Interactive comment on "Late Holocene channel pattern change from laterally stable to meandering caused by climate and land use changes" by Jasper H. J. Candel et al. Anonymous Referee #1 Received and published: 11 June 2018

I read a manuscript in a very well defined shape. The language, organisation, amount of references and overall quality is high and if the figures can be polished/optimised, the technical part will be of very good quality. I consider the topic of the study timely, relevant and well placed in the scope of the journal. The methods appear to be mostly adequate and thoroughly described. I especially welcome the general attempt to account for the uncertainty inherent to several of the inferred parameters, although there are further uncertainties that should be added to reach a more comprehensive capture of the total model uncertainty.

Many thanks for your kind words and enthusiasm about the manuscript, and your critical review, adding very valuable suggestions. We will re-evaluate the chosen uncertainty for the parameters and add additional uncertainties where possible. Please find these details further below.

Technically, I find the use of dotted and dashed lines in many of the figures disturbing. They make it sometimes very difficult to actually see the data that is to be visualised. For example in fig. 10C the dashed lines obscure the course of the data almost completely. Please think of reworking most of the dotted and dashed lines. In many cases they are not needed to make a distinction in the plots.

We agree and changed figures according to suggestions.

I strongly encourage the author(s) to provide along with the study also the code and data they used to generate their results. This would make it possible to reproduce their work and also increase the impact of the study. I have not doubt about the validity, rigour and correctness of the material but without seeing it I can hardly judge these points. Beyond that, readers of the paper will be happy to already have a starting point to proceed with if the code and data were presented along with the article.

We will add a sheet with all the calculations that have been done, so that the reader can start very fast from there with their own calculations. We will also include our own used data in the spreadsheet as an example and a verification.

I had the impression that there are some sections that are too inflated with information and detail, much more than what is actually needed to support the statements they are about to make. For example, the study area section, especially the restoration part, is interesting to read but very detailed, as well. Please consider restricting the content to what you essentially need to support your methods and the subsequent discussion/interpretations. Likewise, there are results reported in great detail that are not used to a reasonable extent, any more. The classic example for this is section 4.1. Such details may become part of supplementary materials but unless you need this for the discussion, it is not needed in the scope of the manuscript.

We removed the section on restoration from the second chapter, also suggested by the other reviewer. Lithogenetic interpretation was moved into a table (as suggested by the other reviewer), including most important details. The manuscript has been shortened by ca. 3500 words, removing all repetitions, abundant results and discussions, in agreement with the three reviews.

The abstract is mostly clear and gives a good overview of the topic and the main findings and their interpretations. It should however shed some more light onto the most detailed part of the study: the development and application of the calculus to describe hydrologic parameters and channel metrics.

We added more detail on the reconstruction of the hydrological parameters and rephrased the potential causes part of the little ice age and peat reclamation.

The introduction is well organised and follows a consistent flow of context. The references might imply that it is almost exclusively Dutch scientists that have worked on that topic. If that is the case, fine. If not, it might be good to also present adequate references from other regions. But this is just a suggestion that may help improving the manuscript.

There are indeed some examples of Dutch cases (De Moor, Vandenberghe, Kasse, Hobo), but also many examples of non-dutch case studies in the 3th and 4th paragraph (Lewin, Slowik, Lespez, Notebaert and Verstraeten, Hoffmann, Kondolf, Piegay, etc.)

The scope of the study as expressed at the end of the introduction is not a good match with what I read later on. The actual study goes way beyond the short summary of "detecting channel pattern change" and "identifying causes". Please give more details about the approach, as well. The field and especially the numeric work is a considerable and innovative part of your work and should be reflected by the scope definition.

We sharpened the aim and focused more on the methodology of the palaeohydrological reconstruction in the introduction. We removed the aim of identifying the causes, but will only shortly elaborate on the potential causes in the discussion. So we put the focus more on the reconstruction than on the identification of the causes.

Concerning the second part of the scope ("identifying causes"), this part is not ideally resolved, neither by your data nor by the discussion. In the latter part, you mainly cite other people's work and make a proposition that the Little Ice Age meteorological conditions and/or land use changes have had an influence on the observed/modelled results. But you do not and cannot easily go beyond this general statement. So maybe this part of the scope should not be a central goal?

We agree and changed the scope, also in line with the other reviewers. We now focus more on the identification of the channel pattern change and methodology. See previous comment

The study area description is fine, though in parts a bit too long. Please see detailed comments.

We removed the section on river restoration from the study area description.

The field methods description is in most cases conclusive and well understandable. See detailed comments below for some adjustments.

Thanks

The calculus description is less consistent. I acknowledge the idea of accounting for parameter uncertainty. But this must be done comprehensively and with justification. For several parameters there are either no uncertainties given or they appear out of the blue. See details below.

We changed this and gave a better reasoning for each parameter on its uncertainty in the method section.

The order of the equations does not match the order in which the text refers to them. So either re-order the equations or tweak the text to match the equations.

Checked and changed

The Chezy coefficient was assumed/estimated by several approaches. This is fine but in the discussion the average of all these approaches was used as the most likely value. I do not see a justification for this attempt. Are all these approaches equally likely or equally valid? If not, how and why was the final average coefficient value estimated?

We agree and we changed the approach. In fact, Brownlie uses variables that are known, and of which we can vary the uncertainty. However, Manning is a subjective estimation of what the river looked like in the past. We changed the approach and only use the Brownlie, and we will compare the calculated Chézy value with values known from rivers of similar size and with similar river pattern.

Overall, sections 3.7 – 3.11 introduce a large set of assumptions and equations/models. These are not well reflected in the introduction and scope of the manuscript. So, do you really need all these models to make your points and interpretations, or the other way around, are your research questions adequately addressed in the beginning to prompt such a large set of concepts and models?

We understand the confusion, thanks. We changed the research questions accordingly. In fact, after we have identified the channel pattern change, we identify which parameters have changed, and we used the empirical models to test whether they can explain the channel pattern change.

The set of parameter values were sampled and computed 200 times in a Monte Carlo approach. Are you sure that 200 MCMC runs are enough to cover the effects of variability adequately enough? From my experience with models that contain way less parameters I always needed much longer Markov chains to reach stable uncertainty estimates. Can you show that 200 is ok? Or have a test of convergence with number of model runs?

We checked this, and raised the computed runs to 10.000 times.

The results are mostly well presented. However, section 4.1 gives a very detailed picture of the lithology that is not used later to an extent that would justify this detail. I suggest to move this section to the supplementary materials to keep the story of the manuscript tight enough to be followed easily. Alternatively, make better use of the details in the discussion.

Lithogenetic interpretation was moved into a table (as suggested by the other reviewer), including most important details. This section is important, because it is the fundament of the palaeohydrological reconstruction in which the palaeodimensions are derived from the cross-sections. Hence, the interpretation of the lithogenetic units is an important element in the manuscript

The discussion sections should be reorganised to be more logical. I suggest to focus on time and not necessarily flow of context. You can/should start with the "laterally stable phase", then "channel pattern change", then "meandering phase", then "channel pattern reorganisation". This would keep the chain of information much more concise. You can implement sections like 5.2 into this system. I would also suggest to shorten section 5.5 considerably and have it as a conclusion theme. See details below.

We agree and followed the suggestions. We reorganised the discussion according to the suggestions. We included the " channel pattern reorganisation" into the meandering phase. We removed section 5.5.

Sections 5.2.1 and 5.2.2 are very detailed but mainly bring together findings from other studies, focusing on potential impacts of climate change and land use change. Please shorten and condense it to what you actually need to support your findings. It would be much more appropriate to have these two sections organised together with section 5.2 (causes of channel pattern change) but also to make more links to your actual results. Actually, it is not really possible to disentangle the effects of "Little Ice Age weather" and "land use change" from your data situation. It can be either or both that may have drive your system of channel pattern change. Please mention this issue. It is no problem to have the effect of both.

Agree, and merged this part with section 5.2. In addition, we shortened this part. See previous comment

P 1, l 13-14, "changes in climate or land cover". There are certainly more that just these two drivers that can lead to changes in a regime. Consider changing to " changes in, for example, climate or land cover".

We followed the suggestion by Referee#3, adding and/or.

P1, l 17, "proven" is not a good term in the scientific approach. Consider replacing by "constrained".

Agree and changed

P2, l 20, consider changing "are documented of channel pattern changes" to "of channel pattern changes are documented".

Agree and changed

P6, l 6-7, hard to understand the value assignments. Consider rewriting to "with an average annular discharge Qm of 22.8 m3 /s and a mean annual flood discharge Qmaf or 160 m3 /s".

Agree and changed

P6, l 15-22, too detailed. Consider shortening significantly to an extent that matches the scope of the study.

Agree and shortened

P6, l 31-35. Actually all you can say is that the cutoff happened before 1720 AD. There is no information that supports the statements like "shortly before" or "date from the same period". Consider rewriting to stay with the available constraints.

Agree, in this phase of the manuscript we can only take conclusions from its dimensions, but indeed not from the age. The study is needed to investigate this. We rewrote this section.

P7, l 23, check overall the journal's definition of figure reference format rules, i.e., if "(Fig. 1(c)-(d))" is the right way.

Checked and changed

P8, l 6. The use of "respectively" makes it very hard in this sentence to identify the cases in which you used which device. Please rewrite like "In case we we used this device. In case B we use that device".

Agree and changed

P8, l 12, did I read this correctly, that you sieved material from a 3 cm wide auger/corer to estimate the gravel content? Is this a representative sample size, or in other words, over which depth interval did you have to average to get sufficient material for sieving?

The sieving was meant to make an estimation for the gravel content in the lithological description. Purely meant as a field-based method to make a fast estimation, sufficient for the aim of this method: distinguishing the lithogenetic units

P8, l 28, Add manufacturer info to grain size device (Beckman Coulter, Malvern, Horiba, etc.) to make clear which device you used.

Changed

P8, l 29. Check units. Is it 2000 m or µm?

Checked, 2 mm is correct

P8, l 30. Why was the Fraunhofer model valid? Was it "just" sandy material with minimum clay content? If not, the Mie model might be more appropriate.

Yes, almost all sand, see Fig. 6. We changed the text slightly to make this more clear

P8, l 33-34. Consider rewriting to simplify. E.g., "We used the scroll bar OSL burial ages determined by Quik and Wallinga. For details on the method see this reference."

Changed according to suggestions

P9, l 16, what is the consequence of the different age determination procedure for the palaeo channels? Are the Baysian constrained ages comparable to unconstrained ages? Are just the errors larger?

Details for the age estimation and effects of Bayesian constraining are provided in Quik and Wallinga (https://doi.org/10.5194/esurf-2018-30). Some of the younger deposits are particularly poorly-bleached, and for those the cartographic evidence is leading and provided more accurate and precise ages. The Bayesian procedure overall resulted in smaller uncertainties..

We removed this sentence "apart from the final Bayesian.... from historical maps", because we already mention that only the laboratory analysis followed the same procedure. Their Bayesian analysis was a post-laboratory calculation. We added a short explanation why we did not use Bayesian analysis.

P9, l 18, how were the radio carbon samples taken? From a corer or a pit?

Changed, we used a piston corer, forgot to mention.

P9, l 21, add HCl concentration

Changed

P9, l 31, Why did you assume a standard deviation of 5 %? Why this value? Does this come from the uncertainty arising from the GPR results? It should at least be justified somehow. Otherwise I could ask, why was it not assumed to be 0.5 % or 50 %?

We reviewed this assumption. We introduced a standard deviation based on different assumptions for the channel dimensions (see comment to other reviewers), by 1) introducing two knickpoints and 2) determining it for both palaeochannels. Then we calculated the average and standard deviation of Hbf. Consequently, this approach also affects the other channel determined dimensions (A, P, R, W).

P10, l 9, same as above, why the 5 %? Can you say something beyond "expert judgement"? It would considerably improve the impact and value of the study and since there are quite large uncertainty ranges in some of your results these input

uncertainties may be crucial to evaluate the results. You can for example also think of sensitivity analysis. What would happen if you set the standard deviation to 1 % or 15 %?

We agree and changed the assumption. We used the differences in surface and bottom elevation as a measure for the uncertainty of H_{bf}. See previous comment.

P14, l 13. Is there any uncertainty available for the porosity value? Can you estimate a plausible value?

We included an uncertainty range for the porosity of sand based on literature

P14, l 14. Is there any uncertainty available for the age differences? Yes there is. So this should be included in the MCMC approach.

There indeed is an uncertainty in the ages as shown by Quik & Wallinga (submitted), but the order of development of the scrolls in the scroll-bar sequence is known. Here we are primarily interested in the trend of the palaeodischarge over time, in particular comparison of the palaeohydrological conditions that existed at the start of the meandering phase.

The age estimate uncertainties are relevant for comparing the reconstruction to possible drivers, and are considered in our (condensed) discussion of these. Including these uncertainties in the figures showing trends in time is extremely complex, and if possible, would resulting in a blurred picture masking trends over time. Therefore we choose not to include the uncertainty of the ages.

P14, l 24-25, the sentence does not fit very well, here. Consider shifting it to a more appropriate place where it does not cause a break in context.

We moved the sentence a few sentences down.

P15, l 6, Is there any uncertainty available for n? Can you justify why you chose 0.028 for this parameter?

We found that taking a range of the Manning coefficient, the uncertainty becomes so high that it's rather useless. In fact, estimating the Manning coefficient was a matter of estimating what the river could have looked like (vegetation, irregularity) and comparing it with similar rivers, but this information is unknown. Based on reviewer comments, we have decided to only use the Brownlie formula, because it includes known variables and their uncertainty. We now compare the calculated Chézy with literature values.

P15, l 12, Which type of rivers were these 79? sand bed? low land? Some detail is needed to understand the validity of averaging over this number of rivers.

We moved this comparison to the discussion and added more detail on the rivers for which we averaged the Chézy value.

P15, l 15, Who was the expert that suggested the value of the Chezy coefficient?

Sentence was removed, because no details were given on how they estimated the Chézy.

P15, l 24-25, give uncertainty estimate for intermittency and porosity parameters. Or say there is no uncertainty.

We added the uncertainty for the porosity based on Nimmo's work. For the intermittency there is no uncertainty.

P15, l 27, consider new paragraph between "available" and "In the second".

Agree and changed

P16, l 8-14. This is vital information about the stability diagram. Please deliver this earlier to the reader, e.g., when you first mention this diagram type. What is meant by "interpreted as a lower threshold, rather than a hard threshold"?

We agree that the stability diagram is an essential part of the reconstruction. However, we refer in the introduction to the use of empirical channel models, which we further elaborate in the methodology section (here). We decided not to move this section to the introduction as it would make the introduction too long and unbalanced.

P21, l 12, define or quantify the term "very similar", you have the data to do so.

Changed

P21, l 17, define or quantify the term "extremely slow", you have the data to do so. Also, you can make use of the uncertainty information.

Changed

P22, l 8, provide uncertainty information for slope of X.

Changed

P22, l 11, provide uncertainty information for slope of Q.

Changed

P22, l 11, what mean "relatively linear"? You should test and quantify. Actually I could also interpret a piecewise linear model with a break around 1850.

We removed the comment

P25, l 8-10, why did you choose the "middle of the ranges" and what is the "middle"? See above, why should the full range of estimated values for C be equally valid or likely? If they were equal, why would you make a distinction between "all rivers", "rivers without bars" and so on? Why did you use a standard deviation of 2 units? Please justify these apparently arbitrary assumptions. It is fine to include uncertainties, but their foundations must be reasonable.

We removed this comment as Chezy is now based on the Brownlie equation, we don't use the other approaches anymore. See previous comments.

P25, l 12, the values 32 and 38 are really really hard to map out on figure 9 a. And anyway does not everything in this figure drown in the uncertainty polygon? Please discuss your values with respect to the large uncertainty range.

We added some discussion on the uncertainty in the graphs in section 4.4. An equal bankfull discharge would mean a large change of the parameters for Palaeochannel X&Q, which are unrealistic.

P26, l 7, "was probably limited". . . not necessarily. You simply cannot resolve this statement with your data. Just that the phenomenon could be explained with option A (sediment transport is higher than bar growth) does not mean that option B (external sediment input) is not also contributing. Or would these two options be mutually exclusive?

Removed this statement

P29, l 7-14, this part contains very limited information but instead many repetitions of already discussed material.

We rewrote this section. The repetition is caused because most of the discussion was already written in the results, therefore we moved it from the results into this section.

P29, l 19-28, there is a lot of general information and unknown statements in this section. Please make a better connection to the results section. You have a lot of quantitative results, so please use them to support the statements made, here.

We agree and rewrote this section.

P31, l 31-32, if this is no tin the scope of the paper, then why referring to this topic?

Removed this phrase.

P32, l 11-12, I do not think it is actually possible to resolve whether or not increased sediment input played a role, so I would not mention this, here. See comment somewhere above.

Removed this line

P32, l 14-33, very broad and general. The main point I read from this paragraph is that we need more detailed field studies to pursue the question. Try to make more out of this material. It would be a valid goal to investigate if the one case you found in your study is an "outlier" or the "regular case". Anyhow, the paragraph in its current shape does not present/discuss your results. You have to make a story out of it or leave it.

We removed it to prevent repetition, and discussed this part in the introduction.

Likewise, the second paragraph comes a bit out of the blue. How does the Geul river come into play and why does it come into play, here? This section needs more context or should be skipped. Currently, it does not really match the section header.

We moved this section to the introduction as suggested by the other reviewer, where it supports the likelihood that more rivers changed from laterally stable to meandering during the Holocene.

P33, l 5-15, this part is also very broad/general and arm waving. Consider shortening significantly and link it much better to your concrete findings, i.e., what your case study can contribute to this overall picture. Overall, I suggest to shorten this part and have it rather a conclusion item than part of the discussion.

We removed this section on stream restoration to shorten the length of the manuscript and to keep the focus.

P33, l 29, change "discharge increased" to "discharge potential increased".

We rewrote the conclusion

P33, l 30, change "exploitation has contributed" to "exploitation has probably contributed".

Rewrote the conclusion

Table 1, It would be better to have the radio carbon and OSL ages at the same scale. This concerns both, years versus kilo years and AD years versus absolute years. At the moment things are hard to bring together.

Final ages are all presented in the same framework; following the revised manuscript of Quik & Wallinga (in press) we adopted the CE framework for this. Intermediate results are also presented reported in the appropriate unit, for the OSL ka ages are presented in addition to CE, as these relate directly to the reported palaeodose and dose-rate.

Figure 1, replace dashed lines in panel b and f. Also, consider using solid lines to illustrate the zoom from panel to panel. Add similar "zoom lines" also from b to c and b to d. Provide a solid or at least partly transparent background to legends. The legend contents are really hard to see. Add legend frame in panel b.

We changed the dashed lines into solid lines and also added them to panel b to c and b to d. The legend is poorly readable due to the low quality of the images. We decided not to add a background, because detail would get lost of the meander bend surroundings, also when transparent the surroundings will be hardly visible. However, the higher quality of the images improves the readability significantly.

Figure 2, image quality is not good. Either this is due to the manuscript stage compression or other. It would be essential to add a higher resolved image of the GPR output. Also, the thick yellow lines are masking the raw data too much. Figure 5 does a much better job by showing both, raw and interpreted options. Alternatively, think of using thinner and semi-transparent lines. In figure caption there is repetition with "modified after Huisink" and "adapted after Huisink".

We agree that the image quality is not optimal. This is because Huisink had a low quality image in her article, which is very likely due to the quality of the GPR output 18 years ago. Here the main goal is to illustrate the different subsurface features (palaeochannel, coversand, fluvioperiglacial) and showing that a symmetrical palaeochannel is present, but lateral accretion surfaces are lacking. This interpretation was not done by ourselves, but by Huisink already. For the actual data we refer to their work. For our own data (Fig. 5) we agree that it is essential to deliver good quality GPR images.

We changed the caption so that it becomes more clear that the interpretation was done by Huisink.

Figure 4, Please decrease the size of the drawings and have all of them on one page. The context density of the drawings is not too high, you can scale them smaller without loosing much of the content. Of course the axes labels and plot drawing texts must be rescaled to an appropriate font size. But currently, there is a mismatch in the size of the figures with respect to what they tell.

The delineation of the scroll bar deposits and palaeochannel is an essential step in the reconstruction, and should be fully visible in Figure 4. We tried making the drawings smaller (so they would fit on one page), but too much detail was lost. We shortened the lithogenetic interpretation, therefore these figures become even more important.

Figure 7, what do the errors want to tell in panels c and d? Overall, the resolution of the images are not really great Consider saving such plots are EPS vector data.

We improved the quality of the images. The caption explains the uncertainty shown in Fig. 7c,d. This is the standard deviation of the Bayesian deposition model determined by Quik and Wallinga.

Figure 8, figure quality/resolution is bad. Please avoid the dashed and dotted lines (e.g., panel g), they make it hard to see the data clean. Shift legend from panel a to panel c and d.

We changed the resolution of the figures. We removed fig. 8gh, because they were not that important for the reader. We keep the legend in panel a, because here there is sufficient space, and the legend immediately explains the lines in panel a.

Figure 10, dashed lines make it hard to see any trends

Removed and replaced the dashed lines. We also added a log-plot to see more detail.

Figure 11, why is Prathoek missing in above panel?

As explained in the method section, we merged both meander bends together, because the same discharge and streampower are expected. For the IP this is different, because the IP is determined by channel-dependent parameters.

Interactive comment on Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2018-31, 2018.

Interactive comment on "Late Holocene channel pattern change from laterally stable to meandering caused by climate and land use changes" by Jasper H. J. Candel et al. Anonymous Referee #2 Received and published: 12 June 2018

The manuscript "Late Holocene channel pattern change from laterally stable to meandering caused by climate and land use changes" aims to identify river channel pattern changes using sedimentary and geochronological data and to identify causes for these changes. The manuscript is well written, the topic is relevant and in the scope of the journal, and the concepts and ideas are sufficiently novel. The methods are consistent and well described. There are some minor to moderate shortcomings, listed below. When these shortcomings are resolved, I consider this manuscript as a valuable contribution to Esurf.

Thanks for your kind words and critical review adding significant value to the manuscript. Below we respond to each of the suggested changes.

- Some sections are written too extensively, and not all information is needed to answer the research questions. For instance, the details on river restoration in section 2 are not needed and can be limited to a minimum. Also section 5.4 and 5.5 can be shortened.

The same suggestions were given by Referee #1. We shortened or removed the suggested sections or merged them together. Our manuscript was shortened by ca. 3500 words, removing repetition and excessive information.

Section 2 (study area): P6, L29-37: A lot of assumption are made in this part. I suggest to move this part to section 4.2 (results). And then in section 4.2, you have to provide all available arguments to state that channel X is predating the meandering phase. Show data to support your statements (eg show the GPR profile). You have to provide good arguments to state that channel X is from a laterally stable phase, since this is an important point for the rest of the story.

We changed this section, removing the assumptions, as also proposed by reviewer #1. We indeed have no information on the age or stability yet, that's one of the outcomes of this research. We leave the introduction of palaeochannel X in this section, so our steps in the methods become more clear why we are investigating this palaeochannel.

Section 3.1 is not needed to my opinion. Aims are already explained in section 1 (Introduction); methods will be described in detail in the next paragraphs (3.2 and next sections).

Agree and changed also in according to the suggestions by the other reviewers.

- P9, line 29: How did you define the knick-point on the bank? What will be the effect on bankfull depth and discharge when using a different knick-point on the bank? You can try a sensitivity analysis to check the effect of the definition of the bankfull depth.

We measured in high resolution the banks of the palaeochannel with a GNSS. However, we now introduce uncertainty by taking the first clear knick-point on both banks, causing differences in channel dimensions.

P9, line 31: Why a standard deviation of 5%? Which arguments do you have? This is an important point, since large parts of your interpretations are based on this standard deviation. If you assume a standard deviation of 10 or 20%, it is possible that your differences explained in figure 8 are not so clear anymore. Can you provide a consistent method to define the standard deviation? Also here, you can try a sensitivity analysis to check the effect of the standard deviation. - Same question for P10, line 9.

We reviewed this assumption. We introduced a standard deviation based on different assumptions for the channel dimensions (see comment to other reviewers), by determining the relative error of Hbf for the meandering phase and assuming a similar relative error for the laterally stable phase, because both estimates are based on coring data. The relative error is ca. 10% of the Hbf. We took the same percentage of relative error for the other determined channel dimensions (A, P, W).

– Section 4.1: You can summarize this section in a table showing the most important characteristics of the different lithogenetic units. The table can then be followed by a short paragraph on defining the scroll bars and scroll bar dimensions.

Agree and changed according to your suggestions. The other reviewers also agreed that section 4.1 should be shortened, hence a table provides a good solution to do so.

Section 4.4: L11: Use statistical tests to check if the reconstructed discharge differs significantly. Given the uncertainty range it is possible that you can not reject the null hypothesis (Q does not differ). The same for L13: 'Q drops relatively fast at 1800 AD': Given the uncertainties, it is possible that Q is not significantly different. Use statistical tests to support your statements. P 29, L20: It is also likely that the discharge does not differ significantly, given the uncertainties. See my previous comment.

We added a section on how much parameters have to change to reach similar results in sect. 4.4. These factors fall outside the range of the uncertainty of these parameters, hence values between the laterally stable phase and meandering phase are significantly different.

- Section 5.2: This section mainly brings together results of previous studies and it is not based on new data. So this section should be shortened and should link better to your own data and findings. Try to better link quantitative data on climate change and land use changes with your findings.

Agree, we rewrote this section and merged it with 5.2.1 and 5.2.2.

- Section 5.2.2: Is there an observed increasing in urbanization in your catchment? Urbanization can cause higher peak discharge, which have been described in catchments in The Netherlands.

Urbanization is an important factor in recent land use changes during the last century, where paved roads cause flood increases. However, during the Middle Ages roads and cities were by far not that well developed compared to recent developments (see also Lanen et al., 2015 on archeological studies on road infrastructure, including the area of interest)

- P31, L6 and L11: 27% of the catchment was covered with peat + yearly average discharges can increase by 40% => ca. 11% increase in average discharge for the entire catchment. How does this compare to your reconstructed increase in discharge?

Thanks, we added this comparison to the text.

- P 31, L 29-31: "Our data strongly suggest": not correct. As you stated in section 5.2 it is likely that the increasing discharge caused the change; you have some good suggestions but no hard evidence.

Changed the entire section according to suggestions of reviewer 1. We removed these strong statements.

"The most likely identified causes": actually these are the only factors checked. You did not checked other contributing factors.

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Changed the text and the aim of the paper in agreement with all reviewers. Identifying the causes is not the main aim of the manuscript anymore, hence we mention the likely causes.

Figure 4: Indicate the location of the datings on Figure 4e.

We added the locations of the datings on Figure 4e and extended the southern part of the figure so they would all be included.

- Figure 10c: this figure is not entirely clear. The dashed lines do not help. Try to simplify this graph to make it more clear.

Changed the figure according to suggestions. We removed the dashed lines and added a log-scale to the y-axis to make everything more visible.

- References: For some references, correct volume, issue and pages are missing: P36, L5-6; P36, L24-26; P36, L56-57; P37, L40-41 (I may have missed more).

Check and changed

Interactive comment on Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2018-31, C3 2018.

Interactive comment on "Late Holocene channel pattern change from laterally stable to meandering caused by climate and land use changes" by Jasper H. J. Candel et al.

P. Houben (Referee)
p.houben@luc.leidenuniv.nl

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The paper on "Late Holocene channel pattern change [. . .]" by Candel et al. reports on the use of floodplain stratagr. records and chronologies to conduct a quantitative assessment of (paleo)hydrological channel planform change over the past 600 years in the NE NL. At a general level the manuscript is organised, the introductory sections provide background to the research, and give sufficient detail of the used methodology. The methodological approach and the subsequent evaluation of obtained results are based on a strong research effort, and the discussion puts the work in the context of previous work and addresses potential implications. All of which fits the journal's scope. All in all, the ms represented a valuable contribution to ESurfD, however, in its current form it requires restructuring and (partially) rewriting at the paragraph level. Regarding given standards a number of statements are misplaced. For example, the Results section includes discussions of the findings, which is why the actual Discussion mostly reverts to a sometimes narrative analysis. The weakest sections, thus, are the Discussion and the Conclusions wherein some thoughts brought up and connections that are sought to be made should be reconsidered with respect to whether they actually add to the paper's significance. In consequence, the abstract should be rewritten because it is not reflecting the actual paper content (and the balance of the featured aspects), and the highlighted findings are not supported by the employed methodology. At places abundant in-text citations in the Introduction can be perceived as a bit too excessive.
Key: rm - remove; rw - rewrite/reword;

Thanks for your kind words and your critical and valuable review on the manuscript. We agree and are thankful that your review made clear that the structure of the text should be improved. We moved large parts of the results to the discussion and focussed the discussion more on the main findings. Also we rewrote the conclusion and abstract.

p1: Title: Actually, the paper does not include hard information that allows for pointing to the actual causes of the described channel change. In the paper, a number of (truly) possible and plausible causes are mentioned but no conclusive evidence can be shown that helped to causally link channel change to either or both of the drivers. Why not highlighting the strength of the paper, the application of quantitative palaeohydrological approaches to answer the actual research question?

With the new input of the reviewers we agree that the title does not match the content anymore. Therefore we changed the title accordingly, highlighting both the channel pattern change and the palaeohydrological reconstruction.

13 - The Abstract . . . "related to changes in climate and/or land"
Changed accordingly

15-18 - Results are reported before the actual scope of the paper is given. And the approach is only explained later on. Rearrange to present a logical flow.A
Agree and we rearranged the order

18 - Actually, no potential causes have been investigated. This is misleading information.

Only other people's work is cited in the Discussion when attempting to explain what possible causes have been around. The nature of that discussion, nevertheless, remains speculative.
Removed the sentence

28 -29 - 'reflecting relative . . . ' this statement should be rephrased because it it ambiguous, and overall not intelligible when only reading the abstract.
Changed

31 - The last sentence is not specific to the paper content, rather will appear like a motherhood statement the the journal's audience. Remove and replace it by strong statements that stress the significance of the own findings. The reason for the weak end of the Abstract, my guess, is the underdeveloped Conclusions section (see below).
Agree and changed

34 - 'Several . . . ' Sentence can be deleted.
Removed

p2 5 - In a braided river system, isn't the temporary presence of laterally stable/ migrating channels (runnels) just a matter of stage at a time?
Here we make a statement that refers to laterally inactive rivers, and rivers that show lateral migration. Both meandering and braided rivers can have channel reaches that are temporary laterally stable. However, both meandering and braided rivers show in general laterally migrating channels. In this case the differences in processes between meandering and braiding rivers are irrelevant.

7 - ' variables like potential . . . '
This is a matter of taste; we prefer our phrasing and made no changes.

7 - rm: ', which is . . . slope'
This information is needed to understand why Qbf is reconstructed, which leads to the stream power. Therefore we leave this sentence.

8 - '2011), bank erodibility (. . .), cohesiveness (. . .), and by vegetation (...).'
Changed, but differently than suggested. Bank cohesiveness and vegetation are important factors determining the bank erodiblity, so they should not be equally summed up.

9-10 - rm: 'which is . . . (Turowski, . . .)'; 'that can increase . . . '
Changed, but differently than suggested. See previous response

6 vs 11 - Statements contradict each other
Changes above have solved this

13 - rm: gradually
Changed

13-19 - shorten para
The paragraph consists of vital information of our current state of knowledge on channel pattern changes, which is entirely based on the change between meandering and braiding planforms.

We removed a few references to shorten the paragraph as suggested later, but did not shorten the sentences.

23 - rw: 'the exception is formed by human intervention'
Changed

23-34- This para does not fit in here. The surrounding text provides background information that should translate into the 'gap' and clearly formulated research goals, however, this para explains processes of channel change. Could be moved together with p2 10-18 to line 18 on p3.
We moved this para together with the suggested para.

33 - Excessive citing . . . Can the information be organised into a table?
We decided to remove references and provide only references that refer to multiple river systems.

p3 11 - It feels as if already here the paper's research question is addressed, but the authors then return to reviewing literature.
Removed last sentence of paragraph

19 - Shouldn't the information be part of the first para on p3?
We merged these lines together with the previous para
20 - '.. stable channels poorly preserve except for . . .' rm all the rest between 21 and 25
Changed, and the removed lines are left for the discussion

31 - ' Huisink, 2000) while the meandering pattern has remained throughout . . .'
Changed accordingly

33 - rm: 'However'
Removed

p6 14-16 - This needs to be moved to the Intro. There, it was already used to justify the research effort. In general, most of the content of p6 should be part f the Intro because it is the background against which the present investigation can be justified. (I.e., it's potential value to inform restoration projects.) This is even more important as this point is picked up in the discussion s one of the more significant implications . . .
Rather than moving it to the intro we removed this para, as suggested by the other reviewers.

34 - In far can could the used features by local peculiarities due to their peculiar morphological context?
Unclear what is meant here, but we changed this section according to suggestions by the other reviewers

p7 7 - First sentences should not lead the Methods sections. Stating the paper goals belongs to the Intro.
We removed this section and stated this part more clear in the introduction
7-21 - The whole para is a mix of review (again) and methods description. Needs to be rectified.
Removed and moved to introduction section

Fig. 2, A - B - C designation is hardly readable.
You refer to use of the Fig2(a) and 2(b) etc.? We changed this for all references to figures.

p8 6 - r: ' (i.e. the full ..)'
Removed

11 - Estimating a statistical parameter for which others apply stacks of sieves by just visual(?!) means? That might work depending on what the information is used for. For me this is a point for of major concern. Actually, the D50 value is key to the calculations performed employing eq. 8, 10, 12, 15, and 16.
This data was only used for the lithological description. The grain size analysis was used for the D16, D50 and D84, so the D50 in the equations was not based on the visual assessment. This is also described in section 3.4. We added a sentence to make this more clear.

While in general the methodology also accounts for ranges or error, I am not convinced that the 5% uncertainty is fair for this error-prone guesstimate. How good (=reliable, =reproducible!) can the far-reaching conclusions drawn be? (E.g., see fig. 10).
We did not use a 5% uncertainty for the D50, but we used the standard deviation derived from the grain size analysis

17-19 - rm: 'GPR . . . 2011).'
Removed
29 - replace: over -> with
Changed
30 - What sort of laboratory prescriptions (= 'instructions')? Sounds like voodoo science, doesn't it?
Removed this additional statement, not needed.
33- rm: the
Changed according to suggestions of other reviewer
33 - rm: 2nd sentence
Changed according to suggestions of other reviewer
35 - 'The scroll bars' . . . can be removed, or reword, or ..
Changed according to suggestions of other reviewer
p9 18 - rm: first sentence
Changed
21-22 rm: whole sentence, it's just nomeclature
This definition is essential to determine where the sand-peat interface is located, and is necessary to report for the repeatability of the study. We decided to leave this sentence.

31 - Why 5%? Can you justify this? Still a rather optimistic estimate.
Agree, see previous response to other reviewers. We reviewed this assumption. We introduced a standard deviation based on different assumptions for the channel dimensions, by determining the relative error of Hbf for the meandering phase and assuming a similar relative error for the laterally stable phase, because both estimates are based on coring data. The relative error is ca. 10% of the Hbf. We took the same percentage of relative error for the other determined channel dimensions (A, P, W).

p10 Insert space between Fig. 3 and the text. The figure even may be left out.
Changed. We will leave the figure in, because it clarifies how the equations 1-3 were derived.

p11, 12 Nice figures. However, would it work for people who printed it in B/W?
Checked, and changed the colours of the lithogenetic units slightly to assure that B/W print will work. For the lithological cross-sections these colours can be distinguished.

p14 29-32 - How was D16, D84 determined? Also visually? From the waterlogged sands that spread to either side when the sample material is pushed out of the Vander-Staay tube? I think this is a soft point of the methodology, in particulary with respect to the heavy mathwork that follows to nail physical, hydraulic parameters of in-channel water and sediment flow.

See comment above. The D16, D50, D84 were derived by the grain size analysis, not by the visual assessment. We added a reference in this line to section 3.4 to make this more clear.

p15 15 - State what was actually used here. Rather an issue of the methodology than a result.

We removed this sentence and decided only to use Brownlie, as suggested by the other reviewers. In fact, Brownlie uses variables that are known, and of which we can vary the uncertainty. However, Manning is a subjective estimation of what the river looked like in the past. We changed the approach and only use the Brownlie, and we will compare the calculated Chézy value with values known from rivers of similar size and with similar river pattern.

27 - New para.

Changed

p16 28-33 - rm: 2nd sentence

Removed

p18 All in all, the whole Methods section could be more concise, focused. It would be worth to focus on the most important aspects and move the remainder to the Appendix.

We applied all the suggested changes by the 3 reviewers making the methods more concise. Reviewer 1 and 2 are in general positive about the methodology section, therefore we decided not to move any section to the appendix.

p19 6-11 - Reword.

Partly rewritten

10 - rm: 'Such a clear . . .Prathoek'

Changed

11 - rm: last sentence

Changed

20 - rw: abundant above

Text has been removed in response to other reviewers

Whole section 4.1.: Commonly, the ordering of geol. units is from old to young.

Changed in the newly introduced table, and we shortened the text..

p21 22-28 - 'Palaeochannel . . .' All this information interprets the findings. So it has to be moved to the Discussion.

Moved to discussion where we discuss the laterally stable phase

p23 Are all the diagrams necessary? Criterion: To which extent are they covered by the text?

We removed figures 8gh and 9b, because they were not abundantly referred to in the text.

p24 11- p25, line 5 All this information interprets the findings. So it has to be moved to the Discussion.

Agree and moved to discussion

p25 19 - Reword.

Reworded.

20 - rw: reached -> crossed?

Changed

Fig. 9 - Merge with Fig 8.
Because we merged Junnerkoeland and Prathoek in the calculations for discharge and flow velocity, we won't merge Fig9 and 8, because in Fig. 8 they are still separated. In addition, Fig. 9 is important and deserves more attention, so it can better be separated.

p26 6-11 - All this information interprets the findings. So it has to be moved to the Discussion.
Moved to discussion

16-20 - All this information interprets the findings. So it has to be moved to the Discussion.
Moved to discussion

p27 It is hard to read out information from figure 10c To much included into a single diagram. Simplify!
We simplified the graph, mainly by removing the dashed lines and making the y-axis logarithmic.

p28 I am not sure whether this is essential to the paper's scope . . . I see some potential to shorten the paper by moving this to some Appendix.
This part is essential to our key message, because with these empirical models we test the likelihood that discharge increase has led to the channel pattern change. So can we use the palaeohydrological parameters (including their uncertainties) and understand why the channel pattern has changed to meandering.

p29 20 - rm: 'by a factor ..' Do not repeat results already reported on earlier. Instead, conduct a more clear-cut write-up of the obtained results.
Removed

21 - This gives a minimum age (only). And only for a strong phase that has never been stronger afterwards. That is, the meandering may have been triggered at an earlier point in time, but the pertinent strata was just cannibalised by the denoted activity.
Yes, we improved the argumentation for this point. If earlier, the meandering activity has not been preserved, but we would still expect to find more channel cut-offs or meander scars in the floodplain, or some older scroll bar deposit. Even when the new meander cannibalised the old one.

22-23 - A strong statement. Still, is it actually supported by the calculated data given the inherent uncertainties? What if sediment transport rates (?quantity per unit time) was constant from an earlier time on? Isn't it possibly the same phenomenon as with terminal moraines? The most distal ones mark the last phase immediately before the 'dynamics' decreased. So they mark the onset of the decline. See the all the diagrams from 8 to 10, they all suggest a progressively declining meander activity.
Removed the sentence. However, we reconstructed the sediment transport based on the reconstructed channel dimensions, so the actual sediment transport at that time. The scroll bar growth is not a lagged effect, but is determined by the actual amount of erosion and deposition, and hence the sediment availability. In this case, we refer to the moment of the channel pattern change, not to the decline during the meandering. Scroll bar growth can only be this high during the channel pattern change because of an increase in sediment transport, which has increased as a result of the discharge.

p30 5-9 - Is perceived as speculative. Remove.
Removed this section

16-23 - Only speculation. Remove it, it is not connected to anything based on your methodology. Also, using climate data from the current climate normal carries a strong

signal of climate change with characteristics being different from the pre-1980 period. The relationships that are constructed here are, therefore, very questionable.
Removed this section

Section 5.2.2 - Interesting, but how does it immediately relate to the methodology that was used? All the information is good for is to point out future avenues of research to clarify causes of what you observed on the floodplain (only). So this section should be shortened, dissolved, and merged with the hints that can be made regarding the role of post-Middle Ages climate fluctuations.
Followed the recommendations, also in agreement with the other reviewers.

p32 14-26 - All of this only repeats content of the Introduction. Actually, there it was used to justify the research undertaken. But its occurrence in the context of the Discussion section means that is an outcome of the study? Delete the section.
Agree and deleted this section

27-33 - . . . and therefore this para should be part of the Intro. There it would add to provide a logical flow of justifying the research question in view of previous research.
Agree and moved to introduction to support the research goals.

Section 5.5. River management and restoration This section mostly reiterates commonplaces about fluvial morphology and stream restoration works. If you would like to keep it, then thoroughly rewrite it by making connections between your own findings and what they'd mean for the management and/or restoration efferts mentioned in section 2 (case-based!). And include a the pertinent background to that in the Introduction. This topic is actually adding significance to the present research, even though the methodological approach as such is not necessarily novel. Try to link your research to the current debate on the meaning of 'natural rivers' and stream restoration goals (e.g., Brown et al., 2018, ESR).
We removed the section, also following suggestions by the other reviewers. In future work we will definitely discuss its relevance to river management and restoration.

p33 The 'Conclusions' - Are no true conclusions but yet another summary of the main findings. Moreover, what was discussed as possible causes and mechanisms in the previous section now is phrased as it was an evidence-based outcome of the study. Here, another complete rewrite was required.
Rewrote the conclusions

Reduce # of in-text citations (adding too many citations does not add credibility): p2 - 8, 15, 17, 29, 33 p3 - 9 p6 - 15 p8 - 18 p30 - 32 p31 - 7, 15, 20 p32 – 19
Removed least important citations for the suggested locations.

Peter Houben Leiden University College
Interactive comment on Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2018-31, 2018.

Below we include the relevant changes made in the manuscript. Because we encountered a corrupt word-file, we include 2x the manuscript with changes made of different moments in time (chronological order). Our apologies.

Late Holocene channel pattern change from laterally stable to meandering - a palaeohydrological reconstruction ~~caused by climate and land use changes~~

Jasper H.J. Candel[1], Maarten G. Kleinhans[2], Bart Makaske[1], Wim Z. Hoek[2], Cindy Quik[1], Jakob Wallinga[1]

[1]Soil Geography and Landscape Group, Wageningen University & Research, Wageningen, PO Box 47, 6700AA, The Netherlands
[2]Department of Physical Geography, Utrecht University, Utrecht, PO Box 80125, 3508TC, The Netherlands

Correspondence to: Jasper H.J. Candel (jasper.candel@wur.nl)

Abstract. River channel patterns may alter due to changes in hydrological regime, related to changes in ~~-~~climate and/or land cover. Such changes are well documented for transitions between meandering and braiding rivers, whereas channel pattern changes between laterally stable and meandering rivers are poorly documented and understood. We hypothesize that many low-energy meandering rivers had relatively low peak discharges and were laterally stable during most of the Holocene, when climate was relatively stable and human impact was limited. Although channel deposits associated with such stable phases are poorly preserved, due to recent increase in dynamics of such systems, detailed palaeohydrological studies can help identifying historical channel pattern changes.

Our objective of this work is ~~to~~ to relate changes in channel pattern of a low-energy river to changes in palaeohydrological conditions. We identified a river that was laterally almost stable throughout the Holocene until the Late Middle Ages, after which large meanders formed at lateral migration rates of about 2 m yr^{-1}. The lateral stability before the Late Middle Ages was constrained using a combination of coring information, ground-penetrating radar (GPR), radiocarbon (^{14}C) dating, and optically stimulated luminescence (OSL) dating. ~~identify the possible causes for the meander initiation.We identified a river that was laterally almost stable throughout the Holocene until the Late Middle Ages, after which large meanders formed at lateral migration rates of about 2 m yr^{-1}. The lateral stability before the Late Middle Ages was proven using a combination of coring information, ground-penetrating radar (GPR), radiocarbon (^{14}C) dating, and optically stimulated luminescence (OSL) dating. Our objective of this work is to identify the possible causes for the meander initiation.~~ We carried out a unique reconstruction of bankfull discharge as a function of time, based on channel dimensions that were reconstructed from the scroll bar sequence using coring information and GPR data, combined with chronological constraints from historical maps and OSL dating. ~~Our investigation shows that~~The bankfull discharge was two to five times higher during the meandering phase compared to the laterally stable phase. ~~.~~ ~~E~~Empirical channel and bar pattern models ~~were used to determine the potential for meandering~~showed that this increase can explain the channel pattern change. ~~and to identify the causes of meander initiation. Several potential causes were investigated, varying from discharge regime changes to increased sediment input. Our~~

~~investigation shows that bankfull discharge was two to five times higher during the meandering phase compared to the laterally stable phase. This~~ The bankfull discharge increase likely reflects climate changes related to the Little Ice Age and land use changes in the catchment, in particular as a result of peat reclamation and exploitation. ~~We hypothesize that many low-energy meandering rivers were laterally stable during most of the Holocene, reflecting relatively low peak discharges during a stable climate and with limited human impact. However, channel deposits associated with such stable phases are poorly preserved, due to recent increase in dynamics of such systems. Considering the importance of climate and land use changes on the river channel pattern, successful river restoration requires an integral approach that includes scenarios of climate and land use changes in the catchment.~~

1. Introduction

Channel patterns describe the planform of a river, which reflects the interaction of the river channel with its floodplain. ~~Several c~~Channel patterns are classically distinguished. Laterally inactive channels consist of straight and stable sinuous planforms, whereas laterally active channels consist of meandering and braiding planforms (Leopold and Wolman, 1957; Nanson and Knighton, 1996). Flume experiments and field data have shown that ~~the~~ channel pattern depends on t~~T~~he ratio between potential specific stream power and bank strength (Kleinhans, 2010; Nanson and Croke, 1992) ~~and stream power eventually determines the channel pattern (Kleinhans, 2010). several variables. Firstly, on the available potential specific stream power, which is the product of the channel-forming discharge and valley slope~~ (Kleinhans and Van den Berg, 2011; Nanson and Croke, 1992; Van den Berg, 1995)~~. Secondly, on the bank erodibility~~ (Ferguson, 1987; Friedkin, 1945; Millar, 2000), of which the latter is determined by the presence of hard-rock in the valley side (Turowski et al., 2008), the bank cohesiveness ~~of the banks~~ (Peakall et al., 2007)~~,~~ and ~~by~~ vegetation ~~that can increase the bank strength~~ (Gurnell, 2014; Millar, 2000). ~~A change in the hydrologic regime may invoke a change to a channel pattern associated with a higher energetic stage (Nanson and Croke, 1992). The ratio between bank strength and stream power eventually determines the channel pattern (Kleinhans, 2010).~~ Channel patterns can ~~gradually~~ change in response to environmental variations (Ferguson, 1987). Many examples of channel pattern changes from braiding to meandering and vice versa are known to be associated with glacial/interglacial oscillations (Vandenberghe, 2002; Vandenberghe, 1995). Especially studies on the last glacial-interglacial transition have shown the simultaneous occurrence of channel pattern changes with a changing climate (Kasse et al., 2016; Vandenberghe et al., 1994). Climate change affects the vegetation, sediment availability and discharge regime, and consequently the bank stability, sediment transport and potential specific stream power resulting in different channel patterns.

Within the Holocene, several examples ~~are documented~~ of channel pattern changes are documented from braiding to meandering rivers and vice versa (Brewer and Lewin, 1998; Lewin et al., 1977; Passmore et al., 1993; Słowik, 2015). However, channel pattern changes between laterally stable and meandering rivers have rarely been reported (Lewin and Macklin, 2010), except where ~~. The exception is formed by~~ human intervention~~, which~~ transforms~~ed~~ ~~many~~ meandering rivers into heavily regulated and laterally stable rivers by introducing weirs, dams, groynes and bank protection measures (Hesselink et al., 2003; Hobo et al., 2014; Słowik, 2013; Surian and Rinaldi, 2003). Also the abandonment of former meandering valleys results in

underfit, laterally stable rivers like the former Rhine branches in the Niers and Ijssel valley (Janssens et al., 2012; Kasse et al., 2005).

~~Both laterally stable and meandering rivers may display sinuous planforms, but the geomorphic processes in both rivers are different. Laterally stable channels are rivers witfhout meandering processes, i.e. helicoidal flows causing bar formation and bank erosion at a significant rate~~ (Candel et al., 2017; Kleinhans, 2010; Kleinhans and Van den Berg, 2011; Nanson and Knighton, 1996; Seminara, 2006)~~. In fact, the bends and channel cut-offs in laterally stable rivers may be the result of random and local disturbances (e.g. falling trees, beavers, bank collapse after heavy rainfall, etc.) leading to very limited and local displacement of the channel. Meandering and laterally stable rivers should therefore be distinguished by their different patterns of bar and floodplain formation, rather than merely by planform~~ (Candel et al., 2017; Kleinhans and Van den Berg, 2011)~~.~~ Many studies have reported increased fluvial activity (e.g. increased discharge, sediment transport and deposition, and bank erosion rates) in relation to human, environmental and climatic pressures during the Holocene (e.g. Hoffmann et al., 2008; Lespez et al., 2015; Macklin et al., 2010; Notebaert et al., 2018; Notebaert and Verstraeten, 2010). An example of increased fluvial activity is known from the Pine Creek (Idaho, USA), where mining and deforestation combined with intensive grazing resulted in an increase of discharge and sediment input, followed by river widening and an increase in bank erosion (Kondolf et al., 2002). The reverse change has been observed in settings as a result of afforestation (Kondolf et al., 2002; Liébault and Piégay, 2001), or increase of riparian vegetation fixing the channel banks (Eekhout et al., 2014; Vargas-Luna et al., 2016)~~. An example of increased fluvial activity is known from the Pine Creek (Idaho, USA), where mining and deforestation combined with intensive grazing resulted in an increase of discharge and sediment input, followed by river widening and an increase in bank erosion (Kondolf et al., 2002). The reverse change has been observed in settings as a result of afforestation (Kondolf et al., 2002; Liébault and Piégay, 2001), or increase of riparian vegetation fixing the channel banks (Eekhout et al., 2014; Vargas-Luna et al., 2016; Wolfert et al., 2001).~~ De Moor et al. (2008) hypothesized that the Geul River in southern Netherlands may have been relatively laterally stable during the Early and Middle Holocene, until the last 2000 years in which the river was actively meandering. Most of the floodplain deposits from the laterally stable phase have not been preserved, but De Moor et al. (2008) were able to reconstruct the bankfull depth for both periods. They estimated the bankfull depth to be a factor two to three higher during the Late Middle Ages compared to the Early and Middle Holocene, caused by human and climate impact. This increase of fluvial activity during the Holocene was corroborated by an extensive review of existing studies concerning sediment accumulation in West and Central European river floodplains by Notebaert and Verstraeten (2010). They concluded sedimentation rates increased during the Middle and Late Holocene due to environmental changes. However, unknown is whether the channel pattern changed simultaneously with the floodplain, because channel deposits of the Early Holocene stable phase were unrecognized.~~The Geul river in the southern Netherlands is an example of a river where a similar channel pattern change from laterally stable to meandering may have occurred. De Moor et al. (2008) hypothesized that this river was relatively laterally stable during the Early and Middle Holocene, until the last 2000 years in which the river was actively meandering. Most of the floodplain deposits from the laterally stable phase have not been preserved, but De Moor et al. (2008) were able~~

~~to reconstruct the bankfull depth for both periods. They estimated the bankfull depth to be a factor two to three higher during the Late Middle Ages compared to the Early and Middle Holocene, caused by human and climate impact. Although they argue that their evidence is limited, our insights support the likelihood of their findings.~~

~~A change in the hydrologic regime may invoke a change to a channel pattern associated with a higher energetic stage (Nanson and Croke, 1992).~~ We conjecture that the change from laterally stable to meandering has occurred in some rivers for which increased Holocene fluvial activity was reported. ~~. T~~The fact that such changes were not reported in the literature, may either mean that critical conditions for channel pattern change were not reached, or that evidence of such transitions is poorly preserved or left unnoticed. Both laterally stable and meandering rivers may display sinuous planforms, but the geomorphic processes in both rivers are different. Laterally stable channels are rivers without meandering processes, i.e. helicoidal flows causing bar formation and bank erosion at a significant rate (Kleinhans and Van den Berg, 2011; Nanson and Knighton, 1996; Seminara, 2006). In fact, the bends and channel cut-offs in laterally stable rivers may be the result of random and local disturbances (e.g. falling trees, beavers, bank collapse after heavy rainfall, etc.) leading to very limited and local displacement of the channel. Meandering and laterally stable rivers should therefore be distinguished by their different patterns of bar and floodplain formation, rather than merely by planform (Candel et al., 2017; Kleinhans and Van den Berg, 2011). We suggest that identifying channel pattern changes requires more detailed historic accounts or a much higher resolution of subsurface data than usually gathered, because palaeochannels of laterally stable ~~rivers~~channels ~~are~~ poorly preserve~~d~~ in the fluvial archive of meandering channel belts (Van de Lageweg et al., 2016) except when they have been cut off by random and local disturbances prior to the meandering phase. ~~. Deposits and dimensions of channel reaches are not preserved when still active during the stable to meandering transition, because channel belt dimensions increase. River reaches of laterally stable rivers can only be preserved when they are cut off by random and local disturbances prior to the meandering phase. Consequently, preservation potential of deposits associated to a laterally stable phase is very small, and only channel reaches that have been subject to perturbations have a chance to be preserved.~~ Using numeric (e.g. Oorschot et al., 2016) or scaled (e.g. Van Dijk et al., 2012) river simulation models is problematic for testing these ideas, because these have not yet been capable of reproducing channel pattern changes. This reflects the lack of understanding of river processes and patterns (Kleinhans, 2010), and the need to gather such information from field studies.

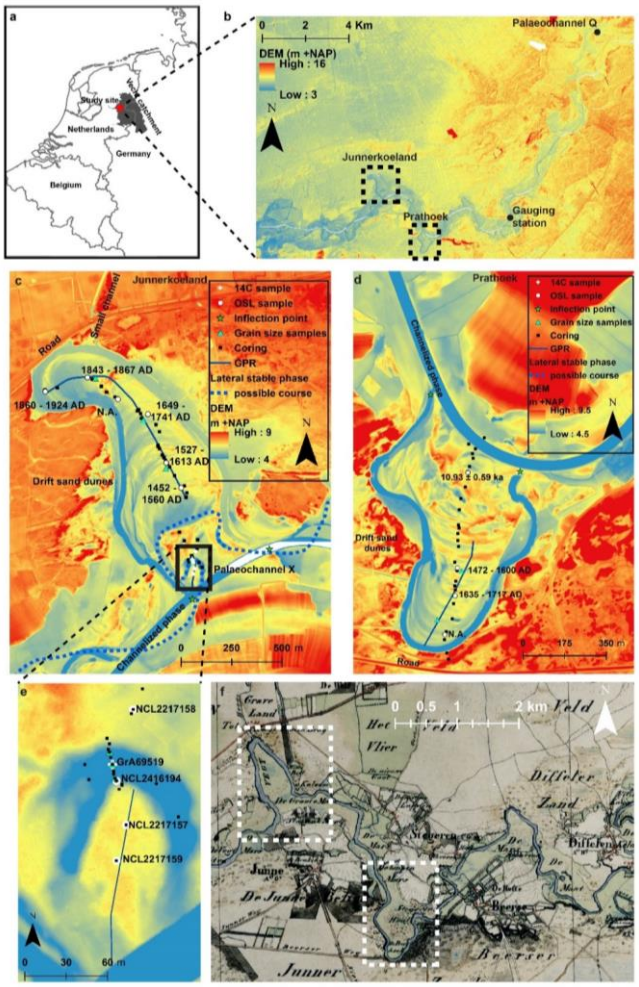
~~Notebaert and Verstraeten (2010) provided an extensive review of existing studies concerning sediment accumulation in West and Central European river floodplains, and concluded sedimentation rates increased during the Middle and Late Holocene due to environmental changes. However, unknown is whether the channel pattern changed simultaneously with the floodplain, because channel deposits of the Early Holocene stable phase were unrecognized.~~
~~We suggest that identifying channel pattern changes requires more detailed historic accounts or a much higher resolution of subsurface data than usually gathered, because palaeochannels of laterally stable rivers are poorly preserved in the fluvial~~

~~archive of meandering channel belts (Van de Lageweg et al., 2016). Deposits and dimensions of channel reaches are not preserved when still active during the stable to meandering transition, because channel-belt dimensions increase. River reaches of laterally stable rivers can only be preserved when they are cut off by random and local disturbances prior to the meandering phase. Consequently, preservation potential of deposits associated to a laterally stable phase is very small, and only channel reaches that have been subject to perturbations have a chance to be preserved. Using numeric (e.g. Oorschot et al., 2016) or scaled (e.g. Van Dijk et al., 2012) river simulation models is problematic for testing these ideas, because these have not yet been capable of reproducing channel pattern changes. This reflects the lack of understanding of river processes and patterns (Kleinhans, 2010), and the need to gather such information from field studies.~~

This research entails a case study focussing on a river where lateral activity during the past 500 to 600 years caused spectacular meandering: the Overijsselse Vecht in The Netherlands (Fig. 1). Previous work on this system has identified a transition from braiding to meandering during the Late-Glacial (Huisink, 2000) while the meandering pattern remained throughout ~~. In that study, and subsequent work, it was assumed that the river meandered throughout~~ the Holocene until the river was channelized in 1914 AD (Huisink, 2000; Neefjes et al., 2011). ~~However,~~ Quik and Wallinga (submitted) reconstructed meander formation using a combination of optically stimulated luminescence (OSL) dating of scroll bars and planform reconstruction based on historical maps, and found that the meanders were relatively young, with the oldest scroll bars dating from ca. 1400 AD. No fluvial deposits were found dating from before this period, except from a Holocene palaeochannel (here referred to as "Palaeochannel Q") in a ground-penetrating radar (GPR) profile recorded by Huisink (2000, p.123) 13 km upstream near Hardenberg (Fig. 1~~(b)~~b and 2). Palaeochannel Q is relatively small compared to the meandering channel, ~~and~~ seems to lack scroll bars and was already cut off on the historical map of 1720 AD. ~~.~~ Therefore, it is questionable whether the Overijsselse Vecht meandered prior to 1400 AD. Alternatively, the river changed from a laterally stable into a meandering river in the Late Middle Ages. Our aims are (1) to identify whether a channel pattern change has occurred, by collecting and combining detailed subsurface and geochronological data of the river prior to and during the pronounced meandering phase, ~~, and~~ (2) ~~to~~ to test whether palaeohydrological changes, which will be reconstructed from the sedimentological record, may explain the potential channel pattern change, ~~identify~~ by applying empirical channel and bar pattern models. ~~To determine whether possible changes in discharge and channel dimensions could have resulted in channel pattern change, the potential for meandering was calculated through time using the stability diagram of Kleinhans and Van den Berg (2011) and the bar regime applying relationships of Struiksma et al. (1985), which will be further elaborated below.~~

~~causes for the exceptional lateral migration rates reported by Quik and Wallinga (submitted), and for the potential channel pattern change. Our study involves a high-resolution palaeohydrological reconstruction of the river prior to and during the pronounced meandering phase to identify the potential causes.~~

~~Both laterally stable and meandering rivers may display sinuous planforms, but the geomorphic processes in both rivers are different. Laterally stable channels are rivers witfhout meandering processes, i.e. helicoidal flows causing bar formation and bank erosion at a significant rate~~ (Candel et al., 2017; Kleinhans, 2010; Kleinhans and Van den Berg, 2011; Nanson and Knighton, 1996; Seminara, 2006)~~. In fact, the bends and channel cut-offs in laterally stable rivers may be the result of random and local disturbances (e.g. falling trees, beavers, bank collapse after heavy rainfall, etc.) leading to very limited and local displacement of the channel. Meandering and laterally stable rivers should therefore be distinguished by their different patterns of bar and floodplain formation, rather than merely by planform~~ (Candel et al., 2017; Kleinhans and Van den Berg, 2011)~~.~~



2. Study area

The Overijsselse Vecht (Fig. 1) is a low-energy, sand-bed river flowing from Germany into The Netherlands, with an average annual discharge (Q_m) of 22.8 $m^3 s^{-1}$ and a mean annual flood discharge (Q_{maf}) ~~of 22.8 and~~of 160 $m^3 s^{-1}$~~, respectively~~, derived from the gauging station in Mariënberg for the period 1995 to 2015 (see location in Fig. 1~~(b)~~b). The river has a length of 167 km, its catchment covers 3785 km^2 with the highest point +110 m above sea level (asl), and a relatively uniform valley slope of $1.42*10^{-4}$ to $1.7*10^{-4}$ in the Dutch part of its trajectory (TAUW, 1992; Wolfert and Maas, 2007). The Overijsselse Vecht incised its current valley during the Late-Glacial within fluvioperiglacial sands, locally covered by aeolian coversands (Huisink, 2000; Ter Wee, 1966; Wolfert and Maas, 2007). During the Late Holocene, aeolian drift-sands formed along the Overijsselse Vecht as a result of agricultural overexploitation (Van Beek and Groenewoudt, 2011).

~~The Overijsselse Vecht is considered a classical example of the challenges of river restoration, due to the wide variety of stakeholders and interests in the area~~ (Maas et al., 2007; Maas and Woestenburg, 2014; Neefjes et al., 2011; Wolfert et al., 2009)~~. Water managers are struggling with the restoration of the Overijsselse Vecht in view of the meandering potential, the land use, recreational, groundwater and flood risk constraints (Damsté and Filius, pers. comm., September 16, 2016). The aim is to restore the river into a "half-natural lowland river", but the practical implementation of the restoration remains inconclusive.~~ The Overijsselse Vecht was an actively meandering river until 1896, when weirs were constructed and parts of the river were channelized. The river was completely channelized in 1914 AD, with five weirs controlling the water levels. Recently, sinuous side channels bypassing the weirs have been created as part of river restoration aiming to restore past physical and ecological characteristics of the river.

At present the topography of the meandering phase is partly still intact in the floodplain (Maas, 1995). Wolfert and Maas (2007) reconstructed the pre-channelization planform from historical maps of 1720, 1850 and 1890 AD. Large differences in meander development and lateral migration rates were found between different river reaches. In particular in areas where non-cohesive aeolian sands formed the channel banks, large meanders formed and lateral migration reached rates up to 3 m yr^{-1}. In this research we will study two of the large meanders, named Prathoek and Junnerkoeland (Fig. 1), where Quik and Wallinga (submitted) reconstructed the scroll bar development using OSL dating in combination with historical maps.

Here we take advantage of the preservation of a palaeochannel ~~predating the meandering phase~~ (here referred to as "Palaeochannel X") with comparable dimensions as Palaeochannel Q (Huisink, 2000, p. 123), preserved in the Junnerkoeland as a sharp bend (Fig. 1~~(c)~~c). Maas (1995) interpreted Palaeochannel X to be connected to the first swale of the scroll bar deposit before Palaeochannel X was cut off (Fig. 1~~(c)~~c). Palaeochannel X was likely abandoned ~~shortly~~ before the scroll bar formation, because large differences in dimensions exist between Palaeochannel X and the meander bend, but the well-preserved nature suggests that Palaeochannel X is relatively young. l~~We assume Palaeochannel X to date from the same period as Palaeochannel Q reported by Huisink (2000, p.123), i.e. prior to the meandering phase (Fig. 2), because Palaeochannel Q has similar dimensions and was already cut off on the historical map of 1720 AD. arge differences in dimensions exist between Palaeochannel X and the meander bend, but the well-preserved nature suggests that Palaeochannel X is relatively young.~~The

small dimensions of both palaeochannels would suggest that the river had comparatively less energy, and may have been relatively laterally stable prior to the meandering phase.

~~We assume Palaeochannel X to date from the same period as Palaeochannel Q reported by Huisink (2000, p.123), i.e. prior to the meandering phase (Fig. 2), because Palaeochannel Q has similar dimensions and was already cut off on the historical map of 1720 AD. The small dimensions of both palaeochannels would suggest that the river had comparatively less energy, and~~

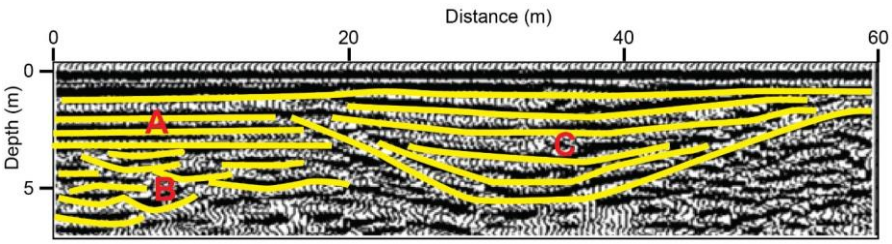


Figure 2: Interpretation by Huisink (2000) of subsurface strata from GPR data collected near Hardenberg 13 km upstream of Junnerkoeland (see location in Fig. 1~~(b)~~b)~~, modified after Huisink (2000)~~. Horizontal strata of coversand deposits (A) on top of the channel deposits of an interpreted braiding system (B). A relatively small, symmetrical palaeochannel is present (C) within the Late-Glacial deposits, hereafter referred to as "Palaeochannel Q". Figure adapted after Huisink (2000).

~~may have been relatively laterally stable prior to the meandering phase.~~

3. Methods

~~3.1 Approach~~

~~The first aim was to identify the possible channel pattern change. Therefore, we inferred the genesis from lithological transects in both study areas. In addition, we dated the cut-off of Palaeochannel X and investigated the lateral stability of the phase represented by the palaeochannel. The second aim was to identify the potential causes of the channel pattern change, if real. To identify whether the potential specific stream power increased, we reconstructed the bankfull discharge (Q_{bf}) for both Palaeochannel X and Q, and the two meanders, using the scroll bar deposition as a geological archive of the former channel dimension. The reconstructed Q_{bf} is the discharge that just fills the channel before spilling on the floodplain, or the discharge at minimum width-depth ratio (Williams, 1978), and is commonly considered an approximation of the channel-forming discharge with a recurrence interval of 1 to 2 years (Dury, 1973; Wolman and Miller, 1960). The Q_{bf} can be used to calculate the potential specific stream power and potential sediment transport, and hence to investigate whether changes thereof may explain the channel pattern change. A disproportionally higher scroll bar formation rate compared to the sediment transport may point at extra sediment input, which may explain the meander initiation (Ferguson, 1987; Nanson and Croke, 1992). To determine whether possible changes in discharge and channel dimensions could have resulted in channel pattern change, the~~

~~potential for meandering was calculated through time using the stability diagram of Kleinhans and Van den Berg (2011) and the bar regime applying relationships of Struiksma et al. (1985), which will be further elaborated below.~~

3.~~2~~1 Lithological description

Corings were performed in a transect perpendicular to the scroll bars of both meander bends (Fig. 1~~(c)~~c-~~(d)~~d). An additional transect was cored perpendicular to Palaeochannel X (Fig. 1~~(e)~~e). In case the deposit consisted of peat we used ~~A~~a gouge auger (Ø: 3 cm), in case of unsaturated sand we used ~~,~~ an Edelman auger and in case of saturated sand we used a~~a~~ Van der Staay suction corer (Van de Meene et al., 1979) ~~were used when the deposit consisted of peat, unsaturated sand or saturated sand, respectively~~. In total, 68 corings were performed to a maximum depth of 7.3 m ~~(i.e. the full length of the employed suction corer with extensions)~~. The surface elevation of each coring site was either determined using a GPS combined with a DEM (Van Heerd and Van't Zand, 1999), or with a Global Navigation Satellite System (GNSS) device. A standard method was used to describe the sediment cores in 10-cm-thick intervals, using the Dutch texture classification scheme, which approximately matches the USDA terminology (Berendsen and Stouthamer, 2001; De Bakker and Schelling, 1966). The median sediment grain size (D_{50}) of non-organic, sandy samples was visually checked in the field by comparison with a sand ruler. Grain size analysis was used to estimate a D_{50} for the entire scroll bar deposit (Sect. 3.3). ~~.~~ In addition, the plant macro-remains, any visible bedding and colour were described. The percentage of gravel (>2 mm) was estimated using field sieves. The lithogenesis was inferred from the lithological properties, facies geometries and DEM topography, distinguishing fluvial, fluvioperiglacial, coversand, drift-sand and residual channel-fill deposits (Huisink, 2000; Ter Wee, 1966).

3.~~3~~2 Ground-penetrating radar

Ground-penetrating radar (GPR) was used to reconstruct the channel dimensions of the scroll bars. ~~GPR is a suitable tool in sandy substrate (Neal, 2004), and regularly used in scroll bar deposits (Bridge et al., 1995; Heinz and Aigner, 2003; Slowik, 2011).~~ GPR measurements were conducted with a pulseEKKO PRO 250Hz with a SmartTow configuration. The GPR transects were placed along the centreline of the meander bends, perpendicular to the ridge and swale morphology (Fig. 1~~(c)~~c-~~(d)~~d). The electromagnetic-wave velocity was 0.060 m ns^{-1}, derived by using isolated reflector points (Neal, 2004; Van Heteren et al., 1998) and by comparing depths of recognizable layers with the coring data.

3.~~4~~3 Grain size analysis

In total 33 samples for grain size analysis were taken from the scroll bar deposits and three samples were taken from Palaeochannel X. The samples of the scroll bar deposits were taken from each 0.5 m interval from the channel lag up to the swale surface at three locations in Junnerkoeland and two locations in Prathoek (Fig. 1~~(c)~~c-~~(e)~~e). The samples of Palaeochannel X were taken from three locations below the residual channel-fill, from the former river bed. Grain size samples were analysed in a laboratory with a LS230 Laser Particle Sizer. This instrument has a measurement range of 0.1 to 2000 µm. Samples were sieved ~~over~~ with a 2 mm sieve, and prepared with HCL (1 M) and H_2O_2 (30%) ~~according to the laboratory prescriptions~~. All

data were processed using a Fraunhofer.rfd optical model, because of the low clay-silt content (Agrawal et al., 1991). Finally, the average and standard deviation were calculated for both the scroll bar deposits and Palaeochannel X, and used in the ~~palaeodischarge~~ palaeohydrological calculations.

3.~~5~~4 OSL dating

We used the modelled age-distance relationships determined ~~We used the scroll bar dates determined~~ by Quik and Wallinga (submitted) in our calculations. Their obtained OSL ages from the scroll-bar deposits were used as priors and combined with historical map data in a Bayesian deposition model using the OxCal software (Bronk Ramsey, 2009). ~~We briefly describe their methods used for the OSL dating~~For details on the method see Quik and Wallinga (submitted). In this study, we took four additional samples for OSL dating on the inner and outer bank of Palaeochannel X. These samples were collected in an opaque PVC-tube (Ø 4.5 cm) mounted on a hand-auger allowing sampling without light exposure. The analysis in the laboratory followed the same procedure as in Quik and Wallinga (submitted)~~, apart from the final Bayesian analysis, which could not be applied to this small OSL dataset because it lacked additional constraints from historical maps. Samples were taken to determine the burial age of the sandy scroll bars (e.g. Wallinga, 2002), using a Van der Staay suction corer (Ø 4 cm) (Wallinga and Van der Staay, 1999). The scroll bars were delineated using the same lithological descriptions and lithogenetic interpretation as in this study. OSL samples were taken above the channel lag, and within the reduction zone to reduce uncertainty in the environmental dose rate due to water content fluctuations.~~ The OSL age was determined at the Netherlands Centre for Luminescence dating, with equivalent doses measured on small aliquots of quartz using the SAR protocol (Murray and Wintle, 2003) and dose rates determined from activity concentrations measured using gamma-ray spectrometry. A bootstrapped version of the minimum age model (Cunningham and Wallinga, 2012) was used to derive the best estimate of the burial dose. ~~The thus obtained OSL ages were used as priors and combined with historical map data in a Bayesian deposition model~~ (see Quik and Wallinga, submitted)~~ using the OxCal software (Bronk Ramsey, 2009). The modelled age-distance relationships were used in our calculations. In this study, we took four additional samples for OSL dating on the inner and outer bank of Palaeochannel X. These samples were collected in an opaque PVC-tube (Ø 4.5 cm) mounted on a hand-auger allowing sampling without light exposure. The analysis in the laboratory followed the same procedure as in~~ Quik and Wallinga (submitted)~~, apart from the final Bayesian analysis, which could not be applied to this small OSL dataset because it lacked additional constraints from historical maps.~~

3.~~6~~5 ^{14}C dating

~~The cut-off of Palaeochannel X was dated using radiocarbon (^{14}C) dating.~~ A sample was taken in the deepest part of the palaeochannel, at the sand-peat interface, using a piston corer (Ø: 6 cm). Macro-remains and leaf fragments from terrestrial species were selected from 1 cm intervals in the laboratory using a light microscope. Samples were stored in diluted HCl. The sand content was measured for each interval to precisely determine the position of the sand-peat interface. Material with

volumetric sand percentages lower than 10 to 20% was considered as peat (Bos et al., 2012). The macro-remains from the centimetre above this interface were selected for the ^{14}C analysis providing a *terminus ante quem* date for the abandonment of the channel. The ^{14}C age was determined by Accelerator Mass Spectrometry (AMS) at the Centre for Isotope Research (Groningen University). For calibration, the IntCal13 curve was used in the OxCal4.2.4 software (Bronk Ramsey, 2009; Reimer et al., 2013).

3.~~7~~6 Channel dimensions

The channel dimensions of Palaeochannel X were determined from the lithological cross-section. ~~-~~The residual channel-fill was delineated along the sand-peat interface. Bankfull depth (H_{bf}) was defined from the bottom of the palaeochannel up to the first clear knick-point on ~~the~~ the bank, which was mapped with the GNSS device, ~~-~~such that the width-depth ratio was minimal (Williams, 1986). Uncertainty of the channel dimensions was introduced by measuring H_{bf} until the first clear knick-point on both banks. ~~The~~Additional dimensions were measured from the delineated channel, involving the bankfull width (W), cross-sectional area (A) and wetted perimeter (P). ~~. These channel dimensions were also measured for Palaeochannel Q from the GPR profile recorded by Huisink (2000, p.123) (Fig. 2).~~ These channel dimensions were also measured for Palaeochannel Q from the GPR profile recorded by Huisink (2000, p.123) (Fig. 2). The average and standard deviation of the channel dimensions were calculated and used in the calculations. ~~The dimensions were measured from the delineated channel, involving the bankfull width (W), cross-sectional area (A) and wetted perimeter (P). We assumed a standard deviation of 5% of the W, A and P measurements. These channel dimensions were also measured for Palaeochannel Q from the GPR profile recorded by Huisink (2000, p.123) (Fig. 2).~~ Additional channel dimensions were calculated ~~using Eq. 4 to 6,~~by applying the same procedure as for the scroll bar deposits (see below).

During the meandering phase the river channel was assumed to have the channel dimensions as shown in Fig. 3. This sketch is based on Allen (1965), Leeder (1973) and Hobo (2015). The bankfull depth (H_{bf}) was estimated from the coring data, taken from the bottom of the channel lag up to the surface elevation in the swales (Fig. 4~~). ~~). Small elevation differences were expected to be caused by local variation rather than real changes in H_{bf}, therefore the average H_{bf} was calculated from the

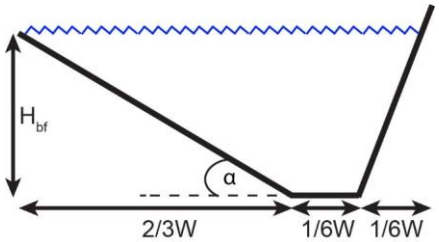


Figure 3: Sketch of the cross-sectional flow area of a meandering channel used for the bankfull palaeodischarge calculations (Allen, 1965; Hobo, 2015; Leeder, 1973).

smoothed ~~Both the~~ bottom and surface elevation~~ were smoothed.~~ ~~, because small elevation differences were expected to be caused by local variation rather than real changes in H_{bf}. We assumed a standard deviation of 5% of the H_{bf} measurements, based on expert judgement~~The standard deviation of H_{bf} was calculated from the actual variable bottom and surface elevation over the length of the scroll bar. The transverse bed slope (α) of the inner bend was determined based on the GPR transects (Fig. 5), in which lateral accretion surfaces could be distinguished. The angle was measured on the steepest parts of the identified lateral accretion surfaces. The calculations of the channel dimensions follow from Fig. 3. The bankfull width (W, m) and cross-sectional area (A, m^2) were determined by Eq. 1 and 2:

$$\boldsymbol{W = 1.5\frac{H_{bf}}{tan(\alpha)}} \quad (1)$$

$$\boldsymbol{A = WH_{avg}} \quad (2)$$

where H_{bf} is the bankfull depth, and $H_{avg} = \frac{7H_{bf}}{12}$ and approximates the average water depth (m). The wetted perimeter (P, m) was calculated from the assumed channel geometry (Fig. 3) following Eq. 3:

$$\boldsymbol{P = \frac{H_{bf}}{sin(\alpha)} + \frac{W}{6} + \sqrt{(H_{bf}^2 + \frac{W}{6})^2}} \quad (3)$$

The hydraulic radius (R, m) was calculated by Eq. 4:

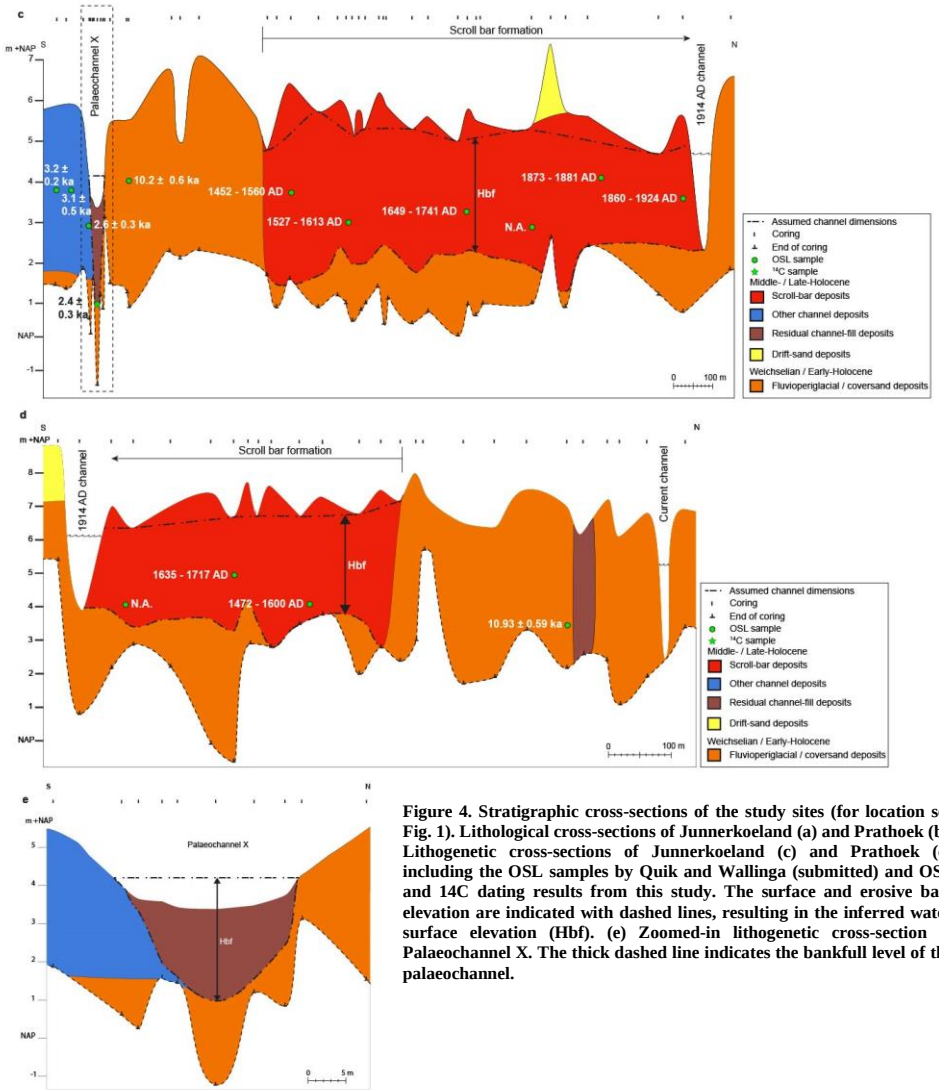


Figure 4. Stratigraphic cross-sections of the study sites (for location see Fig. 1). Lithological cross-sections of Junnerkoeland (a) and Prathoek (b). Lithogenetic cross-sections of Junnerkoeland (c) and Prathoek (d) including the OSL samples by Quik and Wallinga (submitted) and OSL and 14C dating results from this study. The surface and erosive base elevation are indicated with dashed lines, resulting in the inferred water surface elevation (Hbf). (e) Zoomed-in lithogenetic cross-section of Palaeochannel X. The thick dashed line indicates the bankfull level of the palaeochannel.

$$R = \frac{A}{P} \quad (4)$$

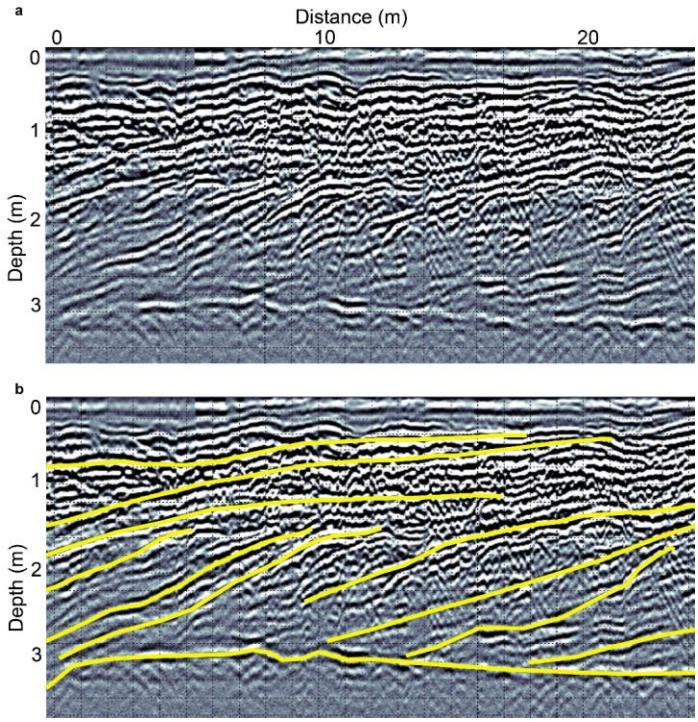


Figure 5. Example of a ground-penetrating radar (GPR) profile (250 Hz) in the Prathoek bend. (a) original GPR profile and (b) interpreted GPR profile with lateral accretion surfaces and the channel lag, indicated by yellow lines.

For each swale visible on the DEM the sinuosity (s), radius of curvature (R_{curv}) and scroll bar surface area (SB_{surf}) was measured. The former channel sinuosity was estimated by the use of the DEM, measuring the distance along the swales relative to the distance along the valley between the inflection points (Fig. 1~~(c)~~c-~~(d)~~d). The sinuosity of Palaeochannel X was ~~assumed to be similar to the start of the meandering phase, based on the assumption that Palaeochannel X was connected to the first~~

~~swale in Junnerkoeland~~measured using the same approach (Fig. 1~~(c)~~c). The channel slope (S_c) was calculated from the sinuosity and valley slope (S_v) from Wolfert and Maas (2007) following Eq. 5:

$$S_c = S_v/s \tag{5}$$

The volumetric rate of scroll bar growth (SB_{vol}, $m^3\ yr^{-1}$) was determined from scroll bar surface area (SB_{surf}, $m^2\ yr^{-1}$) and thickness between each swale and interpolated time interval following Eq. 6:

$$SB_{vol} = \frac{SB_{surf} * H_{bf} * (1-\varphi)}{\Delta age} \tag{6}$$

where φ is the porosity (here 0.3 to 0.35 volume fraction) (Nimmo, 2004), which was included to compare the SB_{vol} with the sediment transport, and Δage is the age difference between the scroll bars (yr) based on the datings by Quik and Wallinga (submitted). Equation 6 was also applied to the inner bank of Palaeochannel X.

3.~~8~~ 7 Palaeodischarge

The channel dimensions were used to calculate the bankfull discharge. We assumed that the bankfull discharge was similar for both Junnerkoeland and Prathoek, regarding the short distance between these river sections (Fig. 1~~(b)~~b). Hence the average bankfull discharge and standard deviation was calculated, combining both meander bends. The bankfull discharge was estimated by applying the Chézy equation, following Eq. 7:

$$Q_{bf} = CA\sqrt{RS_c} \tag{7}$$

where Q_{bf} = bankfull discharge ($m^3\ s^{-1}$), and C = Chézy coefficient ($m^{0.5}\ s^{-1}$). ~~From Eq. 7 the cross-sectionally averaged flow velocity (u_{bf}, m s^{-1}) was calculated by~~ ~~.~~The Chézy coefficient, i.e. flow resistance, was estimated using ~~, is an important unknown parameter in Eq. 7. We used several methods~~ an empirical relation (Brownlie, 1983) following Eq. 8:~~to estimate an acceptable range for the Chézy coefficient for both the meandering and palaeochannels X and Q~~. ~~The first was an empirical relation (Brownlie, 1983) following Eq. 8:~~

$$Q_{bf} = \left(\frac{R}{(0.3724 * S_c^{-0.2542} * \sigma_s^{0.105} * D_{50})}\right)^{1.529} W g^{0.5} D_{50}^{1.5} \tag{8}$$

where σ_s is the sorting of the bed material grain size derived from the grain size analysis (Sect. 3.3) and approximated by $0.5(D_{50}/D_{16} + D_{84}/D_{50})$, D_{16} and D_{84} are the 16th and 84th percentile sediment grain size, respectively, and g is the gravitational acceleration (9.81 $m^2\ s^{-1}$). Equation 8 was substituted in Eq. 7 to calculate C. ~~From Eq. 7 the~~The cross-sectionally averaged flow velocity (u_{bf}, m s^{-1}) was calculated by following Eq. 9:

- ~~.The second method comprised estimating the Manning roughness coefficient (n) to calculate C. We estimated the n value from the streambed characteristics such as cross-section irregularity, channel variations, obstructions, vegetation and the degree of sinuosity, applying the procedure presented byArcement and Schneider (1989)~~ (Arcement and Schneider, 1989); Jarrett (1985)~~ and Cowan (1956). The n value was estimated at 0.0288 for both the meandering and palaeochannels X and Q, and agrees with estimated n values for sand-bed rivers (Chow, 1959). The Chézy coefficient is related to the Manning coefficient (Manning et al., 1890) following Eq. 9:~~

$$u_{bf} = \frac{Q_{bf}}{A} \qquad (9)$$

~~Thirdly, we determined the median Chézy coefficient for a large dataset of 79 rivers for which sufficient data was available~~ (Kleinhans and Van den Berg, 2011; Van den Berg, 1995)~~, and for a subset of 30 rivers and 20 rivers with scroll bars and without bars, respectively. Finally, we compared the estimated Chézy coefficient with a study done on the channelized Overijsselse Vecht (TAUW, 1992), in which the Chézy coefficient was estimated based on expert judgement.~~

3.~~9~~ 8 Sediment transport

The sediment transport was calculated to compare with the SB_{vol}, which was calculated in Eq. 6. Sediment transport was calculated in two different ways. The first method was the slightly modified Engelund and Hansen (1967) relation following Eq. 10:

$$Q_{s,bf} = \frac{0.05\, u^5 W t i}{\left(\frac{\rho_s}{\rho} - 1\right)^2 g^{0.5} D_{50} C^3 (1-\varphi)} \qquad (10)$$

where $Q_{s,bf}$ is the yearly sediment transport derived from the bankfull discharge ($m^3\ yr^{-1}$), t = the number of seconds in a year, i = the intermittency assumed to be 0.05 (no uncertainty taken) (Parker, 2008), ρ_s =the sediment density (kg m^{-3}), ρ = the water density (kg m^{-3}), φ is the porosity assumed to be 0.3 to 0.35 (Nimmo, 2004). The relation of Engelund & Hansen was used, because the relation is suitable for sand-bed rivers with relatively low flow velocities (Van den Berg & Van Gelder, 1993), and the input variables required were available.

In the second method the sediment transport was determined for each discharge magnitude and related frequency ($Q_{s,freq}$) (Wolman and Miller, 1960) from present-day flow conditions, by assuming that the current discharge frequency distribution also applied to the meandering phase. We used the hourly discharge data from 1995 to 2015 of the gauging station in Mariënberg (Fig. 1~~(b)~~b). This gauging station is close to the study location, and has the lowest amount of data gaps compared to the other stations. The flow duration was calculated for intervals of 10 $m^3 s^{-1}$, and for each discharge interval the sediment transport was calculated using Eq. 10, excluding the intermittency factor. When the discharge would be above bankfull, the flow would go across the floodplain. The Chézy coefficient for the floodplain was assumed to be half the Chézy coefficient in the channel, because of the higher roughness of the floodplain compared to the channel. We assumed that the floodplain width was 350 m for the start of the meandering phase, which was estimated from the DEM (Fig. 1~~(c)~~c), and that the width would increase proportionately with the lateral migration rate for each time step during the meandering phase.

3.~~10~~ 9 Potential specific stream power

The potential specific stream power was calculated to plot ~~to plot both channel pattern phases in a~~into a stability diagram. Kleinhans and Van den Berg (2011) distinguished four different stability fields, further building on Van den Berg (1995) and Bledsoe and Watson (2001): rivers with laterally stable channels, meandering rivers with scroll bars, meandering rivers with scroll and chute bars as well as moderately braided rivers, and braided rivers. In this research, only the first two stability fields are relevant. These stability fields are separated by a discriminator that represents the theoretical minimum energy needed for the channel pattern to occur~~. This means that the discriminator should be interpreted as a lower threshold, rather than a hard threshold between the channel patterns~~ (Kleinhans and Van den Berg, 2011). The potential specific stream power was calculated by applying the relationship presented by Kleinhans and Van den Berg (2011) following Eq. 11:

$$\omega_{pv} = \frac{\rho g \sqrt{Q_{bf}} S_v}{\varepsilon} \qquad (11)$$

where ε = 4.7 $\sqrt{s\, m^{-1}}$ for sand-bed rivers (Van den Berg, 1995). The discriminators separating laterally stable rivers from meandering rivers with scroll bars were calculated for the measured median bed grain sizes. Multiple discriminator lines were plotted to take into account the range in the measured bed grain sizes, applying the relationships presented by Makaske et al. (2009) and Kleinhans and Van den Berg (2011) following Eq. 12:

$$\omega_{ia} = 90 D_{50}^{0.42} \qquad (12)$$

where subscript *ia* refers to the discrimination between laterally stable and meandering channels with scroll bars.

3.~~11~~ 10 Bar regime

Bar regime was predicted applying the relationships of Struiksma et al. (1985) and Kleinhans and Van den Berg (2011). ~~Bar regime is based on the interaction between the flow and bed sediment, and their response to disturbances.~~ River bends can be seen as an example of a disturbance to both the flow and bed sediment, which have different adaptation lengths over which they return to equilibrium. This difference in response is expressed by the interaction parameter (IP~~, Eq. 18~~), which is the ratio between the adaptation length of bed disturbance and the adaptation length of flow. The adaptation length of flow was calculated following Eq. 13:

$$\lambda_w = \frac{C^2 H_{avg}}{2g} \tag{13}$$

and the adaptation length of a bed disturbance (m) is calculated following Eq. 14:

$$\lambda_s = \frac{H_{avg}}{\pi^2}\left(\frac{W}{H_{avg}}\right)^2 f(\theta) \tag{14}$$

where f(θ) = the magnitude of the transverse slope effect calculated following Eq. 15 (Talmon et al., 1995):

$$f(\theta) = 9\left(\frac{D_{50}}{H_{avg}}\right)^{0.3}\sqrt{\theta} \tag{15}$$

where θ = the dimensionless shear stress calculated following Eq. 16:

$$\theta = \frac{\tau}{(\rho_s - \rho) g D_{50}} \tag{16}$$

where τ = the shear stress (Pa), calculated following Eq. 17:

$$\tau = \rho g R S_c \tag{17}$$

The interaction parameter (IP) was calculated, following Eq. 18, to determine the bar regime of rivers according to Struiksma et al. (1985), and for comparison with the theoretical thresholds of bar regime (Crosato and Mosselman, 2009; Struiksma et al., 1985) by:

$$IP = \frac{\lambda_s}{\lambda_w} \quad (18)$$

The IP is strongly related to the width-depth ratio, and was therefore separately calculated for the meander bends Junnerkoeland and Prathoek. A low IP means that when a bar forms in response to a local perturbation, such as local curvature, the bar disappears within a short distance of the perturbation (Struiksma et al., 1985). This is called an overdamped regime and occurs in channels with a low width-depth ratio. The threshold can be calculated following Eq. 19:

$$IP \leq \frac{2}{n+1+2\sqrt{2n-2}} \quad (19)$$

where n = the degree of nonlinearity of sediment transport versus depth-averaged flow velocity. Following Crosato and Mosselman (2009) we chose n = 4, which corresponds to values for a sand-bed river. A higher IP, and hence a higher width-depth ratio, results in an underdamped regime associated with bars that also form further downstream of the perturbation. The thresholds can be calculated following Eq. 20:

$$\frac{2}{n+1+2\sqrt{2n-2}} < IP < \frac{2}{n-3} \quad (20)$$

The above described calculations (Eq. 1 to 11, and 13 to 20) were run ~~200~~ 10.000 times to take into account the uncertainty of the input parameters, using Monte Carlo simulations. The uncertainty of these parameters was described above, relating to the transverse bed slope, bankfull depth, valley slope, ~~bankfull depth,~~ porosity and grain size ~~(D_{50}), Chézy coefficient and the measured channel dimensions of palaeochannels X and Q~~. These parameters were used in the calculations applying a normal distribution. All results are plotted with average values from the Monte Carlo simulations, and a range of one standard deviation representing the uncertainty margin.

4. Results

4.1 Lithogenetic units

Several lithogenetic units were distinguished (Fig. 4), following similar interpretations of the sedimentary units as Huisink (2000). The description of the lithogenetic units are summarized in Table 1. The coversand deposits were sometimes difficult to distinguish in borehole descriptions from the fluvioperiglacial deposits, when the latter has a relatively fine grain size. Because our interest is the delineation of the scroll bar and residual channel-fill deposits we combined both the fluvioperiglacial and coversand deposits into one unit.

The fining upward sequence within the scroll bar deposits can be recognized in the grain size analysis done for the scroll bar deposits at Junnerkoeland and Prathoek (Fig. 6). The depth-averaged grain size for both scroll bar complexes is 0.28 ± 0.05

mm. Commonly, at the base of the scroll bar deposits, a sharp transition occurs to the brightly coloured substratum of fluvioperiglacial deposits below, which lack organic material (Table 1). Corings that did not reach the fluvioperiglacial deposits below the scroll bar deposits indirectly indicate the boundary between these units, because relatively resistant layers are present in the fluvioperiglacial deposits that were difficult to core into. An example of a relatively erosion-resistant clay layer can be found in the southern part of the scroll bar deposits at Prathoek (Fig. 4b and d).

The GPR profiles clearly show the lateral accretion surfaces of the scroll bar deposits (see example in Fig. 5). Only where the scroll bar deposits are relatively loamy or clayey on top, the GPR results were poor (i.e. northern parts of Prathoek and

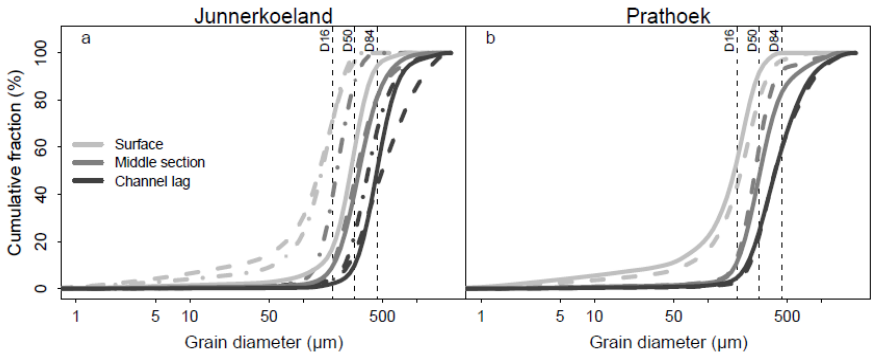


Figure 6: Cumulative grain size distributions of the scroll bar deposits in (a) Junnerkoeland and (b) Prathoek. Three series were made for Junnerkoeland and two for Prathoek, indicated by a different line type. Each sample within a series is indicated by a different colour. The depth-averaged D16, D50 and D84 are plotted. Figure 1c~~(c) (d)~~ indicates the locations of the texture samples.

Table 1: Description of lithogenetic units

	Fluvio-periglacial deposits	Coversand deposits	Other channel deposits	Residual channel-fill deposits	Scroll bar deposits	Drift-sand deposits
Lithology	Mod. sort. 75-2000 µm Lenses of loam and loamy sand	Well sort. 75-210 µm Loamy sand	Mod. sort. 105-600 µm	Sandy peat or peaty sand. Lenses of sand, silty clay loam or clay loam	Mod. sort. 75-600 µm Loamy sand near surface	Well sort. 75-210 µm
Colour	Light grey to brown	Light grey/brown	Light grey/brown or white	Dark brown or black	Light brown to dark grey	Greyish brown
Gravel (%)	0-20	<1	<1	<1	<40	<1
Plant remains	Mostly absent	None	Sporadically near bottom	Abundant	Fragmented and abundant near bottom	Rare
Thickness (m)	>2	<2	4-5	4-5	4-5	1-5
Width (m)	>1000	>1000	<100	20-40	>100	10-100
Beds	cm's to dm's	None	None	None	cm's to dm's	None

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Additional	Palaeo-podzol on top	Slightly coarser near bottom	May be poorly preserved	Fining upward. lateral accretion surfaces (GPR	Micro-podzol on top.

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Junnerkoeland). The bottom of the scroll bar deposits is mostly unrecognizable, because of a low GPR reflection at this depth. In Fig. 5 the bottom of the scroll bars is visible, because this part is located in the southern part of Prathoek where the above-mentioned clay layer was present (Fig. 4), which caused a strong reflection of the GPR signal.

~~**Scroll bar deposits** consist of moderately well sorted clastic sediments varying in grain size from extremely fine to coarse sand (75 – 600 µm). The colour of the unit is light brown to dark grey. Often a clear fining upward sequence is present over the depth of the scroll bar deposits, with sandy loam or loamy sand near the surface and lenses of medium fine to coarse sand containing up to 40% of gravel at the bottom (channel lag) (Fig. 4(a) – (b)). This fining upward sequence could also be recognized in the grain size analysis done for the scroll bar deposits at Junnerkoeland and Prathoek (Fig. 6). The depth-averaged grain size for both scroll bar complexes is 0.28 ± 0.05 mm. The unit can show well developed beds from several centimetres up to several decimetres in thickness. Iron oxide concretions can be found above the lower groundwater table. The unit contains fragments of plant remains, wood and shells, which are especially abundant near the channel lag. When this unit is found at the surface, it consists of a clear scroll and swale topography.~~

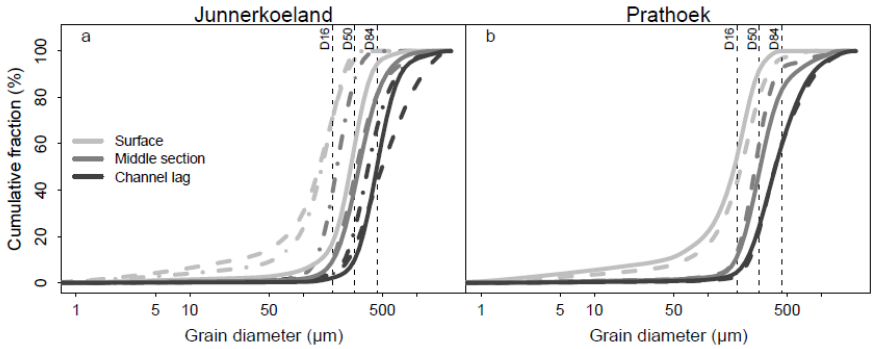

Figure 6: Cumulative grain size distributions of the scroll bar deposits in (a) Junnerkoeland and ~~(b)~~ddddddddddddddddddddddddddddd Prathoek. Three series were made for Junnerkoeland and two for Prathoek, indicated by a different line type. Each sample within a series is indicated by a different colour. The depth-averaged D16, D50 and D84 are plotted. Figure 1(c)-(d) indicates the locations of the texture samples.

~~Commonly, at the base of these deposits, a sharp transition occurs to the brightly coloured substratum of fluvioperiglacial deposits below, which lack organic material. The thickness is mostly 4 to 5 metres at maximum, and the width is several hundred metres. Corings that did not reach the fluvioperiglacial deposits below the scroll bar deposits indirectly indicate the boundary between these units, because relatively resistant layers are present in the fluvioperiglacial deposits that were difficult to core into. Such a clear lower boundary was found for the southern part of the scroll bar deposits at Prathoek (Fig. 4 (b) and (d)), formed by a clay layer. This clay layer is relatively erosion-resistant, possibly limiting channel scour and thus river incision.~~

~~The GPR profiles clearly show the lateral accretion surfaces of the scroll bar deposits (see example in Fig. 5). Only where the scroll bar deposits are relatively loamy or clayey on top, the GPR results were poor (i.e. northern parts of Prathoek and Junnerkoeland). The bottom of the scroll bar deposits is mostly unrecognizable, because of a low GPR reflection at this depth. In Fig. 5 the bottom of the scroll bars is visible, because this part is located in the southern part of Prathoek where the above-mentioned clay layer was present (Fig. 4(b)), which caused a strong reflection of the GPR signal.~~

~~**Other channel deposits** were found on the inner side of the Palaeochannel X bend (Fig. 4(a) and (c)). These deposits consist of moderately sorted clastic sediments varying in grain size from fine sand to coarse sand (105 – 600 µm). The colour of the unit is light grey, light brown or white. Iron oxide concretions are abundantly present above the lower groundwater table. Small fractions of plant remains are only sporadically present near the bottom of the unit, which is slightly coarser than the upper part. Beddings are absent, as well as a clear scroll and swale topography. No lateral accretion surfaces can be observed in the GPR profile that was placed along the centreline of the Palaeochannel X bend. The thickness is similar to the scroll bar deposits, but the width is 100 m at maximum.~~

~~**Fluvioperiglacial deposits** consist of moderately sorted clastic sediments varying in grain size from extremely fine to very coarse sand (75 – 2000 µm). The unit can contain loam and loamy sand, and low percentages of gravel (0 to 20%). The colour of the unit is light grey to brown, and relatively homogeneous with depth. The unit can contain beds of loam and gravel from several centimetres up to several decimetres in thickness. Organic material is mostly absent, and only sporadically found in laminae and beds of several millimetres up to several centimetres in thickness. This unit is found below and lateral to the scroll bar deposits, and can reach a thickness of tens of metres.~~

~~**Coversand deposits** consist of well-sorted clastic sediments varying in grain size from extremely fine to fine sand (75 – 210 µm). The unit may contain small loam fractions (<10%). The colour is light grey or light brown. Organic material is mostly absent. Soil formation, a thick palaeo-podzol, may be found in the top of this unit. This unit is located on top of the fluvioperiglacial deposits, and often near or at the surface. The unit has a maximum thickness of two metres in the study area. This unit may be difficult to distinguish in borehole descriptions from the fluvioperiglacial deposits, when the latter has a relatively fine grain size. Because our interest is the delineation of the scroll bar deposits we combined both the fluvioperiglacial and coversand deposits into one unit.~~

Drift-sand deposits consist of well-sorted clastic sediments varying in grain size from extremely fine to fine sand (75 – 210 µm). The colour is greyish brown. Organic material is rare. A micro-podzol may be present in the top of this unit. The unit is located at the surface, mostly on top of coversand deposits. The coversand palaeo-podzol often forms a distinct boundary between these two units. This unit is easily distinguishable from the other units, because of large topographic differences at the surface of several metres over short horizontal distances (e.g. 100 m).

Residual channel-fill deposits consist of (sandy) peat or peaty sand. Lenses of very fine to fine sand (105 – 210 µm), silty clay loam or clay loam may be present in the unit. The colour of the peat is dark brown, but turns black when exposed to air. Plant remains are abundantly present in the unit. Iron concretions may be present as well. This unit has a relatively low width/depth ratio (5 to 10) in the cross-section, and can have a thickness of up to four metres. In both transects (Fig. 4), peaty residual channel-fill deposits are present within the fluvioperiglacial and coversand deposits. The residual channel-fill at Prathoek is poorly preserved and hardly recognizable at the surface.

Table 1: OSL and ^{14}C dating results from Palaeochannel X. Locations are indicated in Fig. 1(c)-(d) and Fig. 4(c).

Sample Code	Material	Elevation (m +NAP)	^{14}C age (a BP)	Palaeo-dose (Gy)	Dose rate (Gy/ka)	Age (ka)	Lat, Long (RD)
NCL2416194	Fluvial sand	1.10		2.1 ± 0.2	0.81 ± 0.03	2.6 ± 0.3	229242, 505286
NCL2217157	Fluvial sand	3.65		3.3 ± 0.2	1.06 ± 0.05	3.1 ± 0.5	229249, 505254
NCL2217158	Aeolian sand	3.99		12.5 ± 0.5	1.23 ± 0.05	10.2 ± 0.6	229254, 505338
NCL2217159	Fluvial sand	3.55		3.6 ± 0.2	1.14 ± 0.05	3.2 ± 0.2	229242, 505228
GrA69519	Selected macro-fossils	1.14	2300 ± 100			2.4 ± 0.3	229239,505298

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4.2 Palaeo-channel X

The well-preserved Palaeochannel X is a relatively symmetrical palaeochannel (Fig. 4~~(e)e), and)~~, similar ~~very similar~~ to Palaeochannel Q of Huisink (2000) (Fig. 2). ~~). Palaeochannel X forms a very sharp bend, which is often found in low-energy streams where lateral migration is limited (Candel et al., 2018; Candel et al., 2017; Kleinhans et al., 2009). No lateral accretion surfaces are observed on the inside of Palaeochannel X, which can be derived from the GPR profile.~~ The outer bank consists of Weichselian / Early Holocene deposits (Fig. 4~~(c)~~c). The average grain size of the Palaeochannel X bed sediments is 0.23 ± 0.12 mm.

No lateral accretion surfaces can be observed in the GPR profile that was placed along the centreline of the Palaeochannel X bend (Fig. 1e). The channel deposits on the inside of the Palaeochanel X date from 3.2 ± 0.2 ka. Palaeochannel X was cut off at 2.4 ± 0.3 ka (Fig. 1e, Fig. 4c and Table 2).

Table 2: OSL and ^{14}C dating results from Palaeochannel X. Locations are indicated in Fig. 1c-d and Fig. 4c.

Sample Code	Material	Elevation (m +NAP)	^{14}C age (a BP)	Palaeo-dose (Gy)	Dose rate (Gy/ka)	Age (ka)	Lat, Long (RD)
NCL2416194	Fluvial sand	1.10		2.1 ± 0.2	0.81 ± 0.03	2.6 ± 0.3	229242, 505286
NCL2217157	Fluvial sand	3.65		3.3 ± 0.2	1.06 ± 0.05	3.1 ± 0.5	229249, 505254
NCL2217158	Aeolian sand	3.99		12.5 ± 0.5	1.23 ± 0.05	10.2 ± 0.6	229254, 505338
NCL2217159	Fluvial sand	3.55		3.6 ± 0.2	1.14 ± 0.05	3.2 ± 0.2	229242, 505228
GrA69519	Selected macro-fossils	1.14	2300 ± 100			2.4 ± 0.3	229239,505298

~~The average grain size of the Palaeochannel X bed sediments is 0.23 ± 0.12 mm. Palaeochannel X formed by extremely slow channel displacement, shown by the OSL dates taken from the channel~~

Commented [CJ1]: Section 2 (study area): P6, L29-37: A lot of assumption are made in this part. I suggest to move this part to section 4.2 (results). And then in section 4.2, you have to provide all available arguments to state that channel X is predating the meandering phase. Show data to support your statements (eg show the GPR profile). You have to provide good arguments to state that channel X is from a laterally stable phase, since this is an important point for the rest of the story.

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~~deposits on the inside of Palaeochannel X (Fig. 1(e), Fig. 4(c) and Table 1). A channel cut-off probably caused Palaeochannel X to become disconnected from the main river before the meandering phase started. Palaeochannel X was cut off ca. 2.4 ± 0.3 ka, indicated by the ^{14}C dating (Fig. 4(c), Table 1), while inner-bend channel deposits located 50 m from the residual channel were dated at ca. 3.2 ± 0.2 ka. Hence the bend formed with a rate of ca. 6 cm yr^{-1} assuming a constant channel displacement rate. The lateral migration rate of the Junnerkoeland meander bend was ca. 40 times higher (Quik and Wallinga, submitted; Wolfert and Maas, 2007).).~~ ~~Palaeochannel X forms a very sharp bend, which is often found in low-energy streams where lateral migration is limited (Candel et al., 2018; Candel et al., 2017; Kleinhans et al., 2009).~~

4.3 Meander and channel geometry

The reconstructed transverse bed slopes do not show a trend in space (Fig. 7~~(a)~~a-~~(b)~~b), hence the mean and standard deviations were used in the ~~palaeodischarge~~ palaeohydrological calculations. The transverse bed slope at Prathoek is higher (4.5 ± 1.0 °) than at Junnerkoeland (3.3 ± 1.3 °), but much lower than the transverse bed slope of Palaeochannel X (~~23.4~~16.9 ± 1.9 ~~°~~) and of Palaeochannel Q (~~12~~28.8 ~~.8~~± 3.8 ~~°~~ °). The age as function of distance of lateral accretion ~~is a relatively linear relation (Fig. 7(c)-(d)), using dates~~follows from Quik and Wallinga (submitted) (Fig. 7c-d). This relation was used for the meander and channel geometry calculations (Fig. 8). The

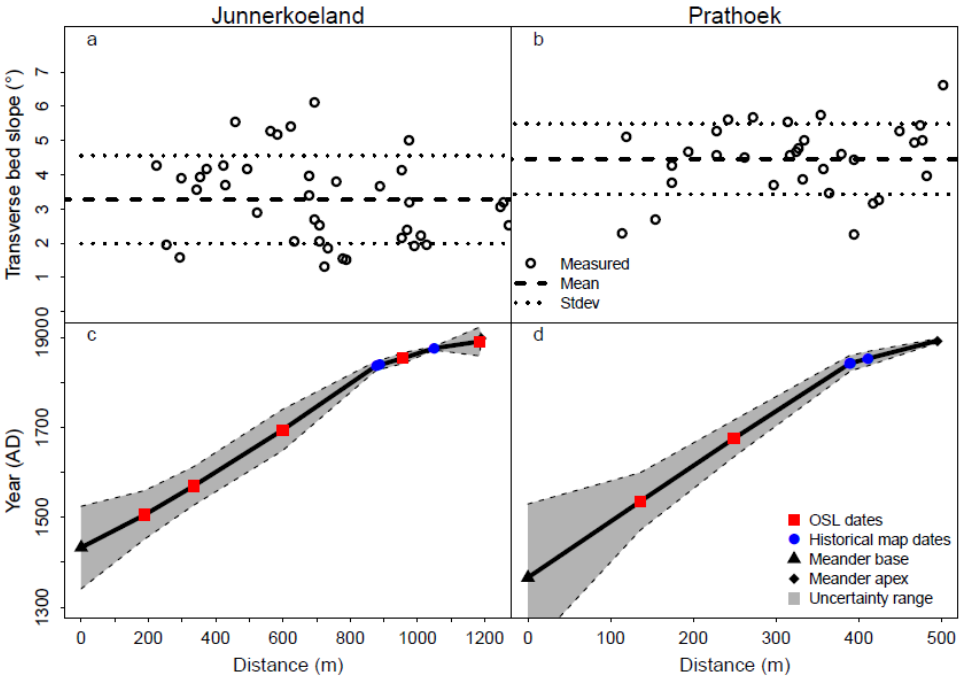

Figure 7: Transverse bed slope derived from GPR cross-sections from the inner point bar to the outer bend for Junnerkoeland (left) and Prathoek (right) as well as lateral migration distance plotted against age for both bends. Panels (a) and (b) show transverse bed slope of lateral accretion surfaces measured in the GPR profile (example in Fig. 4), including the mean and standard deviation of all measurements. Panels (c) and (d) show relation between age and migration distance of the bends. Shading indicates standard deviation of the Bayesian deposition model determined by Quik and Wallinga (submitted) for the OSL and historical map dates.

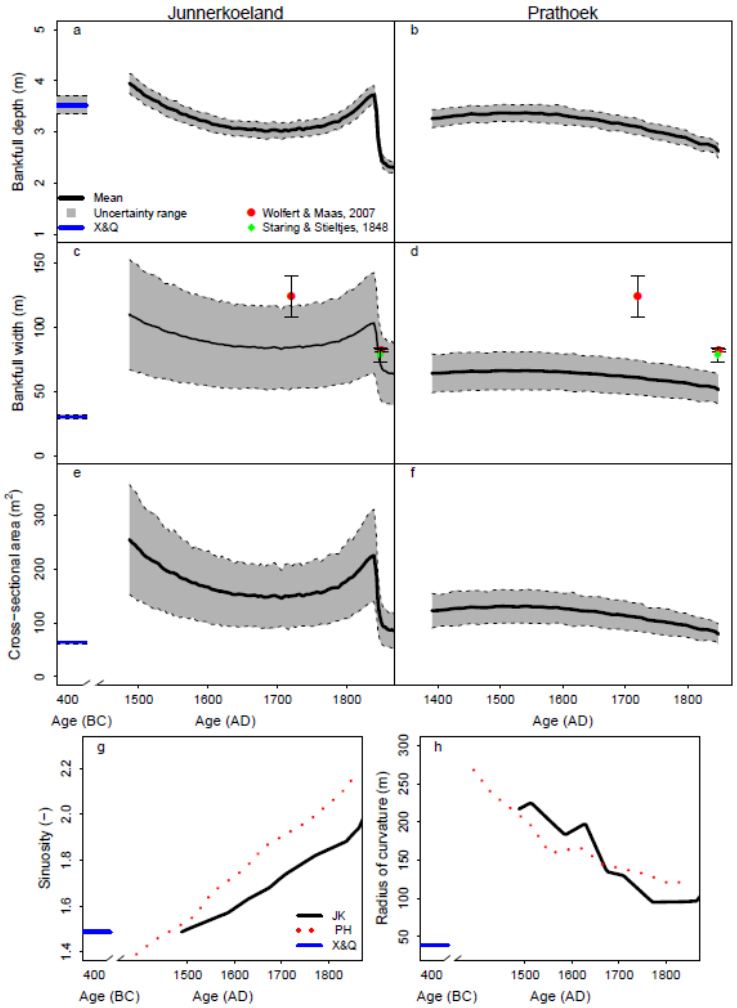

Figure 8: Reconstructed meander and channel geometry over time, assuming the date-distance relations (see Fig. 7~~(c)-(d)~~d) over the scroll bars. Panels (a) and (b) show the bankfull depth (Hbf) derived from the coring data, taken from the bottom of the channel lag to the inferred water surface (Fig. 4~~(c)-(d)~~). Panels (c) and (d) show the bankfull width for both the Junnerkoeland bend (left) and Prathoek (right) derived from the bankfull depth and reconstructed transverse bed slope (Eq. 1). The river width data from Wolfert and Maas (2007) observed on historical maps, and the bankfull river width data from Staring and Stieltjes (1848) were included for comparison. Panels (e) and (f) show the cross-sectional area derived from the bankfull width and water depth (Eq. 2). ~~(g) Sinuosity estimated from available historical maps and DEM (Fig. 1). (h) Radius of curvature (Rcurv) derived from the DEM. (JK = Junnerkoeland, PH = Prathoek, X&Q = Palaeochannel X & Q).~~

bankfull depth of palaeochannels X and Q are comparable to the bankfull depth ~~at the start of the meandering phase at~~of the meanders Prathoek and Junnerkoeland (Fig. 8~~(a)~~a-~~(b)~~b) (3.5 to 4.2 m). The bankfull depth at Junnerkoeland decreases relatively fast at ca. 1800 AD, because the erosive base elevation rises towards the cut-off channel (Fig. 4~~(c)~~c). At Prathoek, the bankfull depth decreases more gradual over time. The reconstructed bankfull width of palaeochannels X and Q is much lower compared to the meandering phase (Fig. 8c-d), resulting in a relatively small cross-sectional area of palaeochannels X and Q (Fig. 8e-f).

~~The reconstructed bankfull width of palaeochannels X and Q is much lower compared to the meandering phase (Fig. 8(c)-(d)), resulting in a relatively small cross-sectional area of palaeochannels X and Q (Fig. 8(e)-(f)). River width observations from previous studies were compared to the reconstructed width. These observations included observations measured from historical maps by Wolfert and Maas (2007) and measurements of the bankfull river width over a large river section in 1848 AD by Staring and Stieltjes (1848). The river width data from Wolfert and Maas (2007) largely fall in the range of reconstructed bankfull widths at Junnerkoeland, and show a similar decreasing trend (Fig. 8(c)-(d)). However, the historical maps used by them may result in large uncertainties, because the water stage that these maps represent is unknown. The measured widths by Staring and Stieltjes (1848) are in line with the predicted width at Junnerkoeland, falling within the uncertainty range. The~~

~~**Table 2: Calculated Chézy coefficients using different methods including the current Chézy coefficient of the channelized Overijsselse Vecht.**~~

~~**Method**~~	~~**Chézy coefficient (s^{-1})**~~	
	~~**Meander bends**~~	~~**Palaeochannel X & Q**~~
~~Brownlie~~	~~48.2 ± 0.5~~	~~46.4 ± 1.1~~
~~Manning (n = 0.0288)~~	~~38.4 ± 0.8~~	~~39.1 ± 1.1~~
~~Median of all rivers with scroll bars in Kleinhans et al. (2011)~~	~~40.5~~	
~~Median of all rivers without bars in Kleinhans et al. (2011)~~	~~34.2~~	
~~Median of all rivers in Kleinhans et al. (2011)~~	~~36.2~~	
~~Current channelized Vecht (Tauw, 1992)~~	~~50~~	
~~Estimation of Chézy~~	~~43.0 ± 2.0~~	~~40.0 ± 2.0~~

~~predicted width at Prathoek is underestimated compared to the measured widths by Wolfert and Maas (2007) and Staring and Stieltjes (1848). This underestimation also results in an underestimated cross-sectional area (Fig. 8(f)) and consequently an underestimated bankfull discharge (Fig. 9(a)). Both at Prathoek and Junnerkoeland, the sinuosity increases during the lateral migration of the channel (Fig. 8(g)), and both bends become sharper because the radius of curvature decreases (Fig. 8(h)).~~

4.4 ~~Palaeodischarge and sediment transport~~Palaeohydrology

~~The Chézy coefficient was needed to calculate the Q_{bf} (Eq. 7). Based on the estimated Chézy coefficients (Table 2), the Chézy coefficient for the meandering phase should fall within the range of 38.0-48.0 $m^{0.5}$ s^{-1}, and for palaeochannels X and Q within the range 34.0-46.0 $m^{0.5}$ s^{-1}. We used the middle of the ranges: 43.0 $m^{0.5}$ s^{-1} and 40.0 $m^{0.5}$ s^{-1}, respectively, both with a standard deviation of 2.0 $m^{0.5}$ s^{-1} to represent the full ranges.~~ The reconstructed Q_{bf} is ~~two~~ two to ~~five~~ fourteen times higher at the start

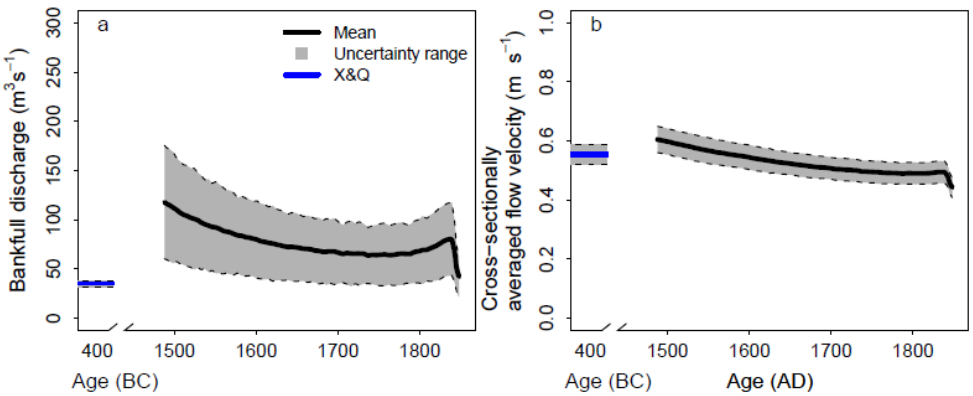

Figure 9: Discharge and flow velocity during bankfull conditions over time, combined for Junnerkoeland and Prathoek, derived from the channel geometry (Fig. 8) and flow resistance (Table 2). (a) Bankfull discharge (Eq. 7). (b) Cross-sectionally averaged flow velocity. (X&Q = Palaeochannel X & Q)

of the meandering phase (~~63~~ 42 – 14~~38~~2 m^3 s^{-1}) than during the preceding ~~laterally stable~~ phase for palaeochannels X and Q (~~32~~ 10 - ~~38~~21 m^3s^{-1}) (Fig. 9~~(a)~~a). The Q_{bf} declines over time, and drops ~~relatively fast at ca. 1800 AD~~to ca. 16 – 66 m^3 s^{-1} ca. 1850 AD.~~.~~ The average flow velocity (u_{bf}) is relatively similar for palaeochannels X and Q and the meandering phase (Fig. 9~~(b)~~b) and does not change much over time.

Combining the frequency of each discharge interval with the sediment transport rate (Fig. 10~~(a)~~a), results in a histogram of the sediment transport contribution as function of discharge ($Q_{s,freq}$, Fig. 10~~(b)~~b). The highest measured discharge at the gauging station Mariënberg between 1995 and 2015 is 185.5 m^3 s^{-1}. The most frequent discharge occurring in the channelized Overijsselse Vecht is 0 to 10 m^3 s^{-1}, with a frequency of 8.2% (Fig. 10~~(a)~~a). This discharge is mainly affected by the weirs currently present in the channelized river. When discharge is still below bankfull, ~~S~~sediment transport ~~increase is highest~~

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increases relatively fast with an increasing discharge. ~~when discharges are low, and decreases w~~Above bankfull~~hen the bankfull stage is reached~~, ~~because~~ additional discharge flows across the more flow-resistant floodplain, and hence sediment transport rates increase less. The effective discharge (Q_{eff}) is 29 $m^3 s^{-1}$, represented by the highest sediment transport contribution (Fig. 10~~(a)~~a-~~(b)~~b).

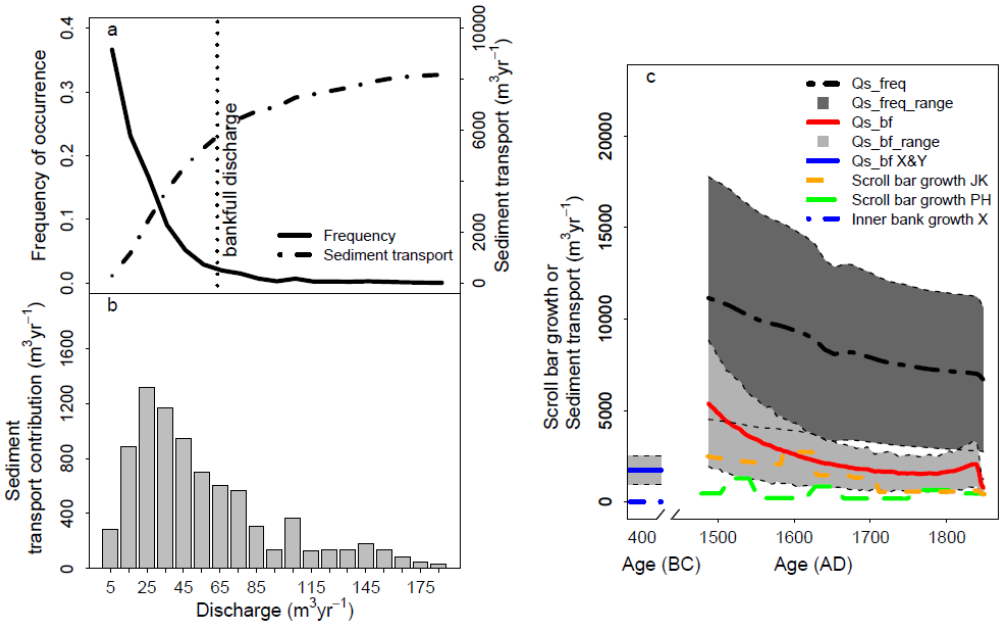

Figure 10: Sediment transport budgets calculated from present-day flow conditions and from meander migration. (a) Discharge and sediment transport characteristics of the Overijsselse Vecht derived from hourly discharge data from 1995 to 2015 of the gauging station Mariënberg, including the frequency of each discharge class over a year, on a frequency scale from 0 to 1, and the sediment transport as function of discharge for the predicted year 1546 AD in the Junnerkoeland meander bend. (b) Histogram of the sediment transport contribution as function of discharge. (c) The sediment transport and scroll bar growth over time (JK = Junnerkoeland, PH = Prathoek, X&Q = Palaeochannel X & Q). The inner bank growth X refers to the growth rate of the channel deposits on the inner bank at Palaeochannel X, assuming a constant lateral migration rate.

Fig. 11a shows that the river theoretically had insufficient stream power for meandering at 400 BC. The stream power seemed just sufficient for meandering at 1500 AD, but the potential for meandering decreased from then on. The bar regime was overdamped at 400 BC. The bar regime was underdamped, and possibly slightly in excitation at 1500 AD until the river was channelized.

~~Figure 10(c) shows that both estimates of sediment transport, $Q_{s,freq}$ and $Q_{s,bf}$, were higher than the scroll bar growth in Junnerkoeland and Prathoek, suggesting that the scroll bar growth could entirely be explained by the sediment transport. Hence external sediment input was probably limited and did not contribute to the meander initiation. The $Q_{s,bf}$ of palaeochannels X and Q is much lower than for the meandering channels, explaining the large difference between the growth rate of the channel deposits on the inner bank at Palaeochannel X (7.4 $m^3 yr^{-1}$) and the scroll bars of Junnerkoeland and Prathoek at the start of the meandering phase ($2.5*10^3 m^3 yr^{-1}$ and $4.6*10^2 m^3 yr^{-1}$, respectively).~~

~~4.5 Potential specific stream power and bar regime~~

~~Palaeochannels X and Q seem to lack the potential to meander given their low position in Fig. 11(a), and are characterized by an overdamped regime (Fig. 11(b)). The stable character of this system is corroborated by the symmetrical channel shape, the absence of scroll bars (Fig. 2 and 4e) and the low sediment transport (Fig. 10(c)), explaining the limited channel displacement found with the ^{14}C and OSL datings (Table 1, Fig. 4(c)). Our data indicates that the bar regime changed from an overdamped regime into an underdamped regime (Fig. 10(c)-(d)), leading to overdeepening of the outer-bend pool and enhancement of the point bars in the inner-bend (Crosato and Mosselman, 2009; Kleinhans and Van den Berg, 2011; Struiksma et al., 1985). The higher bankfull discharge (Fig. 9(a)) explains the potential to meander (Fig. 11(a)), the high sediment transport and the scroll bar growth (Fig. 10(c)) at the start of the meandering phase.~~

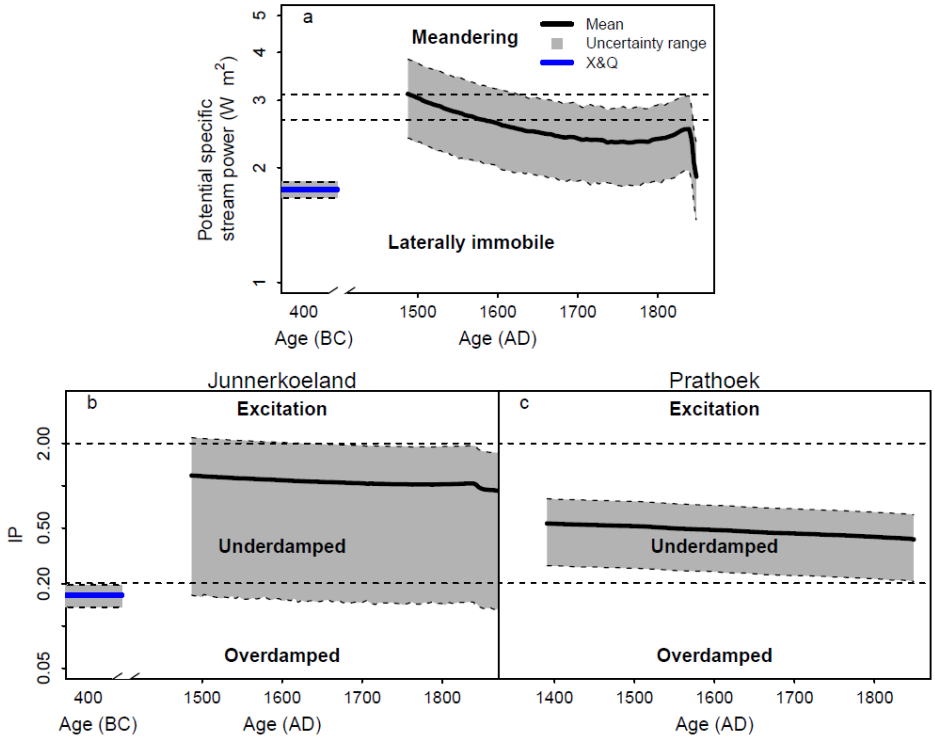

Figure 11: The potential for meandering with time. (a) The potential specific stream power in a stability diagram (Eq. 11). Several discriminators were plotted for a range of median particle sizes of the bed sediment, which is the range of particle sizes found in the scroll bars and Palaeochannel X&Q (Fig. 6). The discriminators should be interpreted as lower thresholds rather than hard thresholds. Panels (b) and (c) show the bar regime for both Junnerkoeland and Prathoek, determined with the interaction parameter (IP) (Eq. 18), and compared to the thresholds (Eq. 19 and 20) (X&Q = Palaeochannel X & Q).

5

5.1 Discussion

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~~The Qbf can be used to calculate the potential specific stream power and potential sediment transport, and hence to investigate whether changes thereof may explain the channel pattern change. A disproportionally higher scroll bar formation rate compared to the sediment transport may point at extra sediment input, which may explain the meander initiation (Ferguson, 1987; Nanson and Croke, 1992).~~**~~5. Discussion~~ 5.1 Laterally stable phase**

The results indicate a relatively laterally stable phase existed prior to the meandering phase. Palaeochannel X formed by extremely slow channel displacement of ca. 6 cm yr^{-1}, assuming a constant channel displacement rate, shown by the OSL dates taken from the channel deposits on the inside of Palaeochannel X (Fig. 1e, Fig. 4c and Table 2). The lateral migration rate of the Junnerkoeland meander bend was ca. 40 times higher (Quik and Wallinga, submitted; Wolfert and Maas, 2007). Palaeochannel Q was expected to date from the same laterally stable phase, because of the large similarities in channel symmetry (Fig. 2 and 4e) and size (51.2 ± 5.0 m^2, Fig. 8e), which was approximately a factor three to eight lower than during the meandering phase (261 ± 116 m^2).

As explained previously (Sect. 1), the preservation potential of deposits associated to the laterally stable phase is likely to be very small. Channel reaches are only preserved when they have been subject to perturbations causing them to be cut off prior to the stable-meandering transition, such as Palaeochannel X, and possibly Palaeochannel Q. In this way these reaches escaped from later lateral erosion during the meandering phase. Consequently, the lateral stability of the river is not immediately evident from these preserved channel reaches, because the perturbations led to very slow channel displacement as was found for Palaeochannel X. However, scroll bar deposits did not form (Fig. 2, Fig. 4e), showing that the displacement was not related to meandering in which helicoidal flows cause bar formation and bank erosion at a significant rate (Seminara, 2006). Palaeochannel X also forms a very sharp bend ($\frac{R_{curv}}{W}$ = 1.4 ± 0.2) compared to the meandering phase ($\frac{R_{curv}}{W}$ = 2.1± 0.4), which is often found in low-energy streams where lateral migration is limited (Candel et al., 2018; Candel et al., 2017; Kleinhans et al., 2009). Large similarities exist between the laterally stable phase reported here and the laterally stable channels in highly cohesive sediment on the intertidal mudflat, which are mostly laterally stable except from some sharp bends where bank failure and flow separation result in very limited and local channel migration (Kleinhans et al., 2009). .

. and the low sediment transport (Fig. 10c), explaining the limited channel displacement found with the ^{14}C and OSL datings (Table 2, Fig. 4c).

A channel cut-off probably caused Palaeochannel X to become disconnected from the main river before the meandering phase started. Palaeochannel X was cut off ca. 2.4 ± 0.3 ka, indicated by the ^{14}C dating (Fig. 4c, Table 2), while inner-bend channel deposits located 50 m from the residual channel were dated at ca. 3.2 ± 0.2 ka. Hence the bend formed with a rate of ca. 6 cm yr^{-1} assuming a constant channel displacement rate.

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Palaeochannels X and Q seem to lack the potential to meander given their low position in Fig. 11a, and are characterized by an overdamped regime (Fig. 11b).

indicate that the river type has changed from laterally stable to meandering. As explained previously, the preservation potential of deposits associated to the laterally stable phase is likely to be very small. Channel reaches are only preserved when they have been subject to perturbations causing them to be cut off prior to the stable-meandering transition, such as Palaeochannel X, and possibly Palaeochannel Q. In this way these reaches escaped from later lateral erosion during the meandering phase. Consequently, the lateral stability of the river is not immediately evident from these preserved channel reaches, because the perturbations led to very slow channel displacement as was found for Palaeochannel X. However, scroll bar deposits did not form, showing that the displacement was not related to meandering in which helicoidal flows cause bar formation and bank erosion at a significant rate (Seminara, 2006). Large similarities exist between the laterally stable phase reported here and the laterally stable channels in highly cohesive sediment on the intertidal mudflat, which are mostly laterally stable except from some sharp bends where bank failure and flow separation result in very limited and local channel migration (Kleinhans et al., 2009).

Deposits and dimensions of channel reaches are not preserved when still active during the stable to meandering transition, because channel-belt dimensions increase. River reaches of laterally stable rivers can only be preserved when they are cut off by random and local disturbances prior to the meandering phase. Consequently, preservation potential of deposits associated to a laterally stable phase is very small, and only channel reaches that have been subject to perturbations have a chance to be preserved.

A disproportionally higher scroll bar formation rate compared to the sediment transport may point at extra sediment input, which may explain the meander initiation (Ferguson, 1987; Nanson and Croke, 1992).

5.1 Laterally stable phase

5.2 Channel pattern change

5.3 Meandering phase

The results indicate that the river type has changed from laterally stable to meandering. As explained previously, the preservation potential of deposits associated to the laterally stable phase is likely to be very small. Channel reaches are only preserved when they have been subject to perturbations causing them to be cut off prior to the stable-meandering transition, such as Palaeochannel X, and possibly Palaeochannel Q. In this way these reaches escaped from later lateral erosion during

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~~the meandering phase. Consequently, the lateral stability of the river is not immediately evident from these preserved channel reaches, because the perturbations led to very slow channel displacement as was found for Palaeochannel X. However, scroll bar deposits did not form, showing that the displacement was not related to meandering in which helicoidal flows cause bar formation and bank erosion at a significant rate (Seminara, 2006). Large similarities exist between the laterally stable phase reported here and the laterally stable channels in highly cohesive sediment on the intertidal mudflat, which are mostly laterally stable except from some sharp bends where bank failure and flow separation result in very limited and local channel migration (Kleinhans et al., 2009).~~

River width observations from previous studies were compared to the reconstructed width. These observations included observations measured from historical maps by Wolfert and Maas (2007) and measurements of the bankfull river width over a large river section in 1848 AD by Staring and Stieltjes (1848). The river width data from Wolfert and Maas (2007) largely fall in the range of reconstructed bankfull widths at Junnerkoeland, and show a similar decreasing trend (Fig. 8c). However, the historical maps used by them may result in large uncertainties, because the water stage that these maps represent is unknown. The measured widths by Staring and Stieltjes (1848) are in line with the predicted width at Junnerkoeland, falling within the uncertainty range. The predicted width at Prathoek is underestimated compared to the measured widths by Wolfert and Maas (2007) and Staring and Stieltjes (1848). This underestimation also results in an underestimated cross-sectional area (Fig. 8f) and consequently an underestimated bankfull discharge (Fig. 9a).

Figure 10c shows that both estimates of sediment transport, $Q_{s,freq}$ and $Q_{s,bf}$, were higher than the scroll bar growth in Junnerkoeland and Prathoek, suggesting that the scroll bar growth could entirely be explained by the sediment transport. Hence external sediment input was probably limited and did not contribute to the meander initiation. The $Q_{s,bf}$ of palaeochannels X and Q is much lower than for the meandering channels, explaining the large difference between the growth rate of the channel deposits on the inner bank at Palaeochannel X (7.4 m^3 yr^{-1}) and the scroll bars of Junnerkoeland and Prathoek at the start of the meandering phase ($2.5*10^3$ m^3 yr^{-1} and $4.6*10^2$ m^3 yr^{-1}, respectively).

5.2 Causes of the channel pattern change

Now that we have found indications of a channel pattern change, we aim to identify the potential causes using the ~~palaeodischarge~~ palaeohydrological reconstruction. It seems likely that the increasing bankfull discharge ~~(by a factor two to five, Fig. 9(a))~~ caused the channel pattern change. The channel pattern change likely occurred ca. 1400 AD, because older scroll bar deposits were not found in the Overijsselse Vecht catchment (Quik and Wallinga, submitted). Scroll bar growth significantly increased as a result of higher sediment transport rates (Fig. 10~~(c)~~c). The increasing bankfull discharge may reflect

an increase in annual discharge, but could also be related to a more irregular discharge regime, because the bankfull discharge partly represents the higher discharges in a river (Dury, 1973; Wolman and Miller, 1960). Consequently, the discharge may have been constant over a year with low peak discharges and a relatively high base flow during the laterally stable phase, changing into a discharge regime with high peak discharges and a relatively low base flow at the start of the meandering phase. Here we discuss potential allogenic factors that may have caused such changes in discharge regime.

5.2.1 Little Ice Age

The Little Ice Age (14th to 19th century) (Grove, 1988) may have contributed to the channel pattern change, given the overlap in time with the meandering phase. Although geomorphological responses differ for each river during the Little Ice Age, enhanced lateral migration or incision was generally observed for most rivers in North-western Europe (Rumsby and Macklin, 1996). Studies on historical observations of nearby rivers (IJssel, Elbe, Lower Rhine and Meuse) suggested a significant higher flooding rate during the Little Ice Age compared to more recent flooding rates (Glaser et al., 2010; Glaser and Stangl, 2003; Mudelsee et al., 2004, 2003). River ice jams contributed to ca. 70% of the floods in the Rhine delta, often in combination with precipitation and/or snow melt (Glaser and Stangl, 2003). These ice jams may have caused enhanced bank erosion, because ice jams can result in fast rising flow stages, whereas river ice break-ups will result in fast lowering flow stages and high peak discharges (Ettema, 2002). The water level in the bank responds fast to these changes in flow stage, hence seepage pressure will be high when the flow stage rapidly lowers. This process reduces the bank stability significantly, and may promote bank collapse of the steeper outer bend (Ettema, 2002).

During the Little Ice Age, the type of precipitation changed significantly, affecting the discharge regime of rivers in North-western Europe. Runoff relative to precipitation may have been higher in winter, due to reduced evapotranspiration rates and frozen soils (Rumsby and Macklin, 1996; Van Engelen et al., 2001). The snowfall/rainfall ratio was probably higher, due to lower winter temperatures in The Netherlands and Germany (Behringer, 1999; Lenke, 1968). Higher snowfall rates were also recorded for the United Kingdom (Manley, 1969), where it led to more flooding during the snowmelt period (Archer, 1992). In the Overijsselse Vecht catchment, snow melt probably also led to higher peak discharges. Currently, the yearly averaged precipitation over the winter months (December, January and February) is 201 mm in the study area. The largest amount of winter precipitation falls as rain, with an average air temperature of 3.4 °C for the period 1981 to 2010 (KNMI, 2010), and rapidly contributes to discharge. However, the 25-year averaged winter-temperature during the Little Ice Age was 1.2 °C, reconstructed by Van Engelen et al. (2001) for The Netherlands, suggesting that snowfall during this period was much more significant. If all precipitation in winter would fall as snow in the Overijsselse Vecht catchment (3785 km^2), which for example would melt in springtime within two weeks, an extra peak discharge of 625 m^3 s^{-1} would be generated when the evapotranspiration and infiltration is neglected. This snowmelt period returns more or less yearly, which matches the approximate recurrence interval of the bankfull discharge (Dury, 1973; Wolman and Miller, 1960).

5.2.2 Land use changes

An additional cause for a changing discharge regime could be land use changes in the catchment such as deforestation (Kondolf et al., 2002), which affects the discharge regime due to the direct relation with evapotranspiration (Fohrer et al., 2001). However, the most intense phase of deforestation occurred during the Iron Age and Roman period in the Overijsselse Vecht catchment (500 BC – 200 AD), as was derived from pollen records (Groenewoudt et al., 2007; Van Beek et al., 2015a). Forest was replaced by agricultural fields and open grass vegetation for grazing. Therefore, deforestation cannot be the main cause for the channel pattern change discussed in this paper, because it dates from a much earlier period.

Interestingly, another major land use change occurred in the catchment at a later stage, when humans started to reclaim land in peat areas to cultivate buckwheat. This land use change started in the 12th and 13th century (Gerding, 1995; Van Beek et al., 2015b), and intensified from the 14th century onwards (Borger, 1992; Van Beek et al., 2015a). Reclamation of peatlands comprised digging of channels to drain the land, and burning the top layer of the peat for fertilisation. After several years the land became exhausted and abandoned, and the next tract got reclaimed (Borger, 1992). After several centuries, focus shifted from peat reclamation to exploitation, excavating large peatland areas for fuel during the 17th and 18th century (Gerding, 1995). The cultivation and exploitation of peatlands may have had a significant impact on the discharge regime of the Overijsselse Vecht system, because approximately 27% of the Overijsselse Vecht catchment area was covered with peat around 1500 AD, of which the largest part has currently disappeared (Casparie and Streefkerk, 1992; Vos et al., 2011). Although the reclamation was mainly limited to the margins of peatlands, the hydrological consequences were large. The margins are a natural seal of the peat bog, with a low hydraulic conductivity compared to the remainder of the bog, ensuring peat dome growth. Destruction of these margins will result in drainage of the entire peat bog (Baird et al., 2008; Van der Schaaf, 1999). Yearly average discharges can increase by 40% in the Dutch climatological setting, due to evapotranspiration differences for reclaimed peat areas compared to undisturbed peat areas (Baden and Eggelsmann, 1964; Streefkerk and Casparie, 1987; Uhden, 1967). The discharge also becomes less well distributed over the year, with higher discharges in winter and lower discharges in summer, because water storage capacity changes after reclamation (Baden and Eggelsmann, 1964; Streefkerk and Casparie, 1987; Uhden, 1967). Especially the volumetric storage capacity of the top peat layer changes from 80 or 90% to less than 10%, because the top peat layer gets destructed by burning and lowering of the groundwater table leading to decomposition and oxidation (Streefkerk and Casparie, 1987; Van der Schaaf, 1999).

Several studies have shown that an increased drainage network in peatlands resulted in higher discharge peaks with a fast discharge response to precipitation (Conway and Millar, 1960; Holden et al., 2004; Holden et al., 2006; Streefkerk and Casparie, 1987). Holden et al. (2006) found that immediately after the drainage the runoff/rainfall ratio increased, probably related to dewatering of the peatland. This response was largest immediately after peat drainage, as ditches become less efficient over time when they fill up with vegetation or sediment (Fisher et al., 1996; Stewart and Lance, 1991). Finally, canals were not only dug for peat reclamation, but also for shipping and effective generation of water power starting in the 11th and 12th century (Driessen et al., 2000), which could have promoted the higher peak flows even more. New canals resulted in a

faster runoff, but also changed the watershed delineation (Driessen et al., 2000). Consequently, peak flows as well as the total discharge likely increased due to land use changes.

5.3 Meandering phase

Our data strongly suggest that the changing discharge regime was the main cause for the channel pattern change in the Overijsselse Vecht. The most likely identified causes are climate changes related to the Little Ice Age and land use changes in the catchment, in particular peat reclamation. Here we will shortly elaborate on the meandering phase, although in-depth understanding of the changes during the meandering phase is beyond the scope of this paper. Interestingly, the bankfull discharge declined over time (Fig. 9~~(a)~~a), leading to decreasing sediment transport relatively to the scroll bar growth (Fig. 10~~(c)~~c) and insufficient potential specific stream power for meandering after 1850 AD (Fig. 11~~(a)~~a). This decline would suggest that the forcing disappeared or diminished, and had a temporary character, which would fit with the hypothesis of the Little Ice Age that ended in the 19th century. However, the river was still laterally migrating until channelization in 1914 AD (Wolfert and Maas, 2007). Historical bank stability changes may have promoted the river meandering during this period. For example, floodplains were intensively used for cattle grazing, which may have weakened the banks, enhancing meandering after 1850 AD (Beschta and Ripple, 2012; Trimble and Mendel, 1995; Wolfert et al., 1996). Also drift-sand activity was initiated by intensive land use since the Late Middle Ages (Fig. 1~~(c)~~c-~~(d)~~d) (Koster et al., 1993), which may have affected the bank stability. Drift-sands may also have acted as an extra sediment supply to the river, altering the river morphodynamics by enhancing the scroll bar growth rate and therefore the bank erosion rate (Ferguson, 1987; Nanson and Croke, 1992). However, we found that the scroll bar growth can easily be explained by the reconstructed sediment transport until 1800 AD (Fig. 10~~(c)~~c). Therefore, it seems unlikely that increased sediment input by drift-sands initiated the meandering, but it may have promoted meandering since 1850 AD.

~~5.4 Channel pattern changes during the Holocene~~

~~We argue that many meandering rivers with a current potential specific stream power close to the lowest empirical threshold (Kleinhans and Van den Berg, 2011; Makaske et al., 2009) may have been laterally stable during most of the Holocene, prior to the Little Ice Age or increased human activity. In general, modified land use and water management for agriculture and urbanization purposes often caused increased high discharge peaks and flooding (Fohrer et al., 2001; Leopold, 1968) and hence increased fluvial activity. In particular, Wolman (1967) related fluvial changes such as channel widening to land use changes, and since then many studies followed (Downs and Gregory, 2014; Gregory, 2006; Notebaert et al., 2018; Notebaert and Verstraeten, 2010). The same applies to the consequences of increased snowfall and ice jams to fluvial activity during the Little Ice Age (Rumsby and Macklin, 1996). However, collected evidence of pattern changes of laterally stable to meandering during the Holocene is limited (Lewin and Macklin, 2010), which may mean that evidence is poorly preserved and/or not interpreted. Also, sinuous laterally stable rivers may have been misinterpreted as meandering. To identify Holocene channel~~

~~pattern changes, a higher resolution of subsurface data is needed than usually gathered, because palaeochannels of laterally stable rivers are poorly preserved in the fluvial archive of meandering channel belts (Van de Lageweg et al., 2016).~~

~~The Geul river in the southern Netherlands is an example of a river where a similar channel pattern change from laterally stable to meandering may have occurred. De Moor et al. (2008) hypothesized that this river was relatively laterally stable during the Early and Middle Holocene, until the last 2000 years in which the river was actively meandering. Most of the floodplain deposits from the laterally stable phase have not been preserved, but De Moor et al. (2008) were able to reconstruct the bankfull depth for both periods. They estimated the bankfull depth to be a factor two to three higher during the Late Middle Ages compared to the Early and Middle Holocene, caused by human and climate impact. Although they argue that their evidence is limited, our insights support the likelihood of their findings.~~

~~5.5 Implications for river management and restoration~~

~~A better understanding of channel pattern changes is of major importance for river restoration, which turned into a multi-billion industry aimed at improving the ecological functioning of rivers (Lewin and Macklin, 2010; Malakoff, 2004; Sear and Newson, 2003). Meandering rivers are often preferred in river restoration because of the high ecological value of such riverine landscapes (Ward et al., 2002; Ward et al., 2001), but the necessity of sufficient stream power to induce lateral migration is often ignored (Kondolf, 2006), and knowledge on the planform evolution is often lacking (Wohl et al., 2005). River restoration will result in increasing numbers of rivers where artificial bank protection is removed and natural processes can thrive. Although most lowland rivers are relatively laterally stable after restoration (Eekhout et al., 2015), they could change into meandering rivers when external forcings change, e.g. related to future climate or land use change (Anisimov et al., 2008). On the other hand, water retention measures in the catchment aiming at reducing flood risk or enhanced groundwater recharge, could result in a shift from active meandering to laterally stable rivers. Considering the importance of land use and climate on the river channel pattern, it is crucial to align plans for future landscape design and climate projections with river restoration goals. Therefore, predicting and understanding channel pattern changes is important to allocate sufficient space for rivers and to protect infrastructure from fluvial erosion, or to take precautions in the catchment to mitigate the impact of climatic changes on the river discharge regime.~~

~~River restoration measures should be approached from the processes (Brierley and Fryirs, 2009; Brierley et al., 2013; Makaske and Maas, 2015), rather than from a historical reference (Bernhardt and Palmer, 2011; Dufour and Piégay, 2009). The stability diagram and bar regime theory offer an easy approach in the restoration of low-energy rivers to estimate the potential for meandering. Our analysis shows that these empirical tools work relatively well to discriminate the laterally stable channel pattern from the meandering channel pattern (Fig. 11).~~

6. Conclusions

The channel pattern of the Overijsselse Vecht changed from a laterally stable into a meandering river during the Late-Holocene. We attribute this change to a two to five times increase in bankfull discharge, based on a ~~palaeodischarge~~ palaeohydrological

reconstruction building on channel dimensions of the different phases. Consequently, the river had sufficient potential specific stream power to erode outer banks and sufficient sediment transport to build scroll bars, in contrast to the preceding laterally stable phase. The bar regime changed from an overdamped to underdamped regime, leading to overdeepening of the outer-bend pool and enhancement of the point bars in the inner-bend. Historical land use and climate change were identified as the most likely causes of the channel pattern change. The bankfull discharge increased partly as a result of the Little Ice Age, due to increased snowfall and ice jams. Moreover, peat reclamation and exploitation has contributed to a changing discharge regime, as well as the digging of new canals for shipping and effective generation of water power. We argue that similar channel pattern changes likely occurred in many other low-energy rivers during the Late Holocene, but these are difficult to identify due to poor preservation of channel deposits associated with laterally stable river phases. Considering the importance of land use and climate on the river channel pattern, it is crucial to align plans for future landscape design and climate projections with river restoration goals.

Acknowledgements

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Late Holocene channel pattern change from laterally stable to meandering – a palaeohydrological reconstruction~~ – a palaeohydrological reconstruction~~

Jasper H.J. Candel[1], Maarten G. Kleinhans[2], Bart Makaske[1], Wim Z. Hoek[2], Cindy Quik[1], Jakob Wallinga[1]

[1]Soil Geography and Landscape Group, Wageningen University & Research, Wageningen, PO Box 47, 6700AA, The Netherlands
[2]Department of Physical Geography, Utrecht University, Utrecht, PO Box 80125, 3508TC, The Netherlands

Correspondence to: Jasper H.J. Candel (jasper.candel@wur.nl)

Abstract. River channel patterns may alter due to changes in hydrological regime, related to changes in climate and/or land cover. Such changes are well documented for transitions between meandering and braiding rivers, whereas channel pattern changes between laterally stable and meandering rivers are poorly documented and understood. We hypothesize that many low-energy meandering rivers had relatively low peak discharges and were laterally stable during most of the Holocene, when climate was relatively stable and human impact was limited.~~ Although channel deposits associated with such stable phases are poorly preserved, due to recent increase in dynamics of such systems, detailed palaeohydrological studies can help identifying historical channel pattern changes,~~

Our objectives of this work a~~is~~re to ~~relate~~ identify a Late Holocene channel pattern change for the low-energy Overijsselse Vecht River, to develop and apply a novel methodology to reconstruct discharge as a function of time following a stochastic approach, and to relate this channel pattern change to reconstructed hydrological changes~~changes in channel pattern of a low-energy river to changes in palaeohydrological conditions~~. We ~~identified~~ established that the Overijsselse Vecht ~~a river that~~ was laterally ~~almost~~ virtually stable throughout the Holocene until the Late Middle Ages, after which large meanders formed at lateral migration rates of about 2 m yr^{-1}. The lateral stability before the Late Middle Ages was constrained using a combination of coring information, ground-penetrating radar (GPR), radiocarbon (^{14}C) dating, and optically stimulated luminescence (OSL) dating. We ~~carried out a unique reconstruction of~~quantified bankfull ~~bankfull discharge~~palaeodischarge as a function of time, based on channel dimensions that were reconstructed from the scroll bar sequence and channel cut-offs using coring information and GPR data, combined with chronological constraints from historical maps and OSL dating. We found that ~~Thth~~e bankfull discharge was ~~was two to five times higher~~significantly greater during the meandering phase compared to the laterally stable phase. Empirical channel and bar pattern models showed that this increase ~~can likely~~can explain~~s~~ the channel pattern change. The bankfull discharge increase ~~likely~~ likely reflect~~s~~s climate changes related to the Little Ice Age and/or land use changes in the catchment, in particular as a result of peat reclamation and exploitation.

1. Introduction

Channel patterns describe the planform of a river, which reflects the interaction of the river channel with its floodplain. ~~C~~Channel patterns are classically distinguished~~.~~: ~~L~~laterally inactive channels consist of straight and ~~stable~~ sinuous stable planforms, whereas laterally active channels consist of meandering and braiding planforms (Leopold and Wolman, 1957; Nanson and Knighton, 1996). Flume experiments and field data have shown that the channel pattern depends on several variables (Kleinhans, 2010). Firstly, on the potential specific stream power, which is the product of the channel-forming discharge and valley slope ~~Flume experiments and field data have shown that channel pattern depends on the ratio between potential specific stream power and bank strength~~ (Nanson and Croke, 1992; Kleinhans and Van den Berg, 2011). Secondly, on the bank erodibility (Friedkin, 1945; Ferguson, 1987), ~~, of~~ which ~~the latter~~ is determined by the presence of bed~~hard~~ rock in the valley side (Turowski et al., 2008), the bank cohesiveness (Peakall et al., 2007) and vegetation (Millar, 2000; Gurnell, 2014). Thirdly, on the type and amount of sediment supply (Nanson and Croke, 1992; Gibling and Davies, 2012).

Channel patterns can change in response to environmental variations (Ferguson, 1987). Many examples of channel pattern changes from braiding to meandering and vice versa are known to be associated with glacial/interglacial oscillations (Vandenberghe, 1995; Vandenberghe, 2002). Especially studies on the last glacial-interglacial transition have shown the simultaneous occurrence of channel pattern changes with a changing climate (Vandenberghe et al., 1994; Kasse et al., 2016). Climate change affects the vegetation, sediment availability and discharge regime, and consequently the bank stability, sediment transport and potential specific stream power resulting in different channel patterns.

Within the Holocene, several examples of channel pattern changes are documented from braiding to meandering rivers and vice versa (Lewin et al., 1977; Passmore et al., 1993; Brewer and Lewin, 1998; Słowik, 2015). However, channel pattern changes between laterally stable and meandering rivers have rarely been reported (Lewin and Macklin, 2010), except where human intervention transforms meandering rivers into heavily regulated and laterally stable rivers by introducing weirs, dams, groynes and bank protection measures (Hesselink et al., 2003; Surian and Rinaldi, 2003; Słowik, 2013; Hobo et al., 2014). Also the partial abandonment of former meandering valleys may result~~s~~ in underfit, laterally stable rivers like the former Rhine branches in the Niers and Oude I~~j~~jssel valley (Kasse et al., 2005; Janssens et al., 2012).

Many studies have reported increased fluvial activity (e.g. increased discharge, sediment transport and deposition, and bank erosion rates) in relation to human, environmental and climatic pressures during the Holocene (e.g. Hoffmann et al., 2008; Macklin et al., 2010; Notebaert and Verstraeten, 2010; Lespez et al., 2015; Notebaert et al., 2018). An example of increased fluvial activity is known from the Pine Creek (Idaho, USA), where mining and deforestation combined with intensive grazing resulted in an increase of discharge and sediment input, followed by river widening and an increase in bank erosion (Kondolf et al., 2002). The reverse change has been observed in settings as a result of afforestation (Liébault and Piégay, 2001; Kondolf et al., 2002), or increase of riparian vegetation fixing the channel banks (Eekhout et al., 2014; Vargas-Luna et al., 2016). ~~De Moor et al. (2008) hypothesized that the Geul River in southern Netherlands may have been relatively laterally stable during the Early and Middle Holocene, until the last 2000 years in which the river was actively meandering. Most of the floodplain~~

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~~deposits from the laterally stable phase have not been preserved, but De Moor et al. (2008) were able to reconstruct the bankfull depth for both periods. They estimated the bankfull depth to be a factor two to three higher during the Late Middle Ages compared to the Early and Middle Holocene, caused by human and climate impact. This~~The increase of fluvial activity during the Holocene was corroborated by an extensive review of existing studies concerning sediment accumulation in West and Central European river floodplains by Notebaert and Verstraeten (2010). They concluded that sedimentation rates increased during the Middle and Late Holocene due to environmental changes. However, it is unknown ~~is~~ whether the channel pattern changed simultaneously with the floodplain, because no Early Holocene channel deposits ~~of the Early Holocene~~ representing a stable phase were ~~unrecognized~~identified. De Moor et al. (2008) hypothesized that the Geul River in southern Netherlands may have been relatively laterally stable during the Early and Middle Holocene, while it was actively meandering during the past 2000 years. Most of the floodplain deposits from the laterally stable phase have not been preserved, but De Moor et al. (2008) were able to reconstruct the bankfull depth for both periods. They estimated the bankfull depth to be a factor two to three higher during the Late Middle Ages compared to the Early and Middle Holocene, and related this change to human and climate impact.

We conjecture that the change from laterally stable to meandering has occurred in some rivers for which increased Holocene fluvial activity~~-~~ was reported. The fact that such changes were not reported in the literature, may either mean that critical conditions for channel pattern change were not reached, or that evidence of such transitions is poorly preserved or left unnoticed. Both laterally stable and meandering rivers may display sinuous planforms, but the geomorphic processes in both rivers are different. Laterally stable channels are rivers without meandering processes, i.e. helicoidal flows causing bar formation and bank erosion at a significant rate (Nanson and Knighton, 1996; Seminara, 2006; Kleinhans and Van den Berg, 2011). In fact, the bends and channel cut-offs in laterally stable rivers may be the result of random and local ~~disturbances~~ perturbations (e.g. falling trees, beavers, bank collapse after heavy rainfall, etc.) leading to very limited and local displacement of the channel. Meandering and laterally stable rivers should therefore be distinguished by their different patterns of bar and floodplain formation, rather than merely by planform (Kleinhans and Van den Berg, 2011; Candel et al., 2017). We suggest that identifying channel pattern changes requires more detailed historic accounts or a much higher resolution of subsurface data than usually gathered, because palaeochannels of laterally stable channels poorly preserve in the fluvial archive of meandering channel belts (Van de Lageweg et al., 2016), except when they have been cut off by random and local ~~disturbances~~ perturbations prior to the meandering phase. Using numeric (e.g. Oorschot et al., 2016) or scaled (e.g. Van Dijk et al., 2012) river simulation models is problematic for testing these ideas, because these have not yet been capable of reproducing channel pattern changes. This reflects the lack of understanding of river processes and patterns (Kleinhans, 2010), and the need to gather such information from field studies.

This research entails a case study focussing on a river where lateral activity during the past 500 to 600 years caused spectacular meandering: the Overijsselse Vecht in The Netherlands (Fig. 1). Previous work on this system has identified a transition from braiding to meandering during the Late-Glacial (Huisink, 2000) while the meandering pattern remained throughout the Holocene until the river was channelized between 1896 and~~in~~ 1914 ~~AD~~CE (Huisink, 2000; Neefjes et al., 2011). However,

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Quik and Wallinga (2018) found that the meanders were relatively young, with the oldest scroll bars dating from ca. 1400 to 1500 CE, by reconstructing~~ed~~ meander formation using a combination of optically stimulated luminescence (OSL) dating of scroll bars and planform reconstruction based on historical maps~~, and found that the meanders were relatively young, with the oldest scroll bars dating from ca. 1400 AD~~. No fluvial deposits were found dating from before this period, except from a Holocene palaeochannel (here referred to as "Palaeochannel Q") in a ground-penetrating radar (GPR) profile recorded by Huisink (2000, p.123) 13 km upstream near Hardenberg (Fig. 1b and 2). Palaeochannel Q is relatively small compared to the meandering channel, seems to lack scroll bars and was already cut off on the historical map of 1720 ~~AD~~CE. Therefore, it is questionable whether the Overijsselse Vecht meandered prior to ca. 1400 ~~AD~~CE. Alternatively, the river changed from a laterally stable into a meandering river ~~in~~ during the Late Middle Ages. Our aims are (1) to identify whether a channel pattern change has occurred from laterally stable to meandering, by collecting and combining detailed subsurface and geochronological data of the river ~~prior to and~~from ~~during~~ the pronounced meandering phase and the preceding phase;~~,~~ (2) to develop a methodology to reconstruct bankfull discharge as function of time, using the scroll bar deposits and channel remnants as a geological archive of the former channel dimensions; ~~-~~(3) to test whether palaeohydrological changes ~~, which will be reconstructed from the sedimentological record,~~ may explain the potential channel pattern change~~, by applying empirical channel and bar pattern models~~; and (4) to elaborate on the potential causes for changes in discharge and channel pattern.

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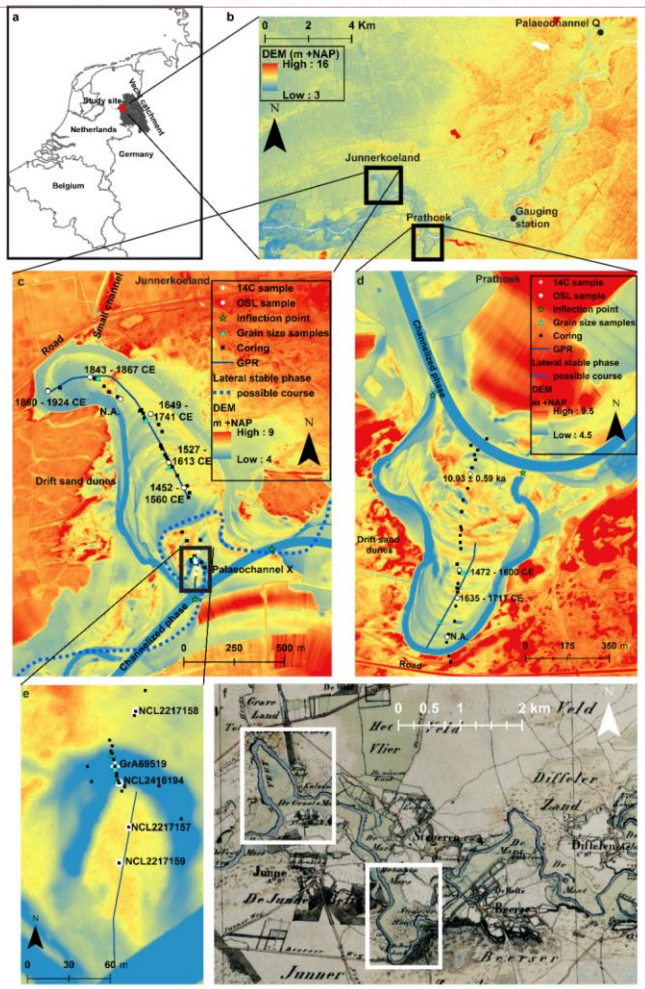

Figure 1: Maps of the Overijsselse Vecht. (a) Map showing the location of the Overijsselse Vecht catchment and the location of the study site. (b) Digital elevation map (DEM, Actueel Hoogtebestand Nederland, 0.5x0.5 m) (Van Heerd and Van't Zand, 1999) of the downstream section of the Overijsselse Vecht River, indicating both study sites: Junnerkoeland and Prathoek. DEM of the Junnerkoeland bend (c) and Prathoek bend (d), including locations of cores, OSL samples by Quik and Wallinga (2018), the OSL and ^{14}C samples from this study, the GPR transects, the grain size samples and inflection points. The possible historical course of Palaeochannel X according to Maas (1995) is indicated. (e) Zoomed-in figure of Palaeochannel X. (f) Topographical military map (TMK) dating from 1851 AD (CC-BY Kadaster, 2018; Van der Linden, 1973), showing the Overijsselse Vecht during its meandering phase.

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2. Study area

The Overijsselse Vecht (Fig. 1) is a low-energy, sand-bed river flowing from Germany into The Netherlands, with an average annual discharge (Q_m) of 22.8 $m^3 s^{-1}$ and a mean annual flood discharge (Q_{maf}) of 160 $m^3 s^{-1}$, derived from the gauging station in Mariënberg for the period 1995 to 2015 (see location in Fig. 1b). The river has a length of 167 km, its catchment covers 3785 km^2 with the highest point +110 m above sea level (asl), and a relatively uniform valley slope of $1.42*10^{-4}$ to $1.7*10^{-4}$ in the Dutch part of its trajectory (TAUW, 1992; Wolfert and Maas, 2007). The Overijsselse Vecht incised its current valley during the Late-Glacial within fluvioperiglacial sands, locally covered by aeolian coversands (Ter Wee, 1966; Huisink, 2000; Wolfert and Maas, 2007). During the Late Holocene, aeolian drift-sands formed along the Overijsselse Vecht as a result of agricultural overexploitation (Van Beek and Groenewoudt, 2011). The Overijsselse Vecht was an actively meandering river until 1896, when weirs were constructed and parts of the river were channelized. The river was completely channelized ~~in~~ after 1914 ~~AD~~CE, with five weirs controlling the water levels. Recently, sinuous side channels bypassing the weirs have been created as part of river restoration aiming to restore past physical and ecological characteristics of the river.

At present the topography of the meandering phase is partly still intact in the floodplain (Maas, 1995). Wolfert and Maas (2007) reconstructed the pre-channelization planform from historical maps of 1720, 1850 and 1890 ~~AD~~CE. Large differences in meander development and lateral migration rates were found between different river reaches. In particular in areas where non-cohesive aeolian sands formed the channel banks, large meanders formed and lateral migration reached rates up to 3 m yr^{-1}. In this research we will study two of the large meanders, named Prathoek and Junnerkoeland (Fig. 1), where Quik and Wallinga (2018) reconstructed the scroll bar development using OSL dating in combination with historical maps.

Here we take advantage of the preservation of a palaeochannel (here referred to as "Palaeochannel X") with comparable dimensions as Palaeochannel Q (Huisink, 2000, p. 123), preserved in the Junnerkoeland as a sharp bend (Fig. 1c). Maas (1995) interpreted Palaeochannel X to be connected to the oldest~~first~~ swale of the Junnerkoeland scroll bar deposits ~~before Palaeochannel X was cut off~~ (Fig. 1c). Palaeochannel X, however, was likely abandoned before the scroll bar formation,

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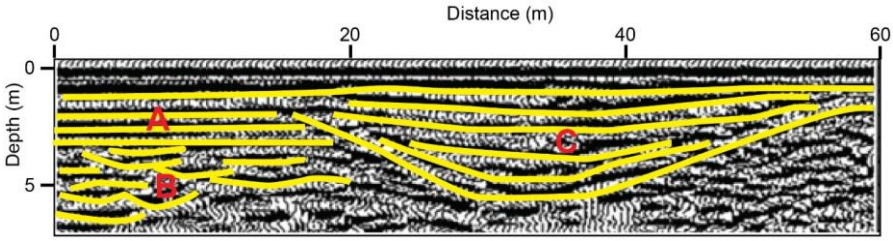

Figure 2: Interpretation by Huisink (2000) of subsurface strata from GPR data collected near Hardenberg 13 km upstream of Junnerkoeland (see location in Fig. 1b). Horizontal strata of coversand deposits (A) on top of the channel deposits of an interpreted braiding system (B). A relatively small, symmetrical palaeochannel is present (C) within the Late-Glacial deposits, hereafter referred to as "Palaeochannel Q". Figure adapted after Huisink (2000).

because large differences in dimensions exist between Palaeochannel X and the meander bend, but the well-preserved nature suggests that Palaeochannel X is relatively young. The small dimensions of both palaeochannels X and Q would suggest that the river had comparatively less energy, and may have been relatively laterally stable prior to the meandering phase.

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3. Methods

3.1 Lithological description

~~Corings~~ Cores were performed in a transect perpendicular to the scroll bars of both meander bends (Fig. 1c-d). An additional transect was cored perpendicular to Palaeochannel X (Fig. 1e). In case the deposit consisted of peat we used a gouge auger (Ø: 3 cm), in case of unsaturated sand we used an Edelman auger, and in case of saturated sand we used a Van der Staay suction corer (Van de Meene et al., 1979). In total, 68 ~~corings~~ cores were performed to a maximum depth of 7.3 m. The surface elevation of each coring site was either determined using a GPS combined with a DEM (Van Heerd and Van't Zand, 1999), or with a Global Navigation Satellite System (GNSS) device. A standard method was used to describe the sediment cores in 10-cm-thick intervals, using the Dutch texture classification scheme, which approximately matches the USDA terminology (De Bakker and Schelling, 1966; Berendsen and Stouthamer, 2001). The median sediment grain size (D_{50}, m) of non-organic, sandy samples was visually checked in the field by comparison with a sand ruler. Grain size analysis was used to estimate a D_{50} for the entire scroll bar deposit (Sect. 3.3). In addition, the plant macro-remains, any visible bedding, and colour were described. The percentage of gravel (>2 mm) was estimated in the field using ~~field~~ sieves. The lithogenesis was inferred from the lithological properties, facies geometries, and DEM topography, distinguishing fluvial, fluvioperiglacial, coversand, drift-sand, and residual channel-fill deposits (Ter Wee, 1966; Huisink, 2000).

3.2 Ground-penetrating radar

Ground-penetrating radar (GPR) was used to reconstruct the channel dimensions of the scroll bars. GPR measurements were conducted with a pulseEKKO PRO 250Hz with a SmartTow configuration. The GPR transects were placed along the centreline of the meander bends, perpendicular to the ridge and swale morphology (Fig. 1c-d). The electromagnetic-wave velocity was 0.060 m ns^{-1}, derived by using isolated reflector points (Van Heteren et al., 1998; Neal, 2004) and by comparing depths of recognizable layers with the coring data.

3.3 Grain size analysis

In total 33 samples for grain size analysis were taken from the scroll bar deposits and three samples were taken from Palaeochannel X. The samples of the scroll bar deposits were taken from each 0.5 m interval from the channel lag up to the swale surface at three locations in Junnerkoeland and two locations in Prathoek (Fig. 1c-e). The samples of Palaeochannel X were taken from three locations below the residual channel-fill, from the former river bed. Grain size samples were analysed in a laboratory with a Beckman Coulter LS230 Laser Particle Sizer. This instrument has a measurement range of 0.1 to 2000 µm. Samples were sieved with a 2 mm sieve, and prepared with HCl~~L~~ (1 M) and H_2O_2 (30%). All data were processed using a Fraunhofer.rfd optical model, because of the low clay-silt content (Agrawal et al., 1991). Finally, the average and standard deviation were calculated for both the scroll bar deposits and Palaeochannel X, and used in the palaeohydrological calculations.

3.4 OSL dating

We used the modelled age-distance relationships determined by Quik and Wallinga (2018) in our calculations. Their obtained OSL ages from the scroll ~~-~~bar deposits were used as priors and combined with historical map data in a Bayesian ~~deposition~~ sequence model using the OxCal software (Bronk Ramsey, 2009). For details on the method see Quik and Wallinga (~~submitted~~2018). In this study, we took four additional samples for OSL dating on the inner and outer bank of Palaeochannel X. These samples were collected in an opaque PVC-tube (Ø 4.5 cm) mounted on a hand-auger allowing sampling without light exposure. The analysis in the laboratory followed the same procedure as in Quik and Wallinga (2018). The OSL age was determined at the Netherlands Centre for Luminescence dating, with equivalent doses measured on small aliquots of quartz using the SAR protocol (Murray and Wintle, 2003) and dose rates determined from activity concentrations measured using gamma-ray spectrometry. A bootstrapped version of the minimum age model (Cunningham and Wallinga, 2012) was used to derive the best estimate of the burial dose and deposition age. Given the limited amount of samples associated with Palaeochannel X, and absence of additional age constraints from historical maps, no Bayesian analysis was performed for these samples. ~~.~~

3.5 ^{14}C dating

A sample was taken in the deepest part of ~~the p~~Palaeochannel X, at the sand-peat interface, using a piston corer (Ø: 6 cm). Macro-remains and leaf fragments from terrestrial species were selected from 1 cm intervals in the laboratory using a light microscope. Samples were stored in diluted HCl (4%) at 5 ºC. The sand content was measured for each interval to precisely determine the position of the sand-peat interface. Material with volumetric sand percentages lower than 10 to 20% was considered as peat (Bos et al., 2012). The macro-remains from the centimetre above this interface were selected for the ^{14}C analysis providing a *terminus ante quem* date for the abandonment of the channel. The ^{14}C age was determined by Accelerator Mass Spectrometry (AMS) at the Centre for Isotope Research (Groningen University). For calibration, the IntCal13 curve was used in the OxCal 4.2.4 software (Bronk Ramsey, 2009; Reimer et al., 2013).

3.6 Channel dimensions

The channel dimensions of Palaeochannel X were determined from the lithological cross-section. The residual channel-fill was delineated along the sand-peat interface. Bankfull depth (H_{bf}) was defined from the bottom of the palaeochannel up to the first clear knick-point on the bank, which was mapped with ~~the~~ a GNSS device, such that the width-depth ratio was minimal (Williams, 1986). Relative error of H_{bf} was assumed to be similar to the relative error of H_{bf} during the meandering phase (ca. 10 %) and used in the calculations (see details below), because both H_{bf}'s were determined by using coring data. ~~Uncertainty of the delineated channel was introduced by measuring H_{bf} until the first clear knick-point on both banks, which differed in elevation. Uncertainty of the channel dimensions was introduced by measuring H_{bf} until the first clear knick-point on both banks.~~ Additional dimensions were measured from the delineated channel, involving the bankfull width (W), cross-sectional area (A) and wetted perimeter (P). ~~Uncertainty of the channel dimensions was introduced by measuring H_{bf} until the first clear knick-point on both banks, which differed in elevation and thus additional dimensions also differed.~~ These channel dimensions were also measured for Palaeochannel Q from the GPR profile recorded by Huisink (2000, p.123) (Fig. 2). ~~.~~ Here we assumed a similar relative error of W, A and P as was taken for H_{bf}. ~~The average and standard deviation of the channel dimensions were calculated and used in the calculations. Additional channel dimensions were calculated by applying the same procedure as for the scroll bar deposits (see below).~~

~~During the meandering phase t~~The river channel was assumed to have the channel dimensions as shown in Fig. 3 during the meandering phase. This sketch is based on Allen (1965), Leeder (1973) and Hobo (2015). The bankfull depth (H_{bf}) was estimated from the coring data, taken from the bottom of the channel lag up to the surface elevation in the swales (Fig. 4). Small elevation differences were expected to ~~be caused~~result from ~~by~~ local variation rather than real changes in H_{bf}, therefore

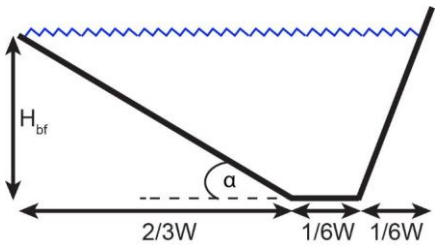

Figure 3: Sketch of the cross-sectional flow area of a meandering channel used for the bankfull palaeodischarge calculations (Allen, 1965; Leeder, 1973; Hobo, 2015).

the average H_{bf} was calculated from the smoothed bottom and surface elevation. The ~~standard deviation~~standard deviation of H_{bf} was calculated from the actual variable bottom ~~and surface~~ elevation over the length of the scroll bar. The transverse bed slope (α) of the inner bend was determined based on the GPR transects (Fig. 5), in which lateral accretion surfaces could be distinguished. The angle was measured on the steepest (middle) parts of the identified lateral accretion surfaces. ~~.~~The average

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and standard deviation of α were calculated and used in the calculations. The calculations of the channel dimensions follow from Fig. 3. The bankfull width (W, m) and cross-sectional area (A, m^2) were determined by Eq. 1 and 2:

$$\boldsymbol{W = 1.5\frac{H_{bf}}{tan(\alpha)}} \tag{19}$$

$$\boldsymbol{A = WH_{avg}} \tag{20}$$

where H_{bf} is the bankfull depth (m), and $H_{avg} = \frac{7H_{bf}}{12}$ and approximates the average water depth (m). The wetted perimeter (P, m) was calculated from the assumed channel geometry (Fig. 3) following Eq. 3:

$$\boldsymbol{P = \frac{H_{bf}}{sin(\alpha)} + \frac{W}{6} + \sqrt{(H_{bf}^2 + (\frac{W}{6})^2}} \tag{21}$$

The hydraulic radius (R, m) was calculated by Eq. 4:

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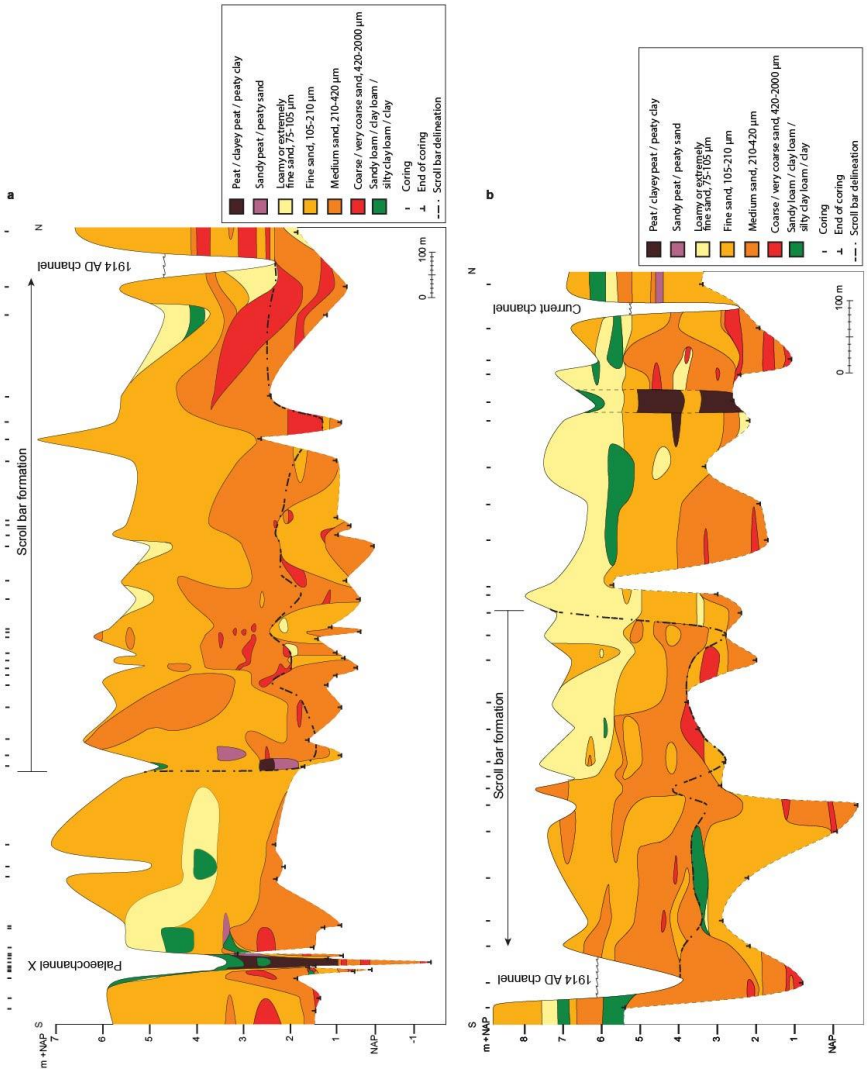
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Sandy peat / peaty sand
Loamy or extremely fine sand, 75-105 µm
Fine sand, 105-210 µm
Medium sand, 210-420 µm
Coarse / very coarse sand, 420-2000 µm
Sandy loam / clay loam / silty clay loam / clay
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1914 AD channel
Scroll bar formation
Current channel
0
100 m
Peat / clayey peat / peaty clay
Sandy peat / peaty sand
Loamy or extremely fine sand, 75-105 µm
Fine sand, 105-210 µm
Medium sand, 210-420 µm
Coarse / very coarse sand, 420-2000 µm
Sandy loam / clay loam / silty clay loam / clay
Coring
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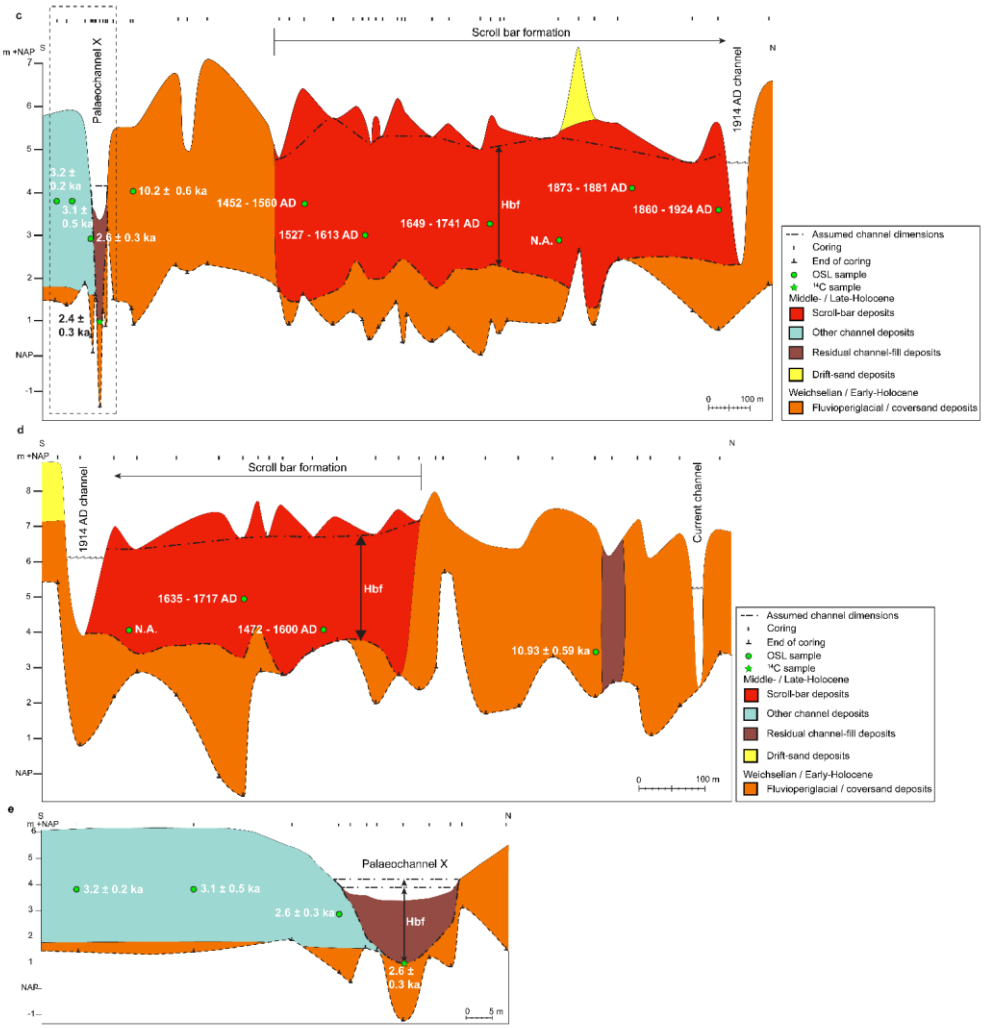

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$$R = \frac{A}{P} \quad (22)$$

For each swale visible on the DEM the sinuosity (s, -), radius of curvature (R_{curv}, m) and scroll bar surface area (SB_{surf}, m^2) was measured. The former channel sinuosity was estimated by the use of the DEM, measuring the distance along the swales relative to the distance along the valley between the inflection points (Fig. 1c-d). The sinuosity of Palaeochannel X was measured using the same approach (Fig. 1c). The channel slope (S_c, -) was calculated from the sinuosity and valley slope (S_v, -) determined by ~~from~~ TAUW (1992) and ~~TAUW and~~ Wolfert and Maas (2007) following Eq. 5:

$$S_c = S_v / s \quad (23)$$

The volumetric rate of scroll bar growth (SB_{vol}, $m^3\ yr^{-1}$) was determined from scroll bar surface area (SB_{surf}, $m^2\ yr^{-1}$) and thickness between each swale and interpolated time interval following Eq. 6:

$$SB_{vol} = \frac{SB_{surf} * H_{bf} * (1-\varphi)}{\Delta age} \quad (24)$$

where φ is the porosity (here 0.3 to 0.35 volume fraction) (Nimmo, 2004), which was included to compare the SB_{vol} with the sediment transport, and Δage is the age difference between the scroll bars (yr) based on the datings by Quik and Wallinga (2018). ~~Equation 6 was also applied to the inner bank of Palaeochannel X.~~ Although scroll bar deposits were absent, following Eq. 6 we also calculated the volumetric sediment transport for the fluvial deposits on the inside of Palaeochannel X.

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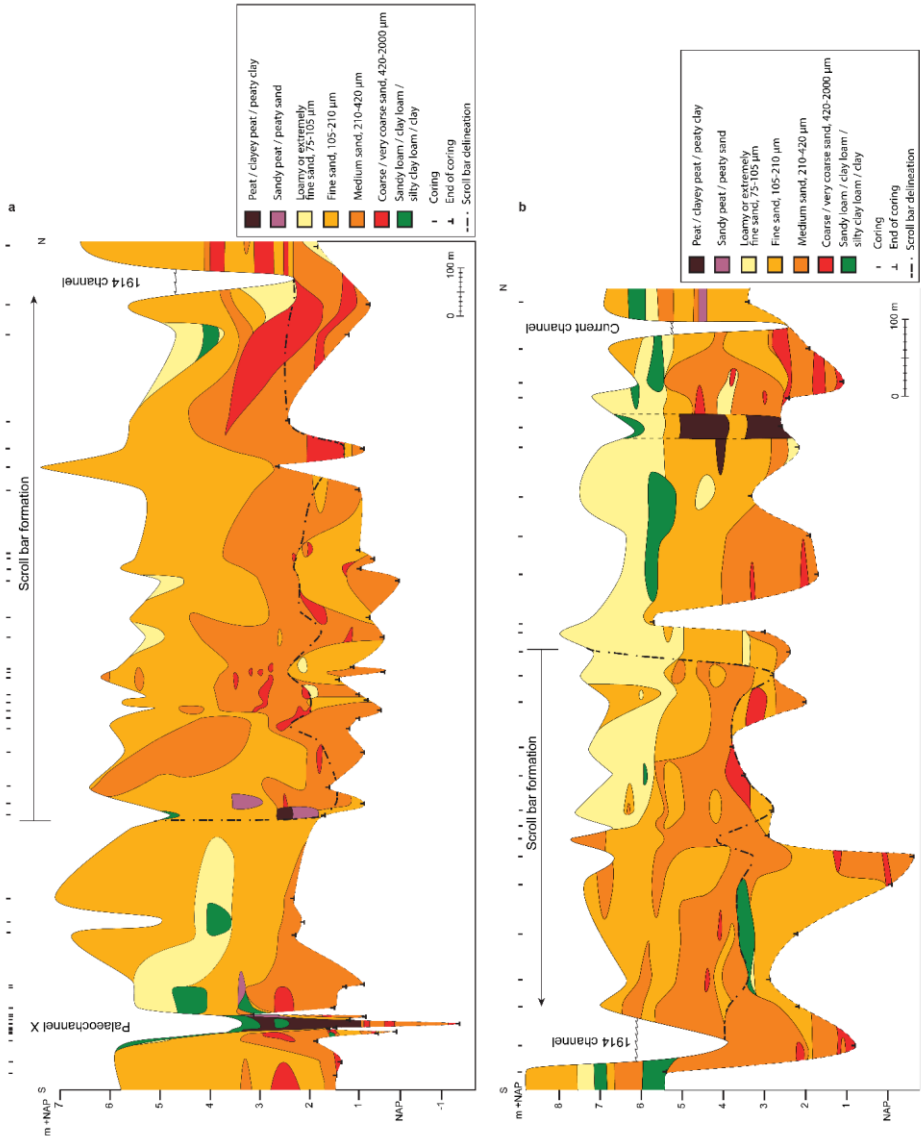

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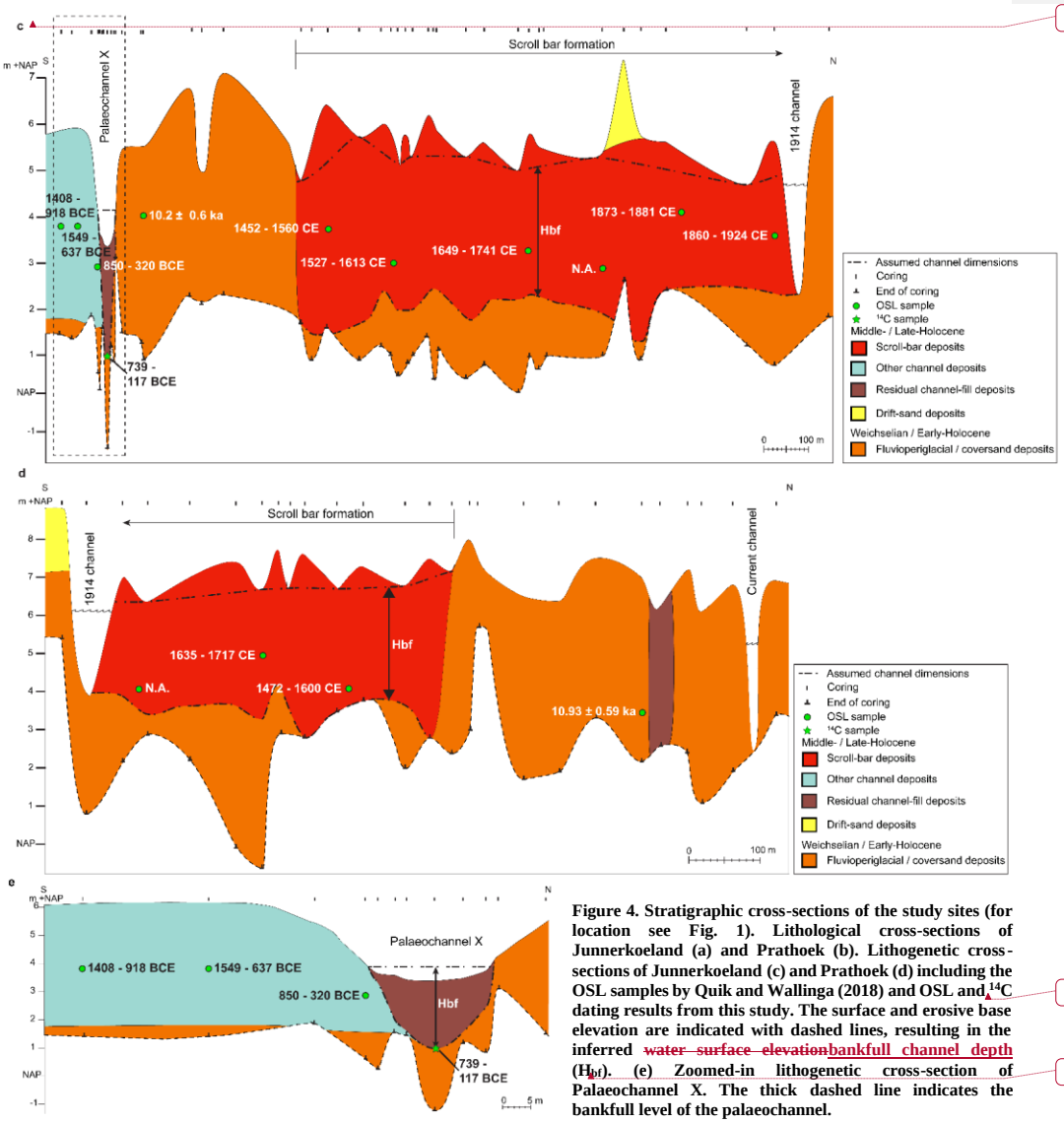

Figure 4. Stratigraphic cross-sections of the study sites (for location see Fig. 1). Lithological cross-sections of Junnerkoeland (a) and Prathoek (b). Lithogenetic cross-sections of Junnerkoeland (c) and Prathoek (d) including the OSL samples by Quik and Wallinga (2018) and OSL and ^{14}C dating results from this study. The surface and erosive base elevation are indicated with dashed lines, resulting in the inferred ~~water surface elevation~~bankfull channel depth (H_{bf}). (e) Zoomed-in lithogenetic cross-section of Palaeochannel X. The thick dashed line indicates the bankfull level of the palaeochannel.

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~~For each swale visible on the DEM the sinuosity (s), radius of curvature (R_{curv}) and scroll bar surface area (SB_{surf}) was measured. The former channel sinuosity was estimated by the use of the DEM, measuring the distance along the swales relative to the distance along the valley between the inflection points (Fig. 1c-d). The sinuosity of Palaeochannel X was measured using the same approach (Fig. 1e). The channel slope (S_c) was calculated from the sinuosity and valley slope (S_v) from Wolfert and Maas (2007) following Eq. 5:~~

$$S_c = S_v / s \quad (5)$$

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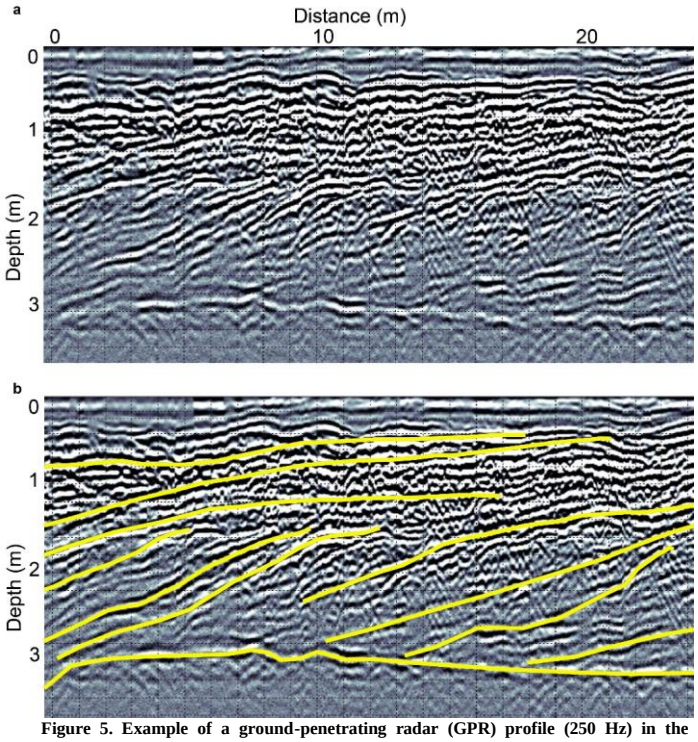

Figure 5. Example of a ground-penetrating radar (GPR) profile (250 Hz) in the Prathoek bend. (a) ~~original~~ Original GPR profile and (b) interpreted GPR profile with lateral accretion surfaces and the channel lag, indicated by yellow lines.

~~The volumetric rate of scroll bar growth (SB_{vol}, $m^2 \cdot yr^{-1}$) was determined from scroll bar surface area (SB_{surf}, $m^2 \cdot yr^{-1}$) and thickness between each swale and interpolated time interval following Eq. 6:~~

$$SB_{vol} = \frac{SB_{surf} * H_{bf} * (1-\varphi)}{\Delta age} \quad (6)$$

~~where φ is the porosity (here 0.3 to 0.35 volume fraction) (Nimmo, 2004), which was included to compare the SB_{vol} with the sediment transport, and Δage is the age difference between the scroll bars (yr) based on the datings by Quik and Wallinga (submitted). Equation 6 was also applied to the inner bank of Palaeochannel X.~~

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3.7 Palaeodischarge

The channel dimensions were used to calculate the bankfull discharge (Q_{bf}, m^3 s^{-1}). Bankfull discharge (Q_{bf}) is commonly considered an approximation of the channel-forming discharge with a recurrence interval of 1 to 2 years (Wolman and Miller, 1960; Dury, 1973). (Williams, 1978)(Dury, 1973; Wolman and Miller, 1960)We assumed that the bankfull discharge was similar for both Junnerkoeland and Prathoek, regarding the short distance between these river sections (Fig. 1b). HHence the average bankfull discharge and standard deviation was presented calculated, by combining the bankfull discharges for both meander bends. The bankfull discharge was estimated by applying the Chézy equation, following Eq. 7:

$$Q_{bf} = CA\sqrt{RS_c} \qquad (25)$$

where Q_{bf} = is the bankfull discharge (m^3 s^{-1}), and C = is the Chézy coefficient ($m^{0.5}$ s^{-1}). The Chézy coefficient, i.e. flow resistance, was estimated by substituting using Eq.uation 8 was substituted in Eq. 7 to calculate C. Equation 8 is an empirical relation (Brownlie, 1983) following Eq. 8:.

$$Q_{bf} = \left(\frac{R}{(0.3724 * S_c^{-0.2542} * \sigma_s^{0.105} * D_{50})}\right)^{1.529} W g^{0.5} D_{50}^{1.5} \qquad (26)$$

where σ_s is the sorting of the bed material grain size (-) derived from the grain size analysis (Sect. 3.3) and approximated by $0.5(\frac{D_{50}}{D_{16}}$ D_{50}/D_{16} + $\frac{D_{84}}{D_{50}}$ $D_{84}/D_{50})$, D_{16} and D_{84} are the 16th and 84th percentile sediment grain size (m), respectively, and g is the gravitational acceleration (9.81 m^2 s^{-1}). As a validation, the calculated Chézy coefficient was compared with average Chézy coefficients of 12 comparable low-energy, sand-bed rivers with scroll bars (S_v < 0.001, 90 < Q_{bf} < 320 m^3 s^{-1}), calculated from a large river dataset (Van den Berg, 1995; Kleinhans and Van den Berg, 2011). Equation 8 was substituted in Eq. 7 to calculate C. The cross-sectionally averaged flow velocity (u_{bf}, m s^{-1}) was calculated by following Eq. 9:

$$u_{bf} = \frac{Q_{bf}}{A} \qquad (27)$$

3.8 Sediment transport

The sediment transport was calculated to compare with the SB$_{vol}$ (~~, which was calculated in~~ Eq. 6). Sediment transport was calculated in two different ways. The first method was the slightly modified Engelund and Hansen (1967) relation following Eq. 10:

$$\boldsymbol{Q_{s,bf}} = \frac{\boldsymbol{0.05u^5Wti}}{(\frac{\rho s}{\rho}-1)^2 g^{0.5} D_{50} C^3 (1-\varphi)} \tag{28}$$

where Q$_{s,bf}$ ~~is~~ is the yearly sediment transport derived from the bankfull discharge (m^3 yr^{-1}), t ~~=~~is the number of seconds in a year, i is~~=~~ the intermittency assumed to be 0.03 to 0.07~~0.05 ± 0.01 (no uncertainty taken)~~ (Parker, 2008), ρ$_s$ is ~~=~~the sediment density (kg m^{-3}), ρ is~~=~~ the water density (kg m^{-3}), φ is the porosity assumed to be 0.3 to 0.35 (Nimmo, 2004). The relation of Engelund & Hansen was used, because the relation is suitable for sand-bed rivers with relatively low flow velocities (Van den Berg & Van Gelder, 1993), and the input variables required were available.

In the second method the sediment transport was determined for each discharge magnitude and related frequency (Q$_{s,freq}$) (Wolman and Miller, 1960) from present-day flow conditions, by assuming that the current discharge frequency distribution also applied to the meandering phase. We used the hourly discharge data from 1995 to 2015 of the gauging station in Mariënberg (Fig. 1b). This gauging station is close to the study location, and has the lowest amount of data gaps compared to the other stations. The flow duration was calculated for intervals of 10 m^3 s^{-1}, and for each discharge interval the sediment transport was calculated using Eq. 10, excluding the intermittency factor. When the discharge would be above bankfull, the flow would go across the floodplain. The Chézy coefficient for the floodplain was assumed to be half the Chézy coefficient in the channel, because of the higher roughness of the floodplain compared to the channel. We assumed that the floodplain width was 350 m for the start of the meandering phase, which was estimated from the DEM (Fig. 1c), and that the width would increase proportiona~~te~~lly ~~y~~ with the lateral migration rate for each time step during the meandering phase.

3.9 Potential specific stream power

The potential specific stream power was calculated to plot into a stability diagram. Kleinhans and Van den Berg (2011) distinguished four different stability fields, further building on Van den Berg (1995)~~ and Bledsoe and Watson (2001)~~ and Makaske et al. (2009): rivers with laterally stable channels, meandering rivers with scroll bars, meandering rivers with scroll and chute bars as well as moderately braided rivers, and braided rivers. In this research, only the first two stability fields are relevant. These stability fields are separated by a discriminator that represents the theoretical minimum energy needed for the channel pattern to occur (Kleinhans and Van den Berg, 2011). The potential specific stream power was calculated by applying the relationship presented by Kleinhans and Van den Berg (2011) following Eq. 11:

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$$\omega_{pv} = \frac{\rho g \sqrt{Q_{bf}} S_v}{\varepsilon} \quad (29)$$

where ω_{pv} is the potential specific stream power (W m^{-2}), $\varepsilon = 4.7\sqrt{s\ m^{-1}}$ for sand-bed rivers (Van den Berg, 1995). ~~The discriminators separating laterally stable rivers from meandering rivers with scroll bars were calculated for the measured median bed grain sizes. Multiple d~~The discriminator line~~s were~~ was plotted ~~to take into account the range in the measured bed grain sizes,~~ applying the relationships presented by Makaske et al. (2009) and Kleinhans and Van den Berg (2011) following Eq. 12:

$$\omega_{ia} = 90 D_{50}^{0.42} \quad (30)$$

where subscript *ia* refers to the discrimination between laterally stable and meandering channels with scroll bars.

3.10 Bar regime

Bar regime was predicted applying the relationships of Struiksma et al. (1985) and Kleinhans and Van den Berg (2011). River bends can be seen as an example of a ~~disturbance~~ perturbation to both the flow and bed sediment, which have different adaptation lengths over which they return to equilibrium. This difference in response is expressed by the interaction parameter (IP), which is the ratio between the adaptation length of bed ~~disturbance~~ perturbation and the adaptation length of flow. The adaptation length of flow was calculated following Eq. 13:

$$\lambda_w = \frac{C^2 H_{avg}}{2g} \quad (31)$$

and the adaptation length of a bed ~~disturbance~~perturbation (m) is calculated following Eq. 14:

$$\lambda_s = \frac{H_{avg}}{\pi^2}\left(\frac{W}{H_{avg}}\right)^2 f(\theta) \quad (32)$$

where f(θ) is~~=~~ the magnitude of the transverse slope effect (-) calculated following Eq. 15 (Talmon et al., 1995):

$$f(\theta) = 9\left(\frac{D_{50}}{H_{avg}}\right)^{0.3} \sqrt{\theta} \quad (33)$$

where θ ~~=~~is the dimensionless shear stress (-) calculated following Eq. 16:

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$$\theta = \frac{\tau}{(\rho_s - \rho) g D_{50}} \qquad (34)$$

where τ is~~=~~ the shear stress (Pa), calculated following Eq. 17:

$$\tau = \rho g R S_c \qquad (35)$$

The interaction parameter (IP, -) was calculated, following Eq. 18, to determine the bar regime for the historical and prehistorical Overijsselse Vecht~~of rivers according to Struiksma et al. (1985)~~, and for comparison with the theoretical thresholds of bar regime (Struiksma et al., 1985; Crosato and Mosselman, 2009) by:

$$IP = \frac{\lambda_s}{\lambda_w} \qquad (36)$$

The IP is strongly related to the width-depth ratio, and was therefore separately calculated for the meander bends Junnerkoeland and Prathoek. A low IP means that when a bar forms in response to a local ~~perturbation~~perturbation, such as local curvature, the bar disappears within a short distance of the ~~perturbation~~ perturbation (Struiksma et al., 1985). This is called an overdamped regime and occurs in channels with a low width-depth ratio. The threshold threshold between overdamped and underdamped can be calculated following Eq. 19:

$$IP \leq \frac{2}{n+1+2\sqrt{2n-2}} \qquad (19)$$

where n is~~=~~ the degree of nonlinearity of sediment transport versus depth-averaged flow velocity (-). Following Crosato and Mosselman (2009) we chose n = 4, which corresponds to values for a sand-bed river. A higher IP, and hence a higher width-depth ratio, results in an underdamped regime associated with bars that also form further downstream of the ~~perturbation~~perturbation. The thresholds can be calculated following Eq. 20:

$$\frac{2}{n+1+2\sqrt{2n-2}} < IP < \frac{2}{n-3} \qquad (20)$$

3.11 Errors and uncertainty

The above described calculations (Eq. 1 to 11, and 13 to 20) were run 10~~.~~,000 times to take into account the random ~~uncertainty~~ errors of the input parameters, following a stochastic approach by using Monte Carlo simulations. The uncertainty of these

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parameters was described above, relating to the transverse bed slope, bankfull depth of the meanders, valley slope, porosity, ~~and~~ grain size, intermittency and the measured channel dimensions of palaeochannels X and Q. Systematic errors were not taken into account, because the palaeohydrological reconstruction was meant to distinguish relative differences between fluvial phases, rather than reconstructing absolute hydrological parameters. ~~These parameters were used in the calculations applying a normal distribution. All r~~Results are plotted with average values from the Monte Carlo simulations when normally distributed, or median values when not-normally distributed, including the 16th and 84th quantile representing the uncertainty margin. ~~from the Monte Carlo simulations, and a range of one standard deviation representing the uncertainty margin.~~ All used formulas and example data are made available ~~to be used~~ in the Supplementary I~~i~~nformation.

4. Results

4.1 Lithogenetic units

Several lithogenetic units were distinguished (Fig. 4), following similar interpretations of the sedimentary units as Huisink (2000). The descriptions of the lithogenetic units are summarized in Table 1. The coversand deposits were sometimes difficult to distinguish in borehole descriptions from the fluvioperiglacial deposits, when the latter has a relatively fine grain size. Because our interest is in the delineation of the scroll bar and residual channel-fill deposits, we combined both the fluvioperiglacial and coversand deposits into one unit. The fining upward sequence within the scroll bar deposits (Table 1) can be recognized in the grain size analysis done for the scroll bar deposits at Junnerkoeland and Prathoek (Fig. 6). The depth-averaged grain size for both scroll bar complexes is 0.28 ± 0.05 mm. Commonly, at the base of the scroll bar deposits, a sharp transition occurs to the brightly coloured substratum of fluvioperiglacial deposits below, which lack organic material (Table 1). Cores that did not reach the fluvioperiglacial deposits below the scroll bar deposits indirectly indicate the boundary between these units, because strongly consolidated layers are present in the fluvioperiglacial deposits that were difficult to core into. An example of a consolidated clay layer can be found directly below the southern part of the scroll bar deposits at Prathoek (Fig. 4b).

The GPR profiles clearly show the lateral accretion surfaces of the scroll bar deposits (see example in Fig. 5). Only where the scroll bar deposits are relatively loamy or clayey on top, the GPR results were poor (i.e. northern parts of Prathoek and Junnerkoeland). The bottom of the scroll bar deposits is mostly unrecognizable, because of a low GPR reflection at this depth. In Fig. 5 the bottom of the scroll bars is visible, because this part is located in the southern part of Prathoek where the above-mentioned clay layer was present (Fig. 4), which caused a strong reflection of the GPR signal. The well-preserved Palaeochannel X is a relatively symmetrical palaeochannel (Fig. 4e), similar to Palaeochannel Q of Huisink (2000) (Fig. 2). The outer bank consists of Weichselian / Early Holocene deposits (Fig. 4c). The average grain size of the Palaeochannel X bed sediments is 0.23 ± 0.12 mm. No lateral accretion surfaces can be observed in the GPR profile that was placed along the centreline of the Palaeochannel X bend (Fig. 1e and Supplementary Information).

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~~± 0.05 mm. Commonly, at the base of the scroll bar dep~~
~~fluvioperiglacial deposits below, which lack organic mat~~
~~below the scroll bar deposits indirectly indicate the boun~~
~~in the fluvioperiglacial deposits that were difficult to co~~
~~found in the southern part of the scroll bar deposits at Pr~~

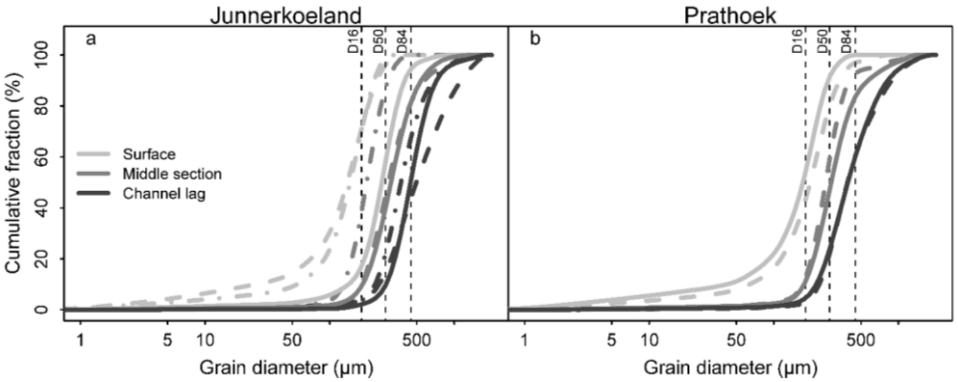

Figure 6: Cumulative grain size distributions of the scroll bar deposits in (a) Junnerkoeland and (b) Prathoek. Three series were made for Junnerkoeland and two for Prathoek, each indicated by a different line type. Each sample within a series is indicated by a different grey tone. The averages of D16, D50 and D84 are plotted. Figure 1c-d indicates the locations of the grain size samples.

Table 2: Description of lithogenetic units.

	Fluvio-periglacial deposits	Coversand deposits	Other channel deposits	Residual channel-fill deposits	Scroll bar deposits	Drift-sand deposits
Lithology	Mod. sort. 75-2000 µm Lenses of loam and loamy sand	Well sort. 75-210 µm Loamy sand	Mod. sort. 105-600 µm	Sandy peat or peaty sand. Lenses of sand, silty clay loam or clay loam	Mod. sort. 75-600 µm Loamy sand near surface	Well sort. 75-210 µm
Colour	Light grey to brown	Light grey/brown	Light grey/brown or white	Dark brown or black	Light brown to dark grey	Greyish brown
Gravel (%)	0-20	<1	<1	<1	<40	<1
Plant remains	Mostly absent	None	Sporadically near bottom	Abundant	Fragmented and abundant near bottom	Rare
Thickness (m)	>2	<2	4-5	4-5	4-5	1-5
Width (m)	>1000	>1000	<100	20-40	>100	10-100
Beds	cm~~'s~~ to dm thick~~'s~~	None	None	None	cm to dm thick~~cm's to dm's~~	None

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Additional	Palaeo-podzol ~~on~~in top	Slightly coarser near bottom	May be poorly preserved	Fining upward,~~.~~ lateral accretion surfaces (GPR)	Micro-podzol ~~on~~in top~~.~~

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Table 1: Description of lithogenetic units

	Fluvio-periglacial deposits	Coversand deposits	Other channel deposits	Residual channel-fill deposits	Scroll bar deposits	Drift-sand deposits
Lithology	Mod. sort. 75-2000 µm Lenses of loam and loamy sand	Well sort. 75-210 µm Loamy sand	Mod. sort. 105-600 µm	Sandy peat or peaty sand. Lenses of sand, silty clay loam or clay loam	Mod. sort. 75-600 µm Loamy sand near surface	Well sort. 75-210 µm
Colour	Light grey to brown	Light grey/brown	Light grey/brown or white	Dark brown or black	Light brown to dark grey	Greyish brown
Gravel (%)	0-20	<1	<1	<1	<40	<1
Plant remains	Mostly absent	None	Sporadically near bottom	Abundant	Fragmented and abundant near bottom	Rare
Thickness (m)	>2	<2	4-5	4-5	4-5	1-5
Width (m)	>1000	>1000	<100	20-40	>100	10-100
Beds	cm's to dm's	None	None	None	cm's to dm's	None
Additional		Palaeo-podzol on top	Slightly coarser near bottom	May be poorly preserved	Fining upward. lateral accretion surfaces (GPR	Micro-podzol on top.

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~~The GPR profiles clearly show the lateral accretion surfaces of the scroll bar deposits (see example in Fig. 5). Only where the scroll bar deposits are relatively loamy or clayey on top, the GPR results were poor (i.e. northern parts of Prathoek and Junnerkoeland). The bottom of the scroll bar deposits is mostly unrecognizable, because of a low GPR reflection at this depth. In Fig. 5 the bottom of the scroll bars is visible, because this part is located in the southern part of Prathoek where the above-mentioned clay layer was present (Fig. 4), which caused a strong reflection of the GPR signal. The well-preserved~~

~~Palaeochannel X is a relatively symmetrical palaeochannel (Fig. 4e), similar to Palaeochannel Q of Huisink (2000) (Fig. 2). The outer bank consists of Weichselian / Early Holocene deposits (Fig. 4c). The average grain size of the Palaeochannel X bed sediments is 0.23 ± 0.12 mm. No lateral accretion surfaces can be observed in the GPR profile that was placed along the centreline of the Palaeochannel X bend (Fig. 1e).~~

~~Table 1: Description of lithogenetic units~~

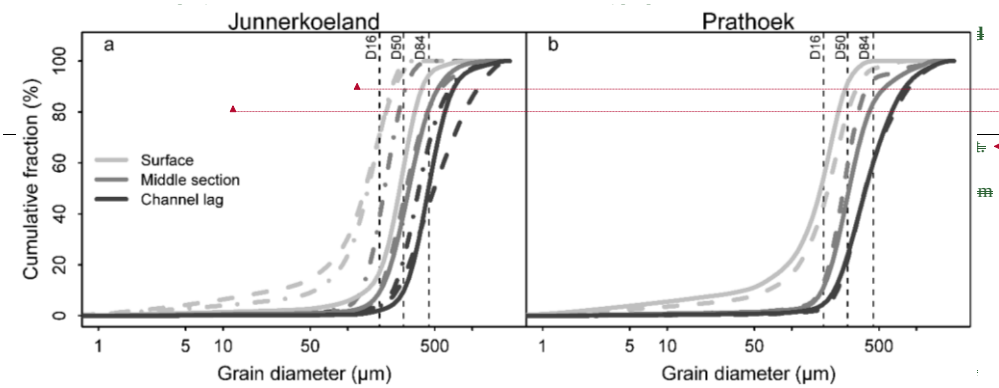

Figure 6: Cumulative grain size distributions of the scroll bar deposits in (a) Junnerkoeland and (b) Prathoek. Three series were made for Junnerkoeland and two for Prathoek, each indicated by a different line type. Each sample within a series is indicated by a different ~~colour~~grey tone. The ~~depth-averaged~~averages of D16, D50 and D84 are plotted. Figure 1c-d indicates the locations of the ~~texture~~ grain size samples.

~~**Gravel (%)**~~	~~0-20~~	~~<1~~	~~<1~~	~~<1~~	~~<40~~	~~<1~~
~~**Plant remains**~~	~~Mostly absent~~	~~None~~	~~Sporadically near bottom~~	~~Abundant~~	~~Fragmented and abundant near bottom~~	~~Rare~~
~~**Thickness (m)**~~	~~>2~~	~~<2~~	~~4-5~~	~~4-5~~	~~4-5~~	~~1-5~~
~~**Width (m)**~~	~~>1000~~	~~>1000~~	~~<100~~	~~20-40~~	~~>100~~	~~10-100~~
~~**Beds**~~	~~cm's to dm's~~	~~None~~	~~None~~	~~None~~	~~cm's to dm's~~	~~None~~
~~**Additional**~~		~~Palaeo-podzol on top~~	~~Slightly coarser near bottom~~	~~May be poorly preserved~~	~~Fining upward. lateral accretion surfaces (GPR~~	~~Micro-podzol on top.~~

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~~4.2 Palaeo-channel X~~

4.2 Dating results

~~The well-preserved Palaeochannel X is a relatively symmetrical palaeochannel (Fig. 4e), similar to Palaeochannel Q of Huisink (2000) (Fig. 2). The outer bank consists of Weichselian / Early Holocene deposits (Fig. 4c). The average grain size of the Palaeochannel X bed sediments is 0.23 ± 0.12 mm. No lateral accretion surfaces can be observed in the GPR profile that was placed along the centreline of the Palaeochannel X bend (Fig. 1e).~~ The channel deposits on the inside of the Palaeochannel X date from 850 – 320 BCE and ~~3.2 ± 0.2~~1408 – 918 ~~ka~~BCE. Palaeochannel X was cut off ~~at 2.4 ± 0.3 ka~~at 739 – 117 BCE (Fig. 1e, Fig. 4c,e and Table 2).

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~~**Table 2: OSL and ^{14}C dating results from Palaeochannel X. Locations are indicated in Fig. 1c-d and Fig. 4c.**~~

~~Sample Code~~	~~Material~~	~~Elevation (m +NAP)~~	~~^{14}C age (a BP)~~	~~Palaeo-dose (Gy)~~	~~Dose rate (Gy/ka)~~	~~Age (ka)~~	~~Lat, Long (RD)~~
~~NCL2416194~~	~~Fluvial sand~~	~~1.10~~		~~2.1 ± 0.2~~	~~0.81 ± 0.03~~	~~2.6 ± 0.3~~	~~229242, 505286~~
~~NCL2217157~~	~~Fluvial sand~~	~~3.65~~		~~3.3 ± 0.2~~	~~1.06 ± 0.05~~	~~3.1 ± 0.5~~	~~229249, 505254~~
~~NCL2217158~~	~~Aeolian sand~~	~~3.99~~		~~12.5 ± 0.5~~	~~1.23 ± 0.03~~	~~10.2 ± 0.6~~	~~229254, 505338~~
~~NCL2217159~~	~~Fluvial sand~~	~~3.55~~		~~3.6 ± 0.2~~	~~1.14 ± 0.05~~	~~3.2 ± 0.2~~	~~229242, 505228~~
~~GrA69519~~	~~Selected macro-~~	~~1.14~~	~~2300 ± 100~~			~~2.4 ± 0.3~~	~~229239,505298~~

Table 2: OSL and ^{14}C dating results from Palaeochannel X. Locations are indicated in Fig. 1c-d and Fig. 4c.

Sample Code	Material	Elevation (m +NAP)	^{14}C age (a BP)	Palaeo-dose (Gy)	Dose rate (Gy/ka)	Age (ka)	Age (BCE)	Lat, Long (RD)
NCL2416194	Fluvial sand	1.10		2.1 ± 0.2	0.81 ± 0.03	2.6 ± 0.3	850 – 320	229242, 505286
NCL2217157	Fluvial sand	3.65		3.3 ± 0.2	1.06 ± 0.05	3.1 ± 0.5	1549 – 637	229249, 505254
NCL2217158	Aeolian sand	3.99		12.5 ± 0.5	1.23 ± 0.05	10.2 ± 0.6	8761 – 7641	229254, 505338
NCL2217159	Fluvial sand	3.55		3.6 ± 0.2	1.14 ± 0.05	3.2 ± 0.2	1408 – 918	229242, 505228
GrA69519	Selected macro-fossils	1.14	2300 ± 100			2.4 ± 0.3	739 – 117	229239, 505298

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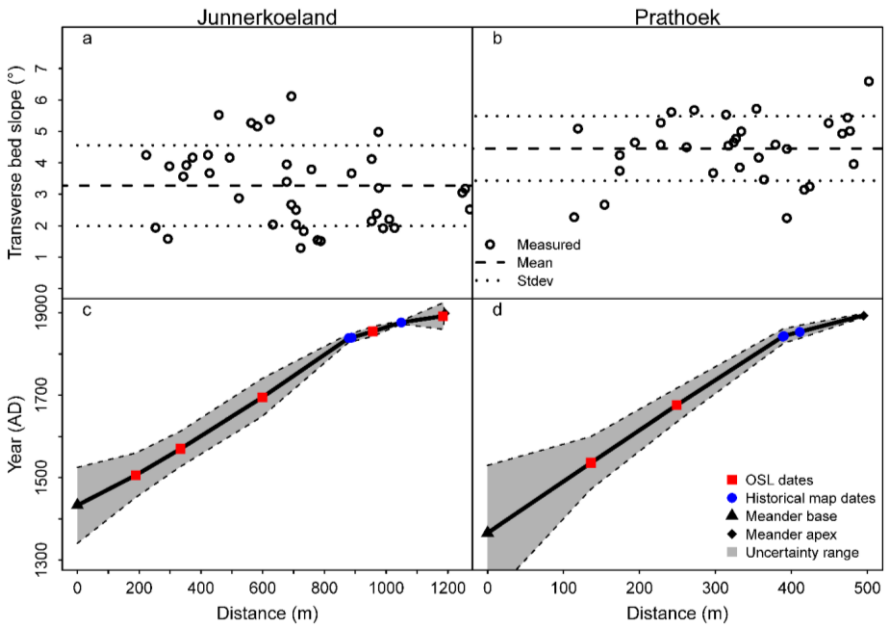
4.3 Meander and channel geometry

The reconstructed transverse bed slopes do not show a spatial trend ~~in space~~ (Fig. 7a-b), hence the mean and standard deviations were used in the palaeohydrological calculations. The transverse bed slope at Prathoek is higher (4.5 ± 1.0 °) than at Junnerkoeland (3.3 ± 1.3 °), but much lower than the transverse bed slope of Palaeochannel X (16.9 ± 1.9 °) and of



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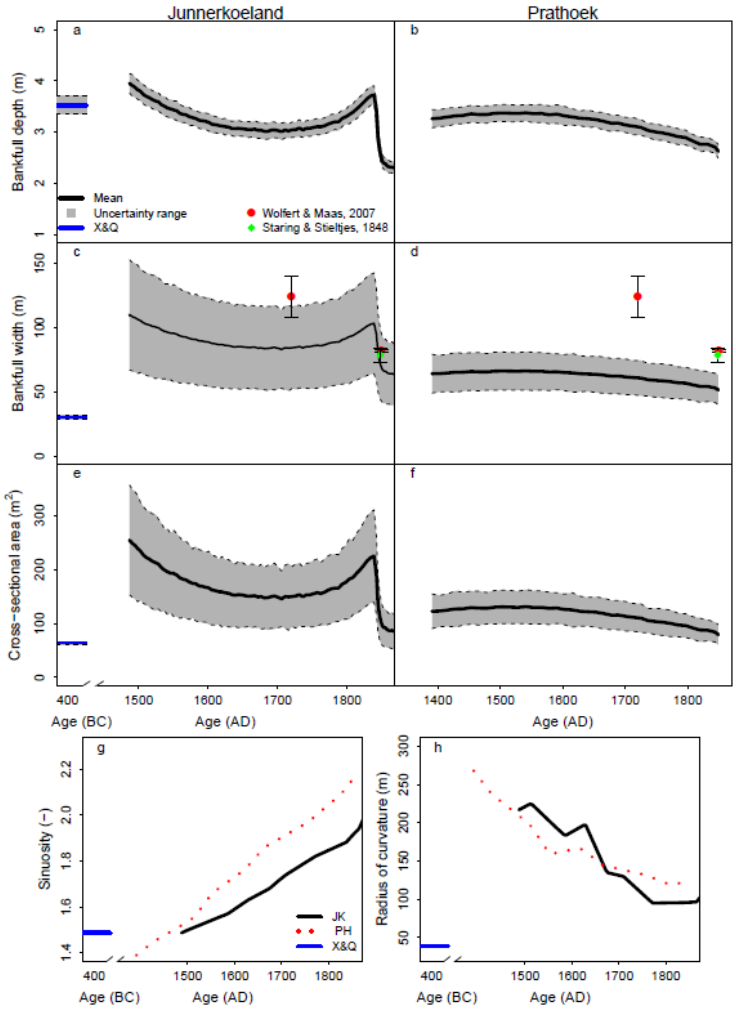
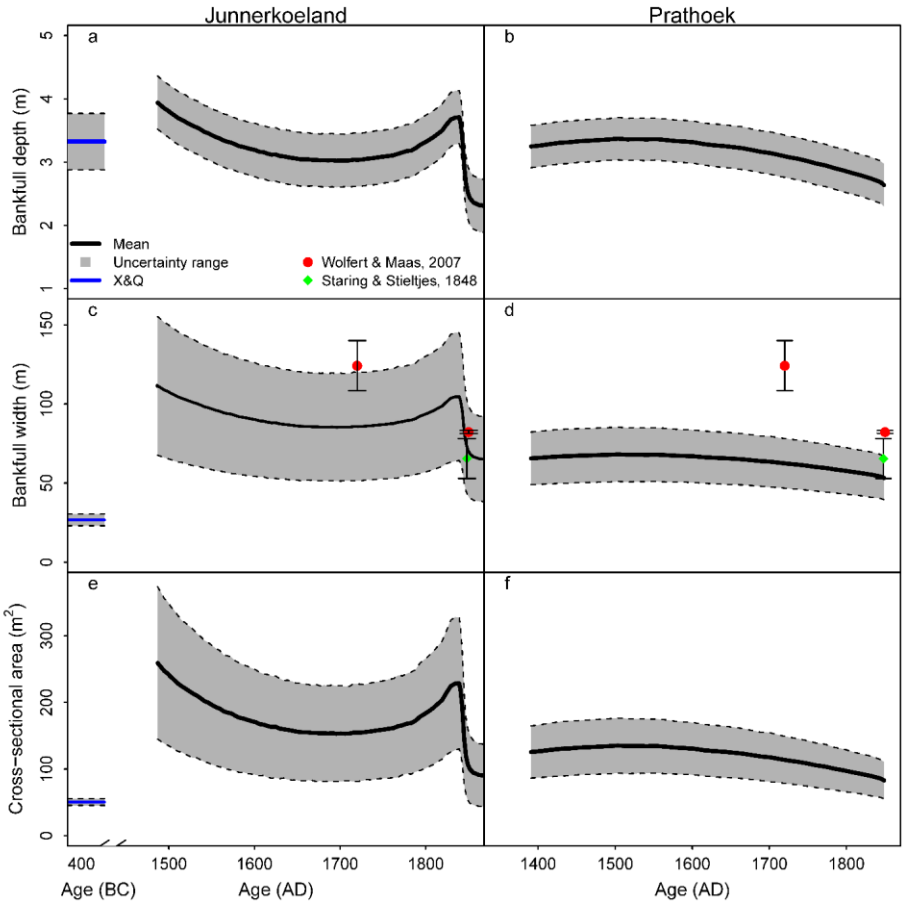


Figure 8: Reconstructed meander and channel geometry over time, assuming the date-distance relations (see Fig. 7c-d) over the scroll bars. Panels (a) and (b) show the bankfull depth (Hbf) derived from the coring data, taken from the bottom of the channel lag to the inferred water surface (Fig. 4c-d). Panels (c) and (d) show the bankfull width for both the Junnerkoeland bend (left) and Prathoek (right) derived from the bankfull depth and reconstructed transverse bed slope (Eq. 1). The river width data from Wolfert and Maas (2007) observed on historical maps, and the bankfull river width data from Staring and Stieltjes (1848) were included for comparison. Panels (e) and (f) show the cross-sectional area derived from the bankfull width and water depth (Eq. 2).

used for the meander and channel geometry calculations (Fig. 8). The



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bankfull depths of palaeochannels X and Q are comparable to the bankfull depths of the meanders Prathoek and Junnerkoeland

ca. 1500 CE (Fig. 8a-b) (3 to ~~4.5 to 4.2~~ m). The bankfull depths at Junnerkoeland decreased~~s~~ relatively fast ~~at~~ ca. 1800 ~~AD~~CE, because the erosive base elevation rises towards the cut-off channel (Fig. 4c). At Prathoek, the bankfull depth ~~decreases~~ decreased more gradual over time. The reconstructed bankfull width of palaeochannels X and Q is much lower compared to the meandering phase (Fig. 8c-d), resulting in a relatively small cross-sectional area of palaeochannels X and Q (Fig. 8e-f).

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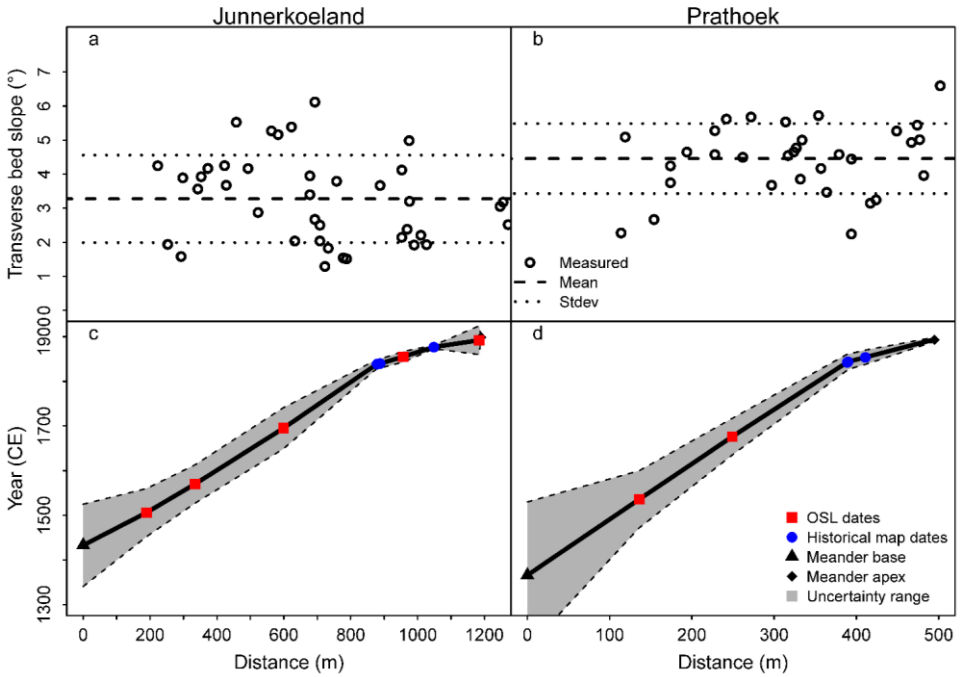

Figure 7: Transverse bed slope derived from GPR cross-sections from the inner point bar to the outer bend for Junnerkoeland (left) and Prathoek (right) as well as lateral migration distance plotted against age for both bends. Panels (a) and (b) show transverse bed slope of lateral accretion surfaces measured in the GPR profile (example in Fig. 4), including the mean and standard deviation of all measurements. Panels (c) and (d) show the relation between age and migration distance of the bends. Shading indicates standard deviation of the Bayesian deposition model determined by Quik and Wallinga (2018) for the OSL and historical map dates.

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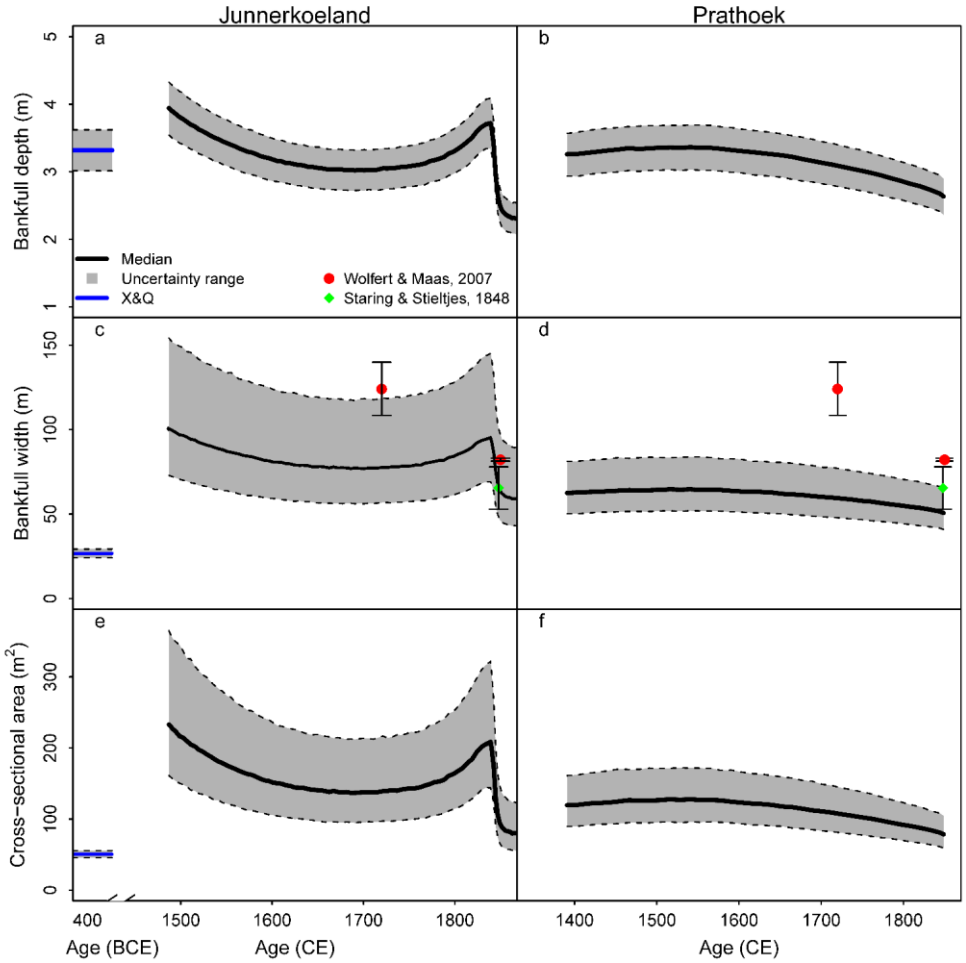

Figure 8: Reconstructed meander and channel geometry over time, assuming the date-distance relations (see Fig. 7c-d) over the scroll bars. Panels (a) and (b) show the bankfull depth (Hbf) derived from the coring data, taken from the bottom of the channel lag to the inferred bankfull water surface (Fig. 4c-d). Panels (c) and (d) show the bankfull width for both the Junnerkoeland bend (left) and Prathoek (right) derived from the bankfull depth and reconstructed transverse bed slope (Eq. 1). The river width data from Wolfert and Maas (2007) observed on historical maps, and the bankfull river width data from Staring and Stieltjes (1848) were included for comparison. Panels (e) and (f) show the cross-sectional area derived from the bankfull width and water depth (Eq. 2).

4.4 Palaeohydrology

The reconstructed Q_{bf} is ~~two~~ three to ~~fourteen~~ nine times higher at the start of the meandering phase (~~42~~ 85 – ~~143~~ 194 $m^3 s^{-1}$) ~~than~~ compared to~~during~~ the preceding phase ~~for~~ represented by palaeochannels X and Q (~~10~~ 19 - ~~21~~32 $m^3 s^{-1}$) (Fig. 9~~a~~). The difference in Q_{bf} between 400 BCE and 1500 CE is significant, despite the relatively large uncertainty. A similar discharge in 400 BCE compared to 1500 CE would require a cross-sectional area five times larger than currently estimated (Fig. 8e), or a 50 times higher valley slope, which falls outside the uncertainty ranges of these parameters. The Q_{bf} eventually declines over time, and drops to ~~ca. 16~~32 – ~~66~~ 70 $m^3 s^{-1}$ ca. 1850 ~~AD~~CE. The calculated Chézy coefficients for the meandering phase (47.5 ± 0.9 $m^{0.5} s^{-1}$, Eq. 7-8) were comparable to average Chézy coefficients derived from 12 low-energy rivers (44.8 ± 13 $m^{0.5} s^{-1}$) from the river dataset by Kleinhans and Van den Berg (2011).

~~The average flow velocity (u_{bf}) is relatively similar for palaeochannels X and Q and the meandering phase (Fig. 9b) and does not change much over time.~~

Combining the frequency of each discharge interval with the sediment transport rate (Fig. 10a), results in a histogram of the sediment transport contribution as a function of discharge ($Q_{s,freq}$, Fig. 10b). The highest measured discharge at the gauging station Mariënberg between 1995 and 2015 ~~-~~is 185.5 $m^3 s^{-1}$. The most frequent discharge occurring in the channelized Overijsselse Vecht is 0 to 10 $m^3 s^{-1}$, with a frequency of 8.2% (Fig. 10a). ~~This discharge is mainly affected by the weirs currently present in the channelized river.~~ When discharge is still below bankfull, sediment transport increases relatively fast with an increasing discharge. Above bankfull, additional discharge largely flows across the more flow-resistant floodplain, and hence the sediment transport rates increase less. The effective discharge (Q_{eff}) is 29 $m^3 s^{-1}$, represented by the highest sediment transport contribution (Fig. 10a-b).

Calculated sediment transport rates were higher than the inner bank growth or scroll bar growth, suggesting the channel deposition can b[illegible]ble phase

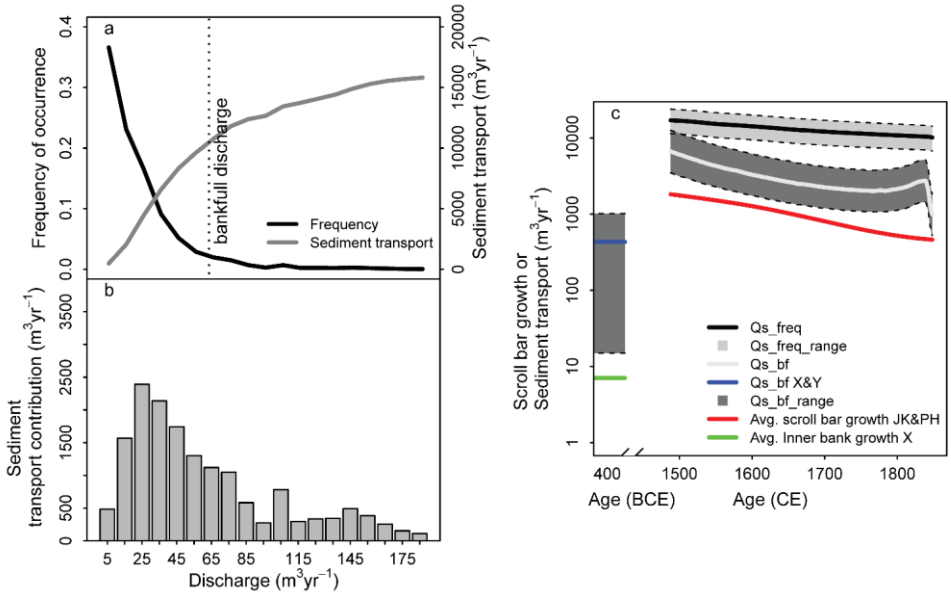

Figure 10: Sediment transport budgets calculated from present-day flow conditions and from meander migration. (a) Discharge and sediment transport characteristics of the Overijsselse Vecht derived from hourly discharge data from 1995 to 2015 of the gauging station Mariënberg, including the frequency of each discharge class over a year, on a frequency scale from 0 to 1, and the sediment transport as function of discharge for a random selected year (1546 CE) in the Junnerkoeland meander bend. (b) Histogram of the sediment transport contribution as function of discharge. (c) The sediment transport and average scroll bar growth over time (JK = Junnerkoeland, PH = Prathoek, X&Q = Palaeochannel X and Q). The abbreviations $Q_{s,freq}$ and $Q_{s,bf}$ are explained in Sect. 3.8. The inner bank growth X refers to the growth rate of the channel deposits on the inner bank at Palaeochannel X, assuming a constant lateral migration rate. Shading indicates the 16th and 84th quantile.

was much lower than for the meandering channels, explaining the large difference between the growth rate of the channel deposits on the inner bank at Palaeochannel X (7.0 m^3 yr^{-1}) and the scroll bars of Junnerkoeland and Prathoek at the start of the meandering phase (1.8*10^3 m^3 yr^{-1}). Both the sediment transport and average scroll bar growth decreased during the meandering phase.

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Fig. 11a shows that the river theoretically had insufficient stream power for meandering ~~at~~ ca. 400 BCE, and the bar regime was overdamped (Fig. 11b). The stream power seemed ~~just~~ sufficient for meandering ca. ~~at~~ 1500 ~~AD~~CE, and ~~, but the potential for meandering decreased from then on. The bar regime was overdamped at 400 BC. T~~the bar regime was underdamped. The potential for meandering gradually decreased during the meandering phase, and became again insufficient when the potential specific stream power drops relatively fast ca. 1850 CE. The damping regime also gradually decreased, but remained underdamped ca. 1850 CE. ~~, and possibly slightly in excitation at 1500 AD until the river was channelized.~~

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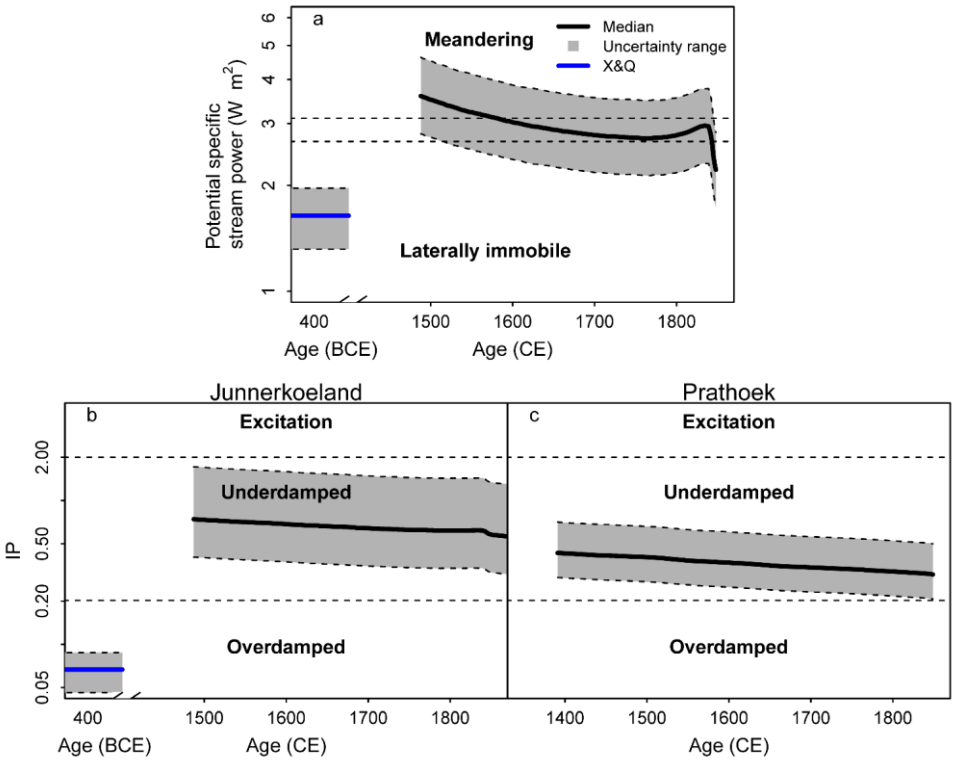

Figure 11: The potential for meandering with time. (a) The potential specific stream power in a stability diagram (Eq. 11). Several discriminators were plotted for a range of median particle sizes of the bed sediment, which is the range of particle sizes found in the scroll bars and Palaeochannel X&Q (Fig. 6). Panels (b) and (c) show the bar regime for both Junnerkoeland and Prathoek, determined with the interaction parameter (IP) (Eq. 18), and compared to the thresholds (Eq. 19 and 20) (X&Q = Palaeochannel X and Q). Shading indicates the 16th and 84th quantile.

5.~~1~~ Discussion

5.1 Laterally stable phase

~~The results indicate a~~A relatively laterally stable phase existed prior to the meandering phase, which is corroborated by the geochronological and palaeohydrological reconstruction. Palaeochannel X formed by extremely slow channel displacement of ca. 6 cm yr^{-1}, assuming a constant channel displacement rate, shown by the OSL dates taken from the channel deposits on the inside of Palaeochannel X (Fig. 1e, Fig. 4c and Table 2). The lateral migration rate of the Junnerkoeland meander bend was

ca. 40 times higher (Wolfert and Maas, 2007; Quik and Wallinga, 2018). The ~~opposite~~outer bank of Palaeochannel X consists of Weichselian and Early Holocene deposits. No Middle Holocene deposits were found in the corings (Fig. 4c,d), reflecting the stable character of the Overijsselse Vecht during this period. ~~ts, similar as Palaeochannel Q, showing the limited presence of Middle-Holocene fluvial deposits.~~ ~~Palaeochannel Q was expected to date from the same laterally stable phase, because of the large similarities in channel symmetry (Fig. 2 and 4e) and size (51.2 ± 5.0 m², Fig. 8e), which was approximately a factor three to eight lower than during the meandering phase (261 ± 116 m²). Palaeochannels X and Q~~

~~Deposits and dimensions of channel reaches are not preserved when still active during the stable to meandering transition, because channel-belt dimensions increase. River reaches of laterally stable rivers can only be preserved when they are cut off by random and local disturbances prior to the meandering phase. Consequently, preservation potential of deposits associated to a laterally stable phase is very small, and only channel reaches that have been subject to perturbations have a chance to be preserved.~~

The preservation potential of deposits associated to the laterally stable phase is likely very small. Deposits and dimensions of active channel reaches are not preserved during the stable to meandering transition, because channel-belt dimensions increase. Hence, channel reaches are only preserved when they were cut off prior to the stable-meandering transition, e.g. due to local perturbations. ~~A~~A channel cut-off probably caused ~~Palaeochannel X~~palaeochannels X and Q of the laterally stable phase to become disconnected from the main river before the meandering phase started. ~~Palaeochannel X was cut off ca. 2.4 ± 0.3 ka, indicated by the ^{14}C dating (Fig. 4c, Table 2). As explained previously (Sect. 1), the preservation potential of deposits associated to the laterally stable phase is likely to be very small. Channel reaches are only preserved when they have been subject to perturbations causing them to be cut off prior to the stable-meandering transition, such as Palaeochannel X, and possibly Palaeochannel Q.~~ In this way these reaches escaped from later lateral erosion during the meandering phase. Consequently, the lateral stability of the river is not immediately evident from these preserved channel reaches, because the ~~perturbations~~ perturbations led to very slow channel displacement as was found for Palaeochannel X. However, scroll bar deposits did not form ~~(Fig. 2, Fig. 4e)~~and lateral accretion surfaces were lacking (Fig. 2, Fig. 4e and Supplementary Information), showing that the displacement was not related to meandering in which helicoidal flows cause bar formation and bank erosion at a significant rate and all along the channel (Seminara, 2006). The laterally stable phase lacked the potential to meander given its low position in Fig. 11a, and is characterized by an overdamped regime (Fig. 11b) and low sediment transport (Fig. 10c). Consequently the formation of bars was suppressed, and the inner bank deposition was small (Fig 10c).

The bend curvature is also an indication for the channel stability. Palaeochannel X comprises of a very sharp bend ($\frac{R_{curv}}{W}$ = 1.4 ± 0.2) compared to the meandering phase ($\frac{R_{curv}}{W}$ = 2.1 ± 0.4), which is often found in low-energy rivers where lateral migration is limited (Hickin and Nanson, 1984; Candel et al., 2018). Large similarities exist between the laterally stable phase reported here and the laterally stable channels in highly cohesive sediment on the intertidal mudflat, which are mostly laterally stable except from some sharp bends where bank failure and flow separation result in very limited and local channel migration (Kleinhans et al., 2009).

5.32 Meandering phaseChannel pattern change

The Overijsselse Vecht River changed from a laterally stable into a meandering river. The palaeohydrological reconstruction allows drawing conclusions, because dDifferences in fluvial regime palaeohydrological conditions between the both phases were large enough to distinguish, despite the large uncertainties in the palaeohydrological reconstruction,. despite the relatively large uncertainties. Bar regime changed from an overdamped regime into an underdamped regime (Fig. 11b-c), leading to overdeepening of the outer-bend pool and enhancement of the point bars in the innerbend (Struiksma et al., 1985; Crosato and Mosselman, 2009; Kleinhans and Van den Berg, 2011). The significantly higher bankfull discharge (factor three to nine, Fig. 9) explains the potential to meander (Fig. 11a), the high sediment transport, and the high scroll bar growth (Fig. 10c) at the start of the meandering phase.

The exact moment of the channel pattern change is between the cut-off of Palaeochannel X (400 ± 300 BCE) and the reconstructed initiation of scroll bar formation (1504 ± 52 CE). Most likely, the transition occurred shortly before the latter, because both point-bars had a relatively similar meander start age (Fig. 2 and 4), the surrounding floodplain is formed by Late-Glacial or Early Holocene deposits (Fig. 4), and there is no evidence of older scroll bar deposits in the vicinity of the studied meander bends. Mature meandering river systems would always leave traces of older scroll bar deposits, channel cut-offs or meander scars, because these are never completely being removed by the river (Toonen et al., 2012; Van de Lageweg et al., 2016).

(Toonen et al., 2012)The palaeohydrological reconstruction shows that the increasing bankfull discharge likely explains the channel pattern change.. The increasing bankfull discharge may reflect an increase in annual discharge, but could also be related to a more irregular discharge regime, because the bankfull discharge largely represents the higher discharges in a river (Wolman and Miller, 1960; Dury, 1973). Consequently, the discharge may have been constant over a year with low peak discharges and a relatively high base flow during the laterally stable phase, changing into a more peaked discharge regime with a relatively low base flow at the start of the meandering phase.

A potential cause of the discharge regime and channel pattern change may be the climate change at the start of the Little Ice Age (14th to 19th century) (Grove, 1988), given the overlap in time with the meandering phase (Fig. 2c-d). Although geomorphological responses differ for each river during the Little Ice Age, enhanced lateral migration or incision was generally observed for most rivers in north-western Europe (Rumsby and Macklin, 1996). The increased bankfull discharge in the Overijsselse Vecht may have been caused by higher runoff relative to precipitation due to reduced evapotranspiration rates and frozen soils (Rumsby and Macklin, 1996; Van Engelen et al., 2001), and/or a higher snowfall/rainfall ratio due to lower winter temperatures in The Netherlands and Germany (Lenke, 1968; Behringer, 1999). Higher snowfall rates were also recorded for the United Kingdom (Manley, 1969), where it led to more flooding during the snowmelt period (Archer, 1992). Studies on historical observations of rivers nearby the Overijsselse Vecht (IJssel, Elbe, Lower Rhine and Meuse) suggested a significant higher flooding rate during the Little Ice Age compared to more recent flooding rates (Glaser and Stangl, 2003; Mudelsee et al., 2003, 2004; Glaser et al., 2010).

An additional cause for an increasing bankfull discharge may have been land use change in the catchment (Kondolf et al., 2002), which affects the discharge regime due to the direct relation with evapotranspiration (Fohrer et al., 2001). For the Overijsselse Vecht catchment, peat reclamation started in the 12th and 13th century (Gerding, 1995; Van Beek et al., 2015a), and intensified from the 14th century onwards (Borger, 1992; Van Beek et al., 2015b). Reclamation of peatlands partly comprised digging of canals to drain the land, and although the reclamation was mainly limited to the margins of peatlands, the hydrological consequences were large. The margins are a natural seal of the peat bog, with a low hydraulic conductivity compared to the remainder of the bog, ensuring peat dome growth. Destruction of these margins will result in drainage of the entire peat bog (Van der Schaaf, 1999; Baird et al., 2008). After several centuries, focus shifted from peat reclamation to exploitation, excavating large peatland areas for fuel during the 17th and 18th century (Gerding, 1995). The largest part of the peat has currently disappeared. Yearly average discharges in peatlands can increase by 40% in the Dutch climatological setting, due to evapotranspiration differences for reclaimed peat areas compared to undisturbed peat areas (Baden and Eggelsmann, 1964; Uhden, 1967; Streefkerk and Casparie, 1987). This increase cannot fully explain the large increase of bankfull discharge in the Overijsselse Vecht (factor three to nine), because peat covered just ca. 27% of the Overijsselse Vecht catchment area during the 14th century (Casparie and Streefkerk, 1992; Vos et al., 2011), hence the yearly average discharge of the catchment increased by ca. 11% due to evapotranspiration differences.

However, ~~S~~several studies have also shown that an increased drainage network in peatlands resulted in higher discharge peaks with a fast discharge response to precipitation (Conway and Millar, 1960; Streefkerk and Casparie, 1987; Holden et al., 2004; Holden et al., 2006). For example, the runoff/rainfall ratio was a factor three higher in a drained Irish peatland compared to an undrained Irish peatland ~~in Ireland~~ (Burke, 1975), which is comparable to the observed bankfull discharge increase in the Overijsselse Vecht. Finally, canals were not only dug for peat reclamation, but also for shipping and effective generation of water power starting in the 11th and 12th century (Driessen et al., 2000), which may have promoted the higher peak flows even more. New canals resulted in a faster runoff, but also changed the watershed delineation (Driessen et al., 2000). We conclude that both climatic and land use changes were likely responsible for an increase in both total discharge and peak flows, resulting in the transition of a relatively stable river to a highly dynamic meandering system.

~~{Ettema, 2002 #680}River width observations from previous studies were compared to the reconstructed width. These observations included observations measured from historical maps by Wolfert and Maas (2007) and measurements of the bankfull river width over a large river section in 1848 AD by Staring and Stieltjes (1848). The river width data from Wolfert and Maas (2007) largely fall in the range of reconstructed bankfull widths at Junnerkoeland, and show a similar decreasing trend (Fig. 8c). However, the historical maps used by them may result in large uncertainties, because the water stage that these maps represent is unknown. The measured widths by Staring and Stieltjes (1848) are in line with the predicted width at Junnerkoeland, falling within the uncertainty range. The predicted width at Prathoek is underestimated compared to the measured widths by Wolfert and Maas (2007) and Staring and Stieltjes (1848). This underestimation also results in an underestimated cross-sectional area (Fig. 8f) and consequently an underestimated bankfull discharge (Fig. 9a).~~

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~~Figure 10c shows that both estimates of sediment transport, $Q_{s,freq}$ and $Q_{s,bf}$, were higher than the scroll bar growth in Junnerkoeland and Prathoek, suggesting that the scroll bar growth could entirely be explained by the sediment transport. Hence external sediment input was probably limited and did not contribute to the meander initiation. The $Q_{s,bf}$ of palaeochannels X and Q is much lower than for the meandering channels, explaining the large difference between the growth rate of the channel deposits on the inner bank at Palaeochannel X (7.4 $m^3 \cdot yr^{-1}$) and the scroll bars of Junnerkoeland and Prathoek at the start of the meandering phase (2.5*10^3 $m^3 \cdot yr^{-1}$ and 4.6*10^2 $m^3 \cdot yr^{-1}$, respectively).~~

~~Palaeochannel X also forms a very sharp bend ($\frac{R_{curv}}{W}$ = 1.4 ± 0.2) compared to the meandering phase ($\frac{R_{curv}}{W}$ = 2.1± 0.4), which is often found in low-energy streams where lateral migration is limited (Candel et al., 2018; Candel et al., 2017; Hickin and Nanson, 1984). Large similarities exist between the laterally stable phase reported here and the laterally stable channels in highly cohesive sediment on the intertidal mudflat, which are mostly laterally stable except from some sharp bends where bank failure and flow separation result in very limited and local channel migration (Kleinhans et al., 2009). .~~

~~Palaeochannels X and Q seem to lack the potential to meander given their low position in Fig. 11a, and are characterized by an overdamped regime (Fig. 11b).~~

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5.3~~2~~ ~~Channel pattern change~~Meandering phase

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~~Our data strongly suggest that the changing discharge regime was the main cause for the channel pattern change in the Overijsselse Vecht. The most likely identified causes are climate changes related to the Little Ice Age and land use changes in the catchment, in particular peat reclamation. Here we will shortly elaborate on the meandering phase, although in-depth understanding of the changes during the meandering phase is beyond the scope of this paper.~~ Interestingly, the bankfull discharge declined ~~over time~~during the meandering phase (Fig. 9a), leading to decreasing sediment transport relatively to the scroll bar growth (Fig. 10c) and insufficient potential specific stream power for meandering after ca. 1850 ~~AD~~CE (Fig. 11a). This decline was corroborated by observations of river width from previous studies, which can be compared to the reconstructed widths (Fig. 8c-d). These observations included measurements from historical maps by Wolfert and Maas (2007) and measurements of the bankfull river width over a large river section in 1848 CE by Staring and Stieltjes (1848). The river width data from Wolfert and Maas (2007) largely fall in the range of reconstructed bankfull widths at Junnerkoeland, and show a similar decreasing trend (Fig. 8c). However, the historical maps used by them may result in large uncertainties, because the water stage that these maps represent is unknown (Quik and Wallinga, 2018). The measured widths by Staring and Stieltjes (1848) are in line with the predicted width at Junnerkoeland, falling within the uncertainty range. The predicted width at Prathoek is underestimated compared to the measured widths by Wolfert and Maas (2007) and Staring and Stieltjes (1848). This underestimation may explain the lower cross-sectional area compared to Junnerkoeland (Fig. 8f), and hence an underestimated bankfull discharge (Fig. 9) and potential specific stream power (Fig. 10).

~~Chezy of sand-bed meandering rivers with a channel-forming discharge lower than 350 m3/s and a valley of < 0.0007. 39.9 +/- 12.3 chezy~~

~~This decline~~ The observed decline of bankfull discharge would suggest that the hydrological forcing disappeared or diminished, and had a temporary character, which would fit ~~with the hypothesis of the~~the Little Ice Age that ended in the 19th century as potential cause. Consequently, it would be expected that the channel pattern reorganized and became laterally stable again. However, the river was still laterally migrating until channelization ~~in~~between 1896 and 1914 ~~AD~~CE (Wolfert and Maas, 2007), which may be related to the presence of an underdamped regime enhancing point bar formation in the inner bend (Fig. 11b-c). Additionally, ~~. H~~historical bank stability changes may have promoted the river meandering during this period. For example, floodplains were intensively used for cattle grazing, which may have weakened the banks, enhancing meandering after 1850 ~~AD~~CE (Trimble and Mendel, 1995; Wolfert et al., 1996; Beschta and Ripple, 2012). Also drift-sand activity was initiated by intensive land use since the Late Middle Ages (Fig. 1c-d) (Koster et al., 1993), which may have affected the bank stability. ~~Drift-sands may also have acted as an extra sediment supply to the river, altering the river morphodynamics by enhancing the scroll bar growth rate and therefore the bank erosion rate (Ferguson, 1987; Nanson and Croke, 1992). However, we found that the scroll bar growth can easily be explained by the reconstructed sediment transport until 1800 AD (Fig. 10c). Therefore, it seems unlikely that increased sediment input by drift-sands initiated the meandering, but it may have promoted meandering since 1850 AD~~

~~. and the low sediment transport (Fig. 10c), explaining the limited channel displacement found with the ^{14}C and OSL datings (Table 2, Fig. 4c).~~

~~A channel cut-off probably caused Palaeochannel X to become disconnected from the main river before the meandering phase started. Palaeochannel X was cut off ca. 2.4 ± 0.3 ka, indicated by the ^{14}C dating (Fig. 4c, Table 2), while inner-bend channel deposits located 50 m from the residual channel were dated at ca. 3.2 ± 0.2 ka. Hence the bend formed with a rate of ca. 6 cm yr^{-1} assuming a constant channel displacement rate.~~

~~Palaeochannels X and Q seem to lack the potential to meander given their low position in Fig. 11a, and are characterized by an overdamped regime (Fig. 11b).~~

~~indicate that the river type has changed from laterally stable to meandering.~~

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~~Deposits and dimensions of channel reaches are not preserved when still active during the stable to meandering transition, because channel-belt dimensions increase. River reaches of laterally stable rivers can only be preserved when they are cut off by random and local disturbances prior to the meandering phase. Consequently, preservation potential of deposits associated to a laterally stable phase is very small, and only channel reaches that have been subject to perturbations have a chance to be preserved.~~

~~A disproportionally higher scroll bar formation rate compared to the sediment transport may point at extra sediment input, which may explain the meander initiation (Ferguson, 1987; Nanson and Croke, 1992).~~

~~5.2 Channel pattern change~~

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~~5.3 Meandering phase~~

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~~**River width observations from previous studies were compared to the reconstructed width. These observations included observations measured from historical maps by Wolfert and Maas (2007) and measurements of the bankfull river width over a large river section in 1848 AD by Staring and Stieltjes (1848). The river width data from Wolfert and Maas (2007) largely fall in the range of reconstructed bankfull widths at Junnerkoeland, and show a similar decreasing trend (Fig. 8e). However, the historical maps used by them may result in large uncertainties, because the water stage that these maps represent is unknown. The measured widths by Staring and Stieltjes (1848) are in line with the predicted width at Junnerkoeland, falling within the uncertainty range. The predicted width at Prathoek is underestimated compared to the measured widths by Wolfert and Maas (2007) and Staring and Stieltjes (1848). This underestimation also results in an underestimated cross-sectional area (Fig. 8f) and consequently an underestimated bankfull discharge (Fig. 9a).~~**

~~**Figure 10c shows that both estimates of sediment transport, $Q_{s,f,eq}$ and $Q_{s,bf}$, were higher than the scroll bar growth in Junnerkoeland and Prathoek, suggesting that the scroll bar growth could entirely be explained by the sediment transport. Hence external sediment input was probably limited and did not contribute to the meander initiation. The $Q_{s,bf}$ of palaeochannels X and Q is much lower than for the meandering channels, explaining the large difference between the growth rate of the channel deposits on the inner bank at Palaeochannel X (7.4 $m^2 \cdot yr^{-1}$) and the scroll bars of Junnerkoeland and Prathoek at the start of the meandering phase ($2.5*10^3$ $m^2 \cdot yr^{-1}$ and $4.6*10^3$ $m^2 \cdot yr^{-1}$, respectively).**~~

~~5.2 Causes of the channel pattern change~~

~~Now that we have found indications of a channel pattern change, we aim to identify the potential causes using the palaeohydrological reconstruction. It seems likely that the increasing bankfull discharge caused the channel pattern change. The channel pattern change likely occurred ca. 1400 AD, because older scroll bar deposits were not found in the Overijsselse Vecht catchment (Quik and Wallinga, submitted). Scroll bar growth significantly increased as a result of higher sediment transport rates (Fig. 10c). The increasing bankfull discharge may reflect an increase in annual discharge, but could also be related to a more irregular discharge regime, because the bankfull discharge partly represents the higher discharges in a river (Dury, 1973; Wolman and Miller, 1960). Consequently, the discharge may have been constant over a year with low peak discharges and a relatively high base flow during the laterally stable phase, changing into a discharge regime with high peak discharges and a relatively low base flow at the start of the meandering phase. Here we discuss potential allogenic factors that may have caused such changes in discharge regime.~~

~~5.2.1 Little Ice Age~~

~~The Little Ice Age (14th to 19th century) (Grove, 1988) may have contributed to the channel pattern change, given the overlap in time with the meandering phase. Although geomorphological responses differ for each river during the Little Ice Age, enhanced lateral migration or incision was generally observed for most rivers in North-western Europe (Rumsby and Macklin, 1996). Studies on historical observations of nearby rivers (IJssel, Elbe, Lower Rhine and Meuse) suggested a significant higher flooding rate during the Little Ice Age compared to more recent flooding rates (Glaser et al., 2010; Glaser and Stangl, 2003; Mudelsee et al., 2004, 2003). River ice jams contributed to ca. 70% of the floods in the Rhine delta, often in combination with precipitation and/or snow melt (Glaser and Stangl, 2003). These ice jams may have caused enhanced bank erosion, because ice jams can result in fast rising flow stages, whereas river ice break-ups will result in fast lowering flow stages and high peak discharges (Ettema, 2002). The water level in the bank responds fast to these changes in flow stage, hence seepage pressure will be high when the flow stage rapidly lowers. This process reduces the bank stability significantly, and may promote bank collapse of the steeper outer bend (Ettema, 2002).~~

~~During the Little Ice Age, the type of precipitation changed significantly, affecting the discharge regime of rivers in North-western Europe. Runoff relative to precipitation may have been higher in winter, due to reduced evapotranspiration rates and frozen soils (Rumsby and Macklin, 1996; Van Engelen et al., 2001). The snowfall/rainfall ratio was probably higher, due to lower winter temperatures in The Netherlands and Germany (Behringer, 1999; Lenke, 1968). Higher snowfall rates were also recorded for the United Kingdom (Manley, 1969), where it led to more flooding during the snowmelt period (Archer, 1992). In the Overijsselse Vecht catchment, snow melt probably also led to higher peak discharges. Currently, the yearly averaged precipitation over the winter months (December, January and February) is 201 mm in the study area. The largest amount of winter precipitation falls as rain, with an average air temperature of 3.4 °C for the period 1981 to 2010 (KNMI, 2010), and~~

~~rapidly contributes to discharge. However, the 25-year averaged winter-temperature during the Little Ice Age was 1.2 °C, reconstructed by Van Engelen et al. (2001) for The Netherlands, suggesting that snowfall during this period was much more significant. If all precipitation in winter would fall as snow in the Overijsselse Vecht catchment (3785 km^2), which for example would melt in springtime within two weeks, an extra peak discharge of 625 m^3 s^{-1} would be generated when the evapotranspiration and infiltration is neglected. This snowmelt period returns more or less yearly, which matches the approximate recurrence interval of the bankfull discharge (Dury, 1973; Wolman and Miller, 1960).~~

~~5.2.2 Land use changes~~

~~An additional cause for a changing discharge regime could be land use changes in the catchment such as deforestation (Kondolf et al., 2002), which affects the discharge regime due to the direct relation with evapotranspiration (Fohrer et al., 2001). However, the most intense phase of deforestation occurred during the Iron Age and Roman period in the Overijsselse Vecht catchment (500 BC – 200 AD), as was derived from pollen records (Groenewoudt et al., 2007; Van Beek et al., 2015a). Forest was replaced by agricultural fields and open grass vegetation for grazing. Therefore, deforestation cannot be the main cause for the channel pattern change discussed in this paper, because it dates from a much earlier period.~~

~~Interestingly, another major land use change occurred in the catchment at a later stage, when humans started to reclaim land in peat areas to cultivate buckwheat. This land use change started in the 12th and 13th century (Gerding, 1995; Van Beek et al., 2015b), and intensified from the 14th century onwards (Borger, 1992; Van Beek et al., 2015a). Reclamation of peatlands comprised digging of channels to drain the land, and burning the top layer of the peat for fertilisation. After several years the land became exhausted and abandoned, and the next tract got reclaimed (Borger, 1992). After several centuries, focus shifted from peat reclamation to exploitation, excavating large peatland areas for fuel during the 17th and 18th century (Gerding, 1995). The cultivation and exploitation of peatlands may have had a significant impact on the discharge regime of the Overijsselse Vecht system, because approximately 27% of the Overijsselse Vecht catchment area was covered with peat around 1500 AD, of which the largest part has currently disappeared (Casparie and Streefkerk, 1992; Vos et al., 2011). Although the reclamation was mainly limited to the margins of peatlands, the hydrological consequences were large. The margins are a natural seal of the peat bog, with a low hydraulic conductivity compared to the remainder of the bog, ensuring peat dome growth. Destruction of these margins will result in drainage of the entire peat bog (Baird et al., 2008; Van der Schaaf, 1999). Yearly average discharges can increase by 40% in the Dutch climatological setting, due to evapotranspiration differences for reclaimed peat areas compared to undisturbed peat areas (Baden and Eggelsmann, 1964; Streefkerk and Casparie, 1987; Uhden, 1967). The discharge also becomes less well distributed over the year, with higher discharges in winter and lower discharges in summer, because water storage capacity changes after reclamation (Baden and Eggelsmann, 1964; Streefkerk and Casparie, 1987; Uhden, 1967). Especially the volumetric storage capacity of the top peat layer changes from 80 or 90% to less than 10%, because the top peat layer gets destructed by burning and lowering of the groundwater table leading to decomposition and oxidation (Streefkerk and Casparie, 1987; Van der Schaaf, 1999).~~

~~Several studies have shown that an increased drainage network in peatlands resulted in higher discharge peaks with a fast discharge response to precipitation (Conway and Millar, 1960; Holden et al., 2004; Holden et al., 2006; Streefkerk and Casparie, 1987). Holden et al. (2006) found that immediately after the drainage the runoff/rainfall ratio increased, probably related to dewatering of the peatland. This response was largest immediately after peat drainage, as ditches become less efficient over time when they fill up with vegetation or sediment (Fisher et al., 1996; Stewart and Lance, 1991). Finally, canals were not only dug for peat reclamation, but also for shipping and effective generation of water power starting in the 11th and 12th century (Driessen et al., 2000), which could have promoted the higher peak flows even more. New canals resulted in a faster runoff, but also changed the watershed delineation (Driessen et al., 2000). Consequently, peak flows as well as the total discharge likely increased due to land use changes.~~

~~5.3 Meandering phase~~

~~Our data strongly suggest that the changing discharge regime was the main cause for the channel pattern change in the Overijsselse Vecht. The most likely identified causes are climate changes related to the Little Ice Age and land use changes in the catchment, in particular peat reclamation. Here we will shortly elaborate on the meandering phase, although in-depth understanding of the changes during the meandering phase is beyond the scope of this paper. Interestingly, the bankfull discharge declined over time (Fig. 9a), leading to decreasing sediment transport relatively to the scroll bar growth (Fig. 10c) and insufficient potential specific stream power for meandering after 1850 AD (Fig. 11a). This decline would suggest that the forcing disappeared or diminished, and had a temporary character, which would fit with the hypothesis of the Little Ice Age that ended in the 19th century. However, the river was still laterally migrating until channelization in 1914 AD (Wolfert and Maas, 2007). Historical bank stability changes may have promoted the river meandering during this period. For example, floodplains were intensively used for cattle grazing, which may have weakened the banks, enhancing meandering after 1850 AD (Beschta and Ripple, 2012; Trimble and Mendel, 1995; Wolfert et al., 1996). Also drift-sand activity was initiated by intensive land use since the Late Middle Ages (Fig. 1c-d) (Koster et al., 1993), which may have affected the bank stability. Drift-sands may also have acted as an extra sediment supply to the river, altering the river morphodynamics by enhancing the scroll bar growth rate and therefore the bank erosion rate (Ferguson, 1987; Nanson and Croke, 1992). However, we found that the scroll bar growth can easily be explained by the reconstructed sediment transport until 1800 AD (Fig. 10c). Therefore, it seems unlikely that increased sediment input by drift-sands initiated the meandering, but it may have promoted meandering since 1850 AD.~~

Field Code Changed

6. Conclusions

We show that bankfull discharge and associated river parameters can be reconstructed by following a stochastic approach, and through detailed geochronological and lithological analysis of scroll bar deposits and palaeochannels. For the Overijsselse Vecht River we demonstrate that an increase in bankfull discharge ca. 1400 to 1500 CE resulted in a river channel pattern change from laterally stable to meandering. ~~These phases were sufficiently constrained by reconstructing the palaeohydrology~~

~~from multiple palaeochannels and scroll bar deposits. This study shows that reconstructions of channel pattern changes in low-energy rivers require a much higher resolution of subsurface data than usually gathered, because palaeochannels of laterally stable rivers are poorly preserved in the fluvial archive of meandering channel belts.~~ Geochronological data confirmed our hypothesis on the lateral stability of the river prior to the meandering phase, in contrast to previous assumptions that were made of continuous meandering during the Holocene.~~. We conjecture that the change from laterally stable to meandering has occurred in some low-energy rivers for which increased Holocene fluvial activity was reported.~~

We ~~also~~ show that the reconstructed ~~palaeodischarge and sediment~~ river parameters ~~transport~~ are consistent with both the laterally stable and meandering channel pattern~~. These phases were sufficiently constrained by reconstructing the palaeohydrology from multiple palaeochannels and scroll bar deposits.~~ by applying empirical channel and bar pattern models. Potential causes for the discharge regime changes include climate change (Little Ice Age) and land use changes (peat reclamation, peat exploitation, digging of canals). We conjecture that the change from laterally stable to meandering has occurred in ~~some low-energy~~other rivers for which increased Holocene fluvial activity was reported.

~~Reconstructions of channel pattern changes in low-energy rivers require a much higher resolution of subsurface data than usually gathered, because palaeochannels of laterally stable rivers are poorly preserved in the fluvial archive of meandering channel belts.~~

~~The channel pattern of the Overijsselse Vecht changed from a laterally stable into a meandering river during the Late-Holocene. We attribute this change to a two to five times increase in bankfull discharge, based on a palaeohydrological reconstruction building on channel dimensions of the different phases. Consequently, the river had sufficient potential specific stream power to erode outer banks and sufficient sediment transport to build scroll bars, in contrast to the preceding laterally stable phase. The bar regime changed from an overdamped to underdamped regime, leading to overdeepening of the outer-bend pool and enhancement of the point bars in the inner-bend. Historical land use and climate change were identified as the most likely causes of the channel pattern change. The bankfull discharge increased partly as a result of the Little Ice Age, due to increased snowfall and ice jams. Moreover, peat reclamation and exploitation has contributed to a changing discharge regime, as well as the digging of new canals for shipping and effective generation of water power. We argue that similar channel pattern changes likely occurred in many other low-energy rivers during the Late Holocene, but these are difficult to identify due to poor preservation of channel deposits associated with laterally stable river phases. Considering the importance of land use and climate on the river channel pattern, it is crucial to align plans for future landscape design and climate projections with river restoration goals.~~

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