I. Associate Editor:

Dear Dr Beerten and co-authors, Your paper now has two thorough reviews. Both are somewhat encouraging but with major reservations on how this 'technique' paper is a step forward from the existing technique. As such, I strongly encourage you to submit a revised version of your paper, as usual fully taking into account and responding to the reviewers' comments. I would appreciate a comment on some misunderstandings that came up regarding how the model differs from previous models. There are a couple of methods for constructing erosion/ages from depth profiles available. It would be nice to see a comparison of these methods and to figure out the real differences including uncertainties between them. Are you able/willing to upload the (modified?) source code as a part of the manuscript or on github so that reviewers (and eventually readers) have access to it? Thank you for submitting your work to Earth Surface Dynamics.
Best wishes, Jane

We thank the AE for this suggestion. We have made clearer what separates our inversion approach from previous work, and have included in our revision a thorough comparison between our approach and the Bayesian approach implemented in the CRONUScalc program (Marrero et al., 2016). We selected the method taken by Marrero et al. (2016) because to the best of our knowledge, it is the current state-of-the-art for probabilistic inversion of CRN profile data. In addition, the Marrero et al. (2016) method can be seen as a Bayesian extension of the (non-Bayesian) Monte Carlo (MC) based approach described by Hidy et al. (2010). See section 3.3 for a theoretical description of our approach and that of Marrero et al. (2016), and section 4.2 for a comparison between the two approaches for the considered case study. Note also that we identified a theoretical flaw in the Marrero et al. (2016) approach in case of model errors are present (see sections 3.3.4 and 4.2.2) and suggest a simple way to fix it (see section 4.2.3).

Lastly, please notice that this revision work has led to changes in authorship, with (among other changes) the formerly second author (Eric Laloy) becoming first author and inversely for the formerly first author (Koen Beerten). Furthermore, all the tested methods were implemented in Python and the resulting codes will be made available after publication at: https://bitbucket.org/ericlaloy/.

II. Reviewer #1:

MAJOR COMMENTS

I think fundamentally there is some confusion over the information realistically preserved in cosmogenic depth profiles. In some cases, a measured depth profile can converge to a unique solution for both of age and erosion rate (as described by Braucher et al. 2009). I would argue that these cases are very rare as it requires characterizing both the spallogenic and muogenic production pathways with the dataset.

We fully agree that one should carefully consider which information can realistically be preserved in CRN depth profiles. In our opinion, Bayesian inference is especially powerful when it comes to determine how well the model parameters can be resolved by the available data. Using Bayesian techniques, we can explore the information content that is hidden in the data, and get an uncertainty on the model estimates. Our Bayesian inverse methodology is a statistically-sound tool for quantifying to what extent the model parameters are constrained by the available measurement data. The Bayesian approach considers the model parameters to be random variables having a joint posterior probability density function (pdf). Once determined, this posterior distribution encodes all the necessary information about the parameters such as degree of (non-) uniqueness, standard deviations, correlations and dependencies (given the chosen prior distribution and likelihood function). We have better highlighted the advantages of Bayesian inference in lines 75 – 90 of the revised manuscript.

Without such characterization and without other independent geologic constraint, a profile will not yield a unique solution for age and erosion rate, but it can still yield a minimum exposure age (or zero erosion age), and a maximum erosion rate for $t \rightarrow \infty$.

To come back to our presented results, we thus consider that they rigorously represent the information content of the investigated profile. The reviewer points out that a single depth profile usually cannot simultaneously resolve *t* (exposure age) and *E* (erosion rate). We would like to stress that this is exactly what our results are showing. With a marginal posterior distribution relatively close to its marginal prior distribution, the exposure age is rather unresolved (see Figures 7b and 8b). In contrast, we demonstrate that the erosion rate can be resolved, yet with a relatively large uncertainty that we quantify rigorously (see Figures 7a and 8a, and lines 315-318).

When the authors interpret the Campine data, they impose an age constraint of 0.5-1 Ma, which essentially restricts their solution space to the erosion asymptote and removes any variance in erosion that would be present if younger ages were permitted. It should be noted that this is perfectly OK to do if the age constraints are robust. However, depth profiles are not necessarily applicable to the timespan since deposition, and unfortunately that seems to be the case for the Campine data…. The authors constrain the age of their profile to between 0.5-1 Ma based on preexisting age constraints for deposition age. However, the landform that developed following deposition could be, and likely is, significantly younger. Any age constraint applied to a depth profile must consider the time over which the surface can be assumed to be in steady-state erosion. … If the age constraint that led to resolving the erosion rate is not viable, then the erosion rate is also not viable. The probability distribution of the erosion rate parameter needs to be re-calculated without a constraint on a lower age limit.

We fully agree with reviewer #1, and have re-run our Bayesian inversion using a wider prior distribution for the exposure age with lower and upper bounds of 0 and 1 Myr, respectively. See section 3.3.5 and figures 7b, 8b and 9b.

The constraint for exposure age of 0.5 to 1 Myr that was used in the former manuscript, came from our initial assumption that the depth profile is only marginally affected by post-depositional erosion. While this assumption might now seem at odds with the current results, there is a general consensus which explains the Campine Plateau as a classical case of relief inversion, with coarse-grained fluvial deposits (gravel, sandy gravel and gravelly sand) on top protecting it from significant erosion (Paulissen, 1983; Paulissen, 1997). Our depth profile is sampled at the crest of the Campine Plateau, i.e. at the top of the geomorphic surface. Our CRN results question the consensus on the stability of the Campine Plateau: when assuming near-zero denudation rates, the apparent exposure age should be congruent with the minimum depositional age of the Rhine sands in this location that is estimated to be ca. 0.5 Myr (absolute lower age estimate, see text). The Quaternary geology of Rhine and Meuse deposits, the entire history of the Meuse terrace staircase and the evolution of the Roer Valley Graben all point to a late Early to early Middle Pleistocene age for the fluvial deposits (see section 2 for references).

MINOR COMMENTS

Bayesian/Monte Carlo-style models have previously been applied to cosmogenic depth profiles (see version 1.2 of Hidy et al. (2010) described in Mercader et al. (2012) supplemental code; see Marrero et al. (2016), CRONUS web-based calculator).

We thank the reviewer for pointing this previous work to us. We have how better described how our inversion approach differs from previous work, and have included for the considered case study a thorough comparison between our approach and that of Marrero et al. (2016) (see also our reply the Associate Editor's comment). To our knowledge, the latter approach is indeed the current state-of-the-art. With respect to the method described by Hidy et al. (2010), as stated in our quick reply it is not Bayesian. From our visual inspection of the unpublished version 1.2, it appears to us that this version does derive an informal posterior distribution but does not account for the contribution of the prior density to the posterior density.

Thicknesses do not appear to be given for the profile samples

The samples are taken over a 10cm depth interval. We have expressed the depth of the samples, by noting the depth of the midpoint of the sampling interval (see Table 1).

Our knowledge of production rate scaling has increased significantly over the past 5 years. The authors may want to use something more up-to-date based on all the recent calibration data

In the former version of the manuscript, we used the same CRN production rates as the ones used by Rixhon et al. (2011) for the sake of comparison. We have now revised our work, and use the most recent information on SLHL production rates for Europe (Martin et al., 2017), and the effective attenuation lengths as published in Braucher et al. (2011) and Marrero et al. (2015). See lines 152-162.

III. Reviewer #2:

We thank referee #2 for having taken the time and effort to read the paper in great detail, and provide us detailed suggestions. We address the most important reviewer's concerns below.

As a preamble, we would like to state that there seems to be a misunderstanding regarding the main objective of the paper, which is (see lines 70-75 of the former manuscript which have become lines 90-97 in the current manuscript and are copied below) to perform a Bayesian inference of a long-term erosion rate from a sampled CRN depth profile. The method is then illustrated using a 10Be concentration depth profile from NE Belgium. In the paper, we do not suggest that the results from the depth profile are representative for the entire Campine area, nor that we aim to determine the impact of landscape evolution in NE Belgium on potential nuclear waste disposal. The latter is not within the scope of this research paper, and we believe that the reviewer's comments related to nuclear waste disposal are therefore not relevant.

Lines 90-97 (lines 70-75 in the former version) now read as follows:

The overall objective of this study is to infer within a Bayesian framework the potential post-depositional denudation of the northwestern Campine Plateau. This part of the Campine Plateau is drained by the Kleine Nete river, which belongs to the larger Scheldt basin.

MAJOR COMMENTS

A large part of the manuscript is dedicated to discussing in detail the geological history of the study area in the last few million years, however, almost completely ignoring at least 5 cold periods in the past 0.5 Myr. The glaciations, which most probably affected this region in many ways on multiple time-scales were taking place just north of the area implying a complex geomorphological history (deflation, permafrost, loess deposition). Additionally, being situated close to the sea, the site might have experienced multiple transgressions due to isotactic rebound and sea level changes (not necessarily 0.5Myr ago or before). The study is also ignoring the fact that the Nete catchment is a highly urbanized area and not immune to recent neo-tectonism.

We agree with reviewer #2 that the long-term topographic evolution of lowland Europe is affected by periglacial processes during glaciations, landscape instability during glacial-interglacial-glacial transitions, uplift and (absolute) base level lowering, and will take this along in our revision of the manuscript. However, we do not agree with the suggestion that “glaciations…, loess deposition, … and multiple transgressions” might also have affected geomorphological processes in the area. Based on previous geomorphological and geological studies in NE Belgium, we can exclude that the northern part of the Campine area in Belgium was affected by an ice sheet during any of the time periods considered in the paper. Also, there are no indications that the area would have been covered with loess (as the site is located in the "European Sand Belt", see introduction and Figure 1). Next, as stated in lines 99-101 (formerly 77-79), the area has not been experiencing marine conditions since the start of the Pleistocene, even though it is situated close to the sea as the reviewer correctly observes. Finally, it is correct that large parts of the Campine area are urbanized, but we believe that this is not relevant for inferring long-term geomorphological processes when sampling locations are adequately selected.

Based on the results from one depth profile, we cannot make conclusive statements on the long-term erosion rates of NE Belgium; but can formulate some hypotheses for further testing. We will clarify this nuance in our revised manuscript. We observe – for example – that the erosion rate at the sampling location is relatively large compared to global compilations of bedrock outcrop erosion rates. This result in itself is novel and diverges from current theories on landscape evolution of NE Belgium that suggested very low erosion rates for the Campine Plateau. In the paper, we suggest that erosion is related to the erosivity of the substrate and potential base level lowering in the North Sea.

My major concern with the current publication is that it suggests a considerable methodological achievement with the Bayesian model and Monte Carlo type simulation based on only 7 data points (as 2 were discarded). However, using only the Be-10 concentration of the top sample in the profile and doing a quick exploratory calculation in CRONUS, using the same parameters as in the paper, yields almost the same value as the complex model, i.e. 31+/-3.11 m/Myr. The similarity in these values might be a simple coincidence, but both of them are equally valid given that there is no evidence to suggest otherwise (see Figure1)

We are a bit puzzled by the reviewer's statement that "*my major concern with the current publication is that it suggests a considerable methodological achievement with the Bayesian model and Monte Carlo type simulation based on only 7 data points (as 2 were discarded)*". We have made clearer what is novel in our inversion approach compared to previous work: see lines 75-90 and sections 3.3.4, 4.2.1, 4.2.2 and 4.2.3. As detailed in our reply to the comments of reviewer #1, we argue that Bayesian inference is a very powerful tool to rigorously evaluate how well the inferred parameters are resolved by the available measurement data. We refer to our reply to reviewer #1 and the sections of the revised manuscript listed above for more technical details.

The reviewer suggests that CRN depth profiles are not necessary to obtain relevant information on erosion rates and states that "*using only the Be-10 concentration of the top sample in the profile and doing a quick exploratory calculation in CRONUS, using the same parameters as in the paper, yields almost the same value as the complex model, i.e. 31+/-3.11 m/Myr.*" This comparison seems flawed to us, as it ignores the impact of pre-deposition inheritance on the total concentration of cosmogenic radionuclides. In alluvial landforms, such as the Campine Plateau, pre-deposition inheritance cannot be neglected (see e.g. Anderson et al., 1996; Braucher et al., 2009; Vassallo et al., 2011; Hedrick et al., 2013). Hence, the importance of CRN depth profiles for determining the exposure age and denudation rates of the sampling site on the Campine Plateau.

Furthermore, we noted that reviewer #2 derived a denudation rate of 31 m/Myr, that is actually different and smaller than the mode of our marginal posterior distribution (the maximum a-posterior (MAP) or most probable value) which is about 39 m/Myr (the latter was about 44 m/Myr in the former manuscript but this has changed following the recommendations of reviewer #1 concerning the production rate parameters and prior distribution for *t*: see our replies to reviewer #1's comments). Also, we believe that the reviewer's uncertainty estimate of +/- 3.11 m/Myr (one sigma) is unrealistically small. Applying a Bayesian inversion framework to the 7 measurement data points, we obtain a standard deviation of 8 m/Myr (see lines 314-317 and Figure 7a). We therefore argue that our estimate and the reviewer's one are not equally valid, and consider our estimate to be much more accurate.

Note in Table 2, Page 18 10Be/9Be ratios have 4% uncertainties but 10Be concentrations have only 1% uncertainties. Obviously this is not possible, as concentration values are obtained from the ratios.

With respect to measurement uncertainty: there was indeed a mistake in the 10Be concentration errors as they were reported in Table 2 of the former manuscript, and we thank the reviewer for pointing this out. The corrected values for the 10Be concentration errors are in the range 6000 – 7000 atoms/g. See Table 1.

This would also imply that the prediction uncertainty interval section in Line 234-240 is incorrect as the authors add a max. analytical measurement error to the dataset of 2000 atoms/g, instead of ~ 20000 atoms/g. This error in data reporting also negates the conclusion of lines 274-282.

After correction, the 10Be concentration errors are max. 7000 atoms/g (and not 20,000 as suggested by the reviewer). Since we infer σ_e jointly with the other parameters, this does not affect the derived posterior parameter distribution. We would also like to stress that this still illustrates the effect of model errors, although this effect is less strong. Our best fitting error is about 10000 atoms/g and the 3000 atoms/g difference can thus be attributed to model errors. All associated discussions have been corrected in the revision: see lines 279-285, 328-329, and sections 4.2.2 and 4.2.3.

I would also question the upward fining trend, as data presented in Figure 5 and Figure 6 are not entirely supporting this conclusion. Further, I would question the exclusion of two crucial points in Unit D and B, ie. MHR-II-04 and MHR-II-06 data points, which coincide with different stratigraphic layers, as these might represent erosional events or depositional events, (i.e., superimposed profiles).

Concerning the sample selection: out of the 9 samples, we selected 7 samples for the Bayesian model. Two samples were excluded from the analysis, as their CRN concentration was measured on the grain size fraction 250-500µm (instead of 500-1000 µm). Our results show that the CRN concentrations of these two samples are higher than expected when one assumes a monotonic decline of CRN concentration with depth.

Currently, it is not possible to know the exact reason for the observed difference in CRN concentration, as this can either reflect a grain-size dependent CRN concentration (see e.g. Schaller et al., 2001 for European river sediments; Carretier et al., 2015), or non-stationary sedimentation. Further analyses are necessary to make a conclusive statement.

The real benefit of the Bayesian approach presented here would be the ability of solving these problematic cases of depth-profiles, otherwise the top sample is enough for a rough age or erosion calculation. In summary, in my opinion, the Be-10 dataset is not suitable for the complex numerical analyses that it is subjected to. These data simply do not support the conclusions of this study.

As pointed out above, we disagree with this statement. For the reasons mentioned above, one cannot infer a site-specific denudation rate and exposure age from one sample taken at the top of an alluvial deposit. In our opinion, the strength of the Bayesian approach is that it provides a robust way for exploring the data information content that is hidden in CRN depth profiles. Hence, we consider that our paper provides a fair illustration of the benefits of the Bayesian approach.

MINOR COMMENTS

Line 44: I think it is possible to resolve processes over the last 2Myr (See Balco et al 2013) instead of 1Myr as the authors mention. Also in terms of general cosmogenic Be-10 literature it might be more suitable to quote Dunai 2010 or Gosse and Phillips 2001 rather than Hancock 1999 and Heine 2009.

That is correct and we have reformulated this sentence and inserted the references suggested. See lines 51-54.

It will not change too much on the results probably, but muon attenuation lengths are different (see Braucher et al 2011), and SLHL production rate closer to 4 at/g/y (see Borchers et al 2015).

(See also reply to reviewer #1): As written in lines 129-130 of our former manuscript, we previously used the same CRN production rates as the ones used by Rixhon et al. (2011). This choice was made for the sake of comparison – as in the study by Rixhon and coworkers a Middle Pleistocene Meuse terrace close to Liège (Belgium) was investigated. However, following a suggestion of reviewer #1, in the new model runs we have used updated SLHL production rate data and effective attenuation lengthsbased on Martin et al. (2017), Braucher et al. (2011) and Marrero et al. (2015). See lines 152-162.

Lines 164-186: Section 3.3 (Bayesian inversion) is word by word the same as in Minet et al 2015.

The first author, Eric Laloy, has written the section on Bayesian statistics in the present manuscript and is the co-author who has done the Bayesian analysis in the paper by Minet et al. (2015), of which he is second author.

Line 262: "-0.13" is not a statistically significant correlation

When writing "significant" we did not mean "statistically significant", which only makes sense in the context of statistical hypothesis testing. To avoid any confusion, we are no longer using the word "significant" when analyzing our inversion results.

Figure 6: Note that unit layering conventionally is starting from top as "A" and progressing downwards, not the other way.

We believe that this is a matter of taste – examples of the ordering we use can be found in the literature.

Presentation of figures might require revisiting

We have checked every figure for this revised manuscript and believe they are fine.

One of the motivations (including funding of this project) behind this study was to understand the implications of long-term landscape evolution of this area on radioactive waste management. Unfortunately this study failed to address this aspect.

We believe that this statement is out of scope. As stated earlier, the aim of the paper is to constrain a site-specific denudation rate using a Bayesian framework. It is nowhere written in our manuscript, neither in the former version nor in the current revision, that our paper contributes to understand the implications of long-term landscape evolution on potential radioactive waste disposal. Research on long-term landscape evolution and denudation rates can be informative for land management, and waste disposal research.

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~~Constraining~~Bayesian inversion of a CRN depth profile to infer Quaternary erosion of the northwestern Campine Plateau (NE Belgium)~~ using Bayesian inversion of an in-situ produced ^{10}Be concentration depth profile~~

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Abstract. The rate at which low-lying sandy areas in temperate regions, such as the Campine ~~area~~plateau (NE Belgium), have been eroding during the Quaternary is a matter of debate. Current knowledge on the average pace of landscape evolution in the Campine area is largely based on geological inferences and modern analogies. We ~~applied~~performed a Bayesian inversion ~~to~~of an in-situ produced ^{10}Be concentration depth profile ~~in fluvial sand, sampled on top of the Campine Plateau, and inferred~~to infer the average long-term erosion rate together with ~~three~~two other parameters~~, i.e.,~~: the surface exposure age~~,~~ and the inherited ^{10}Be concentration. Compared to the latest advances in probabilistic inversion of cosmogenic radionuclide (CRN) data, our approach has the following two innovative components: it (1) uses Markov chain Monte Carlo (MCMC) sampling and ~~sediment bulk density. The~~(2) accounts (under certain assumptions) for the contribution of model errors to posterior uncertainty. To investigate to what extent our approach differs from the state-of-the-art in practice, a comparison against the Bayesian inversion method implemented in the CRONUScalc program is made. Both approaches identify similar maximum a posteriori (MAP) parameter values, but posterior parameter and predictive uncertainty derived by the method taken in CRONUScalc is moderately underestimated. A simple way for producing more consistent uncertainty estimates with the CRONUScalc-like method in the presence of model errors is therefore suggested. Our inferred erosion rate of ~~44 ± 9~~39 ± 8 mm/~~kyr (~~(1σ) is relatively large in comparison with landforms that erode under comparable (palaeo-)climates elsewhere in the world. We evaluate this value in the light of the erodibility of the substrate and sudden base level lowering during the Middle Pleistocene. A denser sampling scheme of a two-nuclide concentration depth profile would allow to better resolve the inferred erosion rate, and to include more uncertain parameters in the ~~model~~MCMC inversion~~ and further reduce their uncertainty~~.

1 Introduction

The Campine area is a sandy region which covers part of northeastern Belgium and the southern Netherlands (Fig. 1). It is part of the European sand belt and is drained by rivers that belong to the Scheldt basin. The Campine area roughly coincides with the geological Campine Basin, being the southeastern part of the North Sea Basin. From a geodynamic point of view, the Campine Basin is located in an intermediate position in between the rapidly subsiding Roer Valley Graben in the north, and the uplifting Brabant and Ardennes Massifs in the south (Fig. 2). The Campine Basin has witnessed a long Cenozoic burial history. Post-Rupelian marine and estuarine deposition during the last 30 ~~Ma~~Myr almost exclusively consists of (glauconite-rich) sand, up to 300 m thick (Vandenberghe et al., 2004). From the Early to Middle Pleistocene onwards, terrestrial conditions become dominant with deposition of a thick series of fluvial sand and gravel from the rivers Meuse and Rhine (Figs. 2 and 3). In contrast to what the basinal setting of the Campine region would suggest, distinctive topographic features are preserved in the landscape. An illustrative example is the Campine Plateau, which shows a topographic relief of ca. 50 m relative to the surrounding areas (Fig. 3). To date, quantitative data on the amount and rate of Quaternary erosion of the Campine landscape and the Scheldt basin in general are missing. This stands in contrast to the availability of long-term erosion data from e.g. in-situ produced cosmogenic nuclides for the Meuse and Rhine basins (e.g., Schaller et al., 2001; Dehnert et al., 2011; Rixhon et al., 2011). Such data on catchment-wide erosion rates at multi-millennial timescales are crucial to determine background geological erosion rates to evaluate anthropogenic morphodynamics (Vanacker et al., 2007a), to provide calibration data for landscape evolution models (Bogaart and van Balen, 2000; Foster et al., 2015; Campforts et al., 2016), and to assess the overall stability of the landscape in the framework of long-term management of radioactive waste (Van Geet et al., 2012).

Cosmogenic radionuclides (CRN's) have proven useful to quantify geomorphological processes over timespans covering the last ~~1 Ma (Schaller~~2 challer et al., 2001). Geomorphological surfaces can be dated by measuring the concentration of in-situ produced cosmogenic nuclides (e.g., ^{10}Be and ^{26}Al) that accumulated at the Earth's surface (Dunai, 2010; Hancock et al., 1999~~; Hein et al., 2009~~). As the observed cosmogenic nuclide concentration of a given outcrop is a function of its exposure age and denudation rate, stable (i.e. non-eroding) landforms provide optimal sampling locations for exposure dating (e.g., Rixhon et al., 2011). Most landforms are subject to erosion during exposure, resulting in a decrease of the cosmogenic nuclide concentrations with increasing surface denudation rate (e.g., Dehnert et al., 2011). Braucher et al. (2009) showed that the exposure age (and post-depositional denudation rate) of eroding landforms can be constrained based on a deep (> 1~~,~~.5 m) depth profile of a single cosmogenic nuclide that is sampled at regular intervals.

The accumulation of in-situ produced cosmogenic nuclides in eroding surfaces is a mathematical function with ~~two~~three parameters that are typically unknown a priori: the ~~exposure age, *t* [y], and the~~ post-depositional denudation rate, *E* [~~cm/y~~m/Myr], the exposure age, *t* [yr], and the inherited concentration or inheritance, N_{inh}, [atoms/g]. Unknown model parameters can be estimated by inverse modeling of CRN concentration vs. depth profiles. In this procedure, one iteratively proposes new parameter values until the model fits the observed data up to a ~~pre-specified~~given precision. This has been done for estimating ~~t~~E and ~~E~~t by, e.g., Siame et al. (2004) and Braucher et al. (2009). Yet, model and measurement errors together with (measurement) data scarcity introduce considerable uncertainty in ~~optimizing~~ the optimized model parameters. The method ~~proposed~~ by Braucher et al. (2009) accounts to some extent for analytical measurement errors, as it generates several CRN concentration profiles consistent with the (analytical) measurement errors, computes for each model parameter set (e.g., a t-E pair) within a grid search the corresponding data misfits and retains the median misfit as the performance associated with a given parameter set. This allows for deriving a robust unique solution but does not ~~consider explicitly~~quantify model parameter uncertainty and ignores model errors (that is, the model is assumed to be perfect). To assess model parameter uncertainty, Hidy et al. (2010) proposed to perform plain Monte Carlo (MC) sampling from the pre-specified prior parameter distributions, rank the resulting solutions according to fitting performance and retain a certain percentage (typically 5%) of the best performing solutions to compute parameter uncertainty estimates.

A more comprehensive quantification of parameter and prediction uncertainty is provided by the Bayesian framework. This approach ~~represents~~ uses Bayes theorem to represent parameter uncertainty by a multivariate “posterior” probability distribution. The latter is given by the (normalized) product of a “prior” probability distribution, which ~~is consistent with both~~represents available prior information ~~and the (~~, with a “likelihood” function, that encodes the deviations of the simulated (CRN) concentration ~~measurements. In this work, we derive the~~ data from the measured ones. Providing that the assumptions underlying the likelihood model ~~parameter~~are met, the posterior probability density function (pdf) contains all necessary information about the inferred parameters. Marrero et al. (2016) implemented Bayes rule into the CRONUScalc program to derive the posterior parameter pdf. The approach taken by Marrero et al. (2016) is based on a MC variant where sampling is performed over a regular, 3-dimensional lattice covering the prior ranges for E, t and N_{inh}. It therefore requires a sufficient grid resolution to minimize the risk of missing E - t - N_{inh} combinations with substantial posterior density. More importantly, the formulation by Marrero et al. (2016) considers solely the CRN measurement error(s) as source of uncertainty. This is theoretically valid only if the CRN model can fit the measurement data within the measurement error(s). In this work, we derive the posterior parameter pdf by state-of-the-art Markov chain Monte Carlo (MCMC) simulation (see, e.g., Robert and Casella, 2004), accounting not only for measurement errors but also (under certain assumptions ~~for both measurement~~) for model errors. Furthermore, we compare our Bayesian inversion approach with that of Marrero et al. (2016), illustrate the similarities and differences between the two approaches, and propose a simple fix for making the uncertainty estimate from Marrero et al. (2016) more consistent in the presence of model errors.

The overall objective of this study is to ~~constrain~~infer within a Bayesian framework the ~~rate and amount of~~potential post-depositional denudation of the ~~headwaters of the Nete catchment. The latter is~~ northwestern Campine Plateau. This part of the Campine Plateau is drained by the Kleine Nete river, which belongs to the larger Scheldt basin ~~and is used herein to test~~

~~and demonstrate the application of Bayesian inversion to CRN concentration vs. depth profiles. The Nete catchment~~. It is an interesting test case because the ~~upstream areas of the catchment are located at the~~ northwestern edge of the Campine Plateau~~, which~~ is covered by coarse gravelly unconsolidated sand from the Early-Middle Pleistocene Rhine and thus constitutes a fluvial terrace ~~from~~for which the depositional age nor the exposure age ~~of the sands~~ is well constrained (Beerten et al., in press).

2 Geomorphological evolution of the Campine area

The post-marine hydrographical evolution of the Campine area started with the final retreat of the sea during the Neogene, as a result of systematic sea level lowering and overall uplift of the bordering areas around the southern North Sea (Miller et al. 2005; Cloething et al. 2007). During the Early Pleistocene, the Meuse followed an eastern course from Liège to the region north of Aachen where it merged with the Rhine (Fig. 2). Tectonic movements along Roer Valley Graben faults, and uplift of the northern margins of the Ardennes-Eifel massif caused the Meuse to breach through its northern interfluve and to follow a completely different course. At the same time, the Rhine shifted its course as well, flowing into the northern part of the Campine area where it merged with the Meuse (Fig. 2). Age control is limited, but this event probably took place around 1 Ma at the earliest, since the confluence area of both rivers was situated in the southeastern part of the Roer Valley Graben prior to 1 Ma, and the area that covers the Campine Plateau today was drained by local 'Belgian' rivers until that time (Westerhoff et al., 2008). Both rivers shifted their course towards a more eastern position by 0.5 Ma at the latest, given the absence of Rhine deposits younger than 0.5 Ma in the depocenter of the Roer Valley Graben (Schokker et al. 2005). The deposits that cover the Campine Plateau are often correlated with the upstream Main Terraces of the Meuse and High Terraces of the Rhine (Paulissen, 1973). Westaway (2001) provides a time window for deposition of Rhine sediments west of the Ville Ridge (High Terraces HT2 and HT3) between 0.5 Ma and 1 Ma. The Rhine sediments on top of the Campine Plateau have been attributed to the Sterksel Formation, which was deposited between ca. 0.6 Ma and 1.1 Ma according to van Balen et al. (2000), and between ca. 0.75 Ma and 1 Ma (post-Jaramillo Early-Pleistocene) according to Gullentops et al., (2001). Recently, deposits from the High Terraces of the Rhine between Bonn (Germany) and Venlo (the Netherlands) have been dated to 750 ± 250 ka and 740 ± 210 ka using in-situ produced cosmogenic radionuclides (Dehnert et al., 2011). Similarly, Meuse terrace deposits in the Liège area (Romont, Belgium) that are generally assumed to correspond with the series of Main Terrace deposits, have been dated to 725 ± 120 ka using the same technique (Rixhon et al., 2011).

During the Middle Pleistocene, the hydrography of northern Belgium drastically changed due to the 'opening' of the English Channel (Vandenberghe and De Smedt 1979; Fig. 2). Various studies (Gibbard 2007; Gupta et al. 2007; Toucanne et al. 2009) link the opening of the English Channel to the catastrophic drainage of a large proglacial lake during marine isotope stage 12 (MIS 12), approximately 450 ka ago (Elsterian). The 450 ka event triggered the formation of a buried palaeochannel system known as the Flemish Valley, with extensions towards the south and the east (Tavernier and De Moor, 1974). The Nete catchment is generally considered as the eastern extension of the Flemish Valley.

At present, the Campine Plateau is a landform that markedly stands out with respect to its surroundings. It is a fluvial terrace covered by coarse gravelly Meuse deposits in the south(east) and sandy Rhine deposits in the north (Fig. 3). The sediments have proven to feature a periglacial palaeoenvironment and were deposited by braided rivers (Paulissen, 1973 and 1983). The Campine Plateau can be considered as a classical case of relief inversion ~~(Fig.~~, given its prominent position in the landscape (Paulissen, 1983; Fig. 4). Undoubtedly, the area west of the Campine Plateau experienced prolonged phases of erosion and denudation after the Rhine had left the region, around 0.5 Ma at the latest (Fig. 4b; Beerten et al., in press).

3 Material and methods

3.1 Cosmogenic radionuclide profiling

Cosmogenic radionuclides (CRN) allow us to quantify geomorphological processes over timespans covering the last 1 ~~Ma~~Myr. In this study, we use the concentration vs. depth profile of a single in-situ produced CRN (^{10}Be) to constrain the post-depositional denudation rate, E [~~cm/y~~m/Myr] of the fluvial terrace. The accumulation of CRN, $N_{total}(z,t)$ [~~at~~atoms/g], in an eroding surface can be described by a mathematical function composed of two terms that represent the inherited CRN concentration of the fluvial sediment, N_{inh} ~~(z) ,~~ [atoms/g]., and the post-depositional production of CRN, $N_{exp}(z)$:

$$N_{total}(z,t) = N_{inh}\cancel{(z)} + \sum_i \frac{P_i(z)}{\lambda + \frac{\rho E}{\Lambda_i}} e^{-(\rho(z_0 - Et)/\Lambda_i} \left(1 - e^{-\left(\lambda + \frac{\rho E}{\Lambda_i}\right)t}\right)$$

(1)

~~with~~where E is expressed in cm/yr (m/Myr × 10^{-4}), t [~~y]~~yr] is the exposure age, λ [1/~~y~~yr] the decay constant ($\lambda = \ln 2 / t_{1/2}$), z_0 the initial shielding depth ($z_0 = E \times t$), ρ [g/cm³] the density of the overlying material, and Λ_i [g/cm²] the attenuation length. The production rate of CRN, $P_i(z)$ [~~at~~atoms/g/~~y~~yr], is a function of the depth, z [cm], below the surface as:

$$P_i(z) = P_i(0) e^{-\frac{z\rho}{\Lambda_i}*} \qquad (2)$$

The subscript 'i' indicates the different production pathways of in-situ produced ^{10}Be via spallation, muon capture and fast muons following Dunai (2010). In this study, ~~we set~~ the relative ~~contribution of neutrons~~spallogenic and ~~muons (negative and fast) to the total ^{10}Be~~muogenic production ~~at resp. 97.85, 1.50 and 0.65%, and set the~~ rates are based on the empirical muogenic to spallogenic production ratios established by Braucher et al. (2011), using a fast muon relative production rate at SLHL of 0.87% and slow muon relative production rate at SLHL of 0.27%. The effective attenuation length ~~at resp. 150,~~ is here equal to the apparent attenuation length as the depth profile was taken on a horizontal surface. The effective attenuation length for the sampling position was obtained using Table 4 in Marrero et al. (2015), and equals 152 g/cm². For fast and stopped muons, the attenuation length was set at resp. 1500 and ~~5300~~4320 g/cm² following Braucher et al. (~~2003~~2011). Production rates were scaled following ~~Dunai (2001~~Stone (2000) with a sea level high latitude production rate of (4.~~5 ± 0.3) at/g/y. This production rate~~ 25 ± 0.18) atoms/g/yr (Martin et al., 2017). The latter represents the regionally averaged SLHL production rate for Europe. The bulk density, ρ, of the studied fluvial sediment was set to 1.7 g/cm^3, which is consistent with the average value ~~that was used earlier on by Rixhon et al. (2011) for dating terraces of the Ardennian rivers.~~of upper Neogene and Quaternary sediments in the region (Beerten et al., 2010). A half-life of (1.387 ± 0.012) × 10^6 y was used for ^{10}Be following Cmeleff et al. (2010). CosmoCalc add-in for Excel was used to calculate the scaling factors. Given the flat topography of the Campine Plateau, topographic shielding was negligible and therefore not corrected for (Norton and Vanacker, 2009).

3.2 Sampling and analytical methods

The depth profile was sampled in a sand pit (SRC-Sibelco NV) on the northwestern edge of the Campine Plateau (Fig. 4a and b). The altitude of the sampling spot is ca. 47 m (Tweede Algemene Waterpassing), while the crest of the plateau further east reaches an altitude of ca. 48 m. The almost 4 m thick sequence is composed of medium-grained quartz-rich fluvial sands, overlain by a thin layer (35 cm thick) of fine-grained aeolian sand (Fig. 5). Detailed grain-size characteristics of the fluvial sand are given in Fig. 6. Note that sample depth is given with reference to the top of the fluvial sands. The lowermost unit A consists of medium sand with mode and median in the range between 250-500 µm, while a significant portion of grains coarser than 500 µm is present. Unit B is finer with a median grain size of ca. 250 µm and virtually no coarse sand (i.e., > 500 µm). Unit C consists of coarse sand (median grain size more than 500 µm) with a significant amount of fine gravel fragments. The next unit (E) is the finest unit of the sequence, with mode and median below 250 µm. Sediments from unit F are generally finer than those of units A and C, but coarser than those from units B and D. Mode and median are in the range between 250-500 µm. Finally, unit G represents a thin layer of fine sand, interpreted as Late Pleistocene aeolian deposits. ~~Based on the grain size analysis, the fluvial sequence can be divided into several fining-upward sequences, where~~Note that samples MHR-II-06 and MHR-II-04 are taken in much finer sand beds compared to the other samples.

From the depth profile, ten samples were collected for CRN analysis at depths ranging from 10 to 320 cm below the fluvial-aeolian contact, from which 9 were ~~analysed~~analyzed. Samples were more or less evenly spread out over the sequence, although the sampling density was higher towards the top (Table ~~2~~1). Samples were taken as bulk samples of 1.5 kg, over a depth interval of 10 cm. Samples were sieved, and the 500-1000 µm grain size fraction was used for sample preparation, except for the fine-grained sand samples MHR-II-04 and MHR-II-06 where the 250-500 µm fraction had to be used.

Samples were prepared at the University of Louvain Cosmogenic Isotope Laboratory (Louvain-la-Neuve). In-situ produced ^{10}Be was extracted from purified quartz using standard separation methods described in von Blanckenburg et al. (1996) and

Vanacker et al. (2007b). Two blanks were processed with the nine samples. Approximately 200 µg of ^{9}Be carrier was added to blanks and samples containing 30 to 35 g pure quartz. The ^{10}Be/^{9}Be ratios were measured in BeO targets with accelerator mass spectrometry on the 0.6 MV Tandy at ETH Zurich (Kubik and Christl, 2010). The ratios were normalized to the ETH in-house secondary standard S2007N with a nominal value of ^{10}Be/^{9}Be of 28.1×10^{-12} (Kubik and Christl, 2010) which is in agreement with a half-life of 1.387 Myr (Chmeleff et al., 2010). Samples are corrected for the number of ^{10}Be atoms in their associated blanks. The analytical uncertainties on the ^{10}Be/^{9}Be ratios of sample and blank are then propagated into the 1σ analytical uncertainty for nuclide concentrations.

3.3 Bayesian inference

3.3.1 Inverse problem

To acknowledge that measurements and modelling errors are inevitable, the inverse problem is commonly represented by the stochastic relationship given by

$$\mathbf{d} = F(\mathbf{x}) \cancel{= \mathbf{d} +} + \mathbf{e} \qquad (3)$$

where $\mathbf{d} = (1, \ldots, N) \in \mathbb{R}^N, N \geq 1$ is the measurement data, F is a deterministic~~, error-free~~ forward model ~~that expresses the relation between the uncertain~~with parameters, $\mathbf{x}$~~, and the measurement data, $\mathbf{d}$~~, and the noise term, $\mathbf{e}$, lumps measurement and model errors.

Inversions were performed within a Bayesian framework, which treats the unknown model parameters $\mathbf{x}$ as random variables with posterior probability density function (pdf), $p(\mathbf{x}|\mathbf{d})$, given by

$$p(\mathbf{x}|\mathbf{d}) = \frac{p(\mathbf{d}|\mathbf{x})p(\mathbf{x})}{p(\mathbf{d})} \propto L(\mathbf{x}|\mathbf{d})p(\mathbf{x}) \qquad (4)$$

where $p(\mathbf{x})$ denotes the prior distribution of $\mathbf{x}$ and $L(\mathbf{x}|\mathbf{d}) \equiv p(\mathbf{d}|\mathbf{x})$ signifies the likelihood function of $\mathbf{x}$. The normalization factor $p(\mathbf{d}) = \int p(\mathbf{d}|\mathbf{x})p(\mathbf{x})d\mathbf{x}$ is obtained from numerical integration over the parameter space so that $p(\mathbf{x}|\mathbf{d})$ scales to unity. The quantity $p(\mathbf{d})$ ~~is generally difficult to estimate in practice but~~ is not required for parameter inference. ~~In~~ Unless stated otherwise, in the remainder of this study~~,~~ we will focus on the unnormalized posterior $p(\mathbf{x}|\mathbf{d}) \propto L(\mathbf{x}|\mathbf{d})p(\mathbf{x})$. ~~For numerical stability, it is often preferable to work with the log-likelihood function, $\ell(\mathbf{x}|\mathbf{d})$, instead of $L(\mathbf{x}|\mathbf{d})$. If we assume the error $\mathbf{e}$ to be normally distributed, uncorrelated and with unknown constant variance, σ^2, the log-likelihood function can be written as~~

$$\cancel{\ell(\mathbf{x}|\mathbf{d}) = -\frac{N_d}{2}\ln(2\pi) - \frac{N_d}{2}\ln(\sigma^2) - \frac{1}{2\sigma^2}\sum_{i=1}^{N_d}[d_i - F_i(\mathbf{x})]^2 \quad (5)}$$

~~where σ^2~~If we assume the residual errors, $\mathbf{e}$, to be normally distributed, uncorrelated and with unknown constant variance, σ_e^2, the log-likelihood function can be written as

$$e_i = d_i - F_i(\mathbf{x}) \quad (5)$$

$$L(\mathbf{x}|\mathbf{d}) = \frac{1}{\sqrt{2\pi}\sigma_e}\exp\left[\frac{-1}{2\sigma_e^2}\sum_{i=1}^{N} e_i^2\right] \quad (6)$$

For numerical stability, it is however often preferable to work with the log-likelihood function, $\ell(\mathbf{x}|\mathbf{d})$, instead of $L(\mathbf{x}|\mathbf{d})$

$$\ell(\mathbf{x}|\mathbf{d}) = -\frac{N}{2}\ln(2\pi) - N\ln(\sigma_e) - \frac{1}{2\sigma_e^2}\sum_{i=1}^{N} e_i^2 \quad (7)$$

The variance of the residual errors, σ_e^2, can be fixed beforehand or sampled jointly with the other model parameters $\mathbf{x}$. ~~It is worth noting~~Note that by fixing $\cancel{\sigma}\sigma_e^2$ to a known measurement error, σ_m^2, one implicitly assumes that the model is able to describe the observed system up to the observation errors. This might not be realistic in environmental modelling, where models are always fairly simplified descriptions of a more complex reality. In this work, we therefore jointly infer ~~σ with $\mathbf{x}$.~~ σ_e with $\mathbf{x}$. This accounts for both measurement and model errors, under the assumption that both types of errors obey a zero-mean uncorrelated and homoscedastic normal distribution.

3.3.2 Markov chain Monte Carlo sampling

The ~~main goal of the~~ inference ~~is~~seeks to estimate the posterior parameter distribution of the model parameters, $p(\mathbf{x}|\mathbf{d})$. As an exact analytical solution for $p(\mathbf{x}|\mathbf{d})$ is not available, we resort to Markov chain Monte Carlo (MCMC) simulation to generate samples from this distribution. The basis of this technique is a Markov chain that generates a random walk through the search space and iteratively finds parameter sets with stable frequencies stemming from the posterior pdf of the model parameters (see, e.g., Robert and Casella, 2004, for a comprehensive overview of MCMC simulation). In practice, the MCMC sampling efficiency strongly depends on the assumed proposal distribution used to generate transitions in the Markov chain. In this work, the state-of-the art ~~DREAM_{ZS}~~$\text{DREAM}_{(ZS)}$ (ter Braak and Vrugt, 2008; Vrugt et al., 2009; Laloy and Vrugt, 2012) algorithm is used to generate posterior samples. A detailed description of this sampling scheme including convergence proof can be found in the ~~literature cited and is thus not reproduced herein.~~cited literature and is thus not reproduced herein. Note that the considered CRN data inversion is a fairly simple problem (the model in Eqs. (1-2) is quick and well behaved whereas both the parameter and measurement data spaces are rather low-dimensional). The use of $\text{DREAM}_{(ZS)}$ will become even more attractive when considering larger parameter dimensionality.

~~**To constrain the post-depositional erosion rate, E, of the sampling site on the Campine Plateau, we apply Bayesian inference on the mathematical expression of the CRN concentration vs. depth profile (Eq. (1)). Details on the model parameter settings are given above. The following marginal prior distributions were defined for the sampled five model parameters, based on the current geological knowledge of the region, as well as the measured ^{10}Be data (Table 1 and 2). For 3 out of 5 parameters, i.e., post-depositional erosion (*E*), exposure age (*t*) and bulk density (*ρ*), we specified truncated Gaussian prior distributions using mid-range points of the adopted interval as means and 0.4 times the interval range as standard deviations. Our justification for this choice is as follows. On the one hand, the prior distribution is sufficiently vague to avoid over-constraining the search (mid-range prior probability is only about twice that of the boundary values), and, on the other hand, it discourages the search to pick up values close to the boundaries as they are considered to be (a priori) less likely. The exposure age of the terrace, *t* [y], was allowed to vary between 0.5 Ma and 1 Ma, based on the presumed burial age of the Rhine sands covering the Campine Plateau at that location from geological evidence (see Section 2). This results in a prior mean of 0.75 Ma, and a standard deviation of 0.2 Ma. These estimates are fully consistent with CRN burial ages of 750 ± 250 ka and 740 ± 210 ka that were established for the High Terrace deposits from the Rhine in Germany and the Netherlands (Dehnert et al., 2011). The denudation rate (*E*) prior distribution was translated into a mean of 30 m/Myr and standard deviation of 24 m/Myr, with upper and lower bounds of 60 m/Myr and 0 m/Myr, respectively. The maximum value is based on**~~**3.3.3 Prior distribution**

The prior pdf is a key element of Bayesian inference. This distribution encodes the available prior information about the parameters and balances the effect of the likelihood function on the posterior pdf (Eq. (4)). We assumed the individual prior parameter pdfs to be independent

$$p(\mathbf{x}) = \prod_{i=1}^{N_p} p(x_i) \qquad (8)$$

with $N_p = 4$ the dimension of $\mathbf{x}$.

Based on the current geological knowledge of the region, we specified a truncated Gaussian prior distribution for *E*, with mean of 30 m/Myr, standard deviation of 30 m/Myr and range of [0, 60] m/Myr. The upper bound of 60 m/Myr is based on (1) geomorphological evidence presented in Fig. 4b, using the altitude difference between the Campine Plateau and the adjacent Kleine Nete floodplain, and ~~taking into account the youngest possible age for the Rhine sediments. The minimum value is set to equal the null-hypothesis, to encompass the scenario of the Campine Plateau being a residual relief due to erosion resistance of the substrate. The mean prior bulk density of the studied fluvial sediments was set to 1.65 g/cm^3, which is consistent with the average value of upper Neogene and Quaternary sediments in the region (Beerten et al., 2010). The full range of the prior for bulk density was set between 1.5-1.8 g/cm^3, to allow for some variation in grain size, sorting and sediment packing. Bulk densities below 1.5 g/cm^3 are typical for clay-rich and or organic-rich soils, while densities in excess of 1.8 g/cm^3 are typical for gravel bearing sediments. However, none of these lithologies have been observed in such quantities so as to justify a wider prior range for the bulk density.~~

~~In contrast to the other model parameters, the~~(2) the youngest possible age for the Rhine sediments. The lower bound of 0 m/Myr corresponds to the scenario where the Campine Plateau is a residual relief due to erosion-resistance of the covering sediments. Overall, the resulting $p(E)$ is sufficiently vague to avoid over-constraining the inversion while nevertheless discouraging the search to pick up values close to the boundaries that are considered to be (a priori) less likely. A uniform prior distribution in the range [0, 1] Myr was selected for *t*. This is based on the presumed burial age of the Rhine sands covering the Campine Plateau (between 0.5 Ma and 1 Ma) together with geologic evidence on the evolution of the Scheldt basin and more in particular the Nete catchment after the opening of the English Channel (0.45 Ma, see Section 2). In addition, we put a uniform prior pdf with range [1, 35] m on the product $E \times t$. This limits the total erosion that can possibly be inferred from the measurement data to 35 m, as we expect that 35 m of total erosion on top of the Campine Plateau is an absolute maximum. When adding the thickness of Rhine sediment that are covering the top of the Campine Plateau (i.e. 5 to 10 m) to the maximum total erosion, we obtain a maximum initial thickness of 40 m to 50 m, which corresponds to the thickness of Rhine deposits that are preserved in the deepest part of the Roer Valley Graben (Beerten, 2006; Deckers et al., 2014). The minimum amount of total erosion is set to 1 m, given the altitude of the sampling position which is slightly (ca. 1 m) lower than the crest of the plateau. The prior distribution for the inherited ^{10}Be concentration, N_{inh}, was assumed to be uniform. This is because solutions for N(z,t) in Eq. (1) always converge to N_{inh} as z tends to infinity while no N_{inh} measurements are available at z larger than 3.5 m. The N_{inh} parameter was therefore allowed to vary uniformly between ~~two extreme values. The maximum value~~ 1×10^4 atoms/g and 9×10^4 atoms/g. The upper bound of 9×10^4 at/g is consistent with the highest concentration measured in the profile (Table 2; the inherited concentration cannot be higher than this value). The lower bound was somewhat arbitrarily set at $1 \times$ ~~10^4~~ 10^3 at/g, given the fact that zero inheritance is considered to be very unlikely. Lastly, a so-called Jeffreys (1946) prior of the form $p(\sigma_e) \propto 1/\sigma_e$ was used for σ_e. This classical choice basically means that one wants to achieve σ_e values that are both as small as possible and large enough to be consistent with the data misfit.

~~Lastly, a so-called Jeffreys (1946) prior of the form $p(\sigma) \propto 1/\sigma$ is used for σ. This classical choice basically means that one wants to achieve σ values that are both as small as possible and consistent with the data misfit.~~

~~3.3.3~~

3.3.4 Comparison with the Bayesian approach in CRONUScalc

For comparison, we implemented the approach taken by Marrero et al. (2016) in CRONUScalc (CR). For brevity, in the reminder of this paper we will refer to this method as CRB for "CRONUScalc Bayes". Similarly as our approach, CRB seeks to estimate $p(\mathbf{x}|\mathbf{d})$ using Eq. (4). However, CRB does not generate a set of samples with frequencies stemming from $p(\mathbf{x}|\mathbf{d})$. Instead it samples the prior pdf, $p(\mathbf{x})$, over a high-resolution 3-dimensional evenly-spaced lattice and computes the (normalized) posterior pdf, $p(\mathbf{x}|\mathbf{d}) = L(\mathbf{x}|\mathbf{d})p(\mathbf{x})/p(\mathbf{d})$, for each grid point. This requires evaluation of $p(\mathbf{d}) = \int L(\mathbf{x}|\mathbf{d})p(\mathbf{x})d\mathbf{x}$, which is done by a trapezoidal integration scheme.

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The need to evaluate $p(\mathbf{d})$ by trapezoidal integration implies that CRB cannot use $\ell(\mathbf{x}|\mathbf{d})$ but requires using $L(\mathbf{x}|\mathbf{d})$. The $L(\mathbf{x}|\mathbf{d})$ formulation taken by CRB is similar as Eq. (5), except for two aspects. First CRB includes the more general heteroscedastic case as well. In other words, the residual errors, $\mathbf{e} = [e_1, \dots, e_N]$, can have different variances, $\sigma_{e_1}^2, \dots, \sigma_{e_N}^2$. Second and most important, CRB sets the σ_{e_i} to analytical measurement errors, σ_{m_i}. Using similar notations as in Marrero et al. (2016), CRB uses

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{e_i}{\sigma_{m_i}}\right)^2 \qquad (9)$$

$$L(\mathbf{x}|\mathbf{d}) = \prod_{i=1}^{N} \left(\frac{1}{\sqrt{2\pi}\sigma_{m_i}}\right) \exp\left[-\frac{\chi^2}{2}\right] \qquad (10)$$

where χ^2 is a weighted sum of squared residuals (WSSR) also referred to as the chi-square statistic. In this study σ_m is assumed to be constant: $\sigma_{m_1}, \dots, \sigma_{m_N} = \sigma_m$. Eq. (10) therefore reduces to Eq. (6) but with the standard deviation of the residual errors, σ_e, fixed to σ_m. Thus CRB considers 3 parameters: E, t and N_{inh}. With respect to the associated 3-dimensional prior distribution, $p(\mathbf{x})$, we used the assumptions as for our approach (see section 3.3.3).

As stated earlier, no matter whether ones uses a constant σ_m or a different σ_{m_i} for each residual, e_i, fixing the standard deviation(s) of the residual errors to the standard deviation(s) of the measurement errors implicitly assumes that the model can fit the concentration data within the standard deviation(s) of the measurement errors. If this assumption is not met, then the resulting $p(\mathbf{x}|\mathbf{d})$ estimation will be biased towards underestimation of uncertainty. For the case of constant σ_e and σ_m in Equations (6) and (10), respectively, the solution that maximizes $p(\mathbf{x}|\mathbf{d})$, or maximum a posterior solution (MAP), should have a root-mean-square error, $RMSE = \sqrt{N^{-1}\sum_{i=1}^{N} e_i^2}$, that is close to σ_e (Eq. (10)) or σ_m (Eq. (6)). Otherwise, the chosen likelihood model is not consistent with the actual data.

3.3.5 Predictive uncertainty intervals

A 95-% uncertainty interval for the simulated CRN concentrations can be calculated by drawing parameter sets, ~~$[\mathbf{x}, \sigma]$,~~ $\mathbf{x}$, from $p(\mathbf{x}|\mathbf{d})$ and removing the 2.5% largest and lowest values from the associated set of $F(\mathbf{x})$ responses. ~~We call the so-derived 95 % uncertainty interval a “95 % uncertainty interval due to parameter uncertainty”. Because of model inadequacy (that is, model errors), this interval may not bracket 95% of the observations though. Consistently with the assumptions underlying Eq. (5), we thus compute a “95% total uncertainty interval” by adding to each $F(\mathbf{x})$ a random noise $\mathbf{e} \propto N(0, \delta)$, with $\delta = \sigma - \sigma_m$ where σ_m is a fixed measurement error which we take as the maximum analytic measurement error of our dataset, that is, σ_m = 2000 atoms/g~~If all prior assumptions about the residual error distribution are met, then this 95 % predictive uncertainty interval should encompass 95% of the measurement data.

4 Results

4.1 CRN ~~profiling technique~~measurement data

~~Table 2 lists sample input parameters, and measured ^{10}Be concentrations with analytical errors. The depth is given below the contact with the overlying aeolian sand cover.~~ In general, there is a clear decrease in ^{10}Be concentration with depth, except for two samples (-04 and -06) which ~~clearly~~ contain higher CRN concentrations (Table 1 and Fig. 6). It is striking that the CRN concentrations are consistently higher for the two samples were the finer (250-500 µm) grain size fraction was ~~analysed~~analyzed. Grain size-dependent ^{10}Be concentrations can point to differences in geomorphological process rates in the regions of sediment provenance as suggested by Carretier et al. (2015). Alternatively, the negative relation between in-situ produced CRN and grain size might also result from non-stationary sedimentation rates, where samples from the fine-grained layers accumulated CRN during the final stage of the sedimentation cycle prior to a phase of non-deposition and/or steady state. Apart from the -04 and -06 samples~~-~~, the CRN concentrations decrease non-linearly with depth, from (1.5 ± 0.02) × 10^5 ~~at~~atoms/g at 10 cm to (9.0 ± 0.2) × 10^4 ~~at~~atoms/g at 320 cm~~.~~ (Table 1 and Fig. 6). Because they are not compatible with the other profile data, samples -04 and -06 were excluded from the inversion, thereby leading to a measurement data set of 7 concentrations. These measured concentrations are associated with analytical measurement errors, $\sigma_{m_1}, \ldots, \sigma_{m_7}$, in the range of 6 × 10^3 atoms/g – 7 × 10^3 atoms/g.

If we ~~assume that~~consider the end-member where erosion rates of the Campine Plateau ~~is an erosion-resistant landform with negligibly~~are very low ~~erosion rates~~ ($E \approx 0$ ~~cm/yr),~~m/Myr), as one could assume from its geomorphic setting as an inverted topography, the difference between $N_{total}(z)$ and N_{inh} gives the $N_{exp}(z)$ or the concentration of cosmogenic nuclides that is produced at depth z after deposition of the Rhine sands. The apparent exposure age of the surface, t, can then be reconstructed following Eq. (1). By doing so, we obtain an apparent exposure age of 21.5 ± 1.5 ka, which is in strong contradiction with chronostratigraphical age estimates of the fluvial deposits that cover the Campine Plateau that range between 0.5 Ma and 1 Ma (see Section 2 and 3.3.2). We advocate that post-depositional erosion has strongly altered the ^{10}Be signature of the upper layers of the Rhine sediments at the study site.

4.2 Inversion

4.2.1 Posterior ~~parameter~~ distribution derived by our proposed approach

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We ran DREAM$_{(ZS)}$ for a (serial) total of 150 × 10^3 model evaluations. The marginal posterior distributions of the ~~5~~4 sampled parameters (including the standard deviation of the residual errors~~)~~, σ_e) are depicted in Fig. ~~7. The t distribution shows a weakly expressed mode around the prior mean value (Fig. 7a) whereas no significant correlation is observed between t and the other model parameters except for N_{inh} with which a linear correlation of -0.13 is observed (Fig. 8a-d-f and Table 3). This means that the measurement data do not contain enough information to resolve the exposure age. In other words, depending on the other model parameter values, the model can always fit the data no matter the value of t (within its~~

~~prior range of 0.5 Ma – 1 Ma).~~7 while bivariate posterior scatter plots together with iso-density contour lines are presented in Fig. 8. The erosion rate, E, is ~~much better~~relatively well resolved with a ~~posterior~~clear mode around ~~4.4×10^{-3} cm/yr which is equal to 44 mm/kyr or~~39 m/~~kyr~~Myr (Fig. ~~7b~~7a and 8a-b). The posterior E uncertainty ~~is relatively small, being 9 cm/yr (1σ) and 15 cm/yr (2σ). A~~ remains however large (Fig. 7a and 8ab), with a standard deviation (1σ) of 8 m/Myr and a 95% uncertainty interval of [25.8, 57.5] m/Myr. Furthermore, posterior E and N_{inh} values are positively correlated (Table 2 and Fig. 8b) with a linear correlation coefficient of 0.~~71 is found~~ 57. The t posterior distribution shows a weakly expressed mode between ~~E~~ca. 50 ka and ~~N_{inh}~~200 ka (Fig. 7b, 8a and 8c~~ and Table 3). This suggests that one could try to fix one and only infer~~) but nevertheless resembles the ~~other. The posterior bulk t~~ prior density ~~distribution~~ (Fig. 7b) rather closely, except for t > 0.5 Myr. Also t does not ~~deviate much from its prior distribution (Fig. 7d), and shows a weak (negative)~~correlate with other sampled parameters, except for N_{inh} (Table 2 and Fig. 8c) with which a linear correlation ~~with E (Fig. 8b and Table 3).~~of -0.38 is observed (Table 2). The t parameter is therefore left largely unresolved by the inversion. The N_{inh} parameter shows a clear mode around ~~6.5~~8.4 × 10^4 atoms/g~~,~~ (Fig. 7c, 8b and 8c), which is lower than the lowest measured value in the profile of about 9.09 × 10^4 atoms/g (~~Fig. 7d;~~ Table ~~2~~1). As mentioned already, a ~~strong~~moderately large dependence with E ~~was found~~is observed (Fig. ~~8c~~8b and Table ~~3~~2). The ~~standard deviation of the residual errors, σ,~~σ_e parameter shows ~~a~~an approximately log-normal marginal posterior with a clear mode around 1 × 10^4 atoms/g (Fig. ~~7e~~7d). This is consistent with the achieved ~~root mean square error (~~RMSE~~)~~ values between measured and simulated ^{10}Be~~ that follow~~. Indeed, the MAP solution induces a ~~similar distribution with a mode about 1~~RMSE of 9.8 × 10^4 atoms/g~~ (not shown). It is interesting to note~~. Notice that with ~~a range~~values ranging between ~~1.4~~6 × 10^3 and ~~2~~7 × 10^3 atoms/g, the analytical measurement errors are ~~more than 5~~1.4 to 1.7 times smaller than the ~~values taken by σ.~~RMSE of the MAP solution. This ~~nicely~~ illustrates the effect of model errors. If the model would have been perfect, the ~~achieved RMSE values and σ distribution~~MAP solution should ~~indeed~~ have been associated with a RMSE that is within ~~this~~the measurement error range of ~~1.4~~6 × 10^3 ~~to 2~~-7 × 10^3 atoms/g~~.~~ (section 4.1).

Fig. 9 presents the 95 % ~~predictive uncertainty interval due to parameter uncertainty (dark gray area) together with the 95 % total predictive uncertainty~~ uncertainty interval ~~(light gray area). Indeed, the 95 % uncertainty~~ associated with model predictions. This interval ~~due to parameter uncertainty~~ brackets ~~only 6~~ 5 (71% of the data) or 6 (86% of the data) observations out of 7, ~~which is less that what would be expected from a 95 % confidence level. This gap is likely caused by model inadequacy. The derived 95 % total predictive uncertainty interval is much larger and encapsulates all of the 7 observed~~ depending on how to consider the situation of measurement data~~.~~

~~5 Discussion~~

~~Five parameters of the CRN model were considered to be uncertain within the MCMC inversion: E, t, N_{inh}, ρ and σ.~~ point -03 (Table 1) that is located at the limit of the uncertainty band. With ~~only seven measurement~~7 data~~, the chosen marginal prior distributions for these parameters are obviously strongly influencing the sampled posterior distribution. Moreover, as stated~~

~~earlier, we used relatively flat distributions with wide ranges such that the search towards the maximum a posteriori (MAP) prediction is not much constrained by the prior. This resulted in a poor resolution for the *t* and *ρ* parameters (Fig. 7a and 7c) for which marginal prior and posterior distributions are quite similar. In contrast, the inherited ^{10}Be concentration (N_{inh}) appears to be a well-resolved parameter. This is an important observation, because for eroding surfaces such as the one considered in this study, the inherited concentration contributes significantly to the total ^{10}Be concentration. The target parameter in this study, that is, the erosion rate (*E*), appears to be well-resolved as well, showing a relatively tight posterior distribution that is shifted towards higher mean values compared to the prior (Fig. 7b). In the following, the posterior mean of the *E* distribution, together with a one sigma uncertainty level, i.e. 44 ± 9 m/Myr or mm/kyr, are used to discuss the inferred erosion rate~~ points only it is impossible to further assess the accuracy of the 95% uncertainty band displayed in Fig. 9. Overall, it seems reasonably consistent.

4.2.2 Comparison against~~In Fig. 10,~~ the ~~pooled~~approach taken in CRONUScalc

For CRB we sampled over an evenly-spaced 3-dimensional grid with upper and lower limits defined in section 3.3.5 and 60 grid divisions in each dimension. This leads to a total of 216 × 10^3 model evaluations, which is overall similar to what was used in our proposed approach (120 × 10^3). Moreover, we assumed a constant measurement error: $\sigma_{m_1}, \ldots, \sigma_{m_N} = \sigma_m = 7 \times 10^3$ atoms/g. Using a constant rather than variable measurement error is fully justified here because (1) the analytical error range is only 6 × 10^3 – 7 × 10^3 atoms/g (section 4.1), and (2) as shown in section 4.2.1 the model cannot fit the data up to the maximum measurement error of 7 × 10^3 atoms/g anyway.

The marginal posterior distributions of the 3 sampled parameters are presented in Fig. 10. The CRB finds similar modal or MAP values as our approach (compare Fig. 7a-c with Fig. 10a-c). The *t* posterior distribution obtained by CRB is very close to that derived by our approach, except for a narrower peak around the MAP. For *E* and N_{inh}, the posterior distribution obtained by CRB is a narrower version of that derived by our approach (compare Fig. 7a with 10a and Fig. 7c with 10c). This is caused by the use of $\sigma_m = 7 \times 10^3$ atoms/g in the likelihood function (Eq. (10)). The latter generally induces a more peaky likelihood (and consequently narrower posterior density) than our approach for which σ_e values in the range shown in Fig. (8d) are sampled. Since similarly as for our approach the RMSE of the MAP solution derived by CRB is approximately 9.8 × 10^4 atoms/g, the CRB likelihood function is actually too narrow to be consistent with the achieved data misfit. This leads herein to a moderate underestimation of uncertainty. This becomes more apparent in the resulting predictive uncertainty intervals (Fig. 11). Indeed the 95% uncertainty band only brackets 4 data points out of 7, that is, 57% of the observations.

Lastly, it is worth noting that the fact that the distributions presented in Fig. 7 are less smooth than those showed in Fig. 10 is due to the different natures of grid-based sampling and MCMC. A given bin in Fig. 7 is made of 3000 samples that are drawn from the posterior pdf by the MCMC, while each bin in Fig. 10 corresponds to a single (central-bin) point of the sampled lattice.

4.2.3 Accounting for model errors in CRONUScalc

A simple fix for making the CRB uncertainty estimates more consistent in the presence of model errors is as follows:

I. Identify the minimum RMSE over the sampled lattice, plug it as an estimate of σ_e in Eq. (6) and compute the posterior density of each lattice point.

II. Check whether the resulting MAP solution has a RMSE that is close to the fixed σ_e. These two values will obviously be equal if uniform priors are used, but may not necessarily be similar otherwise.

III. If the above is satisfied, then proceed with the inference. Otherwise, set σ_e to the RMSE of the MAP solution, re-compute the posterior density of each lattice point and go back to II.

For the considered case study, this procedure expectedly leads to fixing σ_e to about 9.8×10^4 atoms/g. This results into increased posterior parameter and predictive uncertainty that get relatively close to that derived by our approach in Fig. 7 and 8. Yet these uncertainty estimates remain slightly smaller than those displayed in Fig. 7 and 8. This is because rather than fixing σ_e our approach infers its complete posterior distribution given the information content of the measurement data.

5 Discussion of the obtained erosion rate ~~data~~estimate

In Fig. 12, erosion rates for outcrops, as published by Portenga and Bierman (2011) are shown, together with the mean erosion rate obtained in the present study. The global erosion data are based on surface samples (thickness ranging between 0.5 cm and 8 cm) from a variety of bedrocks, including igneous, metamorphic and sedimentary rocks, and various climato-tectonic settings. Generally speaking, outcrop erosion rates from Portenga and Bierman (2011) tend to be lower than the ~~one~~39 ± 8 m/Myr determined for the ~~headwaters~~northwestern part of the ~~Nete catchment, with a few exceptions.~~Campine Plateau. Since ~~their~~the data set of Portenga and Bierman (2011) is entirely based on bedrock samples, ~~we argue that~~ the ~~differences in~~higher erosion rate ~~principally~~of the sandy deposits can reflect differences in erosion resistance of the substrate, i.e., consolidated rock versus unconsolidated sediment. ~~Furthermore~~Nevertheless, in a western European context, the erosion rate that we report ~~here~~for the northwestern Campine Plateau seems to be fairly high for a fluvial terrace. For comparison, the Meuse younger Main Terrace (YMT) near Liège does not show any signs of post-depositional erosion following Rixhon et al. (2011). Probably, the coarse-grained and slightly consolidated nature of the Meuse ~~sediment~~gravels can be put forward as an explanation. Similarly, Dehnert et al. (2011) reported that the High Terraces of the Rhine in Germany and the Netherlands were eroded by only 1-3 m, and that the loess cover presumably protected the Rhine sands from significant erosion soon after deposition.

An alternative explanation for the relatively high erosion rate found in the current study may be the proximity of the North Sea, and ~~its changes in~~low base level during ~~sea level lowstands.~~glacial periods. In contrast to the Meuse and Rhine, the Scheldt basin, to which the ~~studied Rhine terrace~~northwestern Campine Plateau belongs today, developed in response to the sudden base level lowering as a result of the opening of the English Channel, ca. 450 ka~~ ago~~ (see Section 2). An important feature of the Scheldt basin is the Flemish Valley, a buried river system~~, which the Nete basin is an eastern extension from. We advocate that the~~. The sudden base level lowering may have caused a regressive erosion wave penetrating into the hinterland, shaping the Flemish Valley and its eastern extension, i.e. the Nete catchment, and cause increased erosion rates in this distal part of the Scheldt basin. The posterior distribution for t, showing an increasing probability for $t < 0.5$ Myr, and peaking between 200 ka and 50 ka supports this hypothesis. In the case of non-stationary erosion, it remains unclear to which extent the erosion rate can be used to infer the total amount of erosion at the site. In this study, we used $E \times t$ as a joint prior for total erosion for which a lower and upper limit of 1 m and 35 m was set, and our results show an erosion estimate distribution as given in Fig. 13. The posterior for $E \times t$ is poorly resolved, which is mainly caused by the poorly resolved posterior for t.

~~An important issue to tackle is to which extent the currently obtained erosion rate can be used to infer the total amount of erosion at the site. Mathematically, this translates into $E \times t$, and would roughly yield a value of between ca. 22 m (for t = 500 kyr) and 44 m (for t = 1 Myr). Adding up with the current thickness of fluvial sediment at the site (i.e., 5-10 m) this would mean that the original thickness of Rhine sediment would have been between ca. 27-54 m. Since this would exceed the thickness of Rhine sediment in the southwestern part of the Roer Valley Graben (Beerten, 2006), we consider this hypothesis to be false. Instead, we suggest that erosion started later, presumably after opening of the English Channel around 450 ka. The ^{10}Be data thus would reflect the arrival of the headward erosion wave in the distal part of the Nete catchment, following the opening of the English Channel, and the reorganisation of the hydrographical network. On the one hand this implies that the total amount of erosion is less than 22 m, according to the formula $E \times t$. On the other hand, at least 5-10 metres of extra sediment would have been needed to completely shield the sampled sediment from cosmogenic radionuclide production before the start of erosion, sometime after 450 ka.~~

~~In any case, there are several implications for the regional evolution of the landscape attached to the observation of sediment removal on top of the Campine Plateau. Firstly, it would mean~~

Our erosion estimates for the top of the northwestern Campine Plateau asks for a revision of regional landscape evolution models. Firstly, our results suggest that the total amount of Rhine sediment would have been larger than what can be observed today in the quarries (Fig. 4); this should be taken into account when correlating Rhine sediment from the Campine Plateau with that in the Roer Valley Graben. Secondly, they indicate that post-depositional fault movement along (segments of) the Feldbiss fault as derived from the stratigraphy of Rhine sands should be considered as a minimum (Fig. 3). Thirdly, the amount of post-depositional erosion west of the plateau (Fig. 2) as can be observed from present-day altitude differences (northwestern Campine Plateau vs. Nete valley; Fig. 4b) should be regarded as a minimum erosion value.

In future work, ~~the aim is~~we plan to consider more parameters ~~in~~within the ~~MCMC~~Bayesian inversion when new and more densely sampled profiles become available. Increasing parameter dimensionality is straightforward with our MCMC sampling, but may quickly become intractable with the pure grid-based approach taken in the CRONUScalc program (Marrero et al., 2016). This limitation also holds for plain MC simulation as done by Hidy et al. (2010). Moreover, in an attempt to account for differences in geomorphological process rates in the regions of sediment provenance or non-stationary sedimentation rates, resulting in grain-size dependent ^{10}Be concentrations, ~~the~~our MCMC ~~simulation~~inversion could be combined with a distributed numerical forward modelling approach instead of the currently used analytical solution.

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6 Conclusion

~~In accordance with previous studies, we conclude and confirm that a single ^{10}Be concentration depth profile can generate meaningful and reliable information on the denudation rates of a given landform, even when several parameters are highly uncertain. An MCMC inverse modeling procedure leads to a maximum a posteriori post-depositional erosion rate of ca. 44 ± 9 m/Myr (mm/kyr) for the studied fluvial terrace of the Rhine which today belongs to the Nete catchment. This derived value of post-depositional erosion rate~~We inverted within a Bayesian framework an in-situ produced ^{10}Be concentration depth profile from the northwestern Campine plateau (NE Belgium) to infer the average long-term erosion rate, surface exposure age and the inherited ^{10}Be concentration in the profile. Compared to the state-of-the-art in probabilistic inversion of CRN profile data, our inversion approach has two new ingredients: it (1) uses Markov chain Monte Carlo (MCMC) sampling, and (2) accounts (under certain conditions) for the contribution of model errors to posterior parameter and predictive uncertainty. We compared our approach to that taken in the CRONUScalc program for the considered case study. Both approaches are found to produce similar maximum a posteriori (MAP) values. Nevertheless, the method implemented in CRONUScalc also moderately underestimates uncertainty. A simple fix for making these uncertainty estimates more consistent in the presence of model errors is therefore proposed. For the studied fluvial terrace of the Rhine which today belongs to the Nete catchment (Scheldt basin), the derived MAP post-depositional erosion rate is ca. 39 ± 8 m/Myr (1σ). This is fairly high compared to published outcrop erosion rate data in the Meuse and Rhine catchment, and elsewhere in the world. ~~It is inferred~~We believe that the unconsolidated and gravel-poor nature of the studied Rhine sediment, the absence of a protecting cover (such as loess) and possibly also headward erosion in response to sudden base level lowering around 450 ka are ~~put forward as a~~ possible ~~explanation. We conclude that~~explanations. Our future work will try to better resolve erosion rate together with several other uncertain parameters from MCMC ~~modelling~~inversion of ~~^{10}Be~~dense two-nuclide concentration depth profiles ~~is a powerful tool to determine rates of landscape evolution and earth surface processes and to assess the associated uncertainties~~.

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7 Code availability

~~A MATLAB code~~Python codes of the two Bayesian inversion approaches used in this study ~~is~~are available ~~upon request to the second author.~~from https://bitbucket.org/ericlaloy/CRN_probabilistic_inversion/.

8 Author contributions

~~K. Beerten designed the study,~~ E. Laloy implemented and performed the ~~sampling~~inversions, and jointly prepared the manuscript with ~~contributions from the second and third authors. E. Laloy implemented the model~~K. Beerten and V. Vanacker. K. Beerten designed the study and performed the ~~simulations.~~field sampling. V. Vanacker prepared the field samples~~, interpreted and~~ for CRN analyses, processed the raw measurement data and ~~performed initial calculations.~~supervised the presented work. B. Rogiers co-designed the study~~ and~~. M. Christl performed the AMS measurements at ETH-Zurich. L. Wouters supervised ~~it.~~ the work on behalf of ONDRAF/NIRAS.

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Figure Captions

Figure 1 – Location of the Campine region within Europe and the European Sand Belt.

Figure 2 – Structural map of northwestern Europe showing the Roer Valley Graben faults and the Brabant and Rhenohercynian (Ardennes) massifs superimposed on a Digital Terrain Model (DTM) of northwestern Europe (GTOPO30; data available from the U.S. Geological Survey), with indication of large rivers (http://www.eea.europa.eu/data-and-maps/data/wise-large-rivers-and-large-lakes) and location of the Scheldt basin, (dashed line), the Nete catchment (dotted line) and the Flemish Valley (solid line). The general palaeohydrography of the Meuse and Rhine between 0.5 Ma and 1.0 Ma is shown in coloured lines. Headward erosion as an explanation for the development of the Nete catchment is indicated with a yellow arrow.

Figure 3 – DTM of the Campine Plateau (Digitaal Hoogtemodel Vlaanderen II, DTM, raster, 1 m) and the extent of Rhine deposits in the study area (shading; based on Beerten (2005) and Deckers et al. (2014)).

Figure 4 – (a): Detailed DTM of the study area (Digitaal Hoogtemodel Vlaanderen II, DTM, raster, 1 m), with indication of the sampling location (white arrow). Note the regularly shaped sand quarries south of profile line A-A' which appear as depressions on the DTM. (b): Topographic cross-section according to the profile line (A-A') shown in (a). The sampling location is schematically shown as a grey rectangle.

Figure 5 – Photograph of the sampled profile with indication of sampling points, field codes, lithological units (A-G) and approximate profile depth.

Figure 6 – ^{10}Be concentration profile and results of the grain size analyses. Note that the elevated ^{10}Be concentrations belong to samples that were analysed using a smaller grain size fraction than the other samples (i.e., 250-500 µm instead of 500-1000 µm). These are indicated by pale gray dots. Depth is given relative to the uppermost sample.

Figure 7 – ~~Posterior~~Marginal posterior distributions of the ~~six~~four sampled parameters~~.~~ by our approach: (a~~):~~) erosion rate, (b) exposure age. (b~~): erosion rate.~~), (c~~): bulk density. (d):~~) inherited ^{10}Be concentration~~. (e):~~ and (d) standard deviation of the residual errors. The blue bars denote the posterior pdfs and the red lines signify the associated prior pdfs.

Figure 8 – Selected ~~correlation~~scatter plots together with iso-density contour lines for the ~~five parameters. Note that~~ ~~N_{inh}~~sampled posterior parameter distribution by our approach. Black dots are posterior parameter sets and ~~E show~~ the ~~strongest correlation.~~density increases with the line color ranging from red (lower density) to yellow (higher density).

Figure 9 – 95 % predictive uncertainty interval ~~due to parameter uncertainty and the 95 % total predictive uncertainty interval (dark~~ (gray area~~).~~) and associated MAP prediction (black line) derived by our approach. The red crosses represent the seven measurement data points used in the inversion. Depth is given in ~~cm below the contact with the overlying aeolian sand cover~~absolute depth.

Figure 10 – Marginal posterior distributions of the three sampled parameters by the Bayesian approach taken in the CRONUScalc program: (a) erosion rate, (b) exposure age. (b), and (c) inherited ^{10}Be concentration. The blue bars denote the posterior pdfs and the red lines signify the associated prior pdfs.

Figure 11 – 95 % predictive uncertainty interval (gray area) and associated MAP prediction (black line) derived by the Bayesian approach taken in the CRONUScalc program. The red crosses represent the seven measurement data points used in the inversion. Depth is given in absolute depth.

Figure 12 – Frequency distribution of ~~the pooled~~ outcrop erosion rates ~~obtained from~~published by Portenga and Bierman (2011), with indication of the mean value obtained for the ~~Nete catchment~~northwestern Campine Plateau (this study).

Figure 13 – Derived posterior distribution for total erosion (denudation) at the study site ($E \times t$).

~~Table 1 - Prior distributions for four parameters: erosion rate, exposure age, bulk density and inherited ^{10}Be concentration.~~

Table 1 - Analytical results from the in-situ produced ^{10}Be analysis. The depth profile is located at 50,95°N and 5,63°W at an altitude of 45 m. A SLHL production rate of 4.25 ± 0.18 atoms/g/yr was used, which represents the regionally averaged SLHL production for Europe (Martin et al. 2015). We refer to the manuscript for more information on the methodology used.

~~Parameter~~Sample label	~~Symbol~~Sample field code	~~Unit~~Relative depth (cm)*	~~Distribution~~Absolute depth (cm)	~~Min-max~~Quartz (g)	~~Mean~~Be carrier (mg)	~~St. dev.~~ ^{10}Be/^{9}Be (× 10^{-12})	^{10}Be conc (× 10^{5}atoms/g qtz)
~~Erosion rate~~TB1204	~~E~~BE-MHR-II-00	~~m/Myr or mm/kyr~~0	~~Truncated Gaussian~~45	34,406	0,208	0~~–60~~,388 ± 0,016	~~30~~1,537 ± 0,065 ~~2~~ 4
~~Exposure age~~TB1205	~~t~~BE-MHR-II-01	~~Ma~~30	~~Truncated Gaussian~~75	33,535	0~~.5 – 1.0~~,207	0~~.75~~,329 ± 0,016	1,328 ± 0~~.2~~,070
~~Bulk density~~TB1206	~~ρ~~BE-MHR-II-02	~~g/cm^3~~50	~~Truncated Gaussian~~95	~~1.5 – 1.8~~33,370	~~1.65~~0,207	0~~.12~~,252 ± 0,016	1,015 ± 0,070
~~Inherited ^{10}Be~~TB1207	~~N_{inh}~~BE-MHR-II-03	~~10^4 atoms/g~~70	~~Uniform~~115	~~1 – 9~~34,467	~~n/a~~0,207	~~n/a~~0,318 ± 0,016	1,245 ± 0,065
TB1940	BE-MHR-II-04	110	NA	23,478	0,164	0,521 ± 0,019	2,397 ± 0,095
TB1208	BE-MHR-II-05	150	195	34,620	0,207	0,231 ± 0,015	0,898 ± 0,061
TB1944	BE-MHR-II-06	190	NA	23,486	0,164	0,709 ± 0,043	3,272 ± 0,204
TB1209	BE-MHR-II-07	230	275	34,186	0,207	0,251 ± 0,014	0,987 ± 0,060
TB1210	BE-MHR-II-09	310	355	33,663	0,207	0,229 ± 0,014	0,909 ± 0,060
TB1211	BE-BLANK-01	NA	NA	0,000	0,207	0,0011 ± 0,0006	
TB1941	BE-BLANK-02	NA	NA	0,000	0,164	0,0041 ± 0,0009	

~~Table 2 - Analytical results from the in-situ produced 10Be analysis. The depth profile is located at 50.95°N and 5.63°W at an altitude of 47 m. A SLHL (sea-level high-altitude) production rate of 4.5 ± 0.3 at/g/y was used in this study. We refer to the text for more information on the methodology used.~~

~~Sample label~~	~~Sample field code~~	~~Relative depth z_{fluv} (cm)*~~	~~Quartz (g)~~	~~Be carrier (mg)~~	~~^{10}Be/^{9}Be (× 10^{-12})~~	~~^{10}Be conc (× 10^{5}at/g qtz)~~
~~TB1204~~	~~BE-MHR-II-00~~	~~10~~	~~34,406~~	~~0,208~~	~~0,388 ± 0,016~~	~~1,537 ± 0,019~~
~~TB1205~~	~~BE-MHR-II-01~~	~~40~~	~~33,535~~	~~0,207~~	~~0,329 ± 0,016~~	~~1,328 ± 0,017~~
~~TB1206~~	~~BE-MHR-II-02~~	~~60~~	~~33,370~~	~~0,207~~	~~0,252 ± 0,016~~	~~1,015 ± 0,015~~
~~TB1207~~	~~BE-MHR-II-03~~	~~80~~	~~34,467~~	~~0,207~~	~~0,318 ± 0,016~~	~~1,245 ± 0,017~~

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~~**TB1940**~~	~~BE-MHR-II-04~~	~~120~~	~~23,478~~	~~0,164~~	~~0,521 ± 0,019~~	~~2,397 ± 0,029~~
~~**TB1208**~~	~~BE-MHR-II-05~~	~~160~~	~~34,620~~	~~0,207~~	~~0,231 ± 0,015~~	~~0,898 ± 0,014~~
~~**TB1944**~~	~~BE-MHR-II-06~~	~~200~~	~~23,486~~	~~0,164~~	~~0,709 ± 0,043~~	~~3,272 ± 0,037~~
~~**TB1209**~~	~~BE-MHR-II-07~~	~~240~~	~~34,186~~	~~0,207~~	~~0,251 ± 0,014~~	~~0,987 ± 0,015~~
~~**TB1210**~~	~~BE-MHR-II-09~~	~~320~~	~~33,663~~	~~0,207~~	~~0,229 ± 0,014~~	~~0,909 ± 0,015~~
~~**TB1211**~~	~~BE-BLANK-01~~	~~NA~~	~~0,000~~	~~0,207~~	~~0,0011 ± 0,0006~~	
~~**TB1941**~~	~~BE-BLANK-02~~	~~NA~~	~~0,000~~	~~0,164~~	~~0,0041 ± 0,0009~~	

**The relative depth z_{fluv} is given as depth below the contact with the overlying aeolian sand cover.*

Table ~~3~~2 – Posterior linear correlation coefficients between the ~~5~~4 sampled ~~variables~~parameters with our approach.

Sampled parameter	*E*	*t*	~~*ρ*~~	N_{inh}	~~σ~~σ_e
E	1				
~~*t*~~	~~0.017~~	~~1~~			
~~*ρ*~~*t*	-0.~~221~~21	~~-0.002~~ 1			
N_{inh}	0.~~709~~67	-0.~~139~~56	~~0.197~~	1	
~~σ~~σ_e	-0.~~110~~13	0.~~007~~08	-0.~~082~~23	~~-0.145~~	1

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