Author responses to referee (1, 2 and 3) comments

RC = comments from referees

AC = author's response and changes in manuscript
(The page and line numbers refer to the revised manuscript where changes have been accepted. See "track changes" version of the manuscript in the end of this document.)

REFEREE #1:

RC (Referee Comment): This manuscript describes the calibration of a depth-averaged Delft3D morphodynamic model for an ephemeral gravel bed river. Subsequent analysis of model predictions, for a small and moderate flood, examine the relative importance of rising and falling hydrograph limbs for erosion and deposition. Pre- and post-event topographic surveys, acquired using mobile terrestrial laser scanning and RTK-GNSS, are used to provide topographic data to provide boundary conditions and evaluate model performance. The use of a spatially-distributed morphodynamic model to gain insight into ephemeral river processes is novel, promising and interesting. I think the manuscript has the potential to make a significant contribution. However, I have some major concerns:

1) The morphological model calibration exercise is not especially novel (see e.g. Schuurman et al., 2013; Williams et al., 2016b). However, the application and analysis of the morphodynamics of a braided ephemeral river is, in my opinion, where this manuscript has the greatest potential for impact. I would recommend that the paper is re-focused (in the introduction, results, discussion, conclusions) to emphasise the geomorphological findings that arise from the morphodynamic model results (as analysed in section 5.2 which considers flood sequencing, rising/falling hydrograph, diagonal bar formation, hysteresis and discharge thresholds). This would distinguish this paper from other published work that has discussed and explained the relative importance of representing different processes in morphodynamic models of gravel-bed rivers.

AC (Author Comment): Thank you for these suggestions. We have modified the manuscript accordingly and refocused the paper in introduction (also aims), results, discussion and conclusions sections to emphasize the geomorphological findings. The paper now aims at analyzing (P 3 line 30 onwards) "the evolution of a gravel bed ephemeral river channel (Rambla de la Viuda, Spain) during consecutive, moderate- (March 2013) and low-magnitude (May 2013), discharge events, by applying a morphodynamic modelling (Deflt 3D) approach. Based on the simulations, we analyze 1) the timing of river bed erosion and deposition in relation to the flow hydrograph phases during moderate- and low-magnitude discharge events, 2) the hydraulic characteristics (e.g. shear stress) explaining these channel and bedform morphodynamics, and 3) the prevailing fluvial processes, and related sediment transport routing, during these different magnitude discharge events in a gravel bed ephemeral stream. Understanding of these processes would be needed particularly for river management works and flood mitigation purposes."

Along with these changes, we have modified the results section so that we have moved the morphodynamic model's calibration results to the supplementary material (as the second reviewer suggested), and present only their summary in methods section. We have added more results related to the morphodynamics (channel bed elevation changes and bed shear stresses) so that we were able to refocus the paper. Because other referees suggested more detailed discussion also related to the modelling, we have also modified the discussion section related to the modelling uncertainties.

RC: 2) The morphological model description does not mention bank erosion. Is bank erosion represented in the model? Bank erosion has been identified as an important process in perennial gravel-bed rivers (Wheaton et al., 2013). Although existing, simplified bank erosion algorithms (e.g. repose schema in Delft3D) may be inadequate in representing natural rates of lateral adjustment (Stecca et al., 2017) there is a need to justify the incorporation (or not) of lateral adjustment in the model.

AC: No lateral erosion algorithm was included in this commercial model version. Based on the laser scanning data, we could see that the channel changes were vertical and not lateral during these medium and small magnitude discharge events. The banks of the channel are bedrock, and the moderate- and low-magnitude discharge events were not able to erode the banks.

RC: 3) The study area description describes how a lobe is forming in the model domain? Is this a result of enhanced sediment supply from upstream? Is an equilibrium sediment supply boundary at the upstream end of the model a suitable assumption?

AC: We consider an equilibrium sediment supply as a valid assumption. The initial boundary conditions of the input and output sediment transport load amount were defined as 0. This is because the flood events started from 0, and no significant transport, i.e. evolution of bedforms was observed upstream and downstream of the simulation area. The model then calculated the transport based on the selected transport equations and using equilibrium concentration for carrying input sand sediment fractions. The selected initial boundary conditions seem to be congruent with the flooding mechanisms of Rambla de la Viuda and also with other published works, i.e. Williams et al (2016b), for loosely consolidated sand and gravel. So, the modelled flow carried each sand sediment fractions (suspended) adapted to the local flow conditions at inflow boundary, and the model assumed that very little accretion or erosion was experienced near the model boundaries. Based on measurements, the presence of sand size particles and their concentration in the study site were also almost non-existent, and no channel changes occurred at downstream boundary of the simulation area. Thus, this equilibrium load condition was considered valid, and it was also the only option for the present modelling approach, as no input suspended load measurements were available. Similarly as Williams et al. (2016b) state, the model results, i.e. the modelled deposition and erosion, when compared to observations, could have been possibly enhanced if the input suspended sediment load observations would have been available.

Despite this lack of the data during the flood events, we had a good control on sediment volume and gravel particle-size moving downstream as the forefront lobe prograded over a flat valley bottom (as gravel bed had been mined). Total volume input and total transport rates observed in earlier study of Rambla de la Viuda by Calle et al. (2015), had already proved the high availability of sorted gravel particles, and were the basis of the decisions made while building up the model. As already mentioned, the channel changes at the output downstream boundary of the studied reach was zero. In addition, the simulation result supports the hypothesis of Calle et al. (2015) that moderate- and low-magnitude events reworked sediment locally within the reach. This means that these flows were not able to establish a sediment connection upstream, i.e. between larger reaches, and the transported sediment originated from the erosion of adjacent areas.

We have described these also in the discussion P 23 lines 10-30 and methods P 12 line 30 - P13 line 4.

RC: 4) Has any analysis of uncertainty in topographic been incorporated into the volumetric calculations of erosion and deposition (see e.g. Wheaton et al., 2010). Although the mobile laser scanning error is quotes as 0.034 m for the March 2012 survey (Table 1) this may still be significant depending upon the magnitude of changes, particularly deposition. In addition, it would be useful to have figures showing patterns of observed and predicted morphological change. I think these would be more useful for evaluating model performance than the maps of observed and post-event predicted topography (within section 4.2).

AC: The error estimates of measured changes had already been estimated in Calle et al. (2015) based on the all available data we had. Therefore, the analyses were not repeated in this study. Based on also the referee #3's comment, i.e. that methods should not be repeated and referencing to earlier studies should be done, we decided not to add more error analyses into this present paper, but we are referring to Calle et al. (2015) (P8 lines 19-20). We had already included comparison between observed and predicted morphological changes from the fine grid simulations, which were better than the coarse grid simulations (moved now as Fig. 3 of the supplementary material of calibration results, however, the same results of simulation 9 and 10 can also be seen from the new Fig. 4 of the main manuscript). We decided to modify the new Fig. 4 of the manuscript so that it now also shows the changes between observed 2012 and observed 2013 topographies, and also change between observed 2012 and simulated (simulation 9) 2013 topographies, in addition to the previous analyses of simulations 9 and 10. In addition, the predicted temporal bed elevation changes can be seen now from the new Fig. 7.

RC: 5) Spatially variable roughness is used for some simulations (description P11 L15). For morphodynamic simulations, is roughness recalculated from the surface grain size distribution or is spatial variation fixed a priori?

AC: The model version was not able to change/update the spatial distribution of roughness values during the simulations. The initial input values were applied. (P11 line 25 – P12 line 1)

RC: 6) The modelling undertaken is calibration rather than a sensitivity analysis (P13 L2).

AC: Thank you for this notification. We have changed the words "sensitivity analysis" to "calibration" throughout the manuscript and the supplementary material.

RC: 7) The presentation of methods and results on the MPM bedload transport formula. On P14 it is stated that this is not integrated into the Delft3D code (which it is, see Williams et al., 2016b) yet this is contradicted on P19 where MPM results are discussed.

AC: We meant that the Bagnold equation was not included in the standard set of equations of the commercial model we had. The MPM was all the time integrated in the model version of ours. During the shortening of the methods section, we ended up deleting the sentence in question.

RC: 8) I am not convinced that the threshold of 30 cumecs is widely applicable (conclusion 7). What about the influence of other river styles, sediment sizes, vegetation interactions)?

AC: We have modified the former conclusion 7 (now conclusions 6) and the discussion 5.2 section so that we are not anymore suggesting this limit to be applicable widely in other areas, and we now just mention that this 30 m^3/s limit was observed in Rambla de la Viuda. Thank you for these thoughts, we have included more about the sediment sizes and different style river processes in the discussion. There was no vegetation present in the modelled inundated area, thus the vegetation could be excluded from the reasons affecting on these simulations.

RC: 9) Some sentences require sharpening / clearer expression (some are identified below). Check methods and results are consistently written in the past tense.

AC: Thank you for noting this. We have sharpened and clarified the expressions throughout the manuscript. We have also modified the language so that it is consistently in past tense in methods and results sections.

RC: 10) Data availability statement: since this is an open access journal I would expect the observed topography and model input files (as a minimum for the calibrated model runs for the small and moderate events) to be packaged up and available for download (perhaps with a dataset doi – see e.g. re3data.org to search suitable repositories). This would promote the "reproducibility" of the research and enable readers to re-run the models, if they were interested in analysing aspects of the results that are not presented in this paper.

AC: We agree, and it is possible for us to open the input topography, the input sediment grain sizes, the AOI of the calibration area, and the observed final topography of the calibration area. These all will be published in shapefile format so that it is easier for wider public to apply those, as not everyone might have Deflt3D model. Because some of the model input data files were from third parties, i.e. the discharge and the original laser scanned data, we are not able to open the whole model for the public.

RC: OTHER COMMENTS Title: Does changes need to be plural? "Gravelly" or "gravel bed" (also consider elsewhere) Delft2D: Delft3D is the name of the software but the simulations are executed in shallow water mode. Use "depth-averaged Delft3D" or similar phrasing rather than Delft2D.

AC: We have modified the title accordingly and also changed the word "gravelly" to "gravel bed" also elsewhere in the paper. The new title is:" Topographical change caused by moderate and small floods in a gravel bed ephemeral river - depth-averaged morphodynamic simulation approach". We have also modified throughout the paper that we are talking about the Delft3D model and its 2D implementation.

RC: P1 L15: Change performed to caused.
AC: This has been changed (P1 line 16).

RC: P1 L18: We pursue is an odd phrase in this context.
AC: While modifying the manuscript, we ended up deleting the sentence.

RC: P1 L20-22: This is the key research question – see my comment 1 above about emphasizing this throughout the manuscript.
AC: We have modified the aims based on your suggestion, and we are emphasizing this throughout the manuscript. Thus, the focus of the paper is now in analyses of the morphodynamics during the discharge events.

RC: P1 L28-31: Is there sufficient evidence from the two simulated events to extrapolate a conclusion about flood sequencing?
AC: Thank you for noting this. You might be right. We have deleted this conclusion.

RC: P2 L19: Yes, dynamics during high flows are difficult to measure but there are some attempts to do this e.g. Williams et al., 2015.
AC: The reference of Williams et al. 2015 is a study done in perennial rivers. Therefore we did not add the reference into this suggested sentence, but a little bit later in the next paragraph (P3 lines 19-21).

RC: P2 L23: Williams et al. citation should be 2016b not 2013
AC: This has been corrected thoughout the manuscript.

RC: P2 L28-29: How did the Hooke et al. (2005) model perform? Be more critical / analytical in the literature review examination (and this also goes for other parts of the introduction e.g. P2 L31 – why do the uncertainties arise?)
AC: We added description of how their model worked: "Their model worked well with simulations using moderately large discharges during clear water conditions, but discharge events with sediment loads had some tendency for excess deposition (Hooke et al., 2005)" (P3 lines 5-7). We also added related to the "P2 L31 comment" more explanation about the uncertainties and also about the quality of new measurement approaches in the introduction (P3 between lines 10-21). We have added more references and modified the background/introduction section into a more analytical form.

RC: P2 L32: References to the use of repeat surveys for morphodynamic modelling could be stated e.g. Lotsari et al., 2013; Williams et al., 2016a
AC: We have added the references (Lotsari et al., 2014a; Williams et al., 2016a) (P3 line 13).

RC: P3 L2: Broader references are needed here e.g. Milan et al., 2009
AC: We have added there now Milan et al., 2007; Vaaja et al., 2011; Calle et al., 2015; Kasvi et al., 2015; Kukko et al., 2015 (P3 lines 15-16).

RC: P3 L1: Within this paragraph you could emphasize more strongly that since ephemeral rivers can be surveyed whilst the river bed is dry, the topographic survey is characterized by lower errors because wet areas are usually associated with greater survey uncertainty.
AC: We have added in the introduction section following sentences to emphasize the advantages of the measurements in an ephemeral channel, and why there are less uncertainties than in perennial rivers. References have been also added (P3 lines 13-21): "Recently, the measurement techniques for deriving this calibration data for morphodynamic modelling have increased. One of them is accurate laser scanning (mobile and terrestrial), which enables to capture the channel topography before and after flooding in detail (Milan et al., 2007; Vaaja et al., 2011; Calle et al., 2015; Kasvi et al., 2015; Kukko et al., 2015). The laser scanning enables rapid measurements of gravel bed rivers at the sub-grain level resolution (Milan et al., 2007). In ephemeral rivers the quality of topographical data can be very good and the uncertainties are less than in perennial rivers, either with laser scanning or traditional RTK-GPS measurements, because these rivers can be surveyed when the river bed is dry. The high uncertainties in topographical measurements of sub-water areas in gravel bed perennial river have been related particularly to the high bed load velocities and temporal variability of bed load (Williams et al., 2015)."

RC: P3 L15: I suggest emphasising the geomorphological research questions rather than the calibration exercise (see comment 1 above).
AC: We have refocused the paper and we now concentrate on the morphodynamics during the discharge events (see also our earlier responses).

RC: P4 L17: Where is the evidence that these sized grains were moved?
AC: We have clarified the sentence as follows (P4 line 32 onwards): "These two discharge events transported 12–41 mm sized gravel (D_{50} values) according to the measurements (see section 3.3 below), which had been performed in the areas of

topographical changes. These have been also published at Calle et al. (2015). The movement of these gravels caused the development of the bar fronts (Calle et al., 2015)."

Every sampling location had been evaluated in detail in Figs. 9 and 12 of Calle et al. (2015), where morphological mapping, DoD and simulation evidences are shown.

We had also already mentioned in methods section that "These measurements represented different active forms, from bars to the channel bed, which had evolved during the 2013 spring floods" (P9 line 33-P10 line 2).

RC: P5 L8: Are morphological and topographic both needed?
AC: You are right. We deleted the word "topographical".

RC: P5 L15: Clarify whether the grain size distributions were spatially distributed.
AC: The word "spatial" has been added to the sentence (P15 line 17).

RC: P6 L12: Clarify in the text whether the re-scaling with linear.
AC: We added a clarification "The hydrographs were re-scaled by using different multipliers to match the peak discharge calculated during the calibration procedure of the model (see Sect. 3.4 below, and from Calle et al., 2015)." (P6 lines 19-21)

RC: Figure 3 legend: More commentary is needed. Abbreviations need to be stated. A location map would be useful.
AC: We added more explanation of the abreviations to the figure caption. We also added the locations of the HWM measurements in the Fig.1.

The caption of the Fig. 3. is now as follows:" Figure 3: The hydrodynamic calibration results based on the coarse grid (1.51–5.31 m cells) and fine grid (0.76–3.03 m cells). In this figure, the high-water marks (HWM) and simulated water levels are presented. In addition, the trendlines fitted along these measurements and simulation results are shown. These calibration results of the fine grid were previously presented in Calle et al. (2015) by the same authors. The Qx1.3, Qx2 and Qx2.5 refer to the discharges scaled to match the peak discharge at the study site. Daily and 5 min refer to the observation interval of discharges at Vall d'Alba station. wl = water level based on HWMs and simulations, trendline = the trendline fitted in the measured HWMs and the simulation results. The location of these HWM measurement points have been shown in the Fig. 1."

RC: P8 L2: Sentence 2 – The three datasets need to be introduced before this sentence.
AC: The sentences have been clarified as "Three topography data sets were applied. These were 1) initial topography (MLS, March 2012), 2) calibration topography between the floods (RTK-GPS, March 2013), 3) final validation topography after the floods (MLS, June 2013)." (P8 lines 10-12)

RC: P8 L18-19: Sentence not clear
AC: We have clarified the sentence as follows: "Cell sizes smaller than the "fine" resolution (i.e. 0.76–3.03 m) did not enhance the results, and those only increased the computational time. Thus, curvilinear grids of two resolutions, "coarse" 1.51–5.31 m cells and "fine" 0.76–3.03 m cells, were created from the topography measurement times." (P9 lines 4-7)

RC: P8 L25: Typo MSL
AC: This has been corrected as MLS (P9 line 9).

RC: P9 L16-20: Sentences not clear.
AC: We modified the sentences as follows: "These observed elevation and volumetric changes between the events were compared to the simulated changes. For calculating the volumetric changes the curvilinear grid topographies were needed to convert into regular grids. To minimize the errors, a 0.5 m regular grid's cell size was selected, as the original cells were mostly divisible by that value." (P9 lines 24-27)

RC: P9 L28: What guidance was used to sample a 10 cm layer?

AC: We used the criteria described in Bunte and Abt 2001, Page 188. After inspection of the surface layer in a near pit, and considering the larges particles, we estimated an embedded depth of 10 cm. We have added clarification in the manuscript (P10 lines 4-5): "The upper layer-sublayer contact was established following the criteria described by Bunte and Abt (2001) considering the size of the largest particles embedded depth."

RC: P9 L30: Is this difference for the upper or sub layer?
AC: Those were all upper layer samples (P10 lines 5-6).

RC: P10: How many size fractions were used in the model?
AC: D50 values were used in the model. We added a sentence: "The D50 grain size values were used in the model." (P11 line 1)

RC: P10 L11: It would be useful to refer to a map here.
AC: We are referring to a map of Calle et al. 2015, and we have now included the sample locations in our Fig. 1 too (P10 line 11).

RC: P11 L1: Insert "solving" after "for".
AC: During the shortening of the methods section, this sentence was deleted.

RC: P11 L5: This event has previously been referred to as March 2013 rather than 6.3.2013. Be consistent
AC: This has been modified as "…WL trendline, of the 6th of March 2013 discharge peak situation." (P11 line 13). We have also checked the consistency throughout the manuscript.

RC: P12 L12: Quantify "sufficiently well"
AC: This was vague selection of words from us. We modified the sentence as "These simulations also reproduced the water levels" (P12 line 19).

RC: Table 6: Separate volumes and
AC: We have separated "the volumes" and "the difference compared to observed" into their own columns. We have splitted this table into two. The original whole table can be seen from the supplementary data of the paper (there the Table 3), and the data related to observations and the simulations 9–10 is also presented in the new Table 5 in the results section of the main manuscript.

RC: Fig 4 / 5: Be consistent in use of "After" in figures (top left corner) but not in other sub-figures.
AC: We have modified the former Figs. 4 and 5 by deleting the word "after". We have moved these two figures in the supplementary material, where they are Figs. 1 and 2.

RC: P20 top paragraph: The morphological change description here is interesting and I think the results / discussion would benefit from more analysis of this style.
AC: We have refocused the paper and thus also modified the results to include/concentrate more on morphological changes during the discharge events. We have also modified the discussion, conclusions and aims.

RC: Section 5.1: This discussion needs to be more closely integrated into the discussion in other, similar Delft3D (or other graded sediment morphological model) calibration findings.
AC: We have morified the 5.1 section thoroughly. We have added more references and discussion related to other studies done with Delft3D model, and the calibration of Delft3D/graded sediment morphological models in other studies (see section 5.1).

RC: P25 L11: "Unique" – from sample of 2?
AC: We have modified the sentences as (P25 line 1): "Our study has shown that geomorphic responses to the two analysed discharge events differed."

RC: P25 L31: "differs" – explain why

AC: We had explained in the paragraph, that they observed most erosion during the rising and peak flow phases, as in Rambla de la Viuda the receding phase was found also important for the channel changes (P25 lines 12-21). We have now also added the following sentences in this paragraph to explain this in more detail: "They found only some scour during sustained high flows following the flood peak (Gendaszek et al., 2013). Noteworthy is that they applied one sensor per reach, and thus the site selection could have greatly affected on their results."

RC: REFERENCES

Lotsari, E., D. Wainwright, G. D. Corner, P. Alho, and J. Käyhkö (2013), Surveyed and modelled one-year morphodynamics in the braided lower Tana River, Hydrological Processes, 28(4), 2685-2716. doi: 10.1002/hyp.9750.

Milan, D. J., G. L. Heritage, and D. Hetherington (2007), Application of a 3D laser scanner in the assessment of erosion and deposition volumes and channel change in a proglacial river, Earth Surface Processes and Landforms, 32(11), 1657-1674. doi:10.1002/esp.1592.

Stecca, G., R. Measures, and D. M. Hicks (2017), A framework for the analysis of noncohesive bank erosion algorithms in morphodynamic modeling, Water Resources Research, doi: 10.1002/2017WR020756.

Schuurman, F., W. A. Marra, and M. G. Kleinhans (2013), Physics-based modeling of large braided sand-bed rivers: bar pattern formation, dynamics and sensitivity, Journal of Geophysical Research: Earth Surface, 118(4), 2509-2527. doi: 10.1002/2013jf002896.

Wheaton, J. M., J. Brasington, S. E. Darby, and D. A. Sear (2010), Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets, Earth Surface Processes and Landforms, 35(2), 136-156. doi: 10.1002/esp.1886.

Wheaton, J. M., J. Brasington, S. E. Darby, A. Kasprak, D. Sear, and D. Vericat (2013), Morphodynamic signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-bed river, Journal of Geophysical Research: Earth Surface, 118(2), 759-779. doi: 10.1002/jgrf.20060.

Williams, R. D., C. R. Rennie, J. Brasington, D. M. Hicks, and D. Vericat (2015), Withinevent spatially distributed bed material transport: linking apparent bedload velocity to morphological change, Journal of Geophysical Research: Earth Surface, 120(3), 604-622. doi: 10.1002/2014JF003346.

Williams, R. D., J. Brasington, and D. M. Hicks (2016a), Numerical Modelling of Braided River Morphodynamics: Review and Future Challenges, Geography Compass, 10(3), 102-127. doi: 10.1111/gec3.12260

Williams, R. D., R. Measures, D. M. Hicks, and J. Brasington (2016b), Assessment of a numerical model to reproduce event-scale erosion and deposition distributions in a braided river, Water Resources Research, 52(8), 6621-6642. doi:10.1002/2015WR018491.

AC: We have gone through these references and added most of these (i.e. the most suitable ones) into the manuscript and its reference list.

REFEREE #2:

RC: The paper provides a detailed account of the calibration of a numerical model (a 2d implementation of Delft 3D) in order to simulate the geomorphic changes during flash flood events. The main novelty and significant findings of the work are the predictions of when sediment transport occurs during flood events of different magnitudes, based on a model simulation calibrated versus observed changes. It is an interesting and thorough piece of research.

However, the purpose of the work and the findings and conclusions get lost in a highly detailed description of the calibration method. The calibration itself is not particularly novel, although as it includes observations spanning two events it is more robust than many other examples. Much of this detail could be moved to supplementary materials, and a concise summary provided in the main manuscript. This would allow the manuscript to be focussed more on the simulations themselves, what they show, and why this is important (I felt this last point was not made clearly enough throughout). The authors at several points refer to sensitivity testing performed on the model. Although evidently there were some tests performed to assess model

behaviour differences with some variations, these are not sufficiently thorough to be considered a sensitivity analysis, and falls short of the level of analysis performed by operators in other modelling fields. For example, the tests performed would not ascertain any non-linear interactions between the parameters being tested. For interest, Ziliani et al (2013) provides a useful and efficient methodology for screening model parameter sensitivity in reach-scale geomorphic models, which might be useful for future work. The authors should be careful using terms such as sensitivity analyses, and the conclusions they draw from the tests should not be presented with as much certainty as they presently are. The tests may be useful for informing the calibration process, but cannot be relied upon to suggest anything concrete about the model behaviour.

AC: Thank you for these thorough comments. We have refocused the manuscript to emphasize the geomorphological findings during the discharge events (also referee #1 had suggested that). Thus, we have modified the aims, results, discussion and conclusions accordingly. We have moved the morphodynamic model's calibration results into the supplementary material and are now presenting a summary of the calibration under the methods section (3.5). Thus, we have also moved the former Figs. 4 and 5 and Tables 5 and 6 into this supplementary material (now Figs. 1 and 2, and Tables 2 and 3 in the supplementary material). We added also Table 4 into the supplementary material (there it is the Table 1), all thought it is also presented in the main manuscript as Table 4. We also present the former Fig. 6 in the supplementary material (Fig. 3 there) and parts of it in the manuscript (now Fig. 4 there), as these are needed in both of the documents so that it is possible to read those separate documents independently. We have also changed the wordings throughout the paper, i.e. we are not anymore talking about the sensitivity analyses, only about calibration. We have now also emphasized more in the introduction section, why this research is important. We have also modified the conclusions so that the emphasis is on geomorphological findings and deleted conclusions related to model calibration results.

RC: Below are some notes for correction or additional clarification:
Page 1, Line 15 – use "caused by the flood" or "resulting from the flood" instead of "performed by"
AC: We have modified it as "caused by a flood" (P1 line 16).

RC: Page 1, Line 16 (and throughout) – strictly speaking, a 2D implementation of Delft 3D
AC: We have modified this throughout the manuscript. Thank you for noticing this mistake of ours.

RC: Page 1, Line 24 – As explained above, I don't think a rigorous enough sensitivity test has been performed to make these conclusions with such certainty
AC: Thank you for pointing this out. We agree, and we have modified the manuscript so that the sensitivity analyses are not anymore mentioned, and we talk only about calibration. Also the calibration section has been reduced: a summary of the morphodynamic model's calibration is now presented in the methods section, and most of the material is presented in as the supplementary material for this paper. We have also modified the abstract based on the modifications done to the manuscript and its conclusions.

RC: Page 1, Line 24-25 – Is the total load equation probabilistic? Or is it implemented in a deterministic way too?
AC: You are right the total load equation had been implemented in a deterministic way. We have removed the sections mentioning the deterministic way. We have modified this throughout the manuscript.

RC: Page 2, Line 13-16 – I'd like to see something here to explain why this is important. Why does it matter that we know this?
AC: We have added the following explanations about the importance of the study in the introduction (P2 lines 3-8):
"The costs of these floods due to their catastrophic nature include major economic, social and environmental aspects (Petersen, 2001). These are caused by both hydro- and morphodynamics during the discharge events. For reducing the emergency costs and enhancing the preventive flood mitigation measures, understanding of the forces of the flow and related channel changes throughout the discharge events would be important. For being able to allocate the measures temporally most efficiently, the understanding of the timing of the morphodynamics and their effects to the adjacent river environment throughout the discharge events are needed."

AND

P2 lines 20-25: "Case studies have reported most erosion during the rising and the peak flow phases in perennial rivers (e.g. Gendaszek et al. 2013), but similar knowledge for ephemeral river channels is still low. It would be important to understand the capacities of ephemeral rivers for sediment deposition and flooding due to the combined effects of water flow and sediment transport during flood situations. If the erosion and deposition would be in total greater during the receding phase than in rising phase, the receding phase should not be ignored while planning flood mitigation measures."

RC: Page 2, Line 30-34 – The authors are also in danger of overparamaterising the model by using a single calibration against a small set of observations. It risks equifinality with the model matching the data well, but there are many ways that the changes could have come about.
AC: We added "of different consecutive flood situations" (P3 lines 9-10), so that it is here pointed out that the calibration and validation can be done by using consecutive flood situations.

RC: Page 3, Line 19 – With two events the authors could have calibrated with one and validated with the other as an extra check.
AC: This is what was done, and we have reworded the text. We modified the sentence as "Thus, the model is calibrated with data from moderate magnitude event, and then validated based on the consecutive low-magnitude event." (P4 lines 5-6).

RC: Page 4, Figure 1 – It would be more useful to see the reach in context with the wider catchment here than its rough location in Spain. How big is the catchment and where is the reach in relation to the gauging station used?
AC: The watershed boundaries, observation station location, detailed study site location, Maria Christina reservoir and river network have been included in the new Fig. 1. The total water shed size and the increase in the watershed size between the gauging station and the study site had been already mentioned in the text.

RC: Page 6, Lines 10-16 – What is happening between in 18km between the gauge and the reach to increase the discharge. Are there more channels flowing in? Has there been more rainfall in between? Convective events are likely not to span 18km so rainfall will not be uniform. This is key as the authors make the assumption that the hydrograph is the same shape when flow makes it to the reach, just scaled larger, yet the reasons for the increased discharge will also likely change the shape of the hydrograph and this potentially invalidates the calibration and the conclusions. More detail needs to provided here to justify the above assumption.
AC: The rain producing floods in this catchment are not typical summer convective events, but Mesoscale Convective Complexes (autumn heavy rains), and those may be up to 100 km in diameter. The rains producing these floods are autumn and spring, and are related to Atlantic fronts, which do not give much spatial variability. We have added a more detailed description about the rain events as follows (P4 lines 13-15): "The rain producing floods in this catchment are caused by mesoscale convective complexes (autumn heavy rains), and those may be up to 100 km in diameter. The rains producing these floods occur in autumn and spring, and are related to Atlantic fronts, which do not give much spatial variability."

AND

P4 lines 26-32: "The two events under study occurred in spring 2013. These were caused by two rain events, which were recorded with 5 minute interval at the precipitation and gauging station provided by the Automatic System of Hydrologic Information (SAIH-Jucar) at Vall d'Alba (Fig. 1 and Calle et al., 2015). The first rain event (March 2013) started on 4th of March lasting for three days with a total 70 mm. The second rain event (April-May 2013) started on 27th April and lasted four days with a total of 72 mm. These rain events caused flows that lasted 13 days (started at 12:00 on 5th March) and 9 days (started 14:10 on 30th April), respectively. The peak discharges of 23 (at 11:05 on 6th March) and 12.5 m^3 s^{-1} (at 9:05 on 1st of May) were registered in the gauging station of Vall D'Alba, respectively."

We can verify that the hydrograph shape at the study site of Rambla de la Viuda is similar to the hydrograph at Vall d'Alba station (see the supplementary material entitled "hydrograph shape"). We had installed water level sensors at the study site later in year 2014. Based on these we can verify that the hydrograph shape of the study site of Rambla de la Viuda is similar

to Vall d'Alba observation station (see the locations from the Fig. 1 of the main paper document) and that the water level is much higher at the study site than the Vall d'Alba station. Thus, these measurements prove that the discharge has to be also much higher in the study area than at Vall d'Alba. In addition, based on the roughness calculations with Limerinos equations and the model calibration results, the Qx2 discharge was the correct one to be applied in the model. Based on the Limerinos equation calculations, the Qx2 was expected to work the best due to the average nature of the derived roughnesses and inclusion of bedform and bank roughness effects.

In addition, it was possible to calculate the daily discharge curve for María Cristina reservoir, which locates downstream of the study site of ours (see the supplementary material). When comparing the March 2013 discharge peak of Qx2 discharges (Fig. 5 in the main manuscript), the resemblance to the daily discharges of María Cristina reservoir can be seen. Due to the fact that only daily data was available from Maria Christina reservoir, the curve of the reservoir is flatter than the one at the study site. Also calibration curves for the reservoir and water loss by infiltration are unclear. Despite these, we can be confident that the shape of the hydrogprah at the study site was realistic and that the Qx2 discharge would be the correct discharge to apply at Rambla de la Viuda study site.

In the main manuscript, we also refer to this supplementary material regarding the hydrograph shape.

RC: Page 6, Lines 17-22 – By calibrating the discharge against water levels there is another assumption that the bed levels were static and had no influence on the water levels in the flood (despite in the discussion stating that bed changes are an important influencer on water levels). This will lead to some uncertainty cascading to the simulations.
AC: This had been taken into account, and the water level was also checked during the morphodynamic simulations. We modified now the sentence in section 3.5 (P13 lines 20-21): "These 61 simulations included simulations with Qx1.3, Qx2 and Qx2.5 discharge hydrographs. During these simulations the match of the simulated water levels to HWMs was also checked. The roughness values were still valid." As the water level had been discussed in earlier section, we had decided not to show these in a figure anymore here, as this section concentrates on topographical comparisons. Also because other referees' comments favored the shortening of the calibration methods section, we decided at this stage not to add any further figures in the methods section.

RC: Page 9, Line 30-31 – What is the expected level of uncertainty in the measurements – is 1.6mm difference significant?
AC: We were not able to detect the level of uncertainty of grain size measurements. In 2012, the measurements were done with Wolman sampling, and in 2014 with sieving. Thus, only the actual difference was possible to show. The Wolman sampling method is more uncertain than the sieving.

RC: Page 11, Line 15-16 – If the Manning's n values were set according the geomorphological elements, did they alter with changes during the model runs, or were they stationary?
AC: Those were stationary. A clarifying sentence has been added in P11 line 25 – P12 line 1: "Note that the assignment of the n values was static throughout the simulations, i.e. the spatial distribution of the roughness values was not possible to change between simulation time steps."

RC: Page 11 Line 18-20 and Table3 – either present the values in the table in the order of Qx1.3, Qx2 and Qx2.5, or present the values in the text in the order of the table.
AC: The order of the values in the Table 3 has been changed.

RC: Page 12, Line 31-32 – Tells you something about model sensitivity to parameters, but not a great deal.
AC: The sentence has been decided to delete, as it did not bring any additional information when compared to the rest of the text. We also overall reduced the text in methods and calibration section of the modphodynamic model.

RC: Page 13, Line 1 – Need to know what the criteria was for this! "best and most interesting" not a rigorous methodology. The authors might have rejected useful information by arbitrarily labelling it as not interesting.

AC: You are right, this was vague. The sentence has been deleted during the modification of the manuscript. We now describe in P14 lines 17-21 "… 11 simulations done during calibration were selected to be presented in the supplementary material of this paper (see also Table 4). Reason for their selection was that these 11 simulations showed the effects of grain size (before [2012] and after [2014] floods, and grain sizes from different layers [2014]), grid size (coarse: 1.51–5.31 m, fine: 0.76–3.03 m), transverse slope (user defined coefficients in the bed load transport equations: default 1.5 and increased to 3) and transportation equations (Engelund-Hansen [EH], Meyer-Peter and Müller [MPM]) on model performance (Table 4, and supplementary material)."

In the supplementary material, these sentences are now: "The best simulation results (from the simulations 1, 2, 3 and 10) in relation to the surveyed volumetric changes were achieved with the fine grid simulation (number 10)".

RC: Page 13, Line 2 – Not a sensitivity analysis.
AC: We have modified this as morphodynamic model's calibration.

RC: Figures 4, 5 and 6 – These would be easier to interpret if they showed the changes over the whole reach, not just in the area used for the analysis. This could still be identified as in Figures 1 and 8.
AC: We had calibrated the model based on this area, where we had data from all the topography measurement times (2012, March 2013 and June 2013). Thus, the reason for showing the calibration area in these figures is, because we were able to perform the goodness-of-fit only in this area. We have modified the manuscript so that we are not anymore talking about the "analyzed area" but about "calibration area". We have now added the whole simulation area to in the new Figs. 6 and 7, i.e. in the results section related to the morphodynamic analyses. In these two figures, the results of the best simulation are shown. We are now showing the whole simulation area also in Fig. 1.

RC: Page 19, Line 18 – "satisfactory" not "satisfying"
AC: During the shortening of the methods section, the sentence had been deleted from the main manuscript.

We have modified this accordingly in the text of supplementary material, where this sentence had been moved.

RC: Page 19, Line 25 – or other factors had an influence? Interaction with other parameters?
AC: We tried the simulations with many different parameters, and the MPM did not produce much movement with any of the parameterizations. We decided to just show in the manuscript (now in the supplementary material) this as an example of the unsuccessful simulations with the MPM equation. The MPM simulation results have been moved to the supplementary material.

RC: Page 22, Line 8 – Has it been shown that it is reliable? It's shown it is able to reproduce the events it was calibrated against, but not others.
AC: We modified the sentence as "The reliability of the model, which is calibrated against the events under interest, can be improved with the quality and temporal density of the available calibration topography, i.e. pre- and post-flood bedform geometries." (P21 lines 25-27).

RC: Page 23, Line 2 – Yes, validation of the calibrated model versus independent events is needed to claim the model is reliable.
AC: Yes, we agree. We have modified the discussion, and modified the sentence and paragraph as follows (P21 line31-P22 line 6) "However, despite the high quality data from two events at Rambla de la Viuda, we think that further research with multiple yet-to-come events needs to be run to assess the repeatability and validation of the model even better. For example, at Rambla de la Viuda, large floods have not yet occurred since the beginning of the MLS measurement approaches. As also earlier has been stated (Verhaar et al. 2008; Lotsari et al., 2015), the roughenss conditions defined for small discharge events, might not be suitable for simulating extreme events. Therefore, the work and refinement of the model will continue, and the applicability of the model for larger floods will be tested, when validation data will be available."

11

RC: Page 23, Line 4 – Yes, the uncertainties need to acknowledged, maybe a little more prominently then there are at present.

AC: We have addressed the uncertainties in more detail throughout the discussion section (5.1), and we have for example added the following text in the discussion (P22 lines 9-27): "The uncertainties of the present model approach thus relate to the lack of sediment transport, flow and topographical data during the events. However, the selected initial boundary conditions

5   seem to be congruent with the flooding mechanisms of Rambla de la Viuda and also with other published works, i.e. Williams et al (2016b), for loosely consolidated sand and gravel. So, the modelled flow carried each sand sediment fractions (suspended) adapted to the local flow conditions at inflow boundary, and the model assumed that very little accretion or erosion was experienced near the model boundaries. Based on measurements, the presence of sand size particles and their concentration in the study site were also almost non-existent, and no channel changes occurred at downstream boundary of the simulation area.

10   Thus, this equilibrium load condition was considered valid, and it was also the only option for the present modelling approach, as no input suspended load measurements were available. Similarly as Williams et al. (2016b) state, the model results, i.e. the modelled deposition and erosion, when compared to observations, could have been possibly enhanced if the input suspended sediment load observations would have been available. However, according to Sanyal (2017) the sediment transport is always inherently approximate in nature, and sediment load added to the model causes uncertainties to the results, despite detailed

15   sediment load measurements have been used as model input.

Despite this lack of the data during the flood events, we had a good control on sediment volume and gravel particle-size moving downstream as the forefront lobe prograded over a flat valley bottom (as gravel bed had been mined). Total volume input and total transport rates observed in earlier study of Rambla de la Viuda by Calle et al. (2015), had already proved the high

20   availability of sorted gravel particles, and were the basis of the decisions made while building up the model. As already mentioned, the channel changes at the output downstream boundary of the studied reach was zero."

RC: Page 23, Line 10 – The authors have not provided enough detail to evidence that the hydrograph is of "a known shape". It may well be, but the gauge is 18km away with half the discharge (according to the calibrations).

25   AC: Based on the later (2014) measurements with water level sensors at the study site and the nature of the rain events, we can state that the hydrograph shape was similar to Vall d'Alba station (see above our earlier more detailed responses, and the supplementary material, regarding the hydrograph shape).

RC: Page 24, Line 13 – Both equations are implemented deterministically are they not?

30   AC: You are right, they are implemented deterministically. We have removed the sections mentioning the deterministic way. We have modified this throughout the manuscript.

RC: Page 25, Line 13 – Are the parameter sets non-stationary or is it the initial conditions which need to be set for each event?

AC: We hope that we understood your comment correctly, and we modified the sentence as "Previously this uniqueness of

35   geomorphic response has been shown for perennial rivers (Pitlick, 1993), where also topographical and sedimentary data has been applied as initial conditions." (P25 lines 2-4)

RC: Page 27, Line 18 – Instead of "goodness" use "feasibility"

AC: We ended up modifying and shortening the conclusions section, and this sentence was deleted during the modifications.

40
RC: Page 28, Line 6 – Both implemented deterministically?

AC: You are right, they are implemented deterministically. We have removed the sections mentioning the deterministic way. We have modified this throughout the manuscript.

45   RC: Page 28, Line 8 – This is a key point, and should be made more prominent earlier in the manuscript as part of the reason why this research is important.

AC: We have refocused the paper and increased the morphological analyses throughout the paper (see also our previous responses). We have raised these as key points already in the introduction section.

RC: Page 28, Line 16-18 – Can this be said with such certainty, or does it just apply to this reach for these events (and also with these parameters)
Ziliani et al (2013) - doi:10.1002/jgrf.20154

AC: We added the following sentences: "These differences between the events were at least evident with these two events and the applied parameterization. However, further studies of this possible hysteresis effect are needed from multiple discharge events." (P28 lines 9-10).

RC: Thank you for an interesting study and manuscript, I look forward to seeing the revised version.
AC: Thank you for your thorough comments, those were really helpful and enhanced the paper greatly.

REFEREE #3

RC: Overview This paper uses a 2D morphodynamic model to assess the impact of small and moderate floods on the evolution of ephemeral rivers. This is an interesting topic which will be of use to the wider community however in its present form I do not think it is suitable for publication. The authors spend over half of the paper describing the model set up and calibration and do not really address the original question. Given a lot of the model inputs were from a previously published paper a lot of the rather dense description could be cut from the paper to allow more time for a detailed analysis of the impacts of flood characteristics. There is also little time devoted to discussing the applicability of this model to scenarios other than the very detailed description in the paper for which there is good input boundary data. Detailed comments and queries are below which the authors needs to address if this paper is to be published.

AC: Thank you for the thorough comments. We have modified the manuscript thoroughly and refocused the paper in introduction (also aims), results, discussion and conclusions sections to emphasize the geomorphological findings (see also responses to referee #1 and #2 comments).
The paper now aims at analyzing (P3 line 30 onwards) "the evolution of a gravel bed ephemeral river channel (Rambla de la Viuda, Spain) during consecutive, moderate- (March 2013) and low-magnitude (May 2013), discharge events, by applying a morphodynamic modelling (Deflt 3D) approach. Based on the simulations, we analyze 1) the timing of river bed erosion and deposition in relation to the flow hydrograph phases during moderate- and low-magnitude discharge events, 2) the hydraulic characteristics (e.g. shear stress) explaining these channel and bedform morphodynamics, and 3) the prevailing fluvial processes, and related sediment transport routing, during these different magnitude discharge events in a gravel bed ephemeral stream. Understanding of these processes would be needed particularly for river management works and flood mitigation purposes."

Along with these changes, we have modified the results section so that we have moved the morphodynamic model's calibration results to the supplementary material (as the second reviewer also suggested), and present only their summary in the methods section. We have added more results related to the morphodynamics (channel bed elevation changes and bed shear stresses) to the manuscript so that we were able to refocus the paper.

We find it important to include the description of the data and hydrodynamic model in the methods of the main manuscript, as otherwise, the manuscript would not be readable independently, i.e. without Calle et al. (2015) paper. In addition, Calle et al. (2015) does not have all the required data explanations. We have referred to Calle et al. (2015) in every case, when that is possible, such as related to the details of the topographical measurements and error analyses. We have modified the discussion section and added there more discussion about the applicability of the model to other (larger) flood scenarios.

RC: Page 2 Line 4 – I would query the word greatest and authors should consider an alternative
AC: We have modified the word as "large" (P2 line 10).

13

RC: Page 2 – Line 19-21 – three papers might be worth reviewing – although not on the context of ephemeral rivers they give useful context Viparelli et al (2011) 'A model to predict the evolution of a gravel bed river under an imposed cyclic hydrograph and its application to the Trinity River' WRR An et al (2017) 'Gravel-bed river evolution in earthquake-prone regions subject to cycled hydrographs and repeated sediment pulses' ESPL An et al (2017) 'Effect of grain sorting on gravel bed river evolution subject to cycled hydrographs: Bed load sheets and breakdown of the hydrograph boundary layer' JGR ES

AC: Because the papers do not relate to the ephemeral rivers, in our opinion, they fitted better to discussion section. Therefore, we have added these into the discussion section (P23 lines 1-4), instead of the introduction.

RC: Page 2 Line 30 – when you say between and after flood topographies do you mean pre and post flood topographies?

AC: Yes, we mean pre- and post-flood topographies. We have modified them as "pre- and post-flood topographies" on P3 line 9.

RC: Page 3 Line 12 – use alternative phrasing for high/ large floods

AC: During the modification of the paper, we have deleted the whole sentence.

RC: Page 3 Line 12/13 – the sentence beginning in addition does not make grammatical sense

AC: During the modification of the paper, we have deleted the whole sentence.

RC: Page 3 Line 25/ 26 – consider 'The river has a braided pattern associated with a high sediment supply' instead of current wording

AC: We have modified this accordingly (P4 lines 9-10): "The river has braided pattern associated with a high sediment supply (Calle et al., 2015)."

RC: Page 4 Line 15 – how far away was the gauging station from the study site?

AC: The detailed gauging station and study site locations have been added into the new version of the Fig. 1.

RC: Page 4 Line 15 – you say the discharges at the field site were estimated to be higher but how much? How did you estimate this?

AC: During the modification of the paper (also based on comments of referees #1 and #2) the sentences were removed. We have now describe the discharge and rain events more in detail in this paragraph (P4 lines 26-32):

"The two events under study occurred in spring 2013. These were caused by two rain events, which were recorded with 5 minute interval at the precipitation and gauging station provided by the Automatic System of Hydrologic Information (SAIH-Jucar) at Vall d'Alba (Fig. 1 and Calle et al., 2015). The first rain event (March 2013) started on 4th of March lasting for three days with a total 70 mm. The second rain event (April-May 2013) started on 27th April and lasted four days with a total of 72 mm. These rain events caused flows that lasted 13 days (started at 12:00 on 5th March) and 9 days (started 14:10 on 30th April), respectively. The peak discharges of 23 (at 11:05 on 6th March) and 12.5 $m^3 s^{-1}$ (at 9:05 on 1st of May) were registered in the gauging station of Vall D'Alba, respectively."

We have added clarification related to the discharge hydrographs in the methods section (P6 line 14-21):

"At the study reach, the hydrograph peak discharge was estimated from continuous lines of flotsam (i.e. high-water marks, HWM) emplaced by the floodwater. The hydrograph shape of the study site can be assumed similar to Vall d'Alba gauge station, due to the widespread continuous character of the rain events. The hydrograph shape was verified to be similar to Vall d'Alba observation station also by recent installation of water level sensors (in late 2014) in the study site (see supplementary material). The HWM left by the March 2013 discharge event provided evidence that the peak discharge was greater at the study site than that measured at Vall d'Alba (Figs. 1 and 3). The hydrographs were re-scaled by using different multipliers to match the peak discharge calculated during the calibration procedure of the model (see Sect. 3.4 below, and from Calle et al., 2015)."

AND

Sentences starting P12 lines 8-11 "The "Qx2" (observations multiplied by 2) water surface elevation matched the HWMs using an average n-values calculated from Limerinos (1970) equations. Also, the effects of bedform (from +0.01 to +0.015) and bank roughness (+0.02) had been added to these average n-values (Chow, 1959; Acrement and Schneider, 1989)", P12 lines 14-15 "Based on the Limerinos equation calculations, the Qx2 was expected to work the best due to its average nature and inclusion of bedform and bank roughness effects."

Also, in Calle et al. (2015) (where the same hydrodynamic model had been used), the Qx2 was proven to work the best regarding the velocities and shear stresses needed for sediment movement. In Calle et al. (2015) paper we demonstrated with geomorphological indicators, i.e. grain size and observed morphologic change, that our model calibration was correct. See Fig. 12 in Calle et al. (2015), where this is discussed in terms of velocities. Thus, the same parameters worked also for the subsequent morphodynamic simulation that resulted in this paper.

RC: Page 6 Lines 9-15 - you have assumed that the discharge between the gauging station and the reach is increasing but that the hydrograph shape remains the same but how is this so? This has important implications for the validity of the calibration of your model. Much more detail is needed to justify this assumption

AC: We can verify that the hydrograph shape at the study site of Rambla de la Viuda is similar to the hydrograph at Vall d'Alba station (see the previous responses and the supplementary material entitled "hydrograph shape").

We had installed water level sensors at the study site later in year 2014. Based on these we can verify that the hydrograph shape of the study site of Rambla de la Viuda is similar to Vall d'Alba observation station (see the locations from the Fig. 1 of the main paper document) and that the water level is much higher at the study site than the Vall d'Alba station. Thus, these measurements prove that the discharge has to be also much higher in the study area than at Vall d'Alba. In addition, based on the roughness calculations with Limerinos equations and the model calibration results, the Qx2 discharge was the correct one to be applied in the model. Based on the Limerinos equation calculations, the Qx2 was expected to work the best due to the average nature of the derived roughnesses and inclusion of bedform and bank roughness effects.

In addition, it was possible to calculate the daily discharge curve for María Cristina reservoir, which locates downstream of the study site of ours (see the supplementary material). When comparing the March 2013 discharge peak of Qx2 discharges (Fig. 5 in the main manuscript), the resemblance to the daily discharges of María Cristina reservoir can be seen. Due to the fact that only daily data was available from Maria Christina reservoir, the curve of the reservoir is flatter than the one at the study site. Also calibration curves for the reservoir and water loss by infiltration are unclear. Despite these, we can be confident that the shape of the hydrogprah at the study site was realistic and that the Qx2 discharge would be the correct discharge to apply at Rambla de la Viuda study site.

We have added clarification related to the discharge hydrographs in the methods section (P6 line 14-21):
"At the study reach, the hydrograph peak discharge was estimated from continuous lines of flotsam (i.e. high-water marks, HWM) emplaced by the floodwater. The hydrograph shape of the study site can be assumed similar to Vall d'Alba gauge station, due to the widespread continuous character of the rain events. The hydrograph shape was verified to be similar to Vall d'Alba observation station also by recent installation of water level sensors (in late 2014) in the study site (see supplementary material). The HWM left by the March 2013 discharge event provided evidence that the peak discharge was greater at the study site than that measured at Vall d'Alba (Figs. 1 and 3). The hydrographs were re-scaled by using different multipliers to match the peak discharge calculated during the calibration procedure of the model (see Sect. 3.4 below, and from Calle et al., 2015)."

RC: Page 6 Lines 17-22 – you have assumed that bed level has not changed when you have calibrated discharge to water levels – how valid is this assumption?

AC: The water levels, which were based on the HWM measurements can be assumed valid, as the bed elevation did not change at the area, where the downstream water level boundary was defined (see also P11 lines 18-22): "The Limerinos equation was applied for the whole range of water levels (i.e. hydraulic radiuses) for the March 2012 and March 2013 grain sizes of D_{50} and D_{84}. These represented the best of the preceding conditions of the March 2013 and May 2013 flows. The Limerinos calculations

were performed for a cross-section located at the downstream side of the simulation area. This cross-section was defined from 2012 geometry, i.e. pre-flood geometry, which remained unchanged during the 2013 discharge events."

RC: Figure 3- it is unclear how this relates – more detailed description needed

5   AC: We have clarified the figure caption:
"Figure 3: The hydrodynamic calibration results based on the coarse grid (1.51–5.31 m cells) and fine grid (0.76–3.03 m cells). In this figure, the high-water marks (HWM) and simulated water levels are presented. In addition, the trendlines fitted along these measurements and simulation results are shown. These calibration results of the fine grid were previously presented in Calle et al. (2015) by the same authors. The Qx1.3, Qx2 and Qx2.5 refer to the discharges scaled to match the peak discharge

10 at the study site. Daily and 5 min refer to the observation interval of discharges at Vall d'Alba station. wl = water level based on HWMs and simulations, trendline = the trendline fitted in the measured HWMs and the simulation results. The location of these HWM measurement points have been shown in the Fig. 1."

RC: Page 8 Lines 15 – 21 better justification is needed of cell sizes – e.eg what do you mean 'did not make more difference to

15 the results'?
AC: The sentence has been modified as follows (P 9 lines 4-7): "Cell sizes smaller than the "fine" resolution (i.e. 0.76–3.03 m) did not enhance the results, and those only increased the computational time. Thus, curvilinear grids of two resolutions, "coarse" 1.51–5.31 m cells and "fine" 0.76–3.03 m cells, were created from the topography measurement times."

20 RC: Page 8 Line 25 – MSL or MLS?
AC: We have corrected this as MLS (P9 line 9).

RC: Page 9 – if the water level did not reach the high bank elevations why add that 2009 DEM results to the model – what does it add?

25 AC: This was done so that the high banks would be as realistic as possible. The model was built up for not only to calibrate these moderate and low magnitude events but also for being able to later use the same model to simulate bigger flood events, which have not yet occurred since the beginning of our observations in the area. Thus, measurements and observations are still ongoing at Rambla de la Viuda.

30 RC: Page 9 Line 16 -17 – what do you mean ' the capabilities of the model to result correct channel bed elevations'? This sentence needs restructuring.
AC: As we shortened the methods sections, we also ended up deleting this paragraph.

RC: Page 9 lines 16- 20 – the meaning of this section of text is unclear

35 AC: As we shortened the methods sections, we also ended up deleting this paragraph.

RC: Page 9 Line 30 – is this the difference between the armour and sub surface layer? What was the difference in the D84?
AC: These armour and sub-layer values were not possible to define between 2012 and 2014, as there was no sub-layer measurements in 2012. The D84 values of 2014 have been added to Table 2.

40
RC: Page 13 – what do you mean 'best and most interesting results'? This surely needs justification? What do you deem best or most interesting?
AC: You are right, this was vague. The sentence has been deleted during the modification of the manuscript. We now describe in P14 lines 17-21 "… 11 simulations done during calibration were selected to be presented in the supplementary material of

45 this paper (see also Table 4). Reason for their selection was that these 11 simulations showed the effects of grain size (before [2012] and after [2014] floods, and grain sizes from different layers [2014]), grid size (coarse: 1.51–5.31 m, fine: 0.76–3.03 m), transverse slope (user defined coefficients in the bed load transport equations: default 1.5 and increased to 3) and transportation equations (Engelund-Hansen [EH], Meyer-Peter and Müller [MPM]) on model performance (Table 4, and supplementary material)."

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In the supplementary material, these sentences are now: "The best simulation results (from the simulations 1, 2, 3 and 10) in relation to the surveyed volumetric changes were achieved with the fine grid simulation (number 10)".

RC: Page 13 Lines 2-3 define better performance?
AC: This has been modified as (P13 lines 25-26): "Due to the better correspondence of simulations with Qx2 discharges to the observed channel evolution, all these selected morphodynamic simulations had these input data."

RC: Figures 4-6 – it would have been useful to show the 'analysed area in context with the broader area studied
AC: We had calibrated the model based on this area, where we had data from all the topography measurement times (2012, March 2013 and June 2013). Thus, the reason for showing the calibration area in these figures is, because we were able to perform the goodness-of-fit only in this area. We have modified the manuscript so that we are not anymore talking about the "analyzed area" but about "calibration area". We have now added the whole simulation area to in the new Figs. 6 and 7, i.e. in the results section related to the morphodynamic analyses. In these two figures, the results of the best simulation are shown. We are now showing the whole simulation area also in Fig. 1. We have moved the former Figs. 4-6 into the supplementary material (there Figs. 1-3), and present a new Fig. 4 (includes parts of former Fig. 6) in the main manuscript.

RC: Page 19 line 4 – ok so how many model runs are now relevant?
AC: We decided to delete that sentence. We present now in the main manuscript only the two best (based on comparison to observed data) model runs (i.e. out of 61 total runs). Altogether 11 runs (out of total 61 runs) which were presented in the original version of the manuscript, have been moved into the supplementary material for showing the results of calibration (see also the earlier responses to all referees).

RC: Page 19 Line 19 – should be satisfactory
AC: During the shortening of the methods section, the sentence had been deleted from the main manuscript.

We have modified this accordingly in the text of supplementary material, where this text had been moved.

RC: Page 19 Lines 6 – 19 – would these plots have been better as hysteresis type plots so plotting Q against volumetric changes in bedload? You have not discussed hysteresis at all? The same comments apply for section 4.2.2 Figure 7 – you need axis labels, especially for the Y axis- what is it showing?
AC: The possible hysteresis has been discussed in the discussion section, and also now mentioned in the results section. As the model was calibrated based on the topographical changes, we wanted to present the results based on the topographical changes. Therefore, we find that plotting Q against bedload would not bring extra value to the manuscript. From the Fig. 5 (earlier figure number 7) it is already possible to see the differences in the timing of the channel change peak and discharge peak. This is already an evidence about the hysteresis. However, we state in the discussion that further studies on this matter are still needed, and that this is just the first evidence of the possibility for the hysteresis effect.

The units of the parameters (Y-axis) had been presented in the legend (former Fig. 7 -> now Fig. 5). We have now added both of the units also in the Y-axis too. We have also added a new Fig. 6 to show the spatial bed elevation changes between the key time steps, which are presented in Fig. 5.

RC: Page 22 – what do you mean reliable? How useful is it for predicting other events/ scenarios?
AC: We have not yet applied the model to larger flood events, as we do not yet have observations of those from Rambla de la Viuda. We will test the model against larger discharges, when this will be possible based on the data. We are waiting a bigger flash flood to occur in the area. We have also added more discussion about the possibilities of the model to be applied for predicting larger events (throughout the discussion section, e.g. at P21 line31-P22 line 6):
"However, despite the high quality data from two events at Rambla de la Viuda, we think that further research with multiple yet-to-come events needs to be run to assess the repeatability and validation of the model even better. For example, at Rambla de la Viuda, large floods have not yet occurred since the beginning of the MLS measurement approaches. As also earlier has been stated (Verhaar et al. 2008; Lotsari et al., 2015), the roughenss conditions defined for small discharge events, might not

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be suitable for simulating extreme events. Therefore, the work and refinement of the model will continue, and the applicability of the model for larger floods will be tested, when validation data will be available."

RC: Page 23 Lines 1-4 – you definitely need to discuss the applicability of this model to other events a and need to discuss the limitations of this approach!!!
AC: We have modified the discussion section (section number 5) and added there more discussion about the applicability of the model to other larger events/scenarios, and also about the possible limitations. See also our earlier responses.

RC: Page 23 Line 10 – did you really know the hydrograph shape?
AC: We can verify that the hydrograph shape at the study site of Rambla de la Viuda is similar to the hydrograph at Vall d'Alba station. See the supplementary material and also our earlier responses (above) to the similar questions.

RC: Page 25 Lines 17-18 – have you considered how the role of the changing surface structure could be incorporated into the model as this has been shown to have significant impacts in transport rates?
AC: We are not sure if we understood your comment. However, if we understood correctly, the answer is as follows: We had included the longitudinal and transverse slope functions into the model, but otherwise this was out of the scope of the paper of ours. We did not consider this, as we did not concentrate on coding of the model, but on applying the commercially available version of the model. If looking the model at the study reach scale, we think that the overall transport rate is unrelated to surface structure.

Topographical changes caused by moderate and small floods in a gravel bed~~ly~~ ephemeral river - ~~2D~~ depth-averaged morphodynamic simulation approach

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Abstract. In ephemeral rivers, channel morphology represents a snapshot at the end of a succession of geomorphic changes ~~performed~~ caused by a flood. In most cases, the channel shape and bedform ~~evolution~~ migration during different phases of a flood hydrograph are not recognized from field evidence. ~~Understanding of these processes would be needed particularly for flood mitigation purposes.~~ This paper analyzes the timing o~~n~~f ~~bed~~ river bed erosion and deposition ~~changes~~of a gravel bed ephemeral river channel (Rambla de la Viuda, Spain) during consecutive, moderate- (March 2013) and low-magnitude (May 2013), discharge events, by applying a morphodynamic modelling (Deflt 3D) ~~approach~~calibrated with pre- and -post- events survey by RTK-GPS points and mobile laser scanning. ~~Based on the simulations, we analyze 1) when and to what extent the channel changes occur during the phases of moderate- and low-magnitude discharge events, and 2) which flow characteristics explain these changes throughout the discharge events.~~

~~Based on the simulations, we analyze 1) when and to what extent the channel changes occur during the phases of moderate- and low-magnitude discharge events, and 2) which flow characteristics explain these changes throughout the discharge events.~~This paper analyzes the capabilities of morphodynamic modelling (Delft 2D) for resolving the evolution of a gravelly ephemeral river channel during consecutive, moderate- and low-magnitude discharge events. We pursue for schematic concepts for simulations in ephemeral gravely rivers that provide an outcome with the closest similarity to the post-flood reality. Based on the simulations, we analyze the morphodynamic evolution of Rambla de la Viuda (Spain) to find out when and to what extent the channel changes occur during the phases of moderate- (March 2013) and low-magnitude (May 2013) discharge events, and what influence the discharge has on the rate of morphological changes. The model performance is examined with different parameterizations.

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~~The calibrated model worked well, however, spatially varying grain size data and transport equations were the most important~~

factors, in addition to the quality of recorded discharge, for the simulation results of the channel evolution model performance. The total load equation worked better, compared to the deterministic equation. The studied system reach was is mainly depositional based on the field evidence and all bedload sediment supplied from upstream adjacent areas is trap in the study segment forming gravel lobes. Therefore, estimates of total bedload sediment mass balance can be obtained from pre- and -post field survey for each flood event. . The spatially varying grain size data and transport equations were the most important factors for model calibration, in addition to the flow discharge for the model performance. The channel acted as braided channel during the lower flows of the two discharge events, but when bars were submerged in higher discharges, the high fluid forces followed a meandering river planform. The model results also showed that erosion and deposition can be were in total greater during the hydrograph long-lasting receding phase than during the rising phase of the flood hydrographs. In the case of moderate-magnitude discharge event, The deposition and erosion peaks are were predicted to occur at the beginning of the hydrograph moderate-magnitude discharge event, whereas deposition dominated s throughout the event. On the contrary, the low-magnitude discharge event only experienced s the peak of channel changes after the discharge peak, suggesting a rupture of upper layer before sediment is moved. Thus, both type of discharge events highlight the importance of receding phase for this type of gravel bed ephemeral river channel.

1 Introduction

The hydrology of ephemeral rivers is dominated by occasional large flash floods that cause morphological fluvial changes (Tooth, 2000; Benito et al., 2011). The costs of these floods due to their catastrophic nature include major economic, social and environmental aspects (Petersen, 2001). These are caused by both hydro- and morphodynamics during the discharge events. For reducing the emergency costs and enhancing the preventive flood mitigation measures, understanding of the forces of the flow and related channel changes throughout the discharge events would be important. For being able to allocate the measures temporally most efficiently, the understanding of the timing of the morphodynamics and their effects to the adjacent river environment throughout the discharge events are needed.

Consequently, mMost geomorphological studies have been mainly concentrated on these ~~greatest~~ large ~~flow~~ discharge events, due to their impacts on the river channel changes, related river environments and human infrastructure (Greenbaum and Bergman, 2006; Grodek et al., 2012; Nardi and Rinaldi, 2015; Hooke, 2016b). However, moderate and low flows have also been shown to cause great morphological changes in ~~gravelly~~ gravel bed river channels (Calle et al., 2015; Hooke, 2016a), as a small discharge over long time spans can substantially rework the sediment and fluvial bedforms produced by the greater floods (Greenbaum and Bergman, 2006).

According to Hooke and Mant (2000), the pattern and magnitudes of fluvial morphological changes show the best relationship with the magnitude of peak discharge. However, during flash floods, it is difficult to perform sediment transport or bedform migration measurements to detect the timing of topographical changes, i.e. whether the greatest changes occur for example due to the peak discharge, the slope of the rising limb, or the length of the receding limb. Case studies have reported most erosion during the rising and the peak flow phases in perennial rivers (e.g. Gendaszek et al. 2013), but similar knowledge for ephemeral river channels is still low. It would be important to understand the capacities of ephemeral rivers for sediment deposition and flooding due to the combined effects of water flow and sediment transport during flood situations. If the erosion and deposition would be in total greater during the receding phase than in rising phase, the receding phase should not be ignored while planning flood mitigation measures.

~~Thus, the timing of the morphological changes during the different phases of flow discharge eventshydrographs is still unresolved, and how they differ from the gravelly bed perennial rivers,, with cCase studies have reportinged most erosion during the rising and the peak flow phases of in perennial rivers (e.g. Gendaszek et al. 2013). It would be important to understand the capacities of ephemeral rivers for sediment deposition and flooding due to the combined effects of water flow and sediment transport during the flood situations. If the erosion and deposition would be in total greater during the receding phase than in rising phase, the receding phase should not be ignored while planning flood mitigation measures. The erosion~~

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~~and deposition have been shown to be greater during the rising limb of flood hydrographs in perennial rivers (Gendaszek et al., 2013), but knowledge of the ephemeral river channels is still low.~~

Conventionally, ~~these~~ ephemeral river channel changes associated with specific flood events are interpreted on the basis of the post-flood bedform and grain size distribution (e.g. Euler et al., 2017). New insight on morphodynamic changes and their driving parameters during flash floods can be gained by~~The only way to gain information and to show any concepts about topographical changes during the flash floods is to~~ applying simulation methods. Simulations may provide information about the channel dynamics from the times when it has not been possible to perform measurements (Lotsari et al., 2014a) and thus increase our understanding of sediment dynamics during flood events (Hooke et al. 2005). However, morphodynamic ~~simulations~~ modelling of gravel migration have so far been more common in perennial braided gravel bed rivers (e.g. Williams et al., 2016b3) or laboratory flumes (Kaitna et al., 2011) than in ephemeral rivers. ~~T~~There are examples of simulating sediment transfer in ephemeral channels (Graf, 1996), although most of the few recent simulations ~~of ephemeral rivers~~ have been performed in sandy reaches (Billi, 2011; Lucía et al., 2013) and on alluvial fans (Pelletier et al., 2005). Ephemeral rivers with gravel-sized bedload particles have ~~seldom~~ rarely been simulated. One of the few existing examples was carried by Hooke et al. (2005), simulating morphological changes during flash floods with a cellular automata model. Their model worked well with simulations using moderately large discharges during clear water conditions, but discharge events with sediment loads had some tendency for excess deposition (Hooke et al., 2005). Further examination of different discharge events with modelling approaches is thus required.

It is possible to calibrate the morphodynamic model based on the ~~between~~ pre- and ~~post~~after flood topographies of different consecutive flood situations. This causes uncertainties to the modelling, as calibration and validation data is measurable only during dry channel conditions. However, ~~but~~ it is the best available way to get understanding on the temporal evolution of the ephemeral river channels during flooding. In particular, the differences and similarities in model performance between different flood magnitudes can be detected (Lotsari et al., 2014a; Williams et al., 2016a). Recently, the measurement techniques for deriving this calibration data for morphodynamic modelling have increased. One of them is accurate laser scanning (mobile and terrestrial), which enables to capture the channel topography before and after flooding in detail (Milan et al., 2007; Vaaja et al., 2011; Calle et al., 2015; Kasvi et al., 2015; Kukko et al., 2015). The laser scanning enables rapid measurements of gravel bed rivers at the sub-grain level resolution (Milan et al., 2007). In ephemeral rivers the quality of topographical data can be very good and the uncertainties are less than in perennial rivers, either with laser scanning or traditional RTK-GPS measurements, because these rivers can be surveyed when the river bed is dry. The high uncertainties in topographical measurements of sub-water areas in gravel bed perennial river have been related particularly to the high bed load velocities and temporal variability of bed load (Williams et al., 2015). Mobile laser scanning, for example from ~~car~~vehicle~~,~~ or backpack ~~and boat~~, provides in an ephemeral river a practical scanning angle to survey channel banks, bar lobes and vertical surfaces (Vaaja et al., 2011; Kasvi et al., 2015; Kukko et al., 2015).~~, and a~~ Also data collection over large channel bars has been

enhanced with the~~se~~ method~~s.~~ ~~(Vaaja et al., 2011; Kasvi et al., 2015; Kukko et al., 2015).~~ Digital elevation models produced from ~~LiDAR~~ airborne laser scanning (ALS) data have been applied for detecting the geomorphic effects of different discharge events (Hauer and Habersack, 2009; Croke et al., 2013; Thompson and Croke, 2013; Nardi and Rinaldi, 2015) and for recording and calibrating sediment transport models (Rodriguez-Lloveras et al., 2015). These reveal the reorganization of the channel morphology due to flood events even over large areas with great detail (Thompson and Croke, 2013). These accurate topography data, together with RTK-GPS measurements, enable more detailed ~~analysis~~ calibration of the morphodynamic model than before. ~~Despite these advances in measurement techniques and simulation approaches, there is a need for testing the model performance in comparison to the detailed measurements related to flow events of different magnitudes, and not only to high/large floods. In addition, morphodynamic models are suited with a range of sediment transport equations to further test for simulating moderate and small floods of ephemeral channels.~~

This paper analyzes ~~the capabilities of morphodynamic modelling for resolving~~ the evolution of a ~~gravelly~~gravel bed ephemeral river channel (Rambla de la Viuda, Spain) during consecutive, moderate- (March 2013) and low-magnitude (May 2013), discharge events, by applying a morphodynamic modelling (Deflt 3D) approach~~moderate- and low-magnitude, discharge events~~. Based on the simulations, we analyze 1) the timing of river bed erosion and deposition in relation to the flow hydrograph phases during moderate- and low-magnitude discharge events, 2) the hydraulic characteristics (e.g. shear stress) explaining these channel and bedform morphodynamics, and 3) the prevailing fluvial processes, and related sediment transport routing, during these different magnitude discharge events in a gravel bed ephemeral stream~~Based on the simulations, we analyze 1) the timing on bed river erosion and deposition modes leading hydrodynamic changes in relation to the flow hydrograph phases during moderate- and low-magnitude discharge events, and 2) the hydraulic characteristics (velocity, depth, shear stress) explaining channel and bedform morphodynamics, and 3) the implications of this modelling to infer river flow processes (e.g. sediment rates of bedload transport) in gravel bed ephemeral streams~~. Understanding of these processes would be needed particularly for river management works and flood mitigation purposes. ~~Based on the simulations, we analyze 1) when and to what extent the channel changes occur during the phases of moderate- and low-magnitude discharge events, and 2) which flow characteristics explain these changes throughout the discharge events. We pursue for schematic concepts for simulations in ephemeral gravely rivers that provide an outcome with the closest similarity to the post-flood reality.~~ This study is based on both accurate topographical measurements with RTK-GPS survey and mobile laser scanning, before and after each discharge event, and morphodynamic simulation (2D implementation of Delft ~~2~~3D). Thus, the model is calibrated with data from moderate magnitude event, and then validated based on the consecutive low-magnitude event.~~two flash flood events.~~ ~~Based on the simulations, we analyze the morphodynamic evolution to find out when and to what extent the channel changes occur during the different phases of discharge events, and what influence the discharge has on the rate of morphodynamics.~~ With this simulation method it is possible to improve and deepen the analyses earlier made based on only the survey work (e.g. Calle et al., 2015).
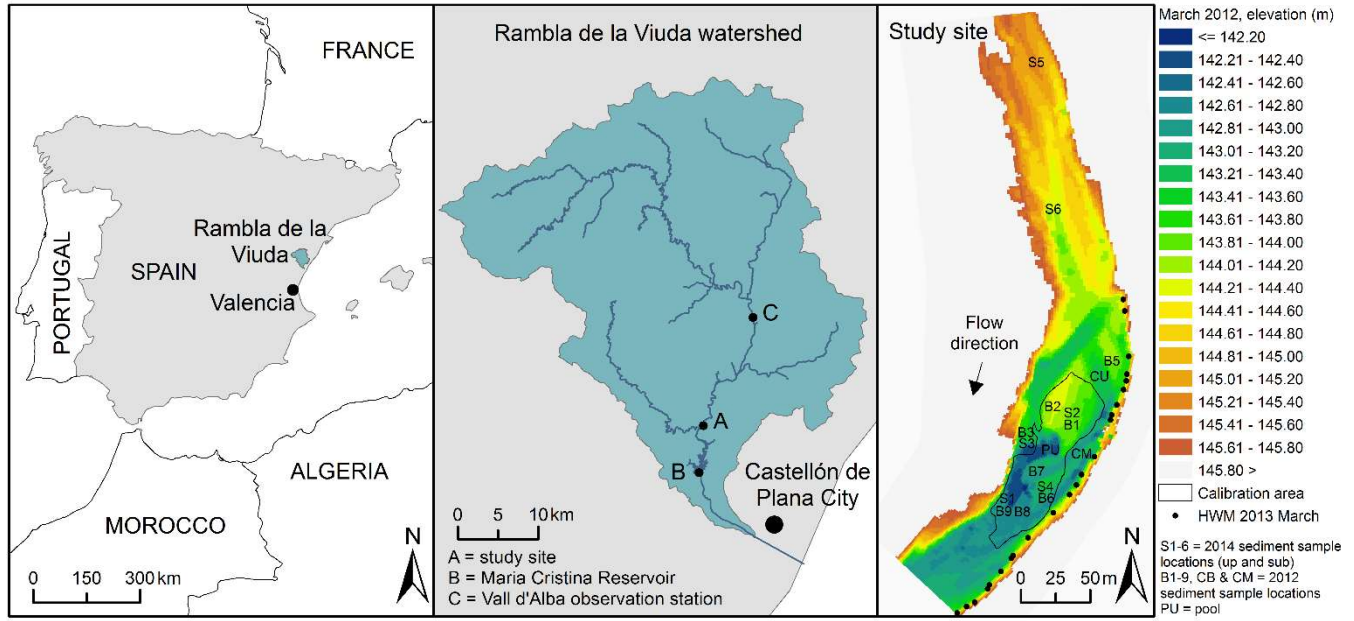
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2 The study area

Rambla de la Viuda is an ephemeral stream with a catchment area of 1523 km^2, located in eastern Spain (Fig. 1). The river has braided pattern associated ~~to~~ with a high sediment supply (Calle et al., 2015). The river is prone to flash floods, and the stream flow occurs on an average of 20 days per year. Due to the high infiltration ~~and sporadic nature of rain events~~, only intensive rains, i.e. a run-off threshold of 65 mm, cause flow in the river corridor (Segura-Beltrán and Sanchis-Ibor, 2013). This run-off threshold may vary between seasons, due to soil moisture and the frequency of rains. The rain producing floods in this catchment are caused by mesoscale convective complexes (autumn heavy rains), and those may be up to 100 km in diameter. The rains producing these floods occur in autumn and spring, and are related to Atlantic fronts, which do not give much spatial variability.

The study site is located 8 km upstream of the dam of the María Cristina reservoir. The simulation area is circa 440 m long (length along the channel) and includes an advancing gravel lobe bar front, which is the lowest 200 m of the simulation area. This lowest 200 m long reach is ~~where this~~ applied as the calibration area ~~study will be focused on~~ (Fig. 1). This area was selected essentially because it was possible to ~~assess~~ estimate the bedload sediment input ~~gravel movement~~ with certainty (Calle et al., 2015). This is due to the gravel extraction ~~/~~ as part of river mining activities in recent decades, which has produced a flat valley bottom on which gravel bars were deposited. Recently, new bars have been deposited by floods, and gravel lobes with a sharp front have been formed in the downstream edge of the area. The gravel bars and lobes of the simulation area are non- or weakly-armoured (see also Table 2) and move freely during low-magnitude flows.

The two events under study occurred in spring 2013. These were caused by two rain events, which were recorded with 5 minute interval at the precipitation and gauging station provided by the Automatic System of Hydrologic Information (SAIH-Jucar) at Vall d'Alba (Fig. 1 and Calle et al., 2015). ~~These intense spring rains caused the two flood events.~~ The first rain event (March 2013) started on 4th of March ~~and~~ last~~ing~~ed for three days with a total ~~. All together~~ 70 mm ~~precipited~~. The second rain event (April-May 2013) started on 27th April and lasted four days with ~~. All together~~ a total of 72 mm ~~precipited during those days~~. These rain events~~Event~~ caused flows that lasted 13 days (started at 12:00 on 5th March) and ~~and~~ 9 days (started 14:10 on 30th April), respectively. ~~Even though~~ The peak discharges of 23 (at 11:05 on 6th March) and 12.5 m^3 s^{-1} (at 9:05 on 1st of May) were registered in the gauging station of Vall D'Alba, respectively. ~~The hydrograph and precipitation data has already been presented at Calle et al. (2015). Due to the continuous widely spread rain events, the peak discharges on the study site were estimated to be greater at the study site than at Vall D'Alba station that due to the rain occurring between the study site and the observation stations (Calle et al. 2015). The hydrograph of the study site can be assumed to be the same shape as measured at Vall D'Alba, due to the widespread continuous character of the rain events. The hydrograph and precipitation data has already been presented at Calle et al. (2015). Thus, no sporadic events occurred. Event flows lasted 13 and 9 days, respectively.~~ These two discharge events transported 12–41 mm sized gravel (D$_{50}$ values) according to the measurements (see

The movement of these gravels caused the development of the bar fronts (Calle et al., 2015).

5   **Figure 1: The study site of the Rambla de la Viuda, Eastern Spain. The elevation on March 2012 is derived mainly from mobile laser scanning data, but the edges are from the 2009 national digital elevation model. The ~~analyzed area~~calibration area was defined, based on the data coverage of March 2013. The high water mark (HWM) measurement locations of 2013 March are shown (their values are plotted in Fig. 3). Also the sediment sample locations are shown (see also Table 2 and Fig. 2).**

Calle et al. (2015) described the main morphological ~~and topographic~~ changes in the same river reach (i.e. around the
10   calibration area of Fig. 1) caused by these moderate (March 2013) and small (May 2013) discharge events based on multi-temporal mobile laser scanning (MLS) and RTK-GPS surveys before and after the floods (Fig. 2). They also related the observed morphological and sediment textural changes with hydraulic parameters (flow velocity, depth and discharge) estimated by a two-dimensional implementation of hydrodynamic model (Delft~~2~~3D) and investigated whether the combination of the applied techniques is a reliable method to study the morphodynamics of a flood event. It was shown that MLS surveys
15   and additional RTK-GPS surveys are suitable for a dryland river environment. In addition, a two-dimensional hydrodynamic simulation was able to estimate the hydraulic characteristics associated with the discharges. Change detection and spatial grain size distribution analyses after flood showed a high availability of material (up to D_{84} of 32–45 mm) and absence of a well-developed armoured layer (Calle et al., 2015). Thresholds for sediment transport were proven to fit with the Hjulström graph (1935) in this ephemeral environment. However, simulations did not include topographical change and its influence on ~~the~~
20   ~~water level and~~ the hydraulic parameters during the floods, and could not answer how ~~sediment transport and~~ topographic changes evolved during rising limb, peak stage and receding limb of the hydrographs. In this paper, we investigate the modelling further for answers to those questions and deepening the analyses based on only with topographical measurements.
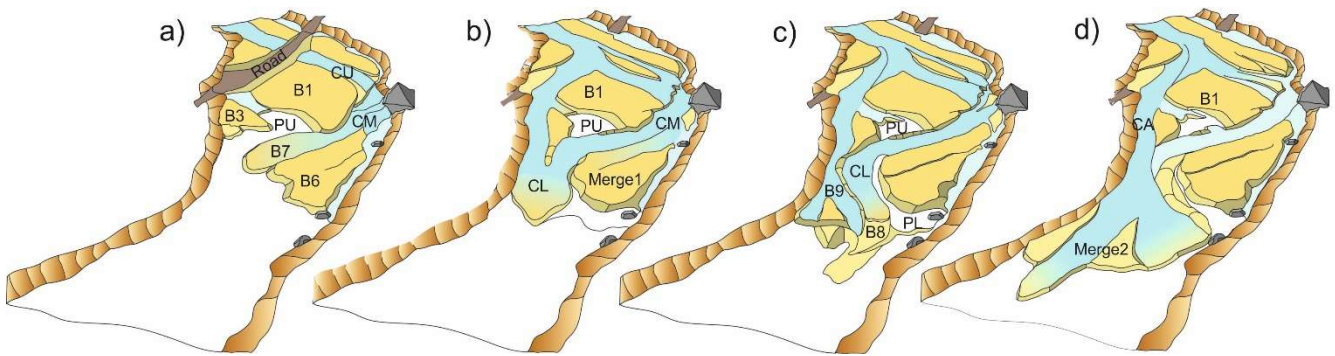
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Figure 2: The conceptual graphic presented by Calle et al. (2015: Figure 10, www.schweizerbart.de/journals/zfg): the pre-stage of 2012 (a), high flood stage during March 2013 event (b), low floor stage during May 2013 event (c) and final stage after May 2013 (d). CU: Upper Channel, CM: Middle Channel, CL: Lower Channel, PU: Upper Pool, PL: Lower Pool, B1-9: gravel Bars (cf. Calle et al., 2015).

3 Morphodynamic simulation approach

3.1 Boundary conditions: discharges and water levels

Two flow hydrographs recorded in 2013 were defined as the upstream boundary condition and the water levels as the downstream boundary condition for the hydro- and morphodynamic model (2D module of Delft3D-flow). As no direct measurements were possible to do at the study reach during the discharge events, such as normally has been done in the case of perennial rivers (Williams et al., 2013), the input data and calibration procedures differ from the traditional ones done for simulating perennial rivers. At the study reach, the hydrograph peak discharge was estimated from continuous lines of flotsam (i.e. high-water marks, HWM) emplaced by the floodwater. The hydrograph shape of the study site can be assumed similar to Vall d~~D~~'Alba gauge station, due to the ~~widespread the~~ widespread continuous character of the rain events. The hydrograph shape was verified to be similar to Vall d'Alba observation station also by recent installation of water level sensors (in late 2014) in the study site (see supplementary material). The ~~high-water marks~~HWM ~~(HWMs)~~ left by the March 2013 discharge event provided evidence that the peak discharge was greater at the study site than that measured at Vall d'Alba (Figs. 1 and 3). ~~Due to the absence of direct discharge measurements at the study site, discharges recorded every 5 minutes at the gauge station of Vall d'Alba (Located 18 km upstream from the study site; cf. Fig. 1) were used. Also daily discharges were calculated from these 5 minutes measurements.~~ The hydrographs were re-scaled by using different multipliers to match the peak discharge calculated during the calibration procedure of the model (see Sect. 3.4 below, and from Calle et al., 2015). ~~The high-water marks (HWMs) left by the March 2013 discharge event provided evidence that the peak discharge was greater at the study site than that measured at Vall d'Alba. Thus, the discharges for the study site were re-scaled by using different multipliers to match the peak discharge calculated during the calibration procedure of the model (see Sect. 3.4 below, and from Calle et al., 2015).~~
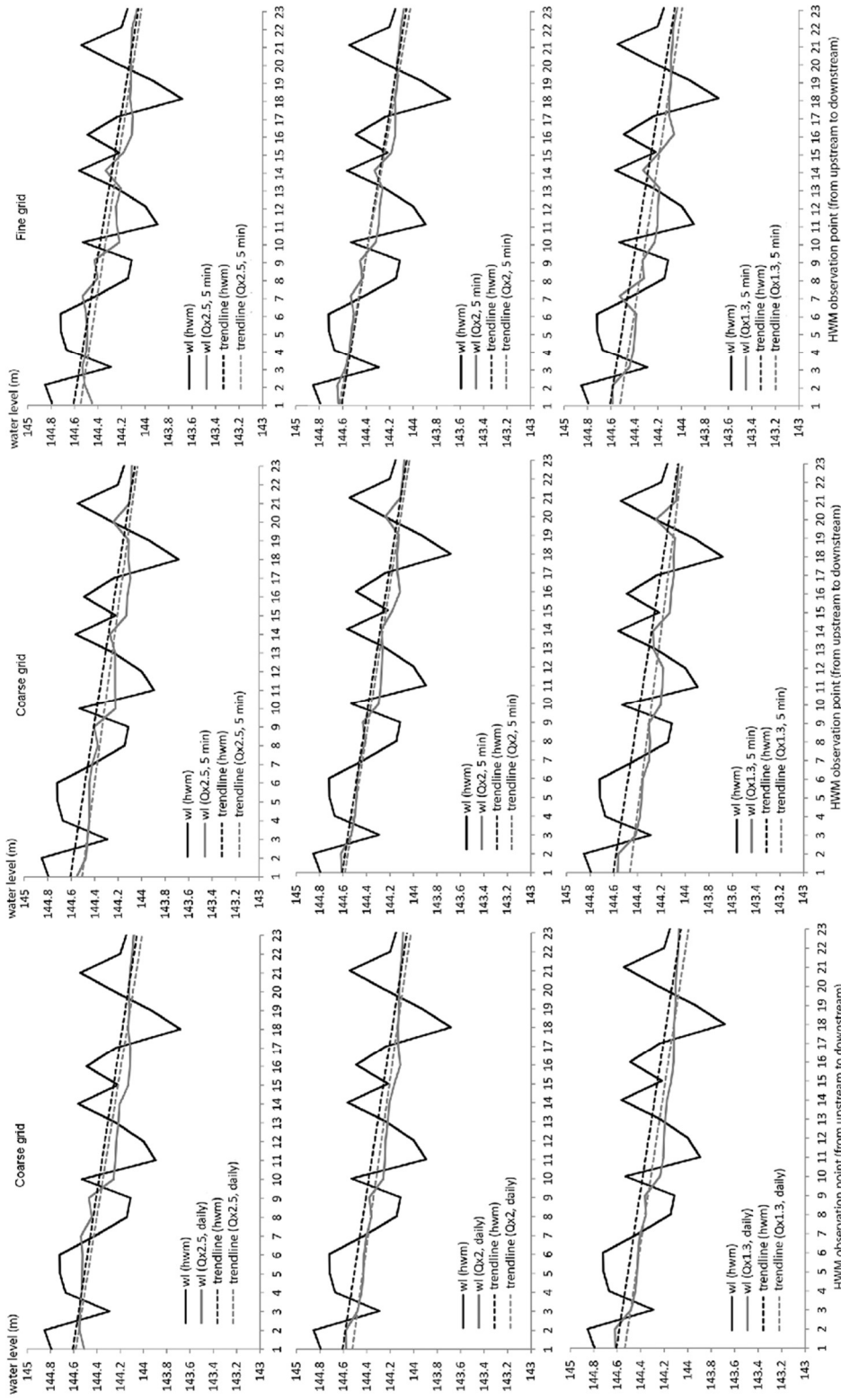
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Figure 3: The hydrodynamic calibration results based on the coarse grid (1.51–5.31 m cells) and fine grid (0.76–3.03 m cells). In this figure, the high-water marks (HWM) and simulated water levels are presented. In addition, the trendlines fitted along these measurements and simulation results are shown. These calibration results of the fine grid were previously presented in Calle et al. (2015) by the same authors. The Qx1.3, Qx2 and Qx2.5 refer to the discharges scaled to match the peak discharge at the study site. Daily and 5 min refer to the observation interval of discharges at Vall d'Alba station. wl = water level based on HWMs and simulations, trendline = the trendline fitted in the measured HWMs and the simulation results. The location of these HWM measurement points have been shown in the Fig. 1.

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Figure 3: The hydrodynamic calibration results based on the coarse grid (1.51–5.31 m cells) and fine grid (0.76–3.03 m cells). These calibration results of the fine grid were previously presented in Calle et al. (2015) by the same authors.

Water level (hereafter WL) was defined, based on the actual ~~HWM~~ high water marks (HWM) measurements along the longitudinal profile (Calle et al., 2015). The HWM measurements varied slightly along the longitudinal profile and the trendline, which was fitted between these field measurements, showed an~~the~~ accurate ~~water surface~~WL slope ~~of the water surface better~~(WL). Note that th~~is~~ese HWM ~~water surface elevation is taken~~were measured at the valley side and it m~~ay~~ight

5   not ~~to~~ have reflected the ~~actual~~ water level~~stage~~ across the whole channel as bed changes ma~~y~~ight have locally influenced water level. Therefore, the trendline constituted a good indicative of water slope and level. The downstream-most value of this WL trendline was applied as the peak WL value of March 2013 discharge event (Fig. 3, and see also Sect. 3.4). The changes in WL over time were calculated for both March and May 2013 events based on the relative change (%) of the discharge between each discharge measurement time interval. ~~The WL curves for both the March and May 2013 discharges were defined~~

10 ~~and used as the downstream boundary conditions~~

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3.2 Channel geometry

The channel topography was measured, using mobile laser scanning (MLS) and RTK-GPS (Calle et al. 2015). T~~hese~~ three topography data sets were applied. These were ~~as~~ 1) initial topography (MLS, March 2012), 2) calibration topography between the floods (RTK-GPS, March 2013), 3) final ~~calibration~~ validation topography after the floods (MLS, June 2013). The MLS was performed in March 2012 (pre-flood situation) and in June 2013 (after the two discharge events of spring 2013) (Calle et al., 2015 and Table 1). The MLS was performed~~,~~ both with a backpack and on a platform mounted on a 4x4 vehicle. A detailed description of the MLS data set can be found in Calle et al. (2015) and Table 1. According to Calle et al. (2015) and Kukko et al. (2015) the RMSE in elevation was 18.2 mm, and it was 36 mm for the 3D position of the targets. In addition, the edges of the bar lobes, which had been moved by the March 2013 discharge event, were measured with RTK-GPS just after the discharge event in March 2013 (Trimble 4700, 1 Hz, accuracies specified by the manufacturer: XY 0.02 m, Z 0.05 m, absolute systematic measurement error ≤ 0.054 m). Thus, these error estimates of the topographic data had been performed in Calle et al. (2015) ~~and therefore are not anymore presented in this paper~~. This RTK-GPS data ~~thus~~ represented the geometry after the March 2013 event and before the May 2013 event, and w~~as~~ereas therefore ~~therefore also~~ applied as a calibration data set. This enabled better estimation of the model performance than only using one ~~calibration~~ data set after the two consecutive flood events.

Table 1. The properties of the MLS measurements of 2012 and 2013 (adapted from Calle et al. 2015).

	2012 March	2013 June
Laser sensor / GPS sensor	FARO Photon 120	FARO Focus 3D 120 S
Receiver	NovAtel DL4+	NovAtel Flexpak6
Inertial measurement unit	Honeywell HG1700 AG11	Northrop-Grumman UIMU-LCI
IMU frequency	100 Hz	200 Hz
Referencing system	GPS (1 Hz)	GNSS (1 Hz)
Wavelength	785 nm	905 nm
Scan frequency	61 Hz	95 Hz
Point acquisition	488 Hz	488 Hz
Angular resolution	0.045º (0.8 mrad)	0.07º (1.2 mrad)
3D RMSE	0.034m	0.019 m

The 2D implementation of Delft~~-2~~3D morphodynamic model require~~d~~s channel geometry in grid format. Orthogonalized curvilinear grids of two different resolution~~s~~ were created from both measured topographies, one with "coarse" 1.51–5.31 m cells and one with "fine" 0.76–3.03 m cells (i.e. circa half of the coarser grid cell sizes). These cell sizes were selected for testing the impacts of cell sizes on simulation results, but also due to their computational effectiveness. Cell sizes smaller~~s~~ ~~finer~~ than the "fine" resolution (i.e. 0.76–3.03 m) did not ~~make more difference to~~enhance the results~~, thus no further finer cell sizes were included in this paper. Furthermore,~~ and ~~cells finer than 0.76–3.03 m~~ those would have also only ~~highly~~ increased the computational time. Thus, curvilinear grids of two resolutions, "coarse" 1.51–5.31 m cells and "fine" 0.76–3.03 m cells, were created from the topography measurement times.~~.~~

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The initial input channel topography for all of the ~~Delft 2D~~ simulations was defined by adding the M~~S~~L<u>S</u> 2012 measurement points to the curvilinear grids, both <u>to the</u> coarse and fine grids ~~(see above)~~, and averaging the point values for the grid cells. There was also available a digital elevation model (DEM) from 2009 (from airborne ~~LiDAR~~<u>laser scanning</u>), which ha~~s~~<u>d</u> a 1 m resolution. After adding the MLS data, this 2009 DEM was added to the grid cells, which located outside the laser scanning perimeter, in order to cover the higher banks. The coarser resolution of the 2009 DEM did not affect the simulation results of the channel, because the high-water levels of the 2013 spring events barely reached these higher bank elevations.

For calibrating <u>and validating</u> the modelling results, the top<u>o</u>graphies were also created from the March 2013 and June 2013 measurements so that those geometries had similar resolution as the initial input channel geometry. The model outputs after each of the discharge events were then compared to these <u>topography</u> grids created from the March and June 2013 measurements. The grid-form geometry of March 2013, i.e. calibration topography between the floods, was created by adding only the GPS measurements to the grid cells, and the rest of the channel was excluded from the area to be analyzed <u>during calibration</u> (Fig. 1). The grid-form geometry of June 2013, i.e. the final ~~calibration~~ <u>validation</u> topography after the ~~two~~ <u>May 2013 flood</u>~~floods~~, was defined by <u>first</u> adding ~~first~~ the laser scanning data set, which had been processed to include both backpack and car MLS data, to the grid cells. Then the 2009 DEM was added to the grid to cover the higher bank areas. However, only the same area, as applied in the case of March 2013 (i.e. the gravel bar lobes area), was used in the ~~final analyses of morpholocial change detection and comparison~~<u>validation</u> of the model performance. <u>These observed elevation and volumetric changes between the events were compared to the simulated changes. For calculating the volumetric changes the curvilinear grid topographies were needed to convert into regular grids. To minimize the errors, a 0.5 m regular grid's cell size was selected, as the original cells were mostly divisible by that value.</u>

~~These calibration curvilinear grids of "between floods" and "after floods" situations were used for analysing the capabilities of the model to result correct channel bed elevations. These simulated and measured bed elevations were compared. For volumetric calculations, these curvilinear grids and the model outputs from the same time steps were also converted into regular grids. To minimize the errors, a 0.5 m regular grid's cell size was selected, as the original cells were mostly divisible by that value.~~

3.3 Grain sizes

Spatially varying grain sizes were measured from the gravel lobes area prior to the first flood and between the floods, using the Wolman (1954) sampling method (Table 2). However, this method did not recover the differences between upper layer and sublayer sediment distribution and what kind of particles the 2013 discharge events had ~~in reality~~ moved. ~~We were able to measure these only after the discharge events had occurred.~~ Therefore, the gravel moved by the 2013 spring events were measured using a US standard gravelometer (US SAH-97 handheld particle analyzer) in summer 2014 (Table 2). <u>This was</u>

possible, as no discharge had occurred between May 2013 and summer 2014. These measurements represented different active forms, from bars to the channel bed, which had evolved during the 2013 spring floods. The bulk sieving measurements (c. 80 kg from 1.1x1.1 m area, 0–10 cm from the surface) were performed at six different locations, and from both the upper layer (UP1–6) and sublayer (SUB1–6, c. more than 10 cm below the surface) to evaluate armouring (Fig. 1 and Table 2). The upper layer-sublayer contact was established following the criteria described by Bunte and Abt (2001) considering the size of the largest particles embedded depth. The difference in the average D50 values of upper layer samples between 2012 (18.5 mm) and 2014 (21.1 mm) measurements was only 1.6 mm (Table 2).

Table 2. The grain sizes measured in 2012–2014 (see their locations from Fig. 1). WCM, WCU and WB1–7 were measured in 2012, WB8 and 9 were measured in March 2013, and SUB1–6 and UP 1–6 were measured in June 2014. W= Wolman, C= channel, B=Bar, SUB=sublayer, UP=upper layer. Most of the samples were within the ~~analyzed area~~calibration area, and their locations can be seen in Fig. 1 and also in Fig~~ure.~~ 11 of Calle et al. (2015). ~~Only the samples UP/SUB 5 and 6 were further in the upstream section of the simulation area.~~ Due to the spatial scarcity of the 2013 measurements (only two samples) were not applied as the surface grain sizes for the model~~, but were used for Limerinos (1970) calculations.~~. The armour ratio was calculated following Lisle and Madej (1992), i.e. ratio of the surface-to-subsurface D_{50}.

	upper layer		sub layer	
Sample	D50 (mm)	D84 (mm)	D50 (mm)	armour ratio
WCM	18	29	-	-
WCU	30	101	-	-
WB1	22	41	-	-
WB2	17	33	-	-
WB3	17	34	-	-
WB5	12	21	-	-
WB6	17	37	-	-
WB7	14	22	-	-
WB8	18	35	-	-
WB9	20	31	-	-
UP1 and SUB1	22.5	-39	18.5	1.216
UP2 and SUB2	35.5	-79	21.3	1.667
UP3 and SUB3	18.8	-31	14.3	1.314
UP4 and SUB4	18.0	30.5-	14.4	1.250
UP5 and SUB5	31.2	55.4-	18.6	1.677
UP6 and SUB6	41.2	80-	16.7	2.467
Average UP1–6	26.3	-	-	-
Average SUB1–6	17.1	-	-	-
Average UP and SUB1–6	21.1	-	-	-

The D_{50} and D_{84} grain sizes of 2012 and March 2013 were first used for the calibration and initial testing of the hydrodynamic model (see Sect. 3.4). For the calibration of the morphodynamic model, the spatial distribution of the D_{50} grain sizes of both 2012 and 2014 were then applied. The grain size values were assigned to equivalent morphological elements defined in the geomorphological map. These grain sizes were transferred to each cell of the curvilinear morphodynamic model's grid.

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Different input grain size distributions were applied in the model tests: 1) spatially varying upper layer grain sizes, 2) spatially varying sublayer grain sizes and 3) constant average grain sizes (average of upper layer, sublayer or both upper layer and sublayer). The values were applied to the whole active layer of the river bed. The D50 grain size values were used in the model.

3.4 Hydrodynamic simulations

5 The same calibrated hydrodynamic model (2D implementationversion of the Delft3D-FLOW) was applied as in Calle et al. (2015). The flow was simulated as depth-averaged flow by using the well-known Navier-Stokes and shallow-water equations. Thus, the modelled fluid was considered vertically homogeneous. These well-known equations can bewere found in the user manual of the model (Deltares, 2011). The model applies the alternating-direction implicit (ADI) time integration method for the shallow-water equations (Leendertse, 1967).

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Table 3.The Manning's n-values and discharges that gave the best simulation results when compared to the measured HWMs and their trend line during the calibration. Qx1.3, Qx2 and Qx2.5 stand for Vall D'Alba's discharges multiplied by 1.3, 2 and 2.5, respectively. This same table is presented in Calle et al. (2015).

Element type	n (Qx1.3)	n (Qx2)	n (Qx2.5)
Channel/active bar	0.063–0.065	0.05–0.053	0.03–0.04
Extract area	0.07	0.06	0.03
Block	0.068	0.058	0.05
Exposed area	0.07	0.06	0.033–0.04
Scarce vegetation bar	0.065	0.055	0.035–0.04
Vegetated bar	0.07	0.06	0.04
Pleistocene terrace	0.07	0.06	0.05
Rocky bank	0.07	0.06	0.035
Vegetated bank	0.07	0.06	0.05
Opencast mine	0.07	0.06	0.04

15 The hydrodynamic model was calibrated by adjusting the Manning's n-values so that the simulated water levels matched with the measured high-water level marks, and their WL trendline, of the 6th of March 20136.3.2013 discharge peak situation (Fig. 3 and Calle et al., 2015). The hydrodynamic model was calibrated by applying first daily discharge values as the upstream boundary condition. The n-values were defined based on Limerinos (1970) equations for D_{50} and D_{84} grain sizes (Table 3). It is noteworthy that vegetation was almost non-existent in the channel. There was only scarce vegetation in the upstream part,

20 and higher up in the banks, i.e. out of reach of the 2013 discharge events. Therefore, the roughness values were possible to define by the particle size on the active river channel. It is noteworthy that there was no vegetation in the river channel area affecting the two (moderate and small) discharge events, and therefore the roughness values were possible to define by the particle size on the active river channel. The Limerinos equation was applied for the whole range of water levels (i.e. hydraulic radiuses) for the March 2012 and March 2013 grain sizes of D_{50} and D_{84}. These represented the best of the preceding conditions

25 of the March 2013 and May 2013 flows. The Limerinos calculations were performed for a cross-section located at the

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downstream side of the simulation area. This cross-section was defined from 2012 geometry, i.e. pre-flood geometry, which remained unchanged during the 2013 discharge events. At the 144.151 m water level, which was the measured high-water mark elevation at this location, the wetted perimeter of the cross-section was 52.09 m and the hydraulic radius was 0.95 m (max flow depth 1.28 m). Each of the geomorphological elements, and thus also grid cells, received their own Manning's n-

5 value during the calibration procedure. Note that the ~~asignement~~assignment of the n values was static throughout the simulations, i.e. the spatial distribution of the roughness values was not possible to change between simulation time steps.

The calibration was first done for the coarser grid of 1.51–5.31 m cell sizes. Because the discharge estimated at the study site was greater than the one recorded at the Vall d'Alba gauge station, three different daily discharges ("Qx1.3", "Qx2" and

10 "Qx2.5") were tested during the calibration of the hydrodynamic model. The "Qx1.3" was defined based on the increase in watershed area (30%) between the study area and the Vall d'Alba observation station. This Qx1.3 discharge simulation matched the ~~high-water level~~HWMs ~~marks~~ using the highest n-values calculated with the Limerinos 1970 equation, i.e. for shallow flow (Table 3). In this Qx1.3 discharge, each of the observations was multiplied by 1.3. The "Qx2" (observations multiplied by 2) water surface elevation matched the HWMs using an average n-values calculated from Limerinos (1970)

15 equations. Also, the effects of bedform (from +0.01 to +0.015) and bank roughness (+0.02) had been added to these average n-values (Chow, 1959; Acrement and Schneider, 1989). The simulated water levels also matched with HWMs when the "Qx2.5" discharge and n-values representing the high-flow stage values (i.e. lower n-values on the value range) calculated from Limerinos (1970) equations were selected. Similar n-value ranges were gained for different water level situations, when either the equation for D_{84} or D_{50} grain sizes was applied. Based on the Limerinos equation calculations, the Qx2 was expected

20 to work the best due to its average nature and inclusion of bedform and bank roughness effects.

When the calibration against the HWMs and their trendline was successful with these daily discharges and coarse grid, the same Manning's n-values were applied for simulations with a hydrograph with a 5-minute measurement interval. The "Qx1.3", "Qx2" and "Qx2.5" versions of these 5-minute hydrographs were tested. These simulations also reproduced the water levels,

25 and the best fit was obtained with "Qx2" (Table 3) ~~sufficiently well, and~~. ~~T~~thus, no more ~~modifications~~adjustments were ~~performed~~done for the ~~Manning's~~ n-values. ~~All in all, the best fit was obtained with "Qx2" (Table 3).~~ Finally, the 5 min hydrograph simulations were performed ~~simulations were also performed~~ with ~~the more detailed grid, i.e.~~ the fine grid ~~with~~ (0.76–3.03 m cells, ~~(~~Fig. 3). The~~se~~ simulation ~~hydrodynamic simulation~~ results corresponded the observations ~~with the fine grid cells were~~ better than ~~with~~ if the coarse grid cell sizes were used ~~(,~~ as also shown in Calle et al., ~~(~~2015).

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~~In addition~~Finally, both March and May 2013 discharge events were ~~tested~~simulated ~~in the final hydrodynamic simulations~~. Similar multipliers (Qx1.3, Qx2, Qx2.5) and Manning values were applied for both events. Both these discharge ~~hydrographs events of 2013~~ were simulated as ~~an~~ unsteady ~~simulation~~flow and by applying the bathymetry derived from 2012 topographical measurements. The Qx2 discharge was proven to best produce the observed hydrodynamics (Fig. 3; see also Calle et al., 2015).

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All in all, 21 ~~hydrodynamic~~ simulations were run during the calibration of the hydrodynamic model.

3.5 Morphodynamic simulations

Calibration of the morphodynamic model consisted on the adjustment of the model parameterization so that the model output geometries matched the ~~first order~~measured bedform geometries as well as possible. The model applie~~d~~s an "upwind" bed update scheme, where the elevation of the bed was dynamically updated at each computational time step. In all simulations, the initial boundary conditions of the input and output sediment transport load amount w~~ere~~as defined as 0. This is because the flood events started from 0, and no significant transport, i.e. evolution of bedforms was observed upstream and downstream of the simulation area. The model then calculated the transport based on the selected transport equations and using equilibrium concentration for carrying input sand sediment fractions. This was similar to earlier studies done in gravel bed river (Williams et al., 2016b), and was selected based on earlier experiences of the river (Calle et al., 2015), and because no suspended load measurements were available and the sand sediment fraction was almost non-existent in the river. Based on the experience in the study site, the load should be in equilibrium particularly in erosional areas of the study site. ~~The simulation area begun further upstream than the actual analyzed area, so that sediment transport input in the study reach was steady.~~ Because the bed level gradient affects the bedload transport, the slope in the initial direction of the transport (referred to as the longitudinal bed slope) and the slope in the direction perpendicular to that (referred to as the transverse bed slope) were utilised. The transverse slope affects transport towards the downslope direction (Deltares, 2011). The Bagnold (1966) equation was applied for the longitudinal slope and Ikeda (1982), as presented by Van Rijn (1993), was applied for the transverse slope.

~~Due to the better performance with Qx2, all these selected morphodynamic simulations have these input data. All simulations with Qx1.3 and Qx2.5 discharges were discarded as those did not reproduce the correct topographical changes. The 11 selected simulations showed the effects of grain size (before [2012] and after [2014] floods, and grain sizes from different layers [2014]), grid size (coarse: 1.51–5.31 m, fine: 0.76–3.03 m), transverse slope (user defined coefficients in the bed load transport equations: default 1.5 and increased to 3) and transportation equations (Engelund-Hansen [EH], Meyer-Peter and Müller [MP]) on model performance (Tables 4 and 5). These parameter tests were selected for the calibration procedure, as these have earlier been found important for Delft 2D model simulations, albeit in perennial rivers (e.g. Kasvi et al., 2014). The morphodynamic simulation results were compared to the measured topographies (Figures 4–6), in particularly the volumetric change of river bed and displacement of the lobe front (Table 6).~~

Table 4. The morphodynamic simulations and applied parameters. The fine grid size is 0.76–3.03 and the coarser size is 1.51–5.31 m. EH=Engelund-Hansen, MPM=Meyer-Peter and Müller. Events: 1=only the March 2013 event was~~has been~~ simulated, 2=both the March and May 2013 events ~~have been~~were simulated. The simulations that were selected for the ~~hourly~~ channel change analyses are bolded~~in bold~~.

Simulation	Transport equation	Discharge events	transverse slope	grid size	grain size
1	EH	1	1.5	coarse	varying, 2012

2	EH	1	1.5	fine	varying, 2012
3	EH	1	1.5	coarse	varying, upper, 2014
4	EH	1	1.5	coarse	varying, sub, 2014
5	EH	1	1.5	coarse	varying, average upper+sub, 2014
6	EH	1	1.5	coarse	constant, average upper, 2014
7	EH	1	1.5	coarse	constant, average sub, 2014
8	EH	1	1.5	coarse	constant, average upper+sub, 2014
9	**EH**	**2**	**3**	**fine**	**varying, upper, 2014**
10	**EH**	**2**	**1.5**	**fine**	**varying, upper, 2014**
11	MPM	2	1.5	fine	varying, upper, 2014

Altogether, 61 morphodynamic simulations were needed for calibrating the morphodynamic model. These 61 simulations included simulations with Qx1.3, Qx2 and Qx2.5 discharges hydrographs. During these simulations the match of the simulated water levels to HWMs was also checked. The roughness values were still valid. ~~While performing the calibration, the sensitivity of the model to the different parameter combination was analyzed.~~

Out of these 61 morphodynamic simulations, 11 simulations done during calibration ~~, which produced the best and most interesting results,~~ were selected to be presented in the ~~detail in this~~ supplementary material of this ~~paper for sensitivity analyses~~ (see also ~~T~~Tables 4 ~~and 5~~). Reason for their selection was that ~~T~~these 11 ~~selected~~ simulations showed the effects of grain size (before [2012] and after [2014] floods, and grain sizes from different layers [2014]), grid size (coarse: 1.51–5.31 m, fine: 0.76–3.03 m), transverse slope (user defined coefficients in the bed load transport equations: default 1.5 and increased to 3) and transportation equations (Engelund-Hansen [EH], Meyer-Peter and Müller [MPM]) on model performance (Table 4, and supplementary material~~Tables 4 and 5~~). These parameter tests were selected for the calibration procedure, as these had earlier been found important for Delft3D (2D implementation) model simulations, albeit in perennial rivers (e.g. Kasvi et al., 2014). The morphodynamic simulation results were compared to the measured topographies within the calibration area, in particular to the volumetric change of river bed and displacement of the lobe front. Due to the better correspondence of simulations with Qx2 discharges to the observed channel evolution, all these selected morphodynamic simulations had these input data. The longitudinal slope did not affect the results, and the default value 1.0 was selected to be used. The model was first calibrated with March 2013 discharge event (simulations 1–11), and then validated with May 2013 discharge event (simulations 9–11).

~~best Reid et al. (1996) showed that the Meyer Peter and Müller (MPM, 1948) equation, which was originally developed for steady flow conditions and used by Reid et al. (1996) in non-armoured gravel bars, performs well and better than the Bagnold (1980) and Parker (1990) equations in ephemeral gravel river channels.~~

~~Because the bed level gradient affects the bedload transport, the slope in the initial direction of the transport (referred to as the longitudinal bed slope) and the slope in the direction perpendicular to that (referred to as the transverse bed slope) were utilised. The transverse slope affects transport towards the downslope direction (Deltares, 2011). The Bagnold (1966) equation was applied for the longitudinal slope and Ikeda (1982), as presented by Van Rijn (1993), was applied for the transverse slope. The~~

longitudinal slope was tested with both the default value (1.0) and double the default value (2.0). However, the longitudinal slope did not affect the results, and it was decided that the default value 1.0 would be used in the selected simulations, which are shown in Tables 4–6. Due to the great effects caused by the transverse slope on the morphodynamic simulations of perennial rivers (e.g. Kasvi et al. , 2014), we were particularly interested in the effects of this transverse transport component on the ephemeral river simulation, and thus tested the model with the component being 3.0, which is double the default value (1.5). These values were defined based on earlier publications (e.g. Kasvi et al., 2014).

Table 5. The simulations used for comparing the effects of different parameters on model performance. x = parameter tested in the simulation.

Simulation	Tested parameters					
	grid size effect	grain size effect: before (2012) & after flood (2014)	grain size effect: different layers	grain size effect: constant vs. varying	transverse slope effect	transportation equation effect
1	x	x				
2	x	x				
3	x	x	x			
4			x			
5			x	x		
6			x			
7			x			
8			x	x		
9					x	
10	x	x			x	x
11						x

The bedload transport was tested initially with the Van Rijn 1993 equation (VR), which is widely used, despite the fact that it was developed with smaller grain sizes than those of the study area. Also, small flow depths may affect the performance of the VR equation (Van Rijn, 1984). The depths of the flow were relatively shallow at the Rambla de la Viuda, in comparison to the channel width. As expected, the channel bed did not evolve at all with VR equation. Thus the VR equation was discarded at once (not included in Tables 4 and 5). Instead, the widely applied equations of "Engelund Hansen 1967" (EH) and "Meyer-Peter and Müller 1948" (MPM) were selected from the Delft 2D model's assortment of equations (cf. Deltares, 2011), because they had been developed by using initially non-armoured bed conditions and were the most appropriate for the study area, according to the D_{50} grain sizes. Also, MPM has previously been proven to perform well, i.e. better than, for example, Bagnold 1980, in flash flood simulations (Reid et al., 1996; Cao et al., 2010). The MPM was expected to perform the best, as it has originally been developed for particles of 0.4–29 mm overall diameters. Earlier simulations done for ephemeral rivers, e.g. Hooke et al (2005), have applied the Bagnold (1966) total load equation. However, it was not included in the set of equations provided by the standard Delft 2D model, and thus it was not applied in this study. Instead, the EH was selected as the total load equation, due to its proven performance in a variety of environments (e.g. Kasvi et al. 2014), even though it has originally been tested on up to 0.93 mm median particle sizes (Engelund and Hansen, 1967).

Two simulations, which show after calibration the best correspondence with the observed riverbed changes and bed formations, were selected for the final channel evolution analysis. Based on these two simulations, the temporal evolution of the riverbed was analyzed during the two hydrographs of moderate- and low- magnitude discharge events.

4 Morphodynamic simulation results

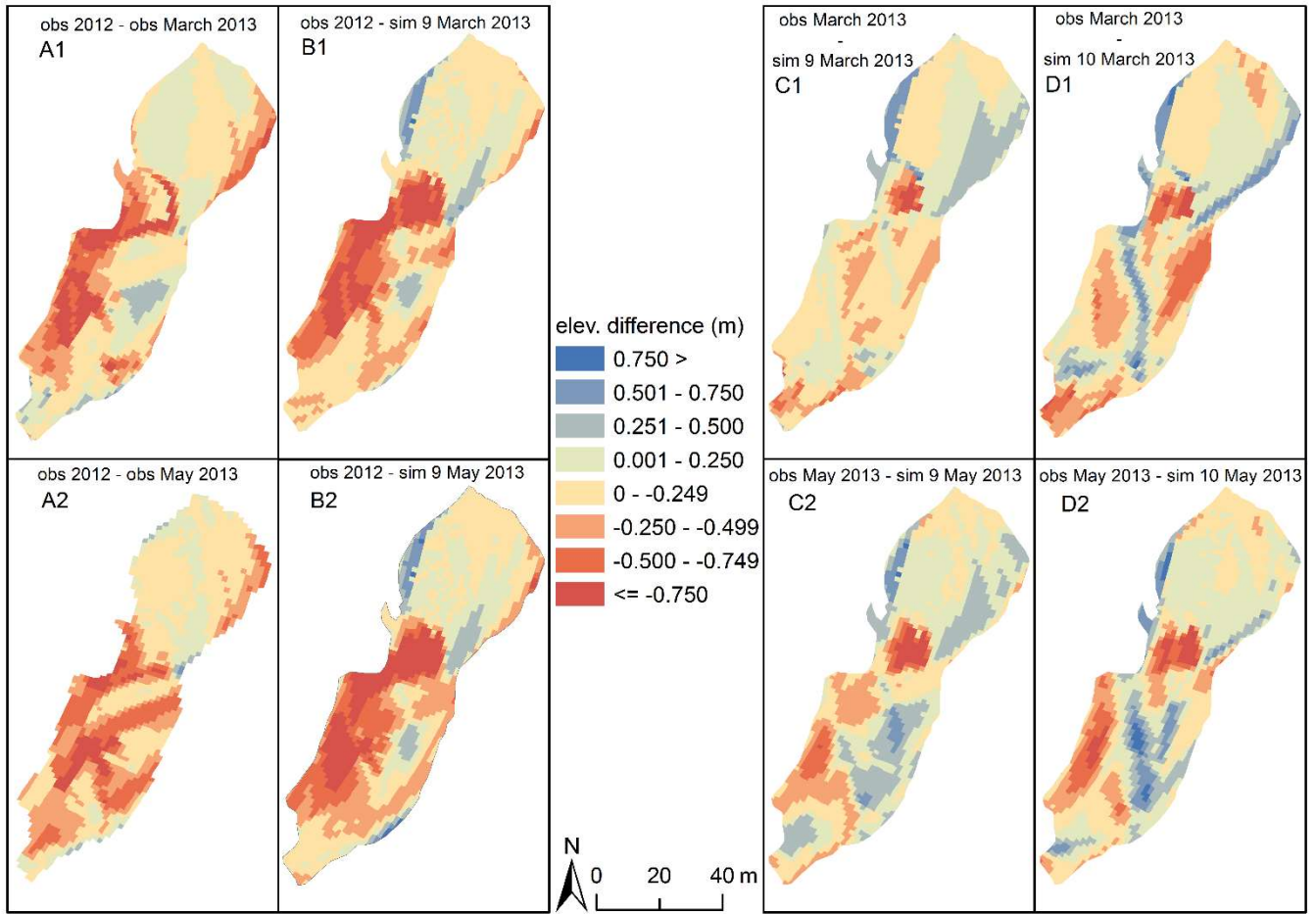**4.1 The morphodynamic model's sensitivity to the parameterization**

4.1.1 Effects of applied grain size on simulation results

The grain size and its spatial variation affected the model results greatly and needed the largest number of tests during the calibration of the model (Tables 4–6, Figures 4–6). This was first analyzed by comparing the measured and simulated topographies and volumetric changes produced by the March 2013 flow. When the spatially varying upper layer sediments (representing the sediments actually moved by the two discharge events, i.e. the ones measured after floods in 2014) were used in the simulation (number 10), the volumetric changes were less and fitted the observations better than if spatially varying "before floods" grain sizes of 2012 were applied (simulation 2). The effects of spatially varying sublayer grain sizes (simulation 4) and spatially varying upper layer grain sizes (simulation 3) were compared: the deposition increased by 352 m^3 when applying spatially varying sublayer grain sizes. The bedforms were also represented better with upper layer sediments. When the spatially varying average grain sizes (average of the upper and sublayer grain sizes) were applied, the simulation (number 5) resulted in a slightly greater deposition than with spatially varying upper layer grain sizes (simulation 3, Table 6). When the constant grain sizes were applied (simulation 8), the deposition was greater and resembled the observations better than a corresponding simulation with spatially varying grain sizes (simulation 5), but the erosion was also greater and thalweg was excavated too deep with constant grain sizes (simulations 6–8). Altogether, the spatially varying upper layer grain sizes (measured in 2014), which were known to have been moved by the discharge events, resulted in the most realistic results.

Table 6. The evaluation of modelled volumetric changes and lobe movement, in comparison to observations. Based on the performance analyses of the model during March 2013 event's simulations, the May 2013 discharge event was only simulated with a fine grid cell size, and using upper layer sediments measured in 2014 (cf. Table 4). The simulations that selected for the final hourly channel change analyses are bolded. Gravel storage was calculated by subtracting the erosion from deposition.

simula-tion	grid size	erosion (total m³; difference compared to observed %)	deposition (total m³; difference compared to observed %)		Gravel storage (total m³; difference compared to observed %)	lobe move-ment (m)
observed	coarse	89.116; 0	1252.066; 0		1162.95; 0	58.5

Figure 46: The comparison between the observed and simulated (simulations 9 and 10) elevations ~~after the March 2013 and May 2013 discharge events~~**. The** ~~negative~~ **negative values (red) mean that the observed (A)/simulated (B: simulation 9) March (1)/May (2) 2013 topographies were higher (i.e. deposition had occurred) than was observed in 2012. The negative values also mean that simulated elevations of March/May 2013** ~~were~~ **were higher** ~~in those locations~~**than was observed in March/May 2013 with simulations 9 (C) and 10 (D)**~~..~~**.** ~~The fine grid cell sizes were applied in these simulations.~~**Simulation 9 corresponded slightly better the observations than simulation 10, and thus its results are shown in more detail. The pool area, in the middle of the area, was the only area where simulation results clearly showed more deposition than observed (see also Fig. 2 PU).**

Here we present the summary of calibration results, which can be found in more detail from the supplementary material of this paper. The best simulation results in relation to the surveyed volumetric changes were achieved with the fine grid simulations. The coarser grid size overestimated incision and was therefore discarded. The grain size and its spatial variation affected the model results greatly and needed the largest number of tests (supplementary material). When the spatially varying upper layer sediments of 2014 (representing the sediments moved by the two discharge events) were used (simulation 10), the volumetric changes were less and fitted the observations better than if spatially varying 2012 "before floods" grain sizes were applied (simulation 2). The bedforms were also best represented when upper layer sediments were applied (simulations 9 and 10).

The deposition and erosion amounts resembled the observed elevations, and the lobe movement distances were the best when the transverse slope was increased (simulation 9). Despite, the best correspondence of the simulated and measured spatial bedform pattern was obtained with simulations number 9 and 10, the default (1.5) transverse slope of simulation 10 resulted in a more excavated thalweg, when compared to the simulation 9 with an increased transverse slope (Fig. 4).

Earlier simulations done for ephemeral rivers, e.g. Hooke et al (2005) and Graf (1996), had applied the Bagnold (1966) total load equation. However, Meyer-Peter and Müller (MPM, 1948) equation had previously been proven to perform well, i.e. better than, for example, Bagnold 1980 and Parker (1990) equations in flash flood simulations and in ephemeral gravel river channels (Reid et al., 1996; Cao et al., 2010). The widely applied equations of "Engelund-Hansen 1967" (EH) and "Meyer-Peter and Müller 1948" (MPM) were selected from the standard Delft3D model's assortment of equations (cf. Deltares, 2011), because they had been developed by using initially non-armoured bed conditions and were the most appropriate for the study area, according to the D_{50} grain sizes. The MPM was expected to perform the best, as it had originally been developed for particles of 0.4–29 mm overall diameters. The EH was selected as the total load equation, due to its proven performance in a variety of environments (e.g. Kasvi et al. 2014), even though it had originally been tested on up to 0.93 mm median particle sizes (Engelund and Hansen, 1967). The transport equation had a crucial role in the simulation results. The EH (simulations 9 and 10) was superior in reproducing the channel morphology. MPM resulted in much smaller and incorrect transport values (simulation 11) during both March and May 2013 discharge events.

Thus, simulations 9 and 10 produced the best correspondence with the observed riverbed changes and bed formations (Fig. 4). These were used for analysing the temporal riverbed evolution during the moderate- and low-magnitude discharge events.

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4.1.2 Effects of grid size on simulation results

The grid size effects on the simulation results were compared between simulations 1 and 2, and simulations 3 and 10 (Tables 4–6, Figures 4–6). The fine grid size tends to overestimate both erosion and deposition, whereas a coarser grid size overestimates incision. When compared to the observed topographic river bed model, the coarse grid simulations show also an underestimation in the depositional amounts. The coarse grid also caused a moderate magnitude flood to flow mostly on the left bank side, which was opposite to the fine grid simulations and reality. The best simulation results (from the simulations 1, 2, 3 and 10) in relation to the surveyed volumetric changes were achieved with the fine grid simulation (number 10). It was decided to discard the coarse grid from the simulations of the May 2013 discharge event, and from further analyses.

4.1.3 Effects of transverse slope on simulation results

The increased transverse slope affected positively the simulation results (simulation 9), when they were compared to the corresponding simulations with the default 1.5 transverse slope (simulation 10) (Table 6, Figures 5–6). The deposition and erosion amounts resembled the observations more, when the transverse slope was increased (Table 6). The lobe movement distance was also the best with an increased transverse slope (simulation 9). Noticeable from the elevation difference analyses is that the simulations with an increased transverse slope resulted in the greatest correspondence to the observed elevations (Fig. 6). However, particularly one location in these simulations had experienced more deposition than observed: the pool area downstream of the large lateral bar (PU: Figure 2 and Calle et al., 2015).

When compared to the geomorphological evolution described in Calle et al. (2015) and the measured topographies, the spatial bedform pattern was visually compared for both the discharge events. Of all simulations, the best results were obtained with these simulations number 9 and 10. However, the default 1.5 transverse slope resulted in a more excavated thalweg (simulation 10), when compared to the simulation with an increased transverse slope (simulation 9) (Figures 5–6). However, simulation 10 also showed satisfying bar accretion from the left bank side of the channel.

4.1.4 Effects of transport equation on simulation results

Based on the comparisons of observed and simulated topographies and volumetric changes (Table 6 and Figure 4–6), the transport equation had a crucial role in the simulation results. The EH equation (simulation 10) was superior in reproducing the channel morphology. MPM resulted in much smaller transport values (simulation 11) during both March and May 2013 discharge events (simulation 10). Basically, no movement occurred when the MPM equation was used. Thus, the MPM equation was proven not to be able to produce the correct movement during the moderate- or low-magnitude discharge events of this ephemeral gravel river. The EH equation (simulation 10) was superior in reproducing the channel morphology. MPM resulted in much smaller transport values (simulation 11) during both March and May 2013 discharge events (simulation 10). Basically, no movement occurred when the MPM equation was used. Thus, the MPM equation was proven not to be able to

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4.~~2~~ The temporal evolution of Rambla de la Viuda

4.~~2~~.1 The evolution during moderate-magnitude ~~flood hydrograph~~discharge event

All in all, lobe movement of c. 60 m was observed during the March 2013 discharge event~~,~~ and additional c. 30 m during the May 2013 discharge event. The bedload sediment mass balance was possible to estimate. Deposition was greater than erosion based on measurements (i.e. in the calibration area) (Table 5). Hydrographs and erosion and deposition rates were also plotted against time for the simulations 9 and 10 (Fig. 6), which had reproduced the best the observed morphodynamics within the calibration area (see Sect. 3.6). Sediment erosion and deposition were calculated from the total channel bed change amount of each hour from this calibration area. In addition, the bed elevation changes between the key time steps, i.e. times of clear changes in discharge or bed evolution, were also defined from the whole simulation area (Fig. 6: simulation 9 as an example).

Table 5. The volumetric changes and lobe movement of observations and the two selected simulations (see also supplementary material). Gravel storage was calculated by subtracting the erosion from deposition.

sim	grid	erosion		deposition		Gravel storage		lobe movement (m)
		total m³;	difference compared to observed %	total m³	difference compared to observed %	total m³	difference compared to observed %	
				1. event (March 2013)				
	fine	154.56	0	984.72	0	830.16	0	58.5
9	**fine**	**164.69**	**+7**	**1119.28**	**+14**	954.59	+15	**59.9**
10	**fine**	**178.69**	**+16**	**1190.85**	**+21**	1012.16	+22	**52.1**
				2. event (May 2013)				
obs	fine	63.67	0	1087.59	0	1023.93	0	87.1
9	**fine**	**182.53**	**+187**	**1222.32**	**+12**	**1039.79**	**+2**	**61.3**
10	**fine**	**160.09**	**+151**	**1289.38**	**+19**	**1129.29**	**+10**	**79.5**

Both simulations experienced more deposition than erosion during March 2013 event (Table 5 and Fig. 5). The greatest total erosion and deposition (m³) occurred at the beginning of th~~is~~e discharge event (Fig. ~~7~~5). However, the initial changes were

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slightly smaller when the default transverse slope was applied (simulation 10). The peak of channel bed changes occurred at the beginning of the moderate-magnitude discharge event, i.e. before the discharge peak. This implies to possible positive hysteresis phenomenon. Significant changes were observed in small peaks at 9h and 71h, which give an idea of the high system response to steep changes in the discharge, rather than a progressive increase (as seen in the absolute peak of 23h). The deposition in simulations 9 and 10 started very slowly decreasing after 13 hours, but the decrease in erosion was slightly faster. However, all in all, the deposition and erosion remained high for a long time and only started clearly declining after 71 hours, i.e. the secondary discharge peak. The erosion and deposition volumes followed the changes in receding discharge more faithfully than during the rising phase, occurring simultaneously to the changes in discharge. Thus, the morphodynamics of both simulations 9 and 10 followed the changes in discharge better during the falling stages of the discharge peak, i.e. when the discharge was 30 m³ s⁻¹ or less (Fig. 5). During the rising phase, there were temporal differences between changes in discharge and changes in deposition and erosion. When the default transverse slope was applied (simulation 10), the erosion and deposition continued to be high longer in the receding phase than when the transverse slope was increased to 3 (simulation 9). The great deposition amount during the receding phase was mainly due to the propagation of the bar lobe front.

When detecting the channel changes spatiallyD during this March 2013 moderate flow event from the whole simulation area (based on simulation 9, as an example), the channel evolved and bar lobes advanced on both sides of the large lateral bar, due to the diverted flows (B1 location of Figs. 1 and 2, and B in Fig. Figs. 4 6 and 86). However, the main flow and bar lobe movement occurred on the right bank side of the channel (B in Fig. 6) and diagonal bar aggradation took place downstream part of the study site. Both topographical observations and model simulations showed the development of the diagonal bar alongside with the cutoff of the bar (B). The model results showed that the initial cutoff and simultaneous initiation of the diagonal bar took place during the rising limb, more precisely the couple of first hours of the flood event (Fig. 6). However, during these first hours of the flood event, the changes in the river bed were local, and greatest elevation changes occurred especially in the bar lobe area, and right upstream of the large lateral bar B1 (A location in Fig. 6). Noteworthy is that the diagonal bar would not have developed to its full extent without the long receding phase of the flood hydrograph. Spatially, the most changes occurred throughout the whole simulation area during the 24 hours following the discharge peak, i.e. between 6ᵗʰ and 7ᵗʰ of March. The diagonal bar formation was slightly greater in the model outcomes than based on observations. Despite this, the model showed potential in producing the channel development following the established theories of gravel bed evolution. Similarly to the diagonal bar movement in the downstream part of the study site (B, Fig. 6), also further upstream another lateral bar (A, Fig. 6) experienced excavation on the right bank side, and the propagation of lobe movement downstream particularly after the discharge peak. Thus, throughout the study area the initial hours of the channel changes caused the selection of the flow and sediment transport routes where the most erosion would take place later during the moderate-magnitude discharge event.

In addition to the braiding structuredisplay of the channelgravel bars, i.e. alternating bars and pools, the river channel has also

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a broader meandering planform. The simulated area can be considered as one bend. The downstream lobe area locates downstream of the bend's apex, and the greatest erosion occurred during the lowering flood phase on the right bank side, which is the inner bank of the bend at the inlet area to the bend (A). This followed also the results of other meandering river studies about the erosion locations (Lotsari et al., 2014b). Thus, during the higher flow stages the flow routing and channel started acting more like in a meandering river, but during lower flow stage, such as during the initial rising flood stages, when not all of the bars were covered with water, the fluvial processes and related channel changes resembled more to braided channel development.

4.2 The evolution during low-magnitude discharge event

During the May 2013 discharge event, the hourly changes in erosion and deposition within the calibration area followed the discharge evolution more than during the March discharge event (Fig. 5). The discharge event of the May 2013 had two peaks, of which the latter discharge peak was greater. The erosion and deposition peak occurred approximately an hour after this greatest peak discharge had been reached. This implies to possible negative hysteresis phenomenon. Thus, the deposition and erosion peaks did not occur immediately at the beginning of the discharge event, as in the case of the March 2013 event. The erosion became greater than the deposition four hours after the beginning of the discharge event (simulation 9). Six hours after the sediment transport peak (at 25 h), the deposition dominated again. During the March discharge event, the erosion was never greater than the deposition. Note also that the discharge remained constant after both peaks, whereas a decrease in the deposition and erosion rates was observed (Fig. 5).

When detecting the whole simulation area (based on simulation 9, as an example), the main flow path was again on the right bank side of the channel, where the greatest changes also occurred during this low-magnitude discharge event (B in Fig. 6). The quick rise in discharge during the 1st hour and between 16th and 19th hours of this discharge event did not cause spatially great changes to the river bed, as most of the changes were within +/- 10 cm throughout the simulation area. Thus, the spatial morphodynamics of this low-magnitude event differed from the moderate-magnitude discharge event. The channel acted more like a braided river during this May 2013 low-magnitude event, as there was continuous small bed elevation changes throughout the event. Thus, there was not such clear high erosion or deposition periods, but continuous steady changes. The bar lobes progressed downstream, as the sediment was transported form the proximal side of the bars to their distal side.
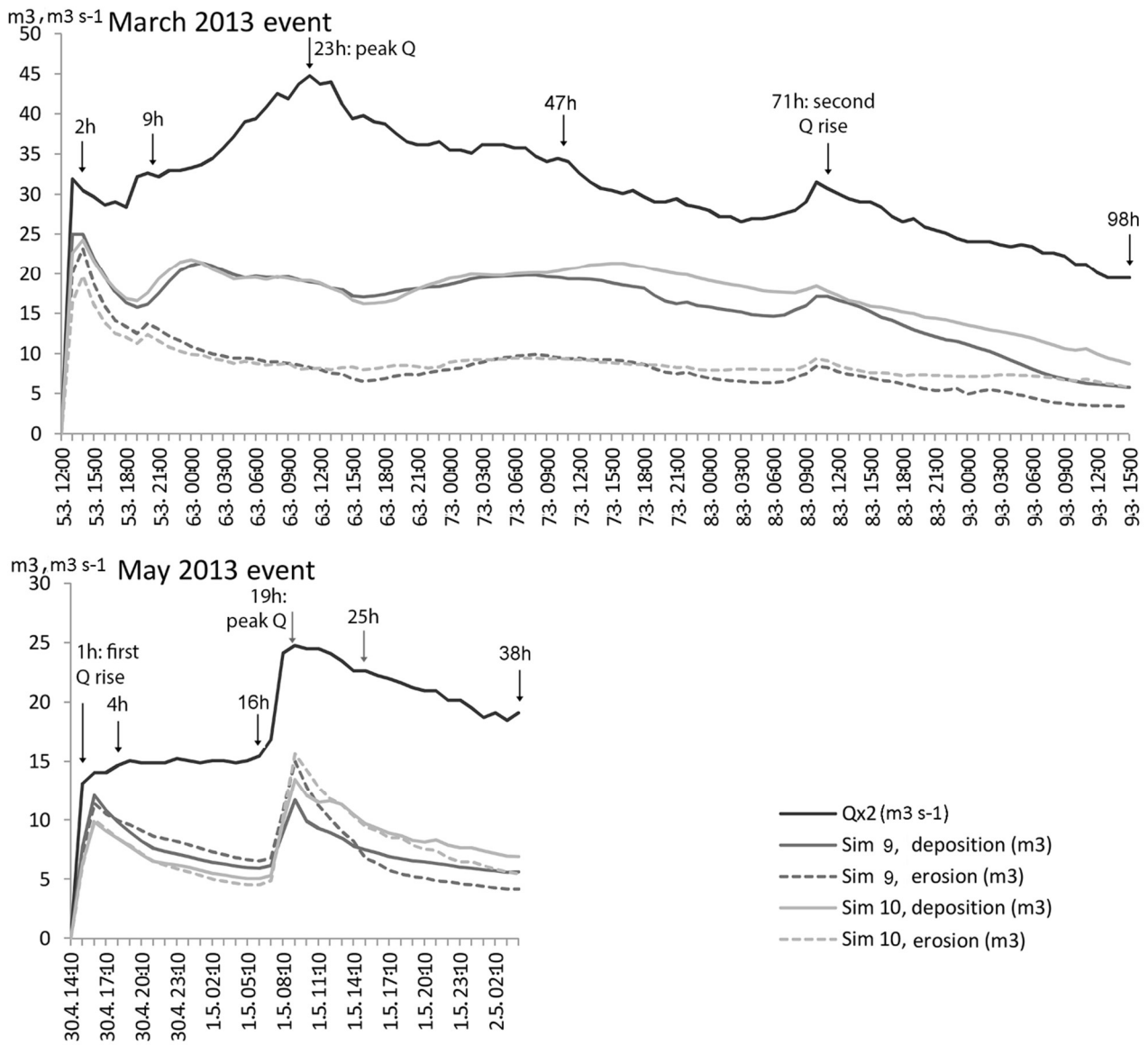
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Figure 5. The hourly volumetric changes during the moderate- and low-magnitude flow events of March and May 2013. The results are based on simulations 9 and 10. The graphs show the erosion and deposition from the beginning of the flow events (12:00 on 5th March and 14:10 on 30th April) until the time when the erosion and deposition had declined and levelled out during the receding phases. The key time stepas are pointed out as hours from the beginning of the flow events.
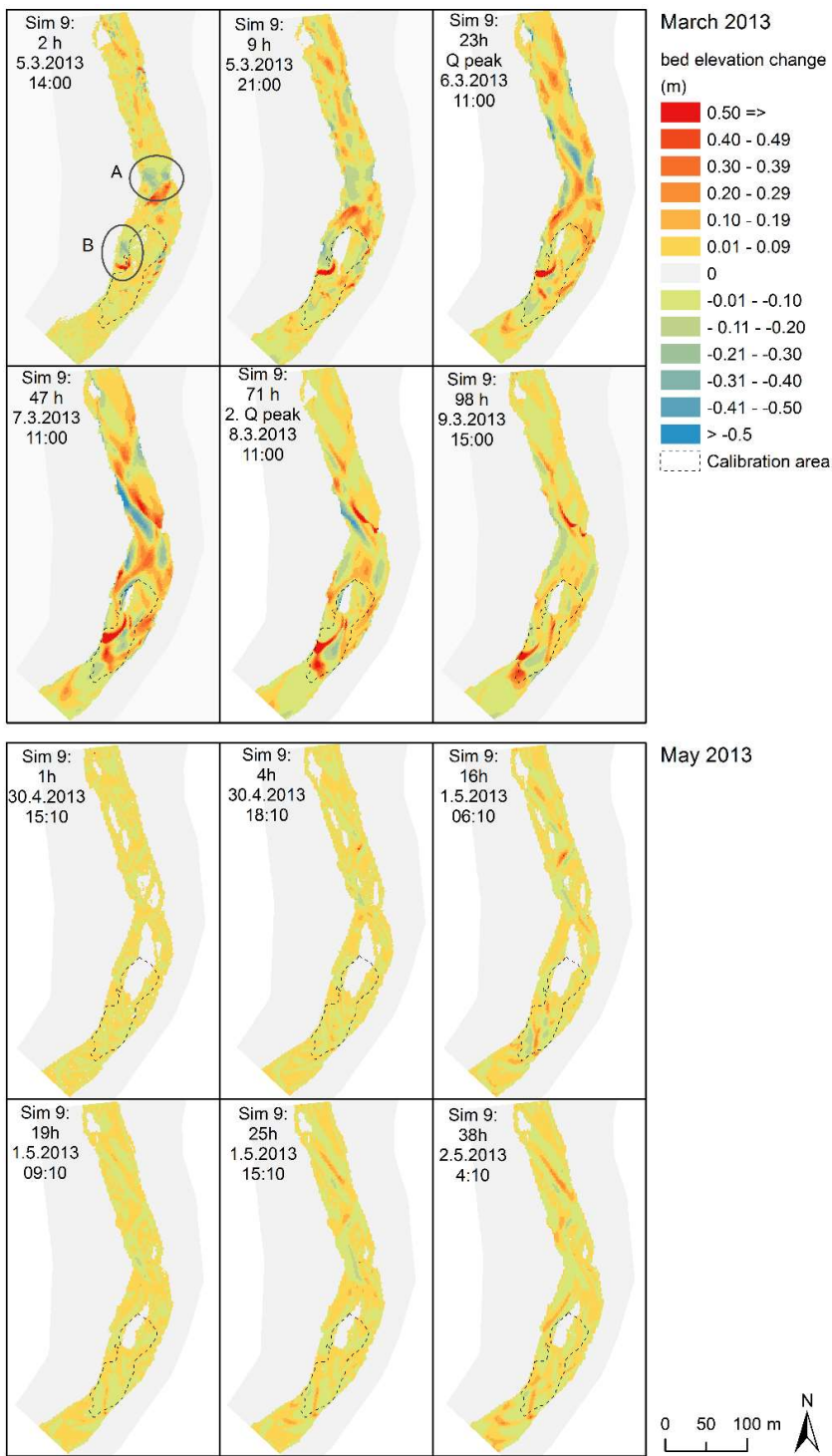
28

Fig. 6. The bed elevation changes between the key time steps of March and May 2013 events (cf. Fig. 5). The changes of the 5th March 2017 at 14:00 are from the beginning of the discharge event.
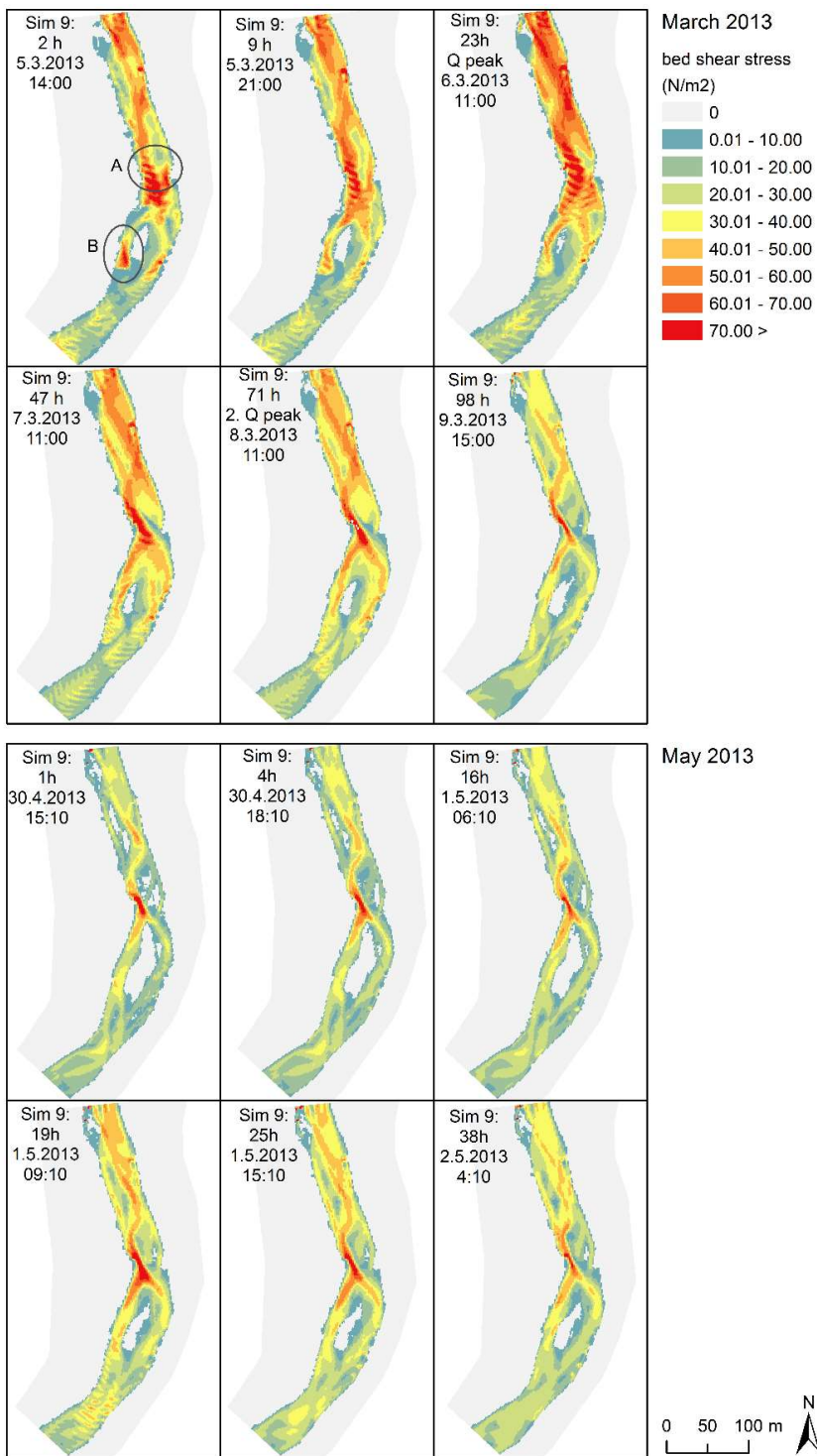
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Figure 7. The bed shear stress of simulations 9 during moderate and small discharge events. The key time steps are presented (cf. Figure 5).

4.3 The flow characteristics during the moderate and small discharge events

The bed shear stress (based on simulation 9, as an example) during the first hours of the March 2013 moderate-magnitude discharge event revealed that the bend apex (A in Fig. 7) and right bank side of the downstream lateral bar (B in Fig. 7) experienced the most fluid forces. These explained the locations of the greatest changes, and the initial cutoff of the lateral bar (B). Noteworthy is that these locations were the initial high erosion and bed load transport locations, but the high bed shear stresses occurred spatially more widely during the rising stage (9th hour) and the peak flow situation (23rd hour). Even though the changes in the river channel had been great between the 24 hours following the discharge peak (Fig. 6), the fluid forces (bed shear stress) had already started to concentrate on the thalwegs of the channel (Fig. 7). Noteworthy is that throughout the receding phase of the moderate-magnitude March 2013 discharge event the greatest shear stresses occurred mainly in thalwegs. Thus, the initial forces of the flood were greater throughout the channel area, but later concentrated on the channel routings formed by the initial stages of the flood discharges, particularly at right bank side at the apex (A) during the receding phase of the flood.

The spatial distribution of the bed shear stresses of the low-magnitude discharge event (May 2013) differed from that of the moderate-magnitude event (Fig. 7). Throughout the discharge event, the greatest fluid forces concentrated in the thalwegs, which had been formed by the preceding moderate-magnitude discharge event of March 2013. Particularly, it could be seen that the bed shear stresses were the greatest at the inner bank side at the apex (A), and then the main flow route was at the right bank side (B) in the lobes area. The greatest bed shear stresses occurred during the second rise of the low-magnitude discharge event, i.e. between 16 and 19 hours from the beginning of the event. Thus, similarly as revealed in Fig. 5, the transport followed the changes in discharge more during this low-magnitude May 2013 event than during the March 2013 event (Figs. 6 and 7).

5 Discussion

5.1 Uncertainties related to the simulations

The morphodynamic simulation of the ephemeral river provides a good quantification of the sequence of channel changes described by Calle et al. (2015). It also deepens the analyses done based on only the topographical data, and is the only way to gain concepts about topographical changes during the flash floods. The reliability of the model, which is calibrated against the events under interest, results improves can be improved with the quality and temporal density of the available calibration topography, i.e. between pre- and after post-flood bedform geometries. We had two high accuracy MLS topographical calibration data setsand one RTK-GPS topographical data sets, which is more than in many other studies. In recent studies done in perennial rivers, where topographical measurements have been sparse, the greatest 2D morphodynamic model uncertainties have related to the channel topographies (Sanyal, 2017). The high uncertainties in topographical measurements

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of sub-water areas in gravel bed perennial river have been related particularly to the high bed load velocities and temporal variability of bed load (Williams et al., 2015). However, despite the high quality data from two events at Rambla de la Viuda, we think that further research with multiple yet-to-come events needs to be run to assess the repeatability and validation of the model even better. For example, at Rambla de la Viuda, large floods have not yet occurred since the beginning of the MLS

5 measurement approaches. As also earlier has been stated (Verhaar et al. 2008; Lotsari et al., 2015), the roughenss conditions defined for small discharge events, might not be suitable for simulating extreme events. Therefore, the work and refinement of the model will continue, and the applicability of the model for larger floods will be tested, when validation data will be available.

10 -Transport rates (suspended and bed load) and flow ~~velocity~~ measurements, which are measured during the events for calibrating models of perennial rivers, ~~would be suitable to calibrate models during the event, but they are always~~are always difficult and dangerous to perform in this particular ephemeral river~~environment~~. ~~The uncertainties related to this have to be acknowledged. The uncertainties related to this have to be acknowledged.~~The uncertainties of the present model approach thus relate to the lack of sediment transport, flow and topographical data during the events. However, the selected initial boundary

15 conditions seem to be congruent with the flooding mechanisms of Rambla de la Viuda and also with other published works, i.e. Williams et al (2016b), for loosely consolidated sand and gravel. So, the modelled flow carried each sand sediment fractions (suspended) adapted to the local flow conditions at inflow boundary, and the model assumed that very little accretion or erosion was experienced near the model boundaries. Based on measurements, the presence of sand size particles and their concentration in the study site were also almost non-existent, and no channel changes occurred at downstream boundary of the simulation

20 area. Thus, this equilibrium load condition was considered valid, and it was also the only option for the present modelling approach, as no input suspended load measurements were available. Similarly as Williams et al. (2016b) state, the model results, i.e. the modelled deposition and erosion, when compared to observations, could have been possibly enhanced if the input suspended sediment load observations would have been available. However, according to Sanyal (2017) the sediment transport is always inherently approximate in nature, and sediment load added to the model causes uncertainties to the results,

25 despite detailed sediment load measurements have been used as model input.

~~However~~Despite this lack of the data during the flood events, ~~, as the forefront lobe prograded over a flat valley bottom (as gravel bed had been mined),~~ we had a good control on sediment volume and gravel particle-size moving downstream as the forefront lobe prograded over a flat valley bottom (as gravel bed had been mined). Total volume input and total transport rates

30 observed in earlier study of Rambla de la Viuda by Calle et al. (2015), had already proved the high availability of sorted gravel particles, and were the basis of the decisions made while building up the model. ~~In fact~~As already mentioned, the channel changes ~~bedload sediment output~~ at the output downstream boundary ~~from~~ of the ~~the~~ studied reach was zero. In addition, the simulation result supports the hypothesis of Calle et al. (2015) that moderate- and low-magnitude events reworked sediment locally within the reach. This means that these flows were not able to establish a sediment connection upstream, i.e. between

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larger reaches, and the transported sediment originated from the erosion of adjacent areas.

In addition, we were able to use a discharge and precipitation stations further upstream of the study area, and thus also a hydrograph with a known shape (cf. supplementary material). Sometimes only the high water marks are known, and for

5   example, Cao et al. (2010) analyzed the bedload transport by using a symmetrical hydrograph. This could be why their simulations showed less transport during the receding phase than ours. An et al (2017a, 2017b) and Viparelli et al. (2011) had raised the issue related to the cyclic hydrographs and hydrograph boundary layer (HBL), which defines the spatial region within which riverbed topography and grain size respond to the hydrograph. They state that the HBL causes problems, if the material is poorly sorted. The calibration area of the present study was in the downstream part of the simulation area, i.e.

10 outside of the influence of the possible HBL. The gravel of Rambla de la Viuda was well sorted and also therefore we can state that the HBL was not an issue for the calibration of our model.

As the curvilinear g~~rii~~rids of fine 0.76–3.03 m and coarse 1.51–5.01 m cells were tested for morphodynamic simulations, the

15 finer grid was proven to better predict the channel evolution, including both flow and bar lobe movement paths. Fine grids of circa 3 m in length have been also found by Williams et al. (2016b) suitable for Deflt3D model applications. Furthermore, the grain sizes and their spatial distribution affected the morphodynamic simulation results greatly.~~–~~ Hooke et al. (2005) have shown that grain sizes have a major effect on the morphological impacts of floods. Simulation results may be enhanced when using techniques that are able to obtain spatially more complete and detailed grain size data (~~such as~~e.g. Wang et al., 2013)

20 from the surface layers, instead of lower resolution site sampling~~,~~ such as Wolman method. Earlier studies have ~~Parker (1990)~~ stated that a calculation of the bedload transport rate of mixtures should be based on the availability of each size range in the surface layer (Parker, 1990), and that during the calibration of Deflt3D model uniform sediment cannot be an acceptable assumption to study the long-term response of natural gravel-bed braided rivers (Singh et al., 2017). The best simulation results of Rambla de la Viuda were indeed gained when spatially varying upper surface layer sediment sizes were applied. However,

25 further ~~detailed~~ analyses of spatial and vertical grain size distribution effects on ephemeral gravel-bed river ~~morphodynamic~~ simulations are suggested. Next step should be to apply the surface grain size variation derived from the laser scanning data ~~sets~~ (Casas et al., 2010a and b; Kukko et al., 2015).

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~~According to Kasvi et al. (2014),~~ The patterns of channels, bars and braiding properties are highly sensitive to the bed slope parameterization, and particularly transverse slope~~the transverse bed slope parameterization~~ affects the sediment transport ~~in the downslope direction particularly~~ in long-term simulations (Schuurman et al., 2013; Kasvi et al., 2014; Singh et al., 2017)~~.~~. ~~However, a~~Also during these rather short-term flood event simulations at ~~gravelly~~gravel bed Rambla de la Viuda, the effects

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of the increasing transverse slope on channel evolution was evident, and the simulation results resembled more the observed topographies. Kasvi et al. (2014) had noticed that ~~the model run with~~the ~~a~~higher ~~the high~~ transverse bed slope effect (i.e. value 3) was, ~~the predicted~~ more filling of ~~the~~ pools occurred in an meandering river~~, when compared with the model run with no transverse bed slope effect~~. Similarly to Kasvi et al. (2014), the pool area of Rambla de la Viuda ~~had~~ experienced more

5   deposition with the increased transverse slope value (Fig. 4). This pool area was the only clearly wrongly simulated location ~~with this higher transverse slope value, but otherwise the lobe movement and elevation resembled the best to the observations~~, when this high transverse slope value was applied, but otherwise the lobe movement and elevation resembled the best to the observations. Thus, in a gravel bed river with short lasting flow events, adjustments are clearly needed in this parameter for being able to replicate the observed changes while simulating with the currently available sediment transport equations. Thus,

10   similarly to the perennial river simulations (e.g. Kasvi et al., 2014), the transverse slope was important for the simulated changes.

~~Earlier, Hooke et al. (2005) and Graf (1996) have applied the Bagnold equation to an ephemeral channel, but we wanted to use the equations that have often been used together with the Delft 2D model.~~ ~~Reid et al. (1996) showed that the Meyer-Peter~~

15   ~~and Müller (MPM, 1948) equation, which was originally developed for steady flow conditions and used by Reid et al. (1996) in non-armoured gravel bars, performs well and better than the Bagnold (1980) and Parker (1990) equations in ephemeral gravel river channels.~~ Despite the ~~This justified the application of the~~ MPM equation had earlier been successfully applied in ~~the~~ ephemeral ~~gravelly~~gravel bed ~~Rambla de la Viuda.~~rivers ~~Reid et al. (1996) stated that the reason for this is partly due to the fact that sediment was not supply-limited by channel-bed armour development~~ (Reid et al., 1996)~~, which is the case in~~

20   ~~many perennial rivers, the~~ . However, the movement was minimal ~~with the MPM equation~~ in Rambla de la Viuda and occurred only in the beginning of the moderate event. ~~The second discharge event could not cause much movement with the MPM equation, even though movement had occurred based on the field measurements.~~ The transport rate is imposed as bed-load transport due to currents in both EH and MPM equations, which are used in Delft3D-FLOW. The MPM is more advanced than EH as the MPM includes a critical shear stress for transport (Deltares, 2011). However, this could be one reason for less

25   movement, if critical stresses for transport required in MPM equation did not exceed during the lower discharges of the hydrographs. According to Barry et al. (2004) the formulae containing a transport threshold typically exhibit poor performance when compared to the observed gravel bed river's bed load data. These equations include MPM (1948) and Bagnold (1960) equations, which have been applied in ephemeral channels. In addition, Singh et al. (2017) state that during variable discharge conditions, the MPM formula can not produce the braided river pattern because MPM is not suitable if the value of the Shields

30   parameter falls outside its applicability range. These above mentioned could explain, why ~~The MPM equation is a deterministic equation. According to Van Rijn (1993), in a strongly decelerating flow, the deterministic formulae do not give realistic results because the mean bed-shear stress approaches zero in the case of flow separation and reattachment, and thus sediment transport also approaches zero. This may have happened in the Rambla de la Viuda, as~~ the MPM equation did not move particles ~~anymore~~ during the lower discharges and during the receding phase of the hydrographs of Rambla de la Viuda, where flow is

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temporally highly variable. The application of the ~~deterministic~~ MPM equation could also partly explain why the receding phase's transport was less ~~according to~~in the study of Cao et al. (2010), than based on the present study. Despite being unable to produce the correct morphodynamics caused by the moderate- or low-discharge events of Rambla de la Viuda, the MPM equation could have potential in the simulation of greater floods of ephemeral gravel bed rivers, similarly as Reid et al. (1996)

5 and Cao et al. (2010) have shown. However, further research on this matter should be done also with higher discharges at the river reach.

Engelund and Hansen (1967) developed their equation, so that the effects of dunes, e.g. transport from stream-side to lee-side and form drag, were included. This could be the reason why the EH worked the best at the Rambla de la Viuda, where clear

10 sharp lobe edges occur, and the local slope varies a lot. In addition, the EH is a total load equation (Engelund and Hansen, 1967), whereas, for example, the MPM equation calculates bedload. ~~Meyer-Peter and Müller (1948) equation applies an energy slope, which, for example, Van Rijn (1984) has stated not to be an appropriate parameter for morphological mathematical modelling. The disadvantages of the use of the energy gradient may be according to Van Rijn (1984) the variations due to non-equilibrium phenomena of rising and falling stages. This could partly explain why the EH worked better than the MPM in this~~

15 ~~ephemeral river.~~
There are no universal sediment transport formulas, which can cover all coarse sediment transport conditions from low discharges to peak discharges (Li et al. 2016; Singh et al., 2017). The grain sizes, which had been moved by the 2013 discharge events, were on the upper limit of the available sediment transport equations. Also a matter of further research is to detect, whether the transport equations would able to move the sediments at higher discharges, if in reality the higher discharges

20 would possible transport even larger sediment particles.

~~According to Barry et al. (2004) the formulae containing a transport threshold typically exhibit poor performance when~~

25 ~~compared to the observed gravel bed river's bed load data. These equations include MPM (1948) and Bagnold (1960) equations, which have been applied in ephemeral channels. Barry et al. (2004) noted that simulation results done with different sediment transport equations show substantial differences in performance, but no consistency has been found between equation performance and the complexity of the equation. Despite being unable to produce the correct morphodynamics caused by the moderate- or low-discharge events of Rambla de la Viuda, the MPM equation could have potential in the simulation of~~

30 ~~greater floods of ephemeral gravelly rivers, similarly as Reid et al. (1996) and Cao et al. (2010) have shown.~~

~~Engelund and Hansen (1967) developed their equation, so that the effects of dunes, e.g. transport from stream-side to lee-side and form drag, were included. This could be the reason why the EH worked the best at the Rambla de la Viuda, where clear sharp lobe edges occur, and the local slope varies a lot. In addition, the EH is a total load equation (Engelund and Hansen,~~

1967), whereas, for example, the MPM equation calculates bedload. Meyer-Peter and Müller (1948) equation applies an energy slope, which, for example, Van Rijn (1984) has stated not to be an appropriate parameter for morphological mathematical modelling. The disadvantages of the use of the energy gradient may be according to Van Rijn (1984) the variations due to non-equilibrium phenomena of rising and falling stages. This could partly explain why the EH worked better than the MPM in this ephemeral river.

However, despite the challenges of applying morphodynamic simulation approaches to ephemeral river channel change analyses, the results are promising, and show the importance of both rising and receding phases. The observations of sediment transport during flow hydrographs would still be important, in addition to the continuous time series of pre- and post-flood topography, but at the moment, their measurement is still a complex and risky issue. By continuing the long-term observations of the ephemeral channel changes with the high-precision equipment, more reliable calibration and validation of the models may be gained.

5.2 Moderate- and low-magnitude flow events as channel modifiers

Our study has shown that geomorphic responses in ephemeral rivers, such as Rambla de la Viuda, to the twoare unique to each analysed discharge events differed., and the model needs to be calibrated based on consecutive discharge events, and not just one event. Previously this uniqueness to of the geomorphic response has been shown for perennial rivers (Pitlick, 1993), where also topographical and sedimentary data has been applied as initial conditions. The methods and conceptual results of this present study can be applicable in ephemeral rivers worldwide (e.g. USA, House and Pearthree, 1995). Hooke (2016a) stated that the flow events of similar magnitude can have differing effects, depending on the state of the system, as the long-term evolution of the ephemeral river channel and its material greatly influence the response to the stream flow. Some events are more erosional and some are more depositional (Hooke, 2016a). Moreover, Hooke et al. (2005) noted the importance of simulating and analysing the feedback effects of consecutive events. At Rambla de la Viuda, the riverbed morphology formed by the March 2013 influenced the later channel changes during the May 2013 flow. For example, the flow was diverted to the right bank side during the first flood (of March 2013), which also therefore acted as the main channel for the May 2013 flow, which was lower in magnitude.

The model was calibrated based on the observations before/between and after the discharge events, because it is knowingly impossible to measure during the risky flash flood events, albeit moderate and low in their magnitude. Therefore, the following discussion is purely based on the model outputs.

The simulation results of the Rambla de la Viuda showed that the differences between rising, peak and receding phases of a

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moderate-magnitude discharge event are very important in an ephemeral river environment. Higher total amount of channel changes occurred during the receding phase than at the early stages of the discharge events. Deposition dominated due to the progradation of the frontal bar lobe, particularly on the right bank side of the channel. Thus, the continuous channel changes were similar to those for braided perennial rivers (Lotsari et al., 2014a). However, the channel changesis differeds from a recent study of Gendaszek et al. (2013), who studied the gravel perennial riverbed changes during moderate- (65 m³ s⁻¹) and high-flow (159 m³ s⁻¹) events. They found that most erosion occurred during the rising and the peak flow phases, but did not mention great changes during the receding phase. .They found only some scour during sustained high flows following the flood peak (Gendaszek et al., 2013). Noteworthy is that they applied one sensor per reach, and thus the site selection could have greatly affected on their results.

Ferguson stated already in 1993 the potential in numerical modelling of the coupling between geometry, flow, and bedload transport, if it can be applied successfully for the braided channels. The results were promising at Rambla de la Viuda, which also has a braided pattern. According to Wheaton et al. (2013) the chute cutoff mechanism, already described by Ferguson (1993), is the most common braiding mechanism, but that the cutoff is not only an erosional process, but more the result of deposition during the construction of diagonal bars. In the our study area of ours, there was a situation resembling to chute cutoff, as the channel was cut more on the right bank side of the bar than before. The modelling was capable in producing this observed chute cutoff from the right bank side during the moderate discharge event (March 2013). The high values of bed shear stresses related to this initial chute cut off (B location in Figs. 6 and 7). Both erosion and deposition related to these changes, as both topographical observations and model simulations showed the development of the diagonal bar alongside with the cutoff of the bar. However, the diagonal bar formation was slightly greater in the model outcomes than based on observations. Despite this, the model showed potential in producing the channel development following the established theories of gravel bed evolution. In addition, the model showed that the initial cutoff and simultaneous initiation of the diagonal bar took place during the rising limb, but the diagonal bar would not have developed to its full extent without the long receding phase of the flood hydrograph. Williams et al. (2015) had found that the choking is the main process for braiding development in their studied perennial river. However, we were not possible to observe choking processes within our study reach. Further analysis of this braiding process are needed to perform from longer river reaches of ephemeral rivers.

In addition to these braiding processes, the fluvial processes at higher discharges resembled more the ones in a meandering river bend. The greatest erosion and bed shear stresses occurred on the right/inner bank side at the inlet area of the bend (A in Figs. 6 and 7) during the peak and receding flood phases of the moderate-magnitude (March 2013) event. This followed also the results of the erosion and high velocity core locations of perennial meandering rivers (Dietrich and Smith, 1983; Lotsari et al., 2014b). However, during lower flow stage, such as during the initial rise of the floods and the whole May 2013 discharge event, the spatial distribution of channel changes resembled more to braided channel development. Therefore, the

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morphodynamics of the low-magnitude May 2013 event differed from the preceding moderate-magnitude discharge event. During May 2013 low-magnitude event, there was continuous steady small bed elevation changes throughout the event. Noteworthy is, that throughout the receding phase of the moderate-magnitude March 2013 discharge event and the whole May 2013 event, the greatest shear stresses occurred mainly at the channel routings formed by the initial stages of the moderate-magnitude flood discharges.

Noteworthy is that during the moderate-discharge event the erosion and deposition peak occurred much earlier than the discharge peak. However, the low-magnitude discharge event experienced the greatest channel changes an hour after the discharge peak. Our model results (e.g. Figs. 7 and 8) suggest the possible existence of hysteresis in the rate of bedform changes, being clockwise or positive in the case of moderate-magnitude flow (bedform change peak occurs before flood peak), and negative in the case of low-magnitude flow (bedform change peak occurs during/after flood peak). The hysteresis phenomenon has been described well in sediment transport studies, and their effect is due, among other factors, to sediment depletion or surface gravel consolidation in the channel (Reid et al., 1985) or a long-lasting portion of the baseflow during the recession limb (Walling, 1974). Cao et al. (2010) have shown, based on their 1D simulations, that bedload transport in an ephemeral river can have similarities to a perennial river. However, even though perennial rivers may have sharp rising phases in their discharge hydrographs (e.g. Long, 2009), they more likely have a greater initial threshold for particle movement by bed-armouring than ephemeral rivers (Reid et al., 1996; Hassan et al., 2009). Although, their armouring can though decrease as bed load concentrations increase (Müller and Pitlick, 2013). Hysteresis of both kinds have also been shown in perennial rivers regarding turbidity, but their flashy storm hydrographs have more often caused anti-clockwise (i.e. negative) hysteresis phenomenon (Lloyd et al., 2016). This would indicate that ephemeral rivers act more similarly to perennial rivers during their low magnitude flow events. Even though further research is needed, the results indicate that the greater the discharge event's magnitude in an ephemeral river is, the more different the channel evolution and its timing are compared to perennial braided gravel bed rivers.

These hysteresis phenomena show a time dependence on the fluvial system outputs, depending on a previous sediment transport size and gravel bar morphology, which affects the internal state and the future morphodynamic response. In our study reach, 30 m^3 s^{-1} was the threshold discharge for the channel changes to become gradual and to follow the discharge changes during the receding phase. According to Hooke (2016a), the threshold values of hydraulic conditions for erosion and deposition in ephemeral channels vary between sites, mostly due to the size and nature of the bed material. Threshold discharge has been observed to be for the deposition and erosion of 15 mm particles 35 m^3 s^{-1} and 1 m^3 s^{-1}, respectively, and of 50 mm particles 14 m^3 s^{-1} and 40 m^3 s^{-1}, respectively (Hooke, 2016a). The average upper and sublayer D$_{50}$ grain sizes at the Rambla de la Viuda were 26.3 mm and 17.1 mm, respectively, and the maximum D$_{50}$ grain size was 40.2 mm. The discharges of the Rambla de la Viuda were overall within the ranges of Hooke's thresholds for the movement of these-sized particles, and the simulations clearly showed their transport. In addition, the threshold discharge of 30 m^3 s^{-1} for starting the channel changes of the Rambla

de la Viuda to follow the discharge changes during the receding phase coincide well with Hooke's (2016a) threshold analysis of deposition. However, the threshold could be also site dependent, such as for Spanish Mediterranean region, where both Hooke et al (2016a) and the present study have been performed.

5 **6 Conclusions**

A 2D morphodynamic model was successfully implemented for inferring the ~~Due to the proven~~ morphological changes caused by ~~low and~~ moderate- and low magnitude discharge events. The morphological starting and final conditions were derived from high-resolution laser scanning topography, bedform mapping and sediment texture analysis of both surface and
10 subsurface layers on the main morphological bars and channel units. The flow hydrograph was based on a continuous (5 min) record from an upstream gauge station, which was re-scaled to the peak flow estimated at the study reach based on flotsam evidences. The model parameters were calibrated to best fit the pre-and post morpho-topographic field evidences. ~~, the preventive measures against flash flood-induced channel changes should take into account moderate- and low-magnitude flows. This has received support from earlier studies (e.g. Hooke, 2016a and b). As the receding phase can cause substantial channel changes, it plays a major role in inducing damages/modifications to the river environments, and it needs to be~~
15 ~~acknowledged while planning flood mitigation measures. We have demonstrated the feasibilitygoodness of 2D implementation of modelling for analysing ephemeral river channel changes.~~ The following ~~schematic concepts can be concluded~~conclusions can be made about the morpho- ~~and hydro~~dynamics ~~and their simulations in~~in an ephemeral river during moderate- and low-magnitude discharge events:

1) The 2D implementation of morphodynamic ~~2D~~ model was proven to work during moderate- and small-magnitude flash
20 flood events in an ephemeral river ~~affected by flash floods. Instead of applying calibration data from only one discharge event, the model results can be enhanced by applying topographical pre- and after flood data from consecutive flood events.~~ The spatially varying grain size data, the applied transverse slope parameter value, ~~and sediment transport equations~~and the streamflow hydrograph were ~~are t~~the most important factors affecting the ~~, apart from the quality of recorded discharge, for the~~ simulation results of the bedform and channel evolution. The selection of sediment transport equations was also critical to
25 match the sediment mass-balance, concluding that the total load equation (Engelund-Hansen, EH)~~],~~ ~~worked the best.~~ When modelling events of moderate and low magnitude in ephemeral rivers of 50 to 100 meters wide, a resolution of at least 1m is recommended (i.e. one cell is 1–2 % of the total width)~~. At Rambla de la Viuda, the curvilinear grid with mesh edge lengths of 0.76–3.03 resulted topographically more realistic outcomes than with coarser grid of i.e. grid size 1.51–5.31 m. A coarser resolution results in incorrect flow and sediment transport routing, as the edges of the bar lobes are smoothed, which affects~~
30 ~~simulation of water level, hydraulics and bed form evolution,~~ because it is ~~. The finer grid was~~ able to show the steep lobes forefront scarp ~~and showed that laser scanned data is the way to produce the detailed scale topography for simulating the bar lobe movement. Otherwise, procedures would need to include manual modification of the topography to include the lobe~~

~~edges.~~

2) <u>M</u>~~2D~~ morphodynamic models can ~~be a good approach for~~ shed~~ding~~ light on the ~~temporal evolution of channel evolution~~<u>channel evolution</u> during flash flood events~~, as measurements during flash floods are risky to perform. With simulations it is possible to improve and deepen the analyses earlier made based on only the survey work or hydrodynamic modelling, as it is possible to analyze whether the greatest changes occur for example due to the peak discharge, the slope of the rising limb, or the length of the receding limb of the flood hydrograph.~~

~~3) The spatially varying grain size data, the applied transverse slope parameter value and sediment transport equations are the most important factors, apart from the quality of recorded discharge, for the simulation results of the channel evolution. The total load equation worked better, compared to the deterministic equation.~~

~~4)~~ Both rising and receding phases of discharge events were predicted to be important for bar movement and channel evolution and thus should not be ignored while planning flood mitigation measures. The erosion and deposition can be greater during the long-lasting receding phase than at the rising phase of moderate- and low-magnitude discharge events, despite the typical hydrograph shape of a flash flood. The receding phase contributed also greatly on the shaping of the bed forms and channel pattern.

3<u>5</u>) The deposition and erosion peak rates <u>we</u>~~a~~re predicted to occur at the beginning of the moderate-magnitude discharge events (e.g. March 2013 ~~event~~), whereas deposition dominate<u>s</u>~~d~~ throughout the event, i.e., even during the rising phase. On the contrary, the low-magnitude discharge event~~s~~ (e.g. May 2013 ~~event~~) only experience<u>d</u> the greatest channel changes after the discharge peak.

4<u>6</u>) These different predicted erosion/deposition patterns suggest <u>that the timing of the channel change peak, compared to the timing of the discharge peak, differs between different magnitude discharge events.</u> ~~a hysteresis effect on the morphodynamic changes,~~ <u>These</u> ~~closely related to sediment transport rates, and~~ stress the importance of previous flood history (timing, succession and magnitude) in understanding the geomorphic response of ~~gravelly~~<u>gravel bed</u> ephemeral rivers. <u>The peak of channel changes during the moderate flood occurred before the discharge peak. On the contrary, the low-magnitude discharge event experienced the peak of channel changes after the discharge peak, suggesting a rupture of upper layer before sediment was moved. These differences between the events were at least evident with these two events and the applied parameterization. However, further studies of this possible hysteresis effect are needed from multiple discharge events.</u>

<u>5) The results showed that the fluid forces of the initial stages of the moderate-magnitude discharge event caused the initiation of chute cutoff and diagonal bar formation, and defined the flow routing of the rest of the moderate magnitude discharge event. The flow during the following low-magnitude discharge event followed these same thalwegs caused by the preceding moderate-magnitude event.</u> ~~r~~

6<u>7</u>) The clearest difference in the predicted riverbed changes between the rising and receding phases <u>wi</u>~~se~~re that erosion and deposition characteristics follow<u>ed</u> the temporal discharge changes more during the receding phase than during the rising phase. The threshold discharge, below which the channel-bed changes started following the discharge changes temporally, was around 30 m^3 s^{-1}. <u>Noteworthy is that this ephemeral channel acted like the braided river channel during these lower flow</u>

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conditions, but when the bars were submerged in higher discharges the high fluid forces followed the meandering river planform of Rambla de la Viuda. Thus, there were different fluvial processes working at different flow stages, particularly during the moderate-magnitude discharge event.

6**7**) ,P the preventive measures against flash flood-induced channel changes should take into account moderate- and low-magnitude flows. This has received support from earlier studies (e.g. Hooke, 2016a and b). A as the receding phase can cause substantial channel changes, it plays a major role in inducing damages/modifications to the river environments, and it needs to be acknowledged while planning flood mitigation measures.

This threshold should be further tested in other ephemeral channels in Mediterranean, and elsewhere.

Data availability

The data has been stored in the universities of the authors. We have provided the initial geometry, calibration area delineation, sedimentary data (2014 samples) and final topography from the calibration area as supplementary material. Due to the great size of the data,Because some of the data was gained from third parties, we are not able to provide the whole model as open access data. Data those can be also accessed by request from the authors. Each request will be processed separately.

Author contribution

Lotsari has done most of the writing and all of the model simulations. Calle and Benito have been also greatly contributed in the writing of the paper and have enabled the study with their projects, as they have initiated the studies of Rambla de la Viuda. All the other authors have contributed to the writing process by commenting the manuscript and its content. All authors have contributed in collecting the field data. Laser scanning has been done by Kukko, Kaartinen, and Alho. The laser scanning data has been processed by Kukko and Kaartinen. Hyyppä J. and Hyyppä H. and have contributed by providing funding for the study and they have also worked on the development of the laser scanning approaches. Benito, Calle and Lotsari have measured the sedimentological data. GPS measurements of topography and high water marks have been done by Benito and Calle.

Competing interests

The authors declare that they have no conflict of interest.

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