

*Dear Editor and Reviewers,*

*Thank you very much for your kind words and appreciation of our manuscript. We will take your constructive comments into account, which form a valuable addition. Thank you for your detailed suggestions regarding text and style, we agree and all related points will be included in the revised version. Please find our continued reply below.*

Interactive comment on "Reconstructing lateral migration rates in meandering systems; a novel Bayesian approach combining OSL dating and historical maps" by Cindy Quik and Jakob Wallinga

E. J. Rhodes (Referee)

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1. Line 42 I suggest you add "and river management" after "land use". I am thinking of things such as weirs, mills, cut-off channels, bank modification etc.  
*We agree; this is what we meant with direct interference with the river; we have clarified the text to make this clear.*
2. Line 53 There are some other papers that do this, e.g. including Kemp and Rhodes (2010) QSR, though I am not suggesting you include the citation.  
*We will include the citation, as well as a paper by Rowland et al., 2005.*
3. Line 70 I very firmly agree that this is underexplored.  
*Thank you.*
4. Line 138 This is an excellent selection of maps.  
*Thank you.*
5. Line 140 Is "normalization" a recognised term here? I would possibly suggest "regularization" (not great) or perhaps simply "channel management works" (better).  
*We have changed it to "channelization", in line with the suggestion by Janet Hooke (see comment 24).*
6. Line 145 It is not clear to me what "otherwise used" includes.  
*We have changed the sentence to improve clarity.*
7. Line 175 It would be informative to know the values of what the range of spatial errors was here.  
*The spatial errors (RMSEs) are available in Table 1, we have added a reference to this table at the end of the sentence.*
8. Line 203 "The moment: : " is not 100% accurate, as some electrons are emitted and recombine shortly after the light source is turned on. I would simply say "When" which has a lesser degree of suggestion of an instantaneous effect.  
*We agree and have changed the sentence.*
9. Line 204 As partial and incomplete bleaching are a feature of some samples, I would try and be more precise here. I suggest you say something like "the OSL signal is reduced (bleached) to a low level, often close to zero".  
*We agree and have included your suggestion.*
10. Line 244 It is useful to include the concentration and time of treatment for the HF here.  
*We have included details on the HF treatment.*
11. Line 260. We need a reference to the measurement conditions, which are presented in Table 2. It is useful to describe the equipment used and the filters used (probably U340 on a Riso set, but let's be sure). Note, in Table 2, "10s cutheat to 180 deg. C" doesn't make full sense. A cutheat by definition is for held for no time. I appreciate that the heat treatment in the second part of the SAR cycle is often referred to as a cutheat to distinguish it from the preheat before the main OSL measurement, so perhaps you could either just use "10s preheat at 180" here, or if you want to preserve cutheat, say "10s "cutheat" at 180"?  
*We agree; indeed we used a heating of 10s for the testdose, but like to preserve "cutheat" to make a distinction with the preheat prior to measurement of the natural and regenerative signal. We therefore added the quotation marks as you suggested.*
12. Line 322 The use of +/- to mean "approximately" is a little misleading, and not recognised scientific usage. Either use the "~" symbol, say "approximately". I was misled when I read this, as I assumed this was an uncertainty value on the width, rather than the width value used. In fact, as you used this width value, there is not really any uncertainty on the value, only on whether it is appropriate (which I think it is!), so I would just say 30m here.  
*We agree and have changed all occasions where +/- was used to indicate "approximately" to the symbol ~.*

13. Line 335 It would be useful to know how much uncertainty in position there was here. Give us some typical or max/min values possibly.  
*We have added the maximum RMSE value and referred to Table 1, which lists the RMSE values for all maps used.*
14. Lines 399-401. Some of this information is repeated from a few line above, so you can contract this first sentence a little.  
*We agree and have reduced the text here.*
15. Lines 440-450 Is it possible that the channel widths varied significantly, for example during the progression downstream of a gavel slug?  
*There are indications that channel width varied through time (Candel et al., 2018), however this will have only have a minor effect on our analysis as the model has low sensitivity to reasonable changes in the z-values (as demonstrated by our sensitivity analysis). We included an additional paragraph in the discussion to address effects of spatial uncertainties.*
16. Table 3 and elsewhere. Did you consider using CE (Common Era) rather than AD?  
*We agree that using CE is better and thank the reviewer for this valuable suggestion. We have changed all writing of BC/AD to BCE/CE notation.*

Interactive comment on "Reconstructing lateral migration rates in meandering systems; a novel Bayesian approach combining OSL dating and historical maps" by Cindy Quik and Jakob Wallinga

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17. It would be useful to have a summary Figure at the end plotting migration rates themselves over time (with error bars) since much of the discussion is about these, though it can be inferred from Fig. 7.  
*Indeed it would be interesting to present such a plot, and we considered it at an earlier stage, and again following the reviewer's suggestion. Nevertheless, we decided not to include such a graph as it can already be deduced from the slope of the graph in Fig. 7. We feel that plotting this information separately (including uncertainty) would be of limited added value, as the precision and resolution of our chronological data does not allow inferences on fluctuations in migration rate. We deduce the average migration rate from Fig. 7 but recommend caution in interpreting rate fluctuations.*
18. 40 not entirely true that historical maps only cover "cultivated" areas.  
*We agree and have modified the sentence.*
19. 53 and elsewhere on p 2 - other literature should be acknowledged, e.g. Rowland et al. (2005). Need to be very careful in naming only one exception that literature search is absolutely comprehensive.  
*We have changed the sentence and included the citation.*
20. 87 give width of channel so we understand its size - very important for subsequent evidence and analysis.  
*We added channel width.*
21. Fig.1 and 120 - cannot refer to a paper that is only submitted and not available.  
*This paper is currently available in interactive discussion on ESurfD (<https://www.earth-surf-dynam-discuss.net/esurf-2018-31/>), we have changed the reference to the paper.*
22. Section 3.2 Need a fuller review of use of historical maps. Hooke and Kain (1982) wrote a book on use of historical evidence, including guidelines on checks to be made. Other subsequent papers give more detail on accuracy in relation to meander changes. Not all older maps necessarily less accurate. Certainly those pre 1840 in Britain were less accurate and not usable for river planform position but late 19thC / early 20thC OS maps at large scale were of high accuracy.  
*We have added references to general background information on using historical sources (including the book by Hooke and Kain, 1982). We added more references on the maps we used, as the historical background on their production and information on cartographers, survey techniques and depiction methods were addressed in previous publications. For checking map quality we rely on these publications and on our analysis with the MapAnalyst software, which is one of the most recent (2011) techniques for checking map accuracy and can be used in combination with modern GIS techniques.*
23. 3.2.1 Discuss scale of maps.  
*We have changed the sentence that mentions differences between the maps to include scale.*
24. 140 - "normalization" is a term to be avoided since straightening is far from normal and is completely artificial ( although it is common translation). Use channelization.  
*We have changed the wording to "channelization".*
25. 150 Finding GCPs is a frequent problem in analysing rivers because of lack of fixed features in floodplains. Is not simply due to nature of maps nut nature of floodplain landscapes.  
*We agree and have changed the text for clarification.*

26. 3.3.1 Explain position of samples in relation to scroll bars and ridges and swales.  
*We have added two sentences to the manuscript text to explain the choice of sampling location and distribution of samples over the scroll bar deposits.*
27. Precision of 3m seems unnecessarily low, Discuss effects on errors.  
*The GPS equipment we used had a precision of up to 3 m. We averaged the precision as recorded with our coordinates, which is ~5 m. As sample spacing was ~200 m, the effects of these uncertainties on final rate estimates and trends are negligible compared to other uncertainties. As demonstrated by our sensitivity analysis, the model has low sensitivity for minor changes in the z-value (GPS position, channel width). We have added a paragraph in the discussion to address effects of spatial uncertainties.*
28. 3.4 Indicate the width of scroll bars. It is possible to plot the trajectory of maximum meander movement if the scroll bars are highly visible on air photo or satellite images. This would be an added check and corroboration. Also indicates direction of meander movement in relation to the assumed profiles taken.  
*The width of the scroll bars is indicated in section 3.4 and used to calculate the  $k_0$ -value for the model (77 and 42 m, for Junner Koeland and Prathoek respectively). The profile of Candel et al. (2018) was taken along a line perpendicular to the point bars. We have added this information to the section on the lithological survey, and refer to the Candel et al. (2018) paper for further details.*
29. 299 Explain in more detail why or what is meant by assumption of randomness in deposition.  
*Randomness relates to the Poisson process; we mean that lateral migration rates can vary. We have added "varying in rate" between the brackets that were already in the sentence.*
30. 312 but position only accurate to 3m  
*We have changed the wording and added the precision of the GPS (see also reply to comment 27).*
31. 318 Channel width is very likely to have varied significantly over the period of the last few centuries. Numerous papers document such changes on European rivers. Thus assumptions about width introduce another uncertainty, which is assessed but the variations could be real. Again, could supplement with measurements of meander scroll widths if visible on images.  
*See reply to comment 15.*
32. 323 Danger of circular argument. Need to be very careful about assumptions on migration rates since it has been shown that rates tend to accelerate with curvature and during bend development (Hickin, Hickin and Nanson, Hooke, numerous papers).  
*We are well aware of this challenge and prevented circular reasoning through the iterative approach, which we believe provides an eloquent solution to circumvent the problem.*
33. 4.1 I found that maps earlier than 1840 tend to be much less accurate, including the 1st Ordnance Survey maps in England. May help to show presence and absence of features but not exact position. Agree with strategy to exclude the older maps (L439).  
*Thank you.*
34. 417 & 464 state that river moves outside valley but river must be in the valley. Do you mean outside floodplain and moving into terraces and/ or valley wall? If extends into such materials they tend to be more resistant than alluvium so tend to impede channel movement, whereas development shown on Fig. 5 is relatively rapid. Need to explain what the channels move into and what was restricting them prior to that.  
*The investigated meanders have moved outside the former valley and through the former valley side, thereby expanding the floodplain and moving into Pleistocene fluvial deposits and cover sands, locally with Holocene drift-sands on top (all unconsolidated sediments). For clarification we added some lines on this in the section Study Area and emphasised the nature of the sediments reworked by the laterally migrating channel in line 417.  
The reason of prior restriction within the former valley side is partly addressed by Candel et al. (2018) and is the topic of our next manuscript, so please stay tuned!*

# Reconstructing lateral migration rates in meandering systems; a novel Bayesian approach combining OSL dating and historical maps

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10 **Abstract.** Identifying lateral migration rates of meandering rivers is relevant both for fluvial geomorphology and  
to support river management. Lateral migration rates for contemporary meandering systems are often reconstructed  
based on sequential remote sensing images or historical maps, however the time frame for which these sources are  
available is limited and hence likely to represent fluvial systems subjected to human influence. Here, we propose  
to use scroll bar sequences as an archive to look further back in time using optically stimulated luminescence  
15 (OSL) dating of sand-sized quartz grains. We develop a modelling procedure for the joint Bayesian analysis of  
(OSL) dating results and historical map data. The procedure is applied to two meanders from the Overijsselse  
Vecht, a medium-sized sand-bed river in The Netherlands. We obtained 9 samples for OSL dating from scroll bars,  
and combined OSL dating results with historical map data for the period 1720 - 1901 CE (Common Era). The  
procedure we propose here incorporates strengths of both data types for reconstructing fluvial morphodynamics  
20 over longer timeframes. Using an iterative modelling approach, we translate spatial uncertainty of historical maps  
into temporal uncertainty of channel position required for Bayesian deposition modelling. Our results indicate that  
meander formation in the Overijsselse Vecht system started around 1400 CE, and lateral migration rates were on  
average 2.6 and 0.9 m/y for the two investigated bends, until river channelization around 1900 CE.

25 **Keywords:** optically stimulated luminescence, Bayesian chronological modelling, OxCal, poor bleaching, fluvial  
geomorphology, Holocene.

## 1 Introduction

Rivers are one of the world's most important geomorphic agents and represent highly dynamic earth surface  
30 systems (Vandenberghe and Maddy, 2000; Güneralp and Rhoads, 2011). Meandering rivers represent the most  
common river type and can be found all over the world (Hooke, 2013). The mobility of their course has a significant  
effect on sediment transport and deposition, floodplain development and landscape change (Kleinhans and Van  
den Berg, 2011). Related consequences for river management, hazards and biodiversity pose a practical need to  
understand the timing and speed of lateral migration (Hooke, 2013; Grabowski et al., 2014; Lespez et al., 2015).

35 To determine whether changes in meander position and morphology have taken place it is often needed to  
consider relatively long time scales (Hooke, 2013). To establish recent lateral migration rates and reconstruct the  
planform of contemporary fluvial systems, sequential aerial photographs or topographical maps are often used  
(e.g. Pišút, 2002; Uribealarea et al., 2003; Hooke and Yorke, 2010; Eekhout et al., 2013). Unfortunately, the lack

of historical sources of this type limits long-term reconstructions of channel position, and reconstructions based on older maps may be grossly affected by spatial uncertainties and mapping inaccuracies. Moreover, as historical maps are often only available for cultivated areas, the fluvial systems displayed are likely to be affected by humans. Such influence can be either through river management (e.g. Hesselink et al., 2003; Frings et al., 2009), or through land-use changes which may change the hydrograph (e.g. Candel et al., 2018) as well as sediment input (e.g. De Moor et al., 2008; Hoffmann et al., 2009). Consequences may be large, as shown in a highly-influential paper by Walter and Merritts (2008), who argued that present-day meandering form of gravel-bedded mid-Atlantic streams in the USA is not a natural phenomenon, but rather an artefact caused by mill ponds. Hence, to understand dynamics of fluvial systems and anthropogenic impacts on those systems, there is a need to extend the period of reconstruction to earlier periods, which requires reconstruction methods that do not rely solely on historical sources and/or remote sensing.

To resolve depositional ages and geomorphological process rates, the use of optically stimulated luminescence (OSL) dating to obtain absolute chronologies of fluvial deposits is becoming widespread (Wallinga, 2002a; Lian and Roberts, 2006; Rittenour, 2008). In addition, OSL is increasingly used to date young (<1000 years) sediments as part of Late-Holocene studies (Madsen and Murray, 2009). Yet, application of OSL dating to reconstruct lateral migration rates has hardly been attempted (with a few notable exceptions, see e.g. Rodnight et al., 2005; Rowland et al., 2005; Kemp and Rhodes, 2010). Such limited application of OSL dating for this purpose may well be related to challenges faced when applying luminescence dating to young fluvial sediments. Successful age determination requires complete resetting of the OSL signal in at least part of the grains; a prerequisite that may not be met due to limited light exposure during subaqueous transport of grains in a turbid river.

Bayesian analysis of depositional sequences allows the construction of more precise and robust chronologies by combining ages obtained through a dating method with prior information on the order of events (Bronk Ramsey, 2008). Following pioneering work by Rhodes et al. (2003), Bayesian analysis is now increasingly applied to sequences of OSL ages, often in combination with ages obtained through other methods (e.g.  $^{14}\text{C}$ : Dreibrodt et al., 2010; U-series: Clark-Balzan et al., 2012; Dendrochronology: Wallinga et al., 2012), or even multiple methods (e.g. Shanahan et al., 2013; Hobo et al., 2014; Guérin et al., 2017).

Several studies have combined OSL dating with evidence derived from historical maps and documentation as independent age control (e.g. Ballarini et al., 2003; Medialdea et al., 2014), age constraints (e.g. Nielsen et al., 2006; Madsen et al., 2007; Tamura et al., 2011; Kunz et al., 2014), or for historical contextualisation of dating results (e.g. Clemmensen et al., 2007). However, direct integration of OSL dates with legacy data provided by historical evidence into a single geochronology, i.e. where historical evidence is used to help determine the geochronology, is underexplored. An exception to this is the study by Hobo et al. (2014), who reconstructed floodplain sedimentation of the Dutch river Waal using Bayesian age-depth models based on heavy metal age estimates, OSL dates and age constraints derived from historical maps.

Here we combine OSL data and historical map evidence using Bayesian chronological modelling to reconstruct planform development and lateral migration rates of the Overijsselse Vecht, a medium-sized sand-bed river in The Netherlands. Our aim is to develop a modelling procedure using the Bayesian depositional sequences tool of OxCal (Bronk Ramsey, 2008) for the joint analysis of OSL dating results and historical map data, that (1) allows quantitative analysis of historical maps in geochronological research and (2) supports the development of robust fluvial chronologies with quantified uncertainty that expand into larger timeframes. With these methods we

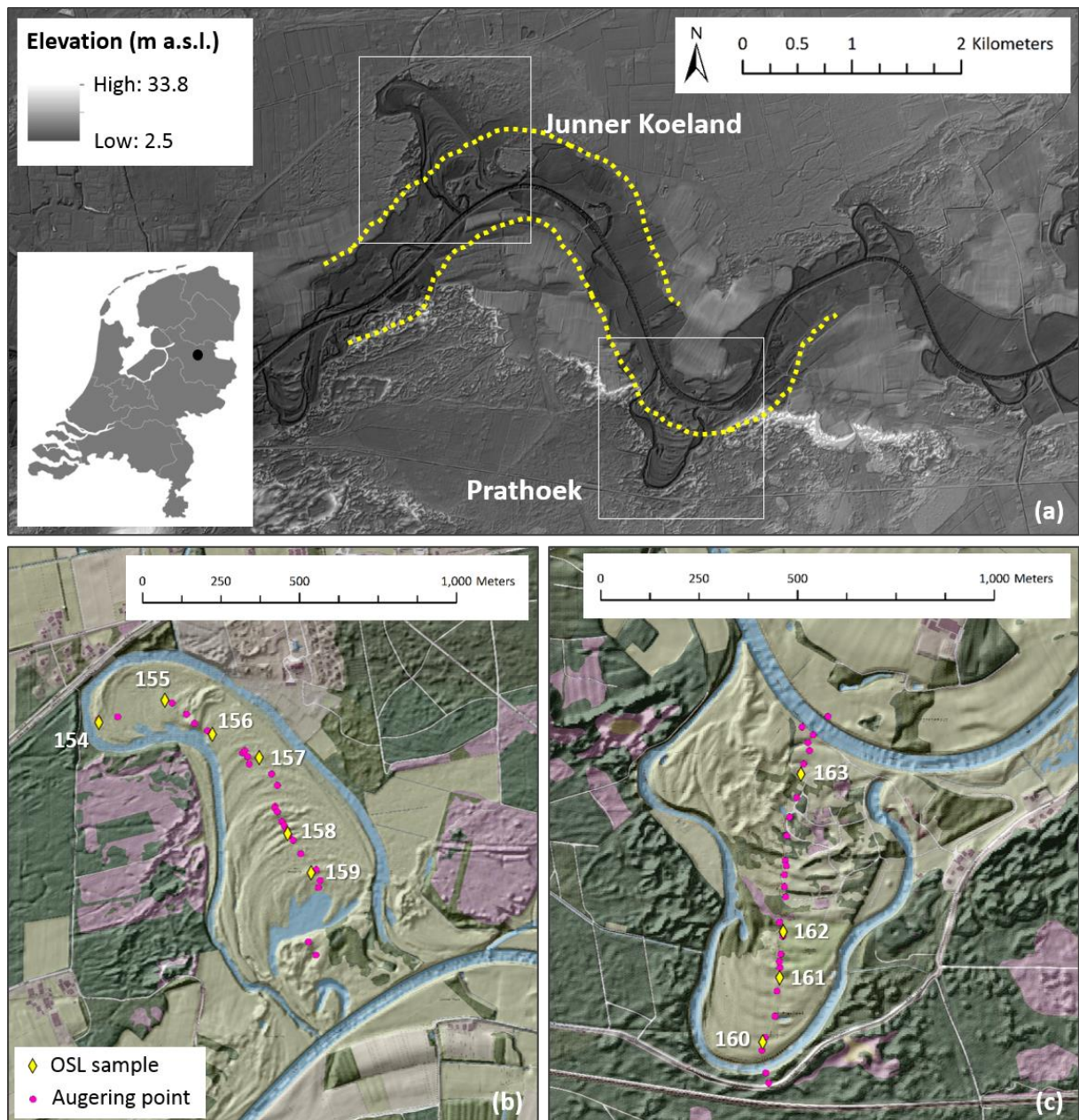
determine the age of scroll bar deposits along the Overijsselse Vecht and the average migration rate of two  
80 meanders that developed during the past 500 years. This information provides the geochronological basis for a  
palaeohydrological study on the Overijsselse Vecht (Candel et al., 2018).

## 2 Study area

The Overijsselse Vecht is a medium-sized river originating in Nordrhein Westfalen in Germany and enters the  
85 Netherlands from the East near the town of Coevorden. This rain-fed river has a catchment size of 3785 km<sup>2</sup> and  
a rather uniform valley gradient on Dutch territory of  $1.4 * 10^{-4}$  (Wolfert and Maas, 2007). The width of the  
abandoned channel (i.e. abandoned upon channelization) in the investigated meanders (see below) is ~30 m, as  
derived from the DEM (Fig. 1). According to measurements in the period 1995-2015 of the discharge station in  
Mariënberg (just upstream from our study area) the average annual discharge and mean annual flood discharge  
90 amount to 22.8 and 160 m<sup>3</sup> s<sup>-1</sup> respectively. Average annual rainfall in the region amounts to 800 - 875 mm and  
average monthly temperatures vary between 4.5 - 5.0°C in January and 22.5 - 23.0°C in July (KNMI, 2017).

The Overijsselse Vecht was channelized in the late nineteenth and early twentieth century. The original river  
length of 90 km on Dutch territory was reduced to 60 km by the cut off of 69 meanders (Wolfert and Maas, 2007).  
Weirs were installed to prevent vertical erosion of the river bed, and groynes and revetments were constructed to  
95 prevent lateral migration of the river channel (Wolfert et al., 1996; Wolfert and Maas, 2007). In recent decades,  
water managers have initiated several projects to restore the physical and ecological functioning of the river, which  
posed the need for increased understanding of river morphodynamics (e.g. Wolfert et al., 1996, 2009; Maas et al.,  
2007; Viveen et al., 2009) and ecological potential (e.g. Duursema, 2004).

The floodplain of the Overijsselse Vecht is flanked on both sides by extensive areas with coversand ridges and  
100 drift-sand dunes, overlying fluvioperiglacial deposits of Pleistocene age (Ter Wee, 1966, 1979; Kuijer and Rosing,  
1994; geomorphological map of the Netherlands [1:50,000], for details refer to Koomen and Maas, 2004). Its  
former valley is rather narrow (indicated by the yellow dotted lines in Fig. 1a) and many meanders appear to be  
laterally confined by relatively stable sides of the former valley. Relief in the area is limited; the floodplain and  
valley sides are located at ~5.5 and ~7 m a.s.l respectively. For this study we focused on two meander bends with  
105 large amplitudes that reach outside the former valley side, named Junner Koeland and Prathoek (Fig. 1).



**Figure 1.** Location of the study area (a), showing the two meander bends Junner Koeland (b) and Prathoek (c). Dotted line in (a) indicates the valley side. M a.s.l. = metres above sea level. White numbers along the coring transects in (b) and (c) indicate OSL sample locations by abbreviated sample code (all should be preceded by NCL-2415). Samples NCL-2415154–162 were collected in scroll bar deposits, sample NCL-2415163 was collected in a terrace remnant. Lithological cross sections and lithogenetic interpretation are provided in Candel et al. (2018). Digital elevation model (AHN2, horizontal resolution 5 m, vertical resolution 0.2 m): AHN (2018); Van Heerd et al. (2000). Topography (3200 pixels/km): OpenTopo, Van Aalst (2017).

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### 115 3 Methods

#### 3.1 Lithological survey

For each meander bend a lithogenetic cross section was constructed based on multiple hand-corings from meander base to apex (Fig. 1bc), following a line perpendicular to the scroll bars, with cores obtained at high and low points in the scroll bar and swale topography. In a separate paper, Candel et al. (2018) provide details of these cross sections (including detailed facies descriptions and an explanation of the lithogenetic interpretation), and use the

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information to reconstruct palaeodischarges. Here we concentrate on those aspects that are directly relevant to the reconstruction of channel position throughout the lifetime of the meander. Most of the cores reached a depth of 4 to 6 metres, penetrating the full point-bar deposits (extremely fine to coarse sand) including the channel lag (medium fine to coarse sand with gravel), which occurred at depths varying from 2.5 to 4 m below the surface. Some aeolian reworking occurred locally, as evident from the DEM (Fig. 1). The lithological and geomorphological information was used to select the suitable depths to collect OSL samples (see below).

### 3.2 Analysis of historical maps

Maps show the position of the river channel at the time of the map survey, however the use of this information for quantitative reconstruction of channel position over time is not straightforward. First of all, historical maps are likely less accurate than their modern counterparts. Hence there is an uncertainty in the exact position of the channel. In this section we outline how we quantify this spatial uncertainty. Next, to allow Bayesian analysis of the sequence, this spatial uncertainty must be translated into a temporal uncertainty. The necessity of this step and the approach we take are outlined in section 3.4.

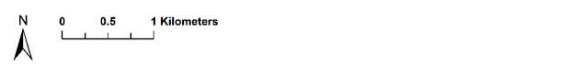
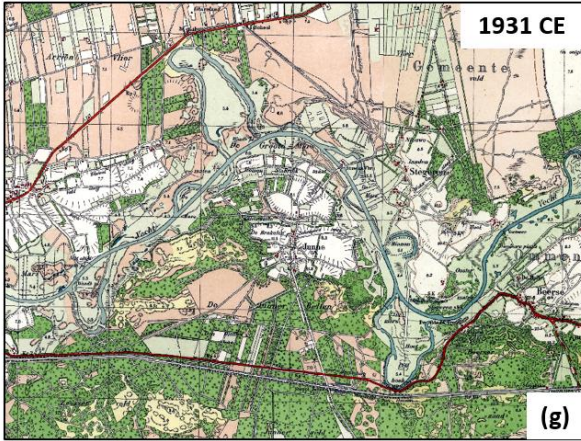
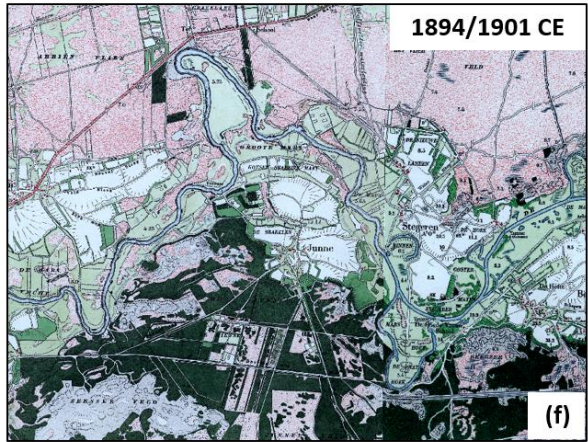
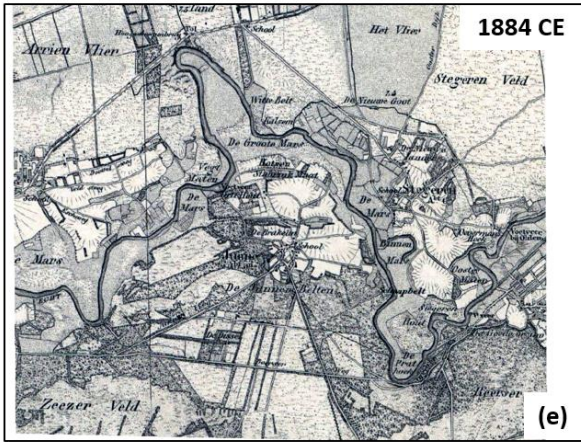
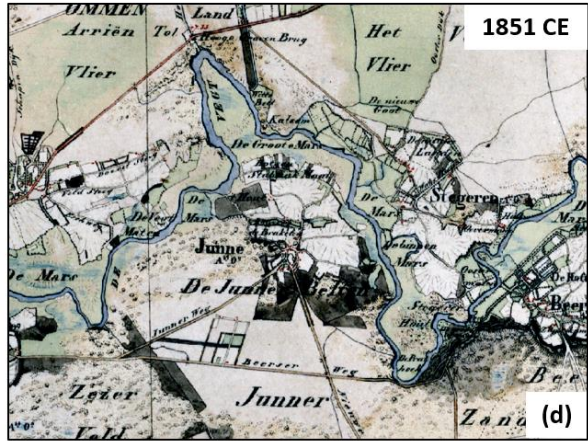
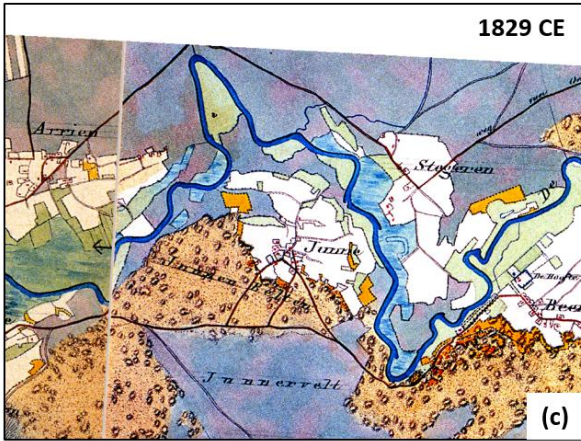
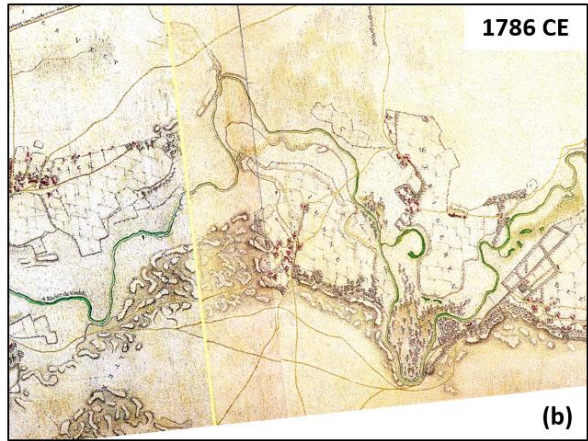
#### 3.2.1 Georeferencing

Six historical maps (dating from 1720 to 1894/1901 CE [Common Era], indicated with letters a-f, Table 1, Fig. 2a-f) were selected for analysis. The selected maps vary in extent (e.g. focused on the Overijsselse Vecht or on The Netherlands as a whole), scale (varying from 1:14,400 to 1:50,000), and original purpose (military or topographical surveys), consequently they vary in their display of the study area. We included these maps in our analysis based on the degree of topographical quality (i.e. sufficient detail for georeferencing), and a quality check to assess geodetic distortion (see 3.2.3). Younger maps (example for 1931 CE provided in Fig. 2g) did not provide relevant information as the meanders under investigation were cut-off during river channelization in the early twentieth century and consequently no longer active. Older maps (>1720 CE) were also available for the area, but had to be excluded from the analysis as georeferencing was impossible due to the limited topographical information on the maps. Historical context of the maps and information on the cartographers, survey techniques, and map depiction methods has been discussed in previous publications (see Table 1 for sources and references). For general background information on the use of historical sources and relevant concepts see e.g. Hooke and Kain (1982; particularly chapter 3 on Accuracy and Analysis), Petts et al. (1989) or Gurnell et al. (2003).

The relevant map parts were used with the given digital image quality or scanned and saved at a resolution of 600 dpi. The maps were georeferenced using Esri's ArcMap (versions 10.3.1 and 10.5) based on static landscape features (e.g. churches, road crossings) that were displayed on both historical and reference maps. For the latter we used a digital elevation model (AHN2, 5 m horizontal resolution, 0.2 m vertical resolution) and a recent topographical map (OpenTopo) (AHN, 2018; Van Heerd et al., 2000; Van Aalst, 2017). Georeferencing maps of river landscapes can be challenging due to limited presence of stable landscape features in floodplains. As the valley of the Overijsselse Vecht is rather narrow (fig. 1a), we were able to adequately georeference the map fragments based on GCPs located close to, but not inside, the floodplain. We predominantly made use of clearly delineated features such as road crossings, but occasionally included features with more irregular edges such as arable fields (ground control points are available in the supplement). Maps were georectified using a first order polynomial transformation (following e.g. Downward et al., 1994; Leys and Werritty, 1999) and nearest neighbour



pixel resampling as this resulted in the sharpest display of the river channel (based on visual assessment). Subsequently all maps were displayed using the Dutch RDnew projection. The ground control points were exported from ArcMap as a \*.txt file to use in the freely available software MapAnalyst (see below). Map quality was analysed using (1) a quantification of geospatial error or planimetric accuracy and (2) with visualisations of geodetic distortions as generated by MapAnalyst. Both aspects are explained below.



170 **Figure 2.** (a - e) Fragments of historical maps displaying the study area (for explanation refer to Table 1), (g) map showing the same area in 1931 CE (publication date). As fragment (f) consists of two map sheets two dates are listed (details in Table 1). Image references: (a) Algemeen Rijks Archief. Genie-archief, situatiekaart 07; (b) Versfelt, 2003; (c) Versfelt and Schroor, 2005; (d - g) CC-BY Kadaster, 2018.

### 3.2.2 Quantifying geospatial error

175 The root mean square error (RMSE) of the displacement vectors of the GCPs is often used as a quantification of geospatial error and was automatically calculated by ArcMap (Esri, 2018) according to:

$$\text{RMSE} = \sqrt{\frac{1}{n} \left( \sum_{i=1}^n (\varepsilon_{x_i}^2 + \varepsilon_{y_i}^2) \right)} \quad (1)$$

180 Where  $\varepsilon_{x_i}$  and  $\varepsilon_{y_i}$  respectively represent the x and y component of the displacement vector that indicates the difference between the location of GCP i on the reference map and the location of the same point on the historical map after first order polynomial transformation. The total number of GCPs is indicated by n. The RMSE was used to assess geospatial error or planimetric accuracy (for the range of spatial errors see RMSEs in Table 1), defined as ‘the extent to which distances and bearings between identifiable objects coincide with their true values’ (cf. 185 Jenny and Hurni, 2011).

After georeferencing the channel centreline was deduced from each map to reconstruct channel position for each time slice. The RMSE was used to draw an error band around each centreline. The centreline and error band represent the positional mean and related standard deviation respectively. The channel centrelines and error bands were subsequently used in the chronological modelling (see section 3.4). The final position of both investigated 190 meanders was based on the abandoned channel as displayed by the DEM of the present-day situation. Historical evidence indicates that Prathoek was channelized between 1884 and 1901 CE (Fig. 2ef). Junner Koeland was channelized between 1894 (Fig. 2f) and 1906 CE, as indicated by the topographical map of the Netherlands 1:50,000; map sheet Coevorden, surveyed between 1900 - 1906 (not shown).

### 195 3.2.3 Visualisation of geodetic distortion

Distortion grids were generated for each map fragment based on the GCPs using the software MapAnalyst (Jenny and Hurni, 2011; <http://mapanalyst.org/>). A world file (\*.txt) was created for the reference image and together with the historical map image loaded in MapAnalyst. In the \*.txt file with GCPs that was generated with ArcMap the first two columns show the map points indicated in pixel rows/columns, using the upper left corner as origin. The 200 third and fourth column show the points of the reference image, using the units of its coordinate system (in our case the Dutch RDnew projection with units in metres). Using a text editor the points for the map and reference image were split into two separate files. In addition each point pair was assigned an ID number in the first column to allow MapAnalyst to link the point pairs from the two files. For the map images MapAnalyst uses the lower left corner as origin instead of the upper left corner as is done in ArcMap, therefore the pixel values in y-direction for 205 the map points were converted prior to loading them in MapAnalyst. Map distortions were calculated using a 1 kilometre raster and exported as \*.png images.

### 3.3 OSL dating

210 Optically stimulated luminescence (OSL) dating makes use of a low-intensity light signal emitted by mineral  
grains (e.g. quartz) upon optical stimulation. The intensity of the signal can be linked to the age of the sediment.  
The (latent) OSL signal builds up as the grains are exposed to natural ionizing radiation in the environment (from  
uranium, thorium, potassium and cosmic rays; known as the environmental dose), which causes accumulation of  
trapped charge in the crystal structure. When the grains are exposed to daylight during transport, the trapped charge  
is released, and the OSL signal is reduced (bleached) to a low level, often close to zero. When the grains are  
215 deposited and buried, they are no longer exposed to light, and the signal can build up again.

Through comparison of the natural luminescence signal with that induced by laboratory irradiation, the  
environmental dose received by the grains since burial can be estimated (the palaeodose). Combined with  
information on the environmental dose rate experienced by the grains, the age can be calculated by:  $\text{age [ka]} =$   
 $\text{palaeodose [Gy]} / \text{dose rate [Gy/ka]}$  (see e.g Rhodes, 2011; Jacobs, 2017 for more information on OSL dating).

220 With dating of fluvial sediments, the assumption in luminescence dating that the OSL signal was completely  
zeroed prior to sediment burial is questionable (Murray et al., 1995), due to the limited exposure of grains to light  
when transported in turbid water (e.g. Wallinga, 2002a). This means that at the time of sediment burial, some  
trapped charge that was built up since previous deposition may remain, which may consequently lead to a remnant  
OSL signal upon deposition, and an overestimation of the age. Poorly bleached sediments mostly consist of a  
225 mixture of poorly bleached and well-bleached grains (Olley et al., 1999), which can be detected by broad and  
skewed equivalent dose distributions (e.g. Wallinga, 2002b). Heterogeneous bleaching in channel site samples  
may result in apparent doses ranging over several orders of magnitude and may limit the accuracy of dates (Murray  
et al., 1995; Olley et al., 1998), although methods have been developed to largely overcome these challenges (e.g.  
Galbraith et al., 1999; Cunningham and Wallinga, 2012).

230

### 3.3.1 OSL sampling

In total 10 samples were collected for OSL dating to determine the time of deposition and burial of the sediments.  
Six samples were collected in the Junner Koeland scroll bar deposits, three samples in the scroll bar deposits of  
Prathoek, and one sample was collected in an Early-Holocene fluvial terrace remnant near Prathoek. To reduce  
235 chances of sampling sediments that were reworked after initial scroll bar formation, we avoided sampling in  
swales. Samples were roughly evenly distributed over the scroll bar sequence (sample spacing ~200 m, see Fig.  
1b and 1c). The scroll bar samples were collected just above the channel lag deposit, because (1) the channel lag  
can generally be recognized easily, thereby preventing accidentally sampling older deposits below the scroll bar  
deposit, (2) at this depth recent aeolian reworking of sediment can be excluded, and (3) the channel lag is located  
240 below the oxidation-reduction zone, supporting the assumption that the sediments have been water saturated since  
deposition (and thus reducing uncertainty in calculating the environmental dose rate).

Samples for OSL dating were obtained through a modified Van der Staay suction corer (Wallinga and Van der  
Staay, 1999). First a hole was augered down to the desired depth, using an Edelman auger above the groundwater  
level and the suction corer below groundwater level. Then, the suction corer, with a loosely fitted PVC sample  
245 tube of 30 cm length at its end, was inserted in the hole and pushed down to the lower sample depth. After retrieving  
the suction corer, the sample tube was removed, and both ends were immediately covered with plastic caps and  
taped with light-impermeable black tape. Sampling locations were recorded with a GPS device with a horizontal  
precision of around 5 m.

### 250 3.3.2. OSL measurements

The samples were analysed in the laboratory of the Netherlands Centre for Luminescence dating in Wageningen, The Netherlands. Under amber safelight conditions, the sample tubes were opened and two subsamples were obtained from each core; material from the light-exposed outer ends of the tube was prepared for dose rate estimation (section 3.3.3), while the material from the inside of the tube was suitable for palaeodose estimation. Luminescence measurements were performed on quartz grains of the fraction 212 - 250  $\mu\text{m}$ . This fraction was obtained by a combination sieving and subsequent treatment with HCl (to remove carbonates),  $\text{H}_2\text{O}_2$  (to remove organic material), and HF (45 min. at 40%, to dissolve feldspars and etch the quartz grains). Samples were measured on a Risø TL/OSL DA-20 reader, using blue LEDs for stimulation, and a 7.5 mm U340 filter for detection. The Single Aliquot Regenerative-dose protocol (SAR) (Murray and Roberts, 1998; Murray and Wintle, 2000, 2003) was used, with details as listed in Table 2. Net OSL signals were obtained using an early background subtraction approach (Cunningham and Wallinga, 2010). The preheat temperature was selected based on pre-heat plateau tests. With the applied procedure a laboratory dose (i.e. exposure to a known amount of radiation) could accurately be recovered, as indicated by the average dose recovery ratio of  $1.03 \pm 0.01$ . At least 22 aliquots each consisting of  $\sim 75$  grains (2 mm mask size) were measured per sample (31 aliquots on average). The equivalent dose distributions were displayed in radial plots, constructed with the Luminescence package (Kreutzer et al., 2015) employed in R (version 3.2.4).

### 3.3.3. Dose rate

Light-exposed material from the outer ends of the sample tubes was prepared for dose rate estimation. Samples were dried and combusted, allowing measurement of water and organic content, and then mixed with wax and moulded into pucks. These were measured on a high resolution broad range gamma-ray spectrometer, to determine radionuclide concentrations of K-40 and several radionuclides in the U and Th decay chains. From these, dose rates experienced by the quartz grains were calculated, taking into account attenuation due to water, organics, and grain size, and adding a contribution from cosmic rays (assuming instant burial to present depth). Methods are detailed in Wallinga and Bos (2010).

### 3.3.4 Palaeodose estimation

We analysed the equivalent dose distributions of all samples from scroll bar deposits using the unlogged version of the bootstrapped Minimum Age Model (bsMAM; Galbraith et al., 1999; Cunningham and Wallinga, 2012). This approach is specifically suited for this project as it takes into account uncertainty of  $\sigma_{\text{MAM}}$  (see below), and allows the construction of likelihood distributions of the palaeodose, which can be used as priors for Bayesian analysis (Cunningham and Wallinga, 2012). The unlogged version of the MAM was used, as the logged version was not applicable to the youngest samples. Being aware of reservations with regard to using the unlogged model to older samples (Arnold et al., 2009), we checked that for older samples results of logged and unlogged models were in agreement.

The (bootstrapped) MAM requires an estimate of overdispersion in the distribution that is not caused by heterogeneous bleaching ( $\sigma_{\text{MAM}}$ ). Ideally, this estimate is based on the observed overdispersion for well-bleached samples from the same lithology, depositional environment and age (e.g. Chamberlain et al., 2018). As none of

the samples obtained from the Holocene scroll bars appeared to be well bleached, we had to take another approach. This alternative is provided by the overdispersion obtained for the oldest and best-bleached sample (NCL-2415163,  $D_e$  distribution available in Fig. 6b), which was collected from an Early-Holocene terrace remnant. Although the depositional environment and age are different, the lithology of the material is nearly identical as the scroll bar deposits consist mostly of reworked fluvial deposits of Late Pleistocene/Early Holocene age. The overdispersion of sample NCL-2415163 was  $0.15 \pm 0.03$  and this value was used as  $\sigma_{\text{MAM}}$  input for the bsMAM model. The bootstrapped MAM analysis of the equivalent dose distribution is combined with the sample dose rate to provide a likelihood distribution of estimated burial ages for each sample (see Cunningham and Wallinga, 2012). These age likelihood distributions are implemented as OSL priors in the Bayesian modelling (see 3.4). Sample NCL-2415163 did not suffer from poor bleaching and based on the normally distributed and relatively narrow equivalent dose distribution for this sample, the Central Age Model (CAM, Galbraith et al., 1999) was adopted for palaeodose estimation.

### 3.4 Bayesian reconstruction of river channel position

Bayesian statistical approaches were used to combine the numerical age data obtained from the historical maps and OSL dating, with auxiliary data on the stratigraphic order. This analysis was performed using the freely available OxCal software (version 3.4, first described by Bronk Ramsey, 1995). Bayesian analyses of deposition sequences are normally based on age versus depth profiles (Bronk Ramsey, 2008). Here we analyse age as a function of lateral migration distance, where the location of the oldest swale (meander base) is taken as origin, and distance is measured along the central axis of the scroll bar deposits. For each of the age constraints (OSL sample age or survey age of a historical map), we have both an age and a location along the central axis. In addition, we know that the meander grew from its base to the final position, providing an order for all information. In the Bayesian approach, all this information is combined to obtain a robust reconstruction of the channel position through time.

To jointly analyse the OSL priors and the historical map data, both were added as entries in a Bayesian deposition model using the P-Sequence (Fig. 3). This command fixes the chronology of the sampling points using the known order of events (based on the known meander expansion direction) and makes use of a Poisson distribution. With this depositional model, channel migration is assumed to be random (i.e. varying in rate, but always positive) giving approximate proportionality to distance (factor  $z$ ) (cf. Bronk Ramsey, 2008). The P-sequence model needs information on the size of the units (deposition events) within the sequence. Here we chose to use the average dimension of a scroll bar as unit, so the mean distance between two swales. Based on meander amplitude and the visual counting of scroll bars from the DEM, this distance was estimated at 77 and 42 m, for Junner Koeland and Prathoek respectively. This provides an event spacing ( $k_0$ -value) of 0.013 events  $\text{m}^{-1}$  for Junner Koeland and 0.024 events  $\text{m}^{-1}$  for Prathoek. By applying the regular Boundary function the entire distributions were allowed to be used in the calculation.

```

Plot()
{
  P_Sequence("Junner Koeland",.013)
  {
    Boundary("Meander base", Date()){ z=1190; };
    Prior("NCL2415159", NCL2415159){ z=1001; };
    Prior("NCL2415158", NCL2415158){ z=856; };
    Prior("NCL2415157", NCL2415157){ z=591; };
    Date("EO1829"){ z=361; };
    Date("EO1851"){ z=356; };
    Date(N(AD(1851),14)){ z=311; };
    Date(N(AD(1829),16)){ z=302; };
    Date("EY1851"){ z=266; };
    Date("EY1829"){ z=256; };
    Prior("NCL2415155", NCL2415155){ z=233; };
    Date("EO1884"){ z=182; };
    Date(N(AD(1884),6)){ z=141; };
    Date("EY1884"){ z=99; };
    Prior("NCL2415154", NCL2415154){ z=6; };
    Date(U(AD(1894),AD(1906))){ z=0.01; };
    Boundary("Meander apex", Date()){ z=0; };
  };
};

```

325

**Figure 3.** OxCal script as used for the fourth iteration for Junner Koeland. A similar script was used for Prathoek.

Likelihood distributions of estimated burial age (see section 3.3.4) were uploaded to the OxCal directory as priors (\*.prior file), with the unit in years CE. For this OSL age data, the position is relatively well known (~5 m), while there is considerable uncertainty in the time domain (age estimate).

330

For the historical map data we assume the age is known exactly (survey date, see Table 1), while reconstructed locations are uncertain (up to 107 m, see RMSEs in Table 1). Incorporating this data in the Bayesian model requires uncertainty to be expressed in the time domain, rather than spatial domain. Moreover, a slight correction is needed as the OSL data provide age information on the scroll bar formation (i.e. inner bank), while the channel centreline was reconstructed from the maps. Channel width varied significantly between the historical maps and may not represent the true low-water channel width of past times. The historical river channel was therefore deduced from each map as a low-water channel centreline. To make sure that the age of the map is assigned to the inner bank instead of the channel centre in the chronological analysis we corrected the distance ( $z$ -value) for each centreline using half the channel width. For this calculation, we assumed that channel width has been relatively stable throughout meander formation, and is represented by the width of the abandoned channel (~30 metres) as derived from the DEM (Fig. 1).

335

340

Uncertainty in the spatial domain was calculated for each map based on sigma (see 3.2.2) and assuming a normal distribution. To transfer this spatial uncertainty in an age uncertainty, the migration rate of the channel is required. This provides a problem, as the procedure aims at a reconstruction of channel position through time, which is needed to determine migration rate. Nevertheless, a crude estimation of migration rate is possible based on available data, and an iterative approach can be used to improve this estimation with the model output. For the first iteration error bands were converted to years using an estimated migration rate based on the bsMAM age of the OSL sample closest to the meander base and historically known maximum channelisation date (1894 and 1906 CE for Prathoek and Junner Koeland respectively), when the channel reached its final position. For subsequent iterations migration speed was calculated for each map individually by dividing the difference between the modelled mean ages for its error boundaries (in years) by the error width (in m). This migration rate was then used

350

to convert RMSE (available in Table 1) to years. The converted RMSE (i.e. sigma) was used together with the map age (i.e. the mean) as input for the next iteration. This process was repeated until model outcome converged and remained stable. This required four iterations of the Bayesian model for both investigated meander bends.

355 Queries were built into the model to generate output for requested distances, including the meander base (calculated by OxCal using extrapolation of the model, consequently the uncertainty for this point will be larger) and the spatial boundaries of each error band to allow calculation of a migration speed for each historical map as described above.

360 Upon convergence and stabilisation of the model outcome the deposition model of the final (i.e. fourth) iteration was used to interpolate ages throughout the scroll bar deposits. Using the graphical options in OxCal interpolation results were plotted versus distance from the meander base as origin toward the meander apex using linear interpolation in between the data points. Plots of the input data were created with the ggplot2 package (Wickham and Chang, 2016) employed in R (version 3.4.0).

365 We performed sensitivity tests to check model sensitivity to (1) the initial migration rate that was used to convert error bands to years, (2) the correction for channel width and (3) a rigid versus variable  $k_0$ -value. Test outcomes indicated that (1) either increasing or decreasing the initial migration rate by a factor of two yielded similar results after several iterations, (2) model outcome with and without using the channel correction differed only a couple of years, and (3) a rigid or variable  $k_0$ -value resulted in age differences of no more than one year. Based on these tests we concluded that model sensitivity to these factors is minor.

370

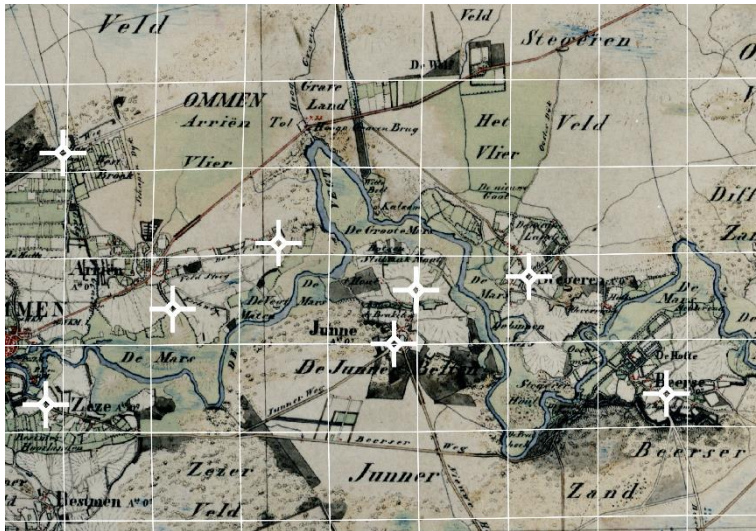
## 4 Results

### 4.1 Historical maps

375 Figure 4 shows the distortion grid for the map of 1851 CE. As the grid appears virtually straight, geodetic distortions in the map fragment are minimal. Distortion grids for the other maps were similar (provided in the supplement).

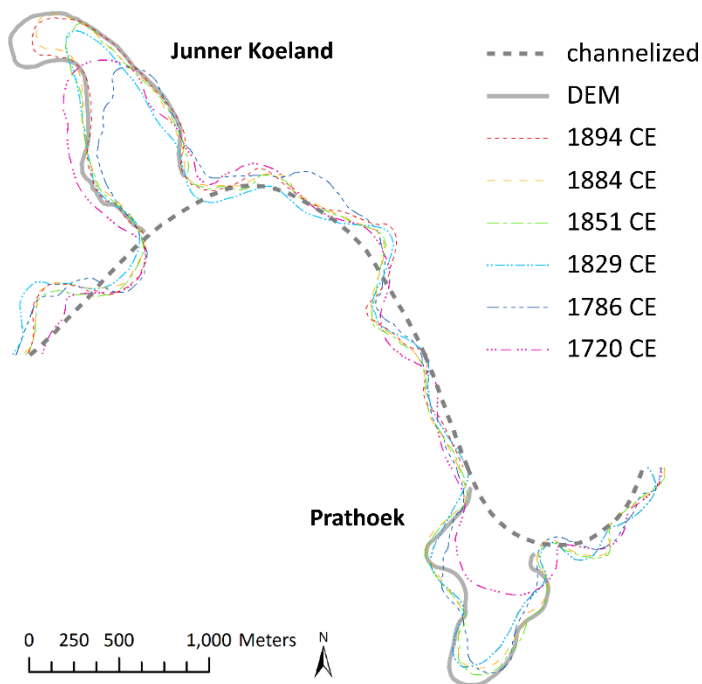
380 The channel centrelines that were deduced from the maps are shown in Fig. 5. On the map of 1894 Prathoek is already channelized (Fig. 2), therefore this line is only drawn for Junner Koeland. Based on the current DEM and coring evidence, the georeferenced map dating from 1720 had to be rejected from the Bayesian modelling based on obvious erroneous representation of the river course. The 1720 map depicted the Junner Koeland meander where corings proved that river deposits were lacking, i.e. too far west by up to 80 metres. We tried to include the georeferenced map of 1786 in the Bayesian modelling, but this map resulted in poor model agreement (further discussed below). The correctness of this map was doubted, because it displays the meander apex at Prathoek directed southwards instead of southwest like the other channel centrelines (Fig. 5). This would indicate that sedimentation towards the inner bend has taken place in order to move the apex westward, which seems unlikely. 385 Based on this improbable meander planform and the statistical issue created by this map in the Bayesian modelling we excluded it from further analyses.





390

**Figure 4.** Fragment of the georeferenced historical map of 1851 CE (details listed in Table 1), displaying ground control points (white crosses) and a distortion grid (in white, maze size of 1 km). The grid approaches a perfect grid, indicating that map distortion is minimal. Grid generated with MapAnalyst software by Jenny and Hurni (2011). Image reference historical map: CC-BY Kadaster, 2018.



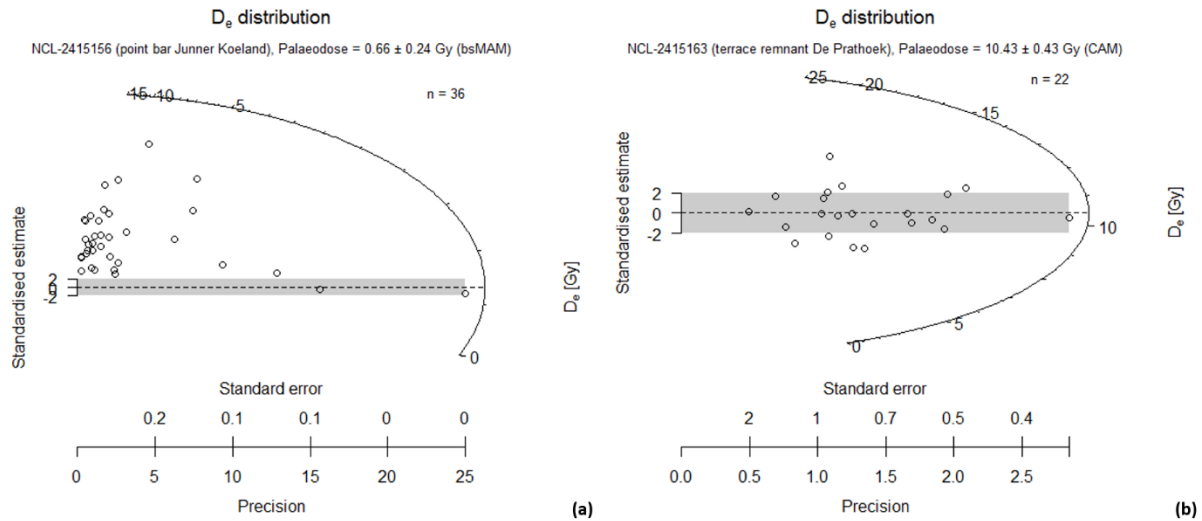
395

**Figure 5.** Channel centrelines as derived from the historical maps listed in Table 1 and shown in Fig. 2. The DEM (digital elevation model) line represents the course of the meanders preserved upon abandonment at the time of channelization (between 1884 - 1901 CE for Prathoek and between 1894 - 1906 CE for Junner Koeland).

#### 400 4.2 OSL ages

The results of the OSL dating and bsMAM calculations are presented in Table 3. The spread in the equivalent doses of single aliquots for the scroll bar samples (example in Fig. 6a) shows that light exposure of the grains prior to deposition and burial was not sufficient to completely reset the quartz OSL signal of all grains. Strikingly the

equivalent dose distribution of many samples shows two distinct peaks; a younger population representing the age of recent transportation and deposition by the river, and an older population with an age of about 11 ka, likely representing the depositional age of the grains prior to erosion and transport of the Late-Holocene Vecht river, as indicated by the OSL age obtained on a terrace remnant at Prathoek (circa 11 ka, Fig. 6b).



**Figure 6.** Two radial plot examples showing (a) a scroll bar sample (NCL-2415156) from Junner Koeland, and (b) the sample collected in a terrace remnant near Prathoek (NCL-2415163). The scroll bar sample in (a) is poorly bleached, showing a large population of grains with a  $D_e$  of about 10 Gy. Such equivalent doses are similar to those of the terrace sample in (b) (CAM:  $D_e$   $10.43 \pm 0.43$  Gy).

### 4.3 Reconstructed channel position and chronology

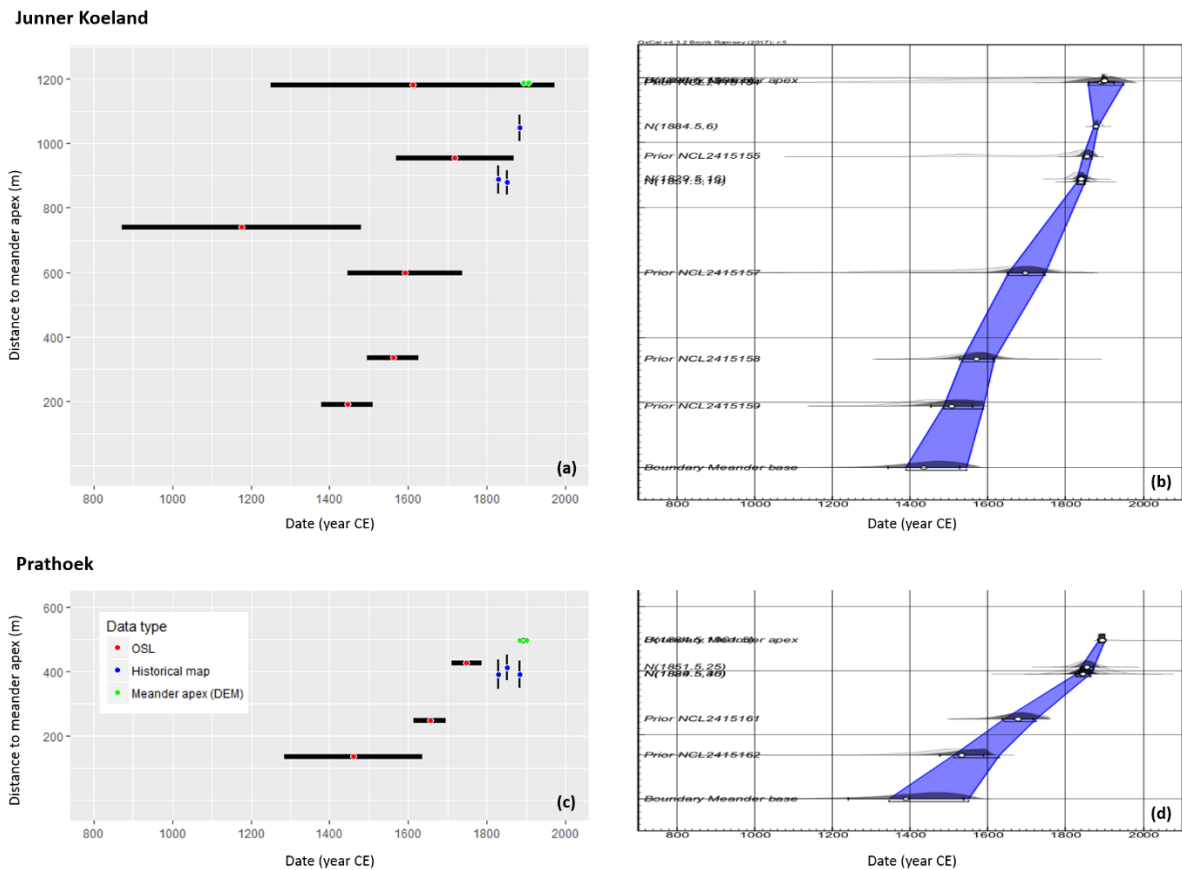
The Bayesian model was iteratively repeated until model results converged to similar output, which occurred after four iterations for both Junner Koeland and Prathoek, therefore the deposition models that resulted from these iterations were used to interpolate ages throughout the scroll bar deposits. Table 4 lists both the unmodelled and modelled ages. The model agreement index (A-value) should be above 60% to indicate proper model functioning (Bronk Ramsey, 1995). The high A-values in Table 4 show that the modelled ages fit the data well. The graphical output of the model as generated by OxCal is displayed at the right in Fig. 7b and 7d and demonstrates the improvement of the geochronology after the Bayesian modelling compared to the unmodelled data points shown at the left in Fig. 7a and 7c.

OSL sample NCL-2415156 suffered from very poor bleaching (Fig. 6a) and therefore had to be rejected from the Junner Koeland model, otherwise the model A-value did not rise above 60%. In addition, the historical map of 1894 had to be excluded, as it resulted in poor agreement that could not be resolved by adjusting the model (e.g.  $k_0$ -value). In the fourth (and final) iteration the model had an A-value of 143.8% (Table 4a). For Prathoek the poorly bleached sample NCL-2415160 resulted in poor agreement; after excluding this entry the A-value of the fourth iteration amounted to 112.2%.

The Bayesian model also allows extrapolation of the results towards the meander base (Fig. 7). In our study area the positions of the two meander bases appear to be located close to the former valley side (Fig. 1), therefore the modelled ages of the meander bases indicate the moment when the meanders sufficiently eroded the valley side to break free from lateral confinement. Model results indicate that this took place during the fourteenth century CE for Prathoek and about 65 years later during the fifteenth century for Junner Koeland. Subsequently the

435 meanders migrated outside the former river valley, reworking unconsolidated Pleistocene fluvial deposits and coversands, locally with Holocene drift-sand on top. This occurred at an average rate of 2.6 and 0.9 m/y for Junner Koeland and Prathoek respectively (calculated by dividing the distance from meander base to apex by the difference between their modelled mean ages). For both meanders, there seems to be an increase in lateral migration rate in the final stages prior to abandonment; roughly between 1825 and 1900 CE.

440



**Figure 7.** Comparison of results before (a, c) and after (b, d) the Bayesian modelling for Junner Koeland (a, b) and Prathoek (c, d). Both (a, b) and (c, d) have equal y-axes. The legend in (c) also applies to (a). In (a, c) the historical map data are indicated with error bars displaying RMSE of the georeferencing procedure (in m), the OSL results of the bootstrapped Minimum Age Model indicate the modelled mean and 1 sigma error bar (in years). In (b, d) the blue areas in the Bayesian models indicate the 68.2% confidence interval. The data point indicating the meander base in (b, d) is calculated through extrapolation by the Bayesian model. The slope of the graphs in (b, d) indicates lateral migration rate.

445

## 450 5 Discussion

Our study demonstrates that the presented Bayesian chronological modelling approach combining OSL and historical map data improves the robustness of fluvial chronologies and can elongate them into longer timeframes, compared to what could be achieved by using either data type separately (Fig. 7).

455

The use of historical maps to determine fluvial migration rates is often challenging due to limited options for georeferencing and uncertainty regarding planimetric accuracy. Historical maps can offer a diachronic perspective on the development of meander shape and channel position (Fig. 2, 5). For our case study this was however limited to recent history (after 1720 CE). When going further back in time, the availability of historical maps was limited and map quality was generally too coarse for a detailed reconstruction of meander migration. Doubts regarding

the correctness of the maps dating from 1720 and 1786 resulted in excluding these maps from the Bayesian analysis  
460 in our study.

With a limited number of GCPs RMSE might underestimate the geospatial error (Esri, 2018; Hughes et al.,  
2006). When used as a rigid buffer around channel centrelines to determine whether channel changes larger than  
the assumed error buffer occurred (i.e. deviations that are so large that they cannot emerge from error) (e.g Urban  
and Rhoads, 2003; Rhoades et al., 2009), this may result in not detecting small channel changes and could lead to  
465 false interpretations of channel stability. Other approaches have been proposed to account for this problem by  
analysing independent test points or using cross-validation techniques to develop spatially variable error buffers  
(Hughes et al., 2006; Lea and Legleiter, 2016). However, these methods were developed for aerial imagery where  
temporal uncertainty is absent and do not convert uncertainty in the spatial domain to uncertainty in the temporal  
domain. Additionally these methods generally require higher numbers of GCPs than could be registered for  
470 georeferencing the historical maps (e.g. 35 per image as used by Lea and Legleiter, 2016). In contrast, the Bayesian  
modelling methodology that we have presented permits a flexible interpretation of the RMSE buffer, which can  
easily be calculated even with lower numbers of GCPs, and the iterative procedure with the Bayesian model allows  
conversion of the geospatial error into temporal uncertainty. This temporal uncertainty is included in the model as  
a probability density function, i.e. allowing all channel positions but each with a specific probability of occurrence.

In our analysis there are two potential sources of spatial uncertainty. The first is error in the GPS-measured  
475 location of OSL samples (~5 m). The second is the distance between channel centreline (derived from the historical  
maps) and scroll bar deposit formed in the inner bend. As the historical maps are likely to display the low-water  
channel, we made use of the width of the low-water abandoned channel (as depicted on the DEM of the present  
situation) for deriving the location of scroll bar deposition from the channel centrelines (assuming a constant  
480 channel width of ~30 m). There are indications that bankfull width varied over time (Candel et al., 2018), which  
would result in an additional spatial error in the location of scroll bar deposition. However, our sensitivity analyses  
indicate that minor changes in the location of model entries (i.e changing their *z*-value by 15 m) has very limited  
effect on model outcome (i.e. only a couple of years), indicating model robustness against channel width changes  
and possible errors due to GPS accuracy of OSL sample locations.

The use of OSL to date young fluvial sediments is challenging, as limited light exposure during subaqueous  
485 transport of grains in a turbid river may lead to incomplete resetting of the OSL signal in at least part of the grains  
(Wallinga, 2002a). As demonstrated by Fig. 6 the sediments were indeed affected by poor bleaching, in some cases  
such extreme that the equivalent dose determined on most aliquots reflected the burial dose of the source material,  
rather than the deposit of interest. The bootstrapped MAM approach yields very large uncertainties in such cases,  
490 and the Bayesian analysis indicates that these uncertainty estimates are reasonable. Only for two samples (NCL-  
2415156 and NCL-2415160, i.e. one from each meander) was the OSL age rejected by the Bayesian model. The  
Bayesian modelling significantly enhanced the interpretation of the OSL dating results and the robustness of the  
geochronology.

Through extrapolation the Bayesian model could estimate the date of meander expansion beyond the former  
495 valley sides. From this pivotal moment in time, the meanders were no longer confined and large meanders formed.  
Our results indicate average lateral migration rates of 2.6 and 0.9 m/y for Junner Koeland and Prathoek  
respectively. It seems likely that migration rates may have been much higher during brief periods, alternating with  
periods of relative standstill (Gurnell et al., 1994). However, our chronological data lacks the precision and

500 resolution to identify such fluctuations, possibly with the exception of a period with rapid migration in the period 1825 - 1900 CE.

The methods outlined in this paper provide the chronological constraints that are needed to relate meander expansion beyond the former valley side and changing river dynamics to climate and land use changes. Such analysis is beyond the scope of this contribution, and reported separately by Candel et al. (2018).

## 505 **6 Conclusion**

Our study demonstrates that combining historical map data and OSL dates in the presented Bayesian modelling approach yields an integrated geochronology with a higher robustness than the sum of its parts. The analysis requires conversion of geospatial error from the historical maps into a temporal uncertainty, and we show that this is possible through an iterative approach. Our method incorporates strengths of both data types (historical maps and OSL dating) for reconstructing fluvial morphodynamics and supports elongating fluvial sequences into larger time frames. Our study indicates that the meanders of the Overijsselse Vecht expanded beyond the former valley sides from about 1400 CE onwards, and that the channels migrated at an average rate of up to 2.6 m/year during their lifetime (1400 - 1900 CE).

## 515 **7 Competing interests**

The authors declare that they have no conflict of interest.

## **8 Acknowledgements**

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750 **10 Tables**

**Table 1.** Overview of the six historical maps used in this study. All dates are indicated in CE (Common Era). Revision date indicates full or partial revision. The date used for analysis is based on the revision date, or if none, on the survey date. For the map sheet of the Hottinger atlas the survey covered three years, we therefore took the middle year to use in further analyses. GCPs = Ground Control Points (as used for georeferencing), RMSE = root mean square error (expressed in metres) based on the residuals (or displacement vectors) of the GCPs after using a first order polynomial transformation in the georectification procedure. JK = Junner Koeland, PH = Prathoek. Map sections are shown in Figure 2. References list map source and publications on cartographers, survey techniques and depiction methods. References are detailed in the subscript.

Name	Original scale	Map sheet	Survey date	Revision date	Publication Date	Date used for analyses	No. GCPs	RMSE (m)	Figure 2	Reference
'Limiten tussen Bentheim en Overijssel' by Pieter de la Rive	1:19,200	-	unknown	unknown	~1720	1720	8	104.482	a	1, 2, 3
De Hottinger-atlas van Noord- en Oost-Nederland	1:14,400	35, 36	1785 – 1787	none	1773-1794	1786	39	106.702	b	4
Atlas of Huguenin	1:40,000	72, 73	1829	none	1829	1829	15	45.229	c	5
Topographische en Militaire Kaart van het Koninkrijk der Nederlanden	1:50,000	22	1851	none	1859	1851	11	39.056	d	6, 7
Topographical map of the Netherlands (Bonne) [i]	unknown	Coevorden	unknown	1884	1897	1884	14	41.038	e	6, 8, 9
Topographical map of the Netherlands (Bonne) [ii]	1:25,000	306 (JK) 307 (PH)	1883 1901	1894 none	1896 1904	1894 1901	10	27.073	f	6, 8, 9

1 Algemeen Rijks Archief. Genie-archief, situatiekaart 07.

2 Wolfert et al., 1996.

3 Box, 2007.

4 Versfelt, 2003.

5 Versfelt and Schroor, 2005.

6 CC-BY Kadaster, 2018.

7 Van der Linden, 1973.

8 Van der Leest et al., 2005.

9 Stam, 2006.

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**Table 2.** The SAR protocol used for equivalent dose measurement, including measurement parameters.

Step	Action	Measured
1	Beta dose (or Natural dose)	
2	10s preheat at 200 °C	
3	20s blue stimulation at 125 °C	$L_n, L_i$
4	Beta test dose	
5	10s "cutheat" at 180 °C	
6	20s blue stimulation at 125 °C	$T_n, T_i$
7	40s blue bleach at 210 °C	
8	Repeat step 1-8 for a regenerative dose, zero and repeat dose	
Extra 1	Repeat step 1-8 with added infrared bleach at 30 °C prior to step 4	

**Table 3.** Results of the OSL dating. JK = Junner Koeland, PH = Prathoek, RD = Dutch coordinate system (Rijksdriehoekstelsel). Palaeodoses and ages are based on the bootstrapped Minimum Age Model for all samples from scroll bar deposits (JK and PH), and the Central Age Model for the terrace sample.

Sample		Location (RD coordinates)		Sample depth below surface (m)		Palaeodose (Gy)		Total dose rate (Gy/ka)		OSL age (ka)		OSL age (year CE)	
Code	Site	x	y	Upper limit	Lower limit	$\mu$	$\sigma$	$\mu$	$\sigma$	$\mu$	$\sigma$	$\mu$	$\sigma$
NCL-2415154	JK	228508	506133	1.9	2.2	0.34	0.30	0.83	0.03	0.40	0.36	1612	362
NCL-2415155	JK	228718	506204	1.2	1.5	0.26	0.13	0.87	0.03	0.30	0.15	1719	149
NCL-2415156	JK	228869	506095	2.4	2.7	0.66	0.24	0.79	0.03	0.84	0.30	1177	304
NCL-2415157	JK	229018	506021	2.4	2.7	0.37	0.13	0.86	0.03	0.42	0.15	1591	146
NCL-2415158	JK	229108	505779	2.3	2.5	0.42	0.06	0.93	0.03	0.46	0.07	1561	66
NCL-2415159	JK	229183	505655	2.8	3.1	0.47	0.05	0.82	0.03	0.57	0.07	1445	65
NCL-2415160	PH	231070	502684	2.2	2.5	0.28	0.04	1.04	0.04	0.27	0.04	1749	38
NCL-2415161	PH	231113	502848	1.6	1.9	0.34	0.04	0.94	0.03	0.36	0.04	1655	42
NCL-2415162	PH	231122	502965	2.8	3.1	0.46	0.15	0.83	0.03	0.56	0.18	1461	176
NCL-2415163	terrace	231167	503366	3.3	3.6	10.43	0.43	0.95	0.03	10.9	0.6	NA	NA

**Table 4.** Results of the Bayesian model for (a) Junner Koeland, iteration 4 and (b) Prathoek, iteration 4.

(a)	Unmodelled (CE)		Modelled (CE)		Indices
	$\mu$	$\sigma$	$\mu$	$\sigma$	$A$
					$A_{\text{model}} = 143.8$
					$A_{\text{overall}} = 149$
<b>Name</b>	<b><math>\mu</math></b>	<b><math>\sigma</math></b>	<b><math>\mu</math></b>	<b><math>\sigma</math></b>	<b>A</b>
P_Sequence Junner Koeland					
Boundary Meander base			1433	92	
Prior NCL2415159	1443	79	1506	54	97.7
Prior NCL2415158	1555	65	1570	43	116.1
Prior NCL2415157	1576	165	1695	46	143.2
EO1829			1813	29	
EO1851			1816	28	
N(1851.5,14)	1851	14	1839	10	91.8
N(1829.5,16)	1829	16	1840	10	100
EY1851			1848	11	
EY1829			1850	12	
Prior NCL2415155	1709	144	1855	12	177.4
EO1884			1867	10	
N(1884.5,6)	1884	6	1877	4	77.6
EY1884			1879	4	
Prior NCL2415154	1515	430	1892	32	161
U(1894.5,1906.5)	1900	3	1899	3	100
Boundary Meander apex			1900	7	

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(b)	Unmodelled (CE)		Modelled (CE)		Indices
	$\mu$	$\sigma$	$\mu$	$\sigma$	$A$
					$A_{\text{model}} = 112.2$
					$A_{\text{overall}} = 114$
<b>Name</b>	<b><math>\mu</math></b>	<b><math>\sigma</math></b>	<b><math>\mu</math></b>	<b><math>\sigma</math></b>	<b>A</b>
P_Sequence Prathoek					
Boundary Meander base			1366	164	
Prior NCL2415162	1431	211	1536	64	115.2
Prior NCL2415161	1672	49	1676	41	107.4
EO1829			1764	47	
EO1884			1794	42	
EO1851			1820	33	
N(1829.5,40)	1829	40	1843	18	122.5
N(1884.5,35)	1884	35	1844	17	76.6
N(1851.5,25)	1851	25	1854	16	118.8
EY1884			1863	16	
EY1829			1868	16	
EY1851			1873	15	
U(1884.5,1901.5)	1892	5	1893	5	100
Boundary Meander apex			1894	10	