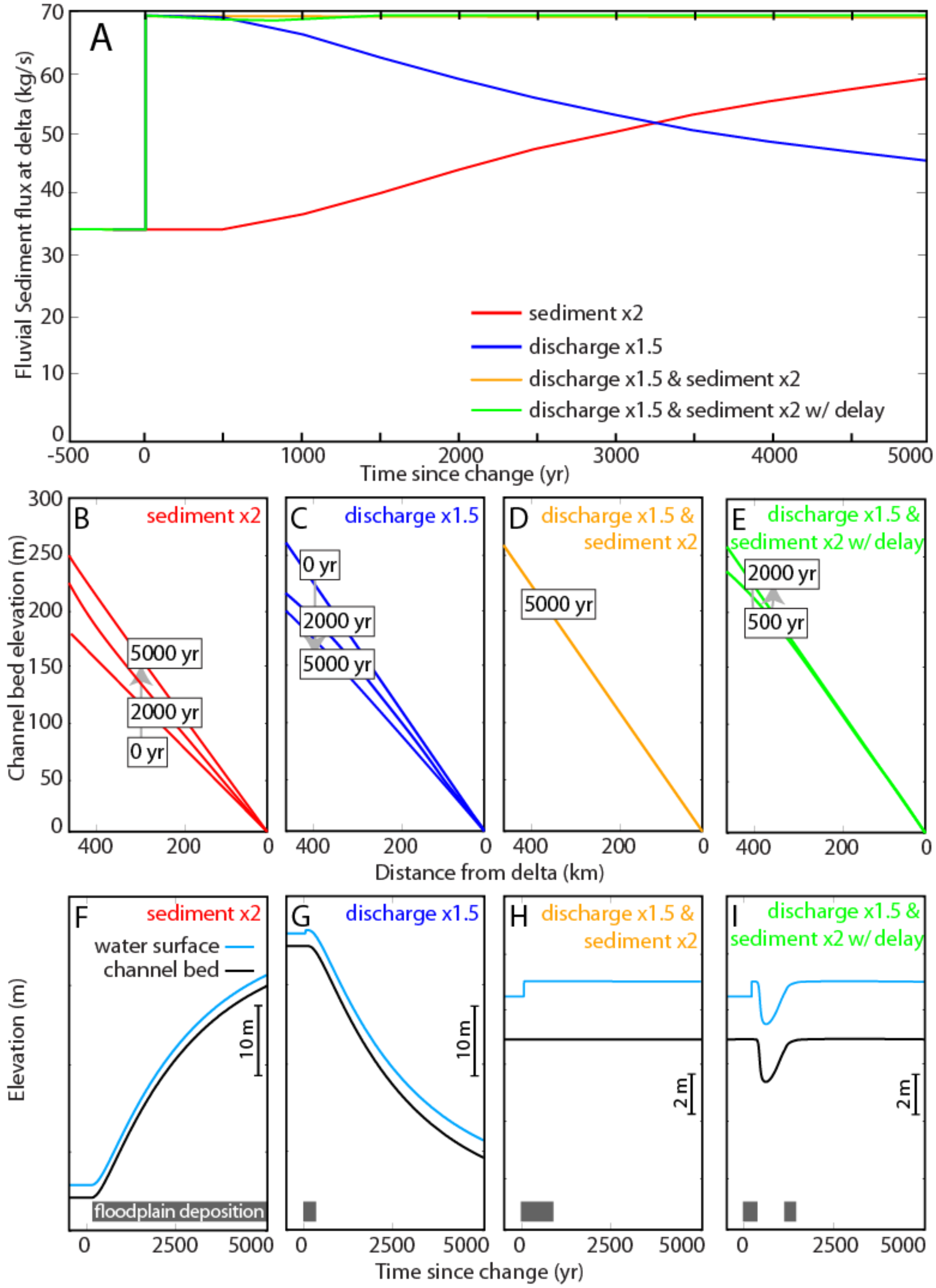

Figure 10. (A) Fluvial sediment flux at the apex of the delta and (B-E) longitudinal river profile evolution from four experiments of the river profile model with an increase in: sediment supply (red), flood discharge (blue), sediment supply and flood discharge (orange), and flood discharge with a lagged sediment supply (green). (F-I) Time evolution of the channel bed and water surface elevation through time, 200 km upstream of the delta at the approximate location of the floodplain records from Benito et al. (2008). **Note the different scales between (F-G) and (H-I). Expected occurrence of floodplain deposits (period of increasing water surface elevation) shown by the grey bars.**