We firstly thank both reviewers for agreeing to review the manuscript and appreciating its originality. Their thoughtful comments helped improving the revised-version.

As the four main concerns of both reviewers (implying a major revision) are broadly consistent (text in black), we first propose a concise answer to each of these (text in blue). A detailed answer to each reviewers' comment is provided afterwards. Four new supplementary materials (A-B-C-D) are attached to our revisions as well.

1) SV-error is not put to good use because it is averaged over all of our sub-reach.

We agree with this remark. We changed our methodology accordingly, which now uses a "node-specific" error. Supplement A and B illustrates and describes our new methodology, respectively.

2) The methodology is not clear enough, especially the way the channels are translated at each run.

We agree that the first draft did not allow the readers to fully understand the methodology. We thus produced a new figure (Supplement A) and rewrote the methodology accordingly (Supplement B). We think it is now possible to thoroughly understand how channels are translated (directions and values) at each MC run. We also propose to integrate Supplement A into a new figure of the revised-manuscript.

3) The use of the proposed SoD is not correct. Reviewers ask for a threshold of change detection.

We agree with this remark. The term SoD has been abandoned. We think it was potentially misleading for readers as it was technically not a detection threshold. We now propose focusing on a well-known and reliable uncertainty indicator: the relative percentage of uncertainty. It allows us to describe variability (and so uncertainty) of our MC results.

Firstly, the relative percentage of (total) uncertainty is calculated as following: 0.5x(max-min)x100/mean

Secondly, we propose the following significance threshold: percentage of uncertainty > 50%. Indeed, if the percentage of uncertainty exceeds 50%, the mean value is then necessarily lower than the total range of measured value (max-min), which leads to the assumption that the uncertainty is too high to consider the change (mean value) as significant.

4) Consequence of the last three points: The hypotheses, as stated (except hypothesis 1), cannot be verified.

We agree with this remark. We thereby reformulate the second and third hypothesis, according to the new methodology, the new results and reviewers' concerns.

They are:

1. Orthophotos are affected by a local significant SV-error;
2. SV-error highly affects variability of MC simulated measurements of eroded and/or deposited surfaces;
3. Uncertainty of surficial changes depends on their magnitude

NB1: In the following author's answers, unless it is clearly specified, page and line numbers refer to the first version of the manuscript.
NB2: In the following author's answers, the terms "Supplement" and "Appendix" refers to (i) material attached to the author's answers and (ii) material attached to the revised-manuscript, respectively.
NB3: According to reviewer#1 comment and to avoid too many figures in this short communication, the Figure 3 of the first version of the manuscript has been removed. Instead, Figure 2 has been completed.

Referee 1

General comments: This paper addresses an important topic in fluvial geomorphology, analyzing channel change from time series of remotely sensed data, and offers a new perspective on evaluating the uncertainty inherent to this approach. Recent studies have shown that image co-registration errors are spatially variable and this paper takes an additional step by performing Monte Carlo simulations to assess the significance of observed changes in channel planform. While the idea has merit, I have some serious reservations about the way the approach is implemented in this study.

We thank the reviewer for appreciating the originality of our study. We think that his/her reservations about the methodology are relevant and we address them in the replies below.

1) The authors produce a continuous spatially variable error surface but then aggregate the error over a reach-scale by spatial averaging, which is an unnecessary loss of information.

We agree with this remark. Whilst we initially thought that error aggregation was necessary to avoid channel distortion, we managed to find a technically possible and geomorphologically valid way to assign a specific error to each node. Details of our new methodological approach is illustrated in supplement A, the latter being incorporated as a supplementary figure in the revised manuscript (either in the main text or as supplementary material). The part 3.4.1 in the initial manuscript has been rewritten accordingly. It is attached as Supplement B.

We think this allows a precise understanding of our methodology, as we are fully aware that it is imperative in this kind of study.

2) The manner in which nodes of digitized bank lines (are moved?) is not explained well and might be conceptually flawed.

We agree with this remark : see Supplement A providing the details of our new methodological approach (and see our reply above). Our “old” methodology consisted in geometrically translating nodes with a unique value for each nodes. This has been changed by using node-specific errors.

3) The surface of detection introduced by the authors should be used as a threshold, not subtracted from the observed changes.

We agree with reviewer 1. We believe that comparing our SoD to Lea and Legleiter’s (2016) LoD indeed was a mistake, as the SoD is technically not comparable to the LoD. We therefore propose to leave the term SoD as it might be confusing for readers.

Instead, we now use in the revised manuscript the relative percentage of uncertainty associated with the variability of the measured changes through the MC runs. Because it is derived from the confidence interval, which is a simple and well-known indicator of variability, we think it will simplify the interpretation and comparison of our results.
The percentage of (total) uncertainty is calculated as following: 0.5x(max-min)x100/mean
Then, the (conservative) significance threshold becomes: percentage of uncertainty > 50%. Indeed, if the percentage of uncertainty exceeds 50%, the mean value is then necessarily lower than the total range of measured value (max-min), which leads to the

assumption that the uncertainty is too high to consider the change (mean value) as significant.
Part 3.4.3 of the revised manuscript has been rewritten accordingly.

Those are the key issues, but please refer to the attached PDF for more detailed comments and text edits. While I think this manuscript has potential, the authors must address the concerns listed above, as well as the various minor edits, before the paper can be published.

We thank the reviewer 1 for highlighting the potential of our manuscript. We believe his concerns have greatly improved the revised manuscript.

Specific comments:

Title: I recommend modifying the title to emphasize that you are accounting for spatially variable error

The title now is : *Short communication: Measuring river planform changes from remotely-sensed data: A Monte-Carlo approach to assess the impact of spatially-variable error*.

Title: I think surficial is a more commonly used term than surfacic, which I have never seen before, so please replace this with surficial throughout.

We modified this term as suggested.

Page 1 Line 1: The more common phrase is remotely sensed data, so please replace throughout.

We replaced it throughout.

Page 1 Line 8: You need to be clear what you mean by this: is it an area where erosion occurred, followed by deposition?

We mean an area where erosion first occurred followed by deposition, as illustrated on Figure 1. We specified it in the revised manuscript as following: "(i.e. *quantification of eroded, deposited, or eroded then deposited surfaces)*" (Page 1 Line 8).
We also specified it in Figure 1 by modifying the legend as following: "*Erosion then deposition*".

Couldn't that lead to no net change and thus not be detectable even if the images were perfect?

It could actually lead to "no net change" only if the channel left its original position and then recovered its original position. This would indeed be undetectable with photos collected before and after the migration. However, according to the evolution of the active channel between both orthophotos, we believe this situation did not happen.

Page 1 Line 18: What is the distinction between these two?

Contrary to exclusively co-registered aerial photos, orthophotos have undergone an orthorectification process. We propose to modify the sentence as following: "*Taking the SV-error into account is strongly recommended even on orthorectified aerial photos, especially in the case of mid-sized rivers* ..." (Page 1 Line 18).

Page 2 Line 4: Missing page numbers in Cadol reference

Page numbers have been added.

Page 2 Line 5: Only use author's last name: Lauer, not Wesley Lauer - please change throughout

This has been changed throughout.

Page 2 Line 18: Replace this with co-registered throughout

This has been replaced throughout.

Page 2 Line 27: Include a URL for this reference.

URL has been added.

Page 3 Line 28: What were the discharges for these two time periods? If the flow was much different, that could lead to a false impression of erosion or deposition.

Unfortunately, the river wasn't gauged before 1965. Nevertheless, as we strictly delineated the channels by referring to the active channel concept, we believe that confusion was not possible. Moreover, according to the observation of both orthophotos, the Bruche river wasn't at bankfull stage at these dates.

We added the following sentence: *"Despite the lack of hydrological data in the lower Bruche before 1965, we assume surveys were conducted during moderate-low water, according to the period of the year during which the photos were taken (09/13/50; 04/17/64) and the observation of the orthophotos. Active channel is a widely used concept to objectively identify channel boundaries on aerial photographs, regardless of the river discharge."* (Page 3 Line 28)

Page 4 Line 7: This figure should use one of the photos, probably the 2015 image used as a base, not the lidar hillshade. The lidar is not even used in this study and seeing the photo used to define the control points would be much more informative.

We agree. To avoid too many figures in this short communication, we thus added the set of GCPs on Figure 2, which already uses the 2015 orthophoto.

Page 4 Line 18: What is "it"? Please clarify by writing out what it is.

We clarified this sentence. It has been changed to: "*Because of the difficulties of selecting a high number of independent control points spatially uniform over time in ancient remotely-sensed data, we argue that IDW is a reliable method to interpolate the registration error in our case.*" (Page 4 Line 18)

Page 4 Line 25: This seems like a big step backward to me, as you're taking a spatially variable error but then averaging it over a large area (the entire reach length) so you lose all of that spatial information. We agree.
Why not just use the actual SV error values at each location rather than aggregating over the reach?

We followed this advice to produce the new results in the revised manuscript (see our first remarks above).

Page 4 Line 26: Exactly, but your whole point is to NOT assume or use a uniform error metric. The way you've approached this, your just making the area assumed to be uniform a bit smaller (i.e., the reach rather than the whole image).

We agree. Our new methodology now takes into account the real SV-error (node specific). See supplement A and B.

Page 4 Line 27: Perhaps to some degree, but the error surfaces you produce by IDW will have a different value at every pixel, not just one value for each of the four reaches. If you're going to emphasize SV error you need to actually use SV error.

We agree. See comment above.

Page 5 Line 9: You could use this pooled-over-the-reach standard deviation to parameterize a unique normal distribution for each pixel, with the mean being the local SV error for that pixel, not just the reach-averaged error.

We thank the reviewer 1 for this suggestion. To produce the new results, we calibrated a Gaussian distribution from the neighborhood (5m buffer) of each node (see Supplement A and B).

Page 5 Line 13: But couldn't that digitization be based on images that were not co-registered accurately? I'm not sure I agree that the digitization should not be altered, so please elaborate on your reasoning for this approach.

We agree with your first point. Indeed, the digitization could have been produced from images that were poorly registered. Then, nodes of the digitized objects could suffer from a strong error in their position but their general shape would not be altered dramatically. Let's imagine that 10 different producers co-registrates the same aerial photo and digitize the same channel. Probably, it will appear a variability in the position of the nodes placed by each user. However, if a similar rule base has been correctly respected by every user, the global shape cannot be changed drastically.

Page 5 Line 13: Please include a figure that illustrates how the digitized bank nodes are shifted, as this is a key part of your method that is not well-described verbally but would be easier to understand with a graphic.

We thank the reviewer 1 for this suggestion. A “methodological figure” has been added as Appendix B to the revised manuscript (Supplement A).

Page 5 Line 15: This is an important point that needs to be described more explicitly and thoroughly.

Because we reshaped our methodology according to both reviews, the part 3.4.1 “Channel boundaries simulation method” has been rewritten in the revised manuscript. It is attached as the Supplement B.

Page 5 Line 17: Wouldn't this only work if the river moves straight north, south, east, or west, but not if it's movement is not in a cardinal direction? In other words, what about cases where x is positive and y is negative or vice versa. Overall, your method of shifting the digitized bank nodes seems oversimplified in some ways and could be refined.

Thanks for your observation. We first imagined that we could move each node of the polygon in a positive or negative X direction as well as a positive or negative Y direction as you said. In the present study, since the distance between two nodes is always higher than the error (its standard deviation) assigned to each node, the operation is feasible and does not alter the shape of the polygons. However, when the distance between nodes is lower than the error assigned to each node (in historical maps for instance, see Herrault et al., 2013), the operation can potentially lead to strong geometrical errors (cf “Butterfly polygon issue” in Supplement A). These errors could be corrected (moving average algorithms, Douglas Peucker, etc..) but the shape of polygons could thus be wrongly modified.

Therefore, we proposed an alternative solution to move nodes in space : (1) nodes from one sub-reach can move in any Y directions (positive or negative) at each run; (2) nodes from one sub-reach can only move in one X direction at each run. That latter rule allows to avoid topological errors while simulating the most probable displacements of polygon channels. See Supplement A for illustration. We also believe this choice is preferable to allow transferability of our method to other fluvial contexts.

We describe this strategy in the revised manuscript as following: “*In this study, as the distance between nodes is significantly higher than the local registration error, it is possible to move nodes of each sub-reach in any x and y directions without significantly impacting the shape. However, when this condition above is violated (in historical maps for instance, see Herrault et al. (2013)), the operation can potentially lead to strong geometrical errors such as “butterfly polygon” or excessive geometric distortions (Appendix A). These errors might be partially corrected (via e.g. the moving average algorithm or Douglas Peucker filtering) but can result in erroneous modifications of the original channel shape. Thus, we proposed an hybrid solution to simulate the node shifting in space : (1) nodes from one sub-reach can move in any y directions (i.e. positive or negative) at each run; (2) nodes from one sub-reach can move in only one x direction at each run. This last operation allows (i) avoiding topological errors while simulating the most probable displacements of channel polygons, and (ii) probably enhancing the transferability of our method to other fluvial settings. The direction of errors in x and y were randomly selected at each MC simulation with equal probability weights (i.e. 50 % each).*” (Page 5 Line 11)

Page 6 Line 9: Subtracting the SOD is not correct. You need to use the SOD as a threshold for assessing whether the measured value is significant. If the measured value exceeds the SOD at a given location, then the change is significant, but if the measured value is less than the SOD, the change is not significant. In either case, the SOD is used to establish the threshold, not subtract from the measured value.

We fully agree with your explanation and we erroneously interpreted this in the first version. We thus propose to calculate the relative percentage of uncertainty as regard to the reported mean value of change, .i.e erosion, deposition or erosion/deposition.
The percentage of (total) uncertainty is calculated as following: 0.5x(max-min)x100/mean
If the reported mean value exceeds the uncertainty threshold equal to 50%, then the change is considered as insignificant. Indeed, if the percentage of uncertainty exceeds 50%, the mean value is then necessarily lower than the total range of measured value (max-min), which leads to the assumption that the uncertainty is too high to consider the change (mean value) as significant.
Part 3.4.3 of the revised manuscript has been rewritten accordingly.

Page 6 Line 12: OK, but you're losing a lot of SV information by aggregating over the entire sub-reach like this.

We agree on this and changed our methodology. See Supplement A and B.

Page 6 Line 12: Please add panels showing the error in the x and y directions separately, as well as the total error you have now.

This is indeed a pertinent proposition. The figure has been reworked to display panels showing the error in x and y separately, as well as the total error. However, we only display the panels for 1950 in the main text; panels for 1964 have been added in supplementary material (Supplement C).

Page 7 Line 1: This is kind of getting at the threshold criteria you should be applying.

We agree. We now propose in the revised manuscript the following threshold: relative percentage of uncertainty > 50%. It corresponds to the following equation : 0.5x(max-min)x100/mean
Indeed, if the percentage of uncertainty exceeds 50%, the mean value is then necessarily lower than the total range of measured value (max-min), which leads to the assumption that the uncertainty is too high to consider the change (mean value) as significant.
Part 3.4.3 of the revised manuscript has been rewritten accordingly.

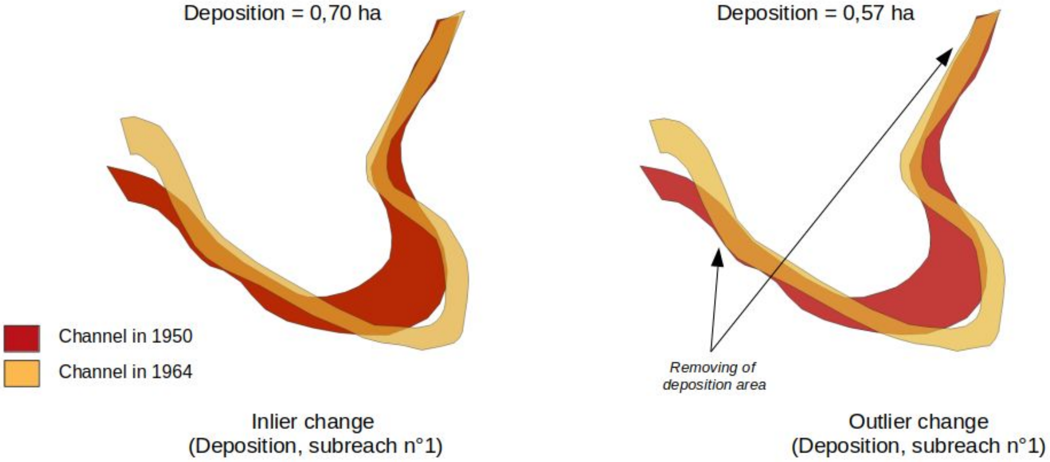
Page 7 Line 13: Do you have any ideas for filtering out or eliminating these outliers?

In our opinion, these outliers should be visually checked to see if they represent geomorphologically plausible situations. This is mentioned in the discussion of the revised manuscript. We also considered the 95% confidence interval in order to propose a less conservative uncertainty percentage. This is mentioned in the discussion of the revised manuscript, as following:

"*Whilst this contrast may call into question whether or not the presence of outliers should be taken into account, visual comparison of specific situations may help unravelling this issue.*" (Page 8 Line 32 of the revised manuscript)

"*Nevertheless, the few outliers (Fig. 5) should still be treated in an empirical manner by visually determining if they should be rejected or not.*" (Page 9 Line 24 of the revised manuscript)

Finally, we propose to add a figure (Fig. 7 in the revised manuscript) which shows how an outlier can look to feed the discussion (see below).



Inlier change
(Deposition, subreach n°1)

Outlier change
(Deposition, subreach n°1)

Page 7 Line 20: Please clarify what you mean by assess

We were suggesting "to assess changes significance". But we agree the sentence was confusing and has been changed to "*This emphasises the need to take the SV-error into account and, importantly, to assess its impact on the uncertainty of the measured changes*." (Page 7 Line 20)

Page 8 Line 16: Your approach would be greatly improved by leaving out this reach-averaging step and using the actual SV error at each location along the bank.

This is done in the revised manuscript. See comments above.

Technical corrections:

Please note that every technical and grammatical corrections have been taken into account in the revised manuscript.

Altogether, we thank the reviewer#1 for his/her in-depth reviewing. Detailed corrections and the integration of his/her thoughtful remarks into the revised version of the manuscript will enhance its quality.

Referee 2

This manuscript outlines a new method to quantify errors in measurements of channel change calculated from repeat aerial image overlays. The method is a valuable contribution in that uncertainty in measurements of channel change are estimated from polygons of erosion and deposition; this makes the method generalizable to multiple river types (e.g., braided). However, the methodology fails to retain the spatial variability of geometric error, which previous studies have demonstrated to be an important source of uncertainty. The proposed methodology uses a spatially variable error to calculate geometric error statistics (e.g., mean and standard deviation) and generate a distribution of geometric errors that are randomly sampled and applied uniformly over each sub-reach. Thus, the proposed methodology assesses how the variability of geometric error influences measurements of channel change, and this differs from the stated aim of the manuscript: to create a generalizable spatially varying error assessment method. While I appreciate that the authors developed a method that can be applied to polygons of erosion and deposition and I believe the use of a Monte Carlo approach as merit, I have significant concerns with the proposed methodology.

We thank the reviewer for appreciating the originality of our study. We think that his/her reservations about our methodology are very relevant. We address them in the comments below.

Technical comments:

Page 2 Line 9: Image co-registration does not affect measurements of channel width because the images do not have to be overlaid to calculate the width.

We agree. This sentence was meant to summarise different kinds of metrics generally extracted from planimetric studies. However, as it might have been confusing for readers, we thus replaced the sentence by: "*Requiring data coregistration and river bank digitisation, these planimetric studies often result in the quantification of lateral migration rates (Hooke and Yorke, 2010; Janes et al., 2017; Mandarino et al., 2019; O'Connor et al., 2003).*" (Page 2 Line 9)

Page 2 Line 30: Why are medium-sized rivers more prone to digitization and coregistration error? I would think that small-sized rivers might be more prone to these issues because the digitization and co-registration error potentially accounts for a larger portion of the active channel.

We agree on the fact that the smaller rivers are, the more prone they are to be affected by spatial errors in planimetric analysis. According to the European Water Framework Directive, the Bruche river however falls into the medium-sized category (catchment >100 to 1000km²). Smaller rivers (streams) are generally too small to be studied with planimetric analysis with the channel polygon method. We added the reference to the Water Framework Directive classification. (Page 2 Line 31)

Page 3 Line 2: You need a sentence defining the channel polygon method.

We added a sentence defining the channel polygon method: "*The latter consists in the extraction of eroded, deposited and eroded then deposited surfaces, from overlaid diachronic channels*." (Page 3 Line 2)

Page 3 Line 7-10: Using the methodology proposed in this manuscript, I believe that you can only test hypothesis 1. This is because the spatial errors are aggregated to estimate a population of uniform errors which are sampled in the Monte Carlo framework. What you are actually testing is how the variability of error affects polygons of erosion and deposition (i.e., the effect of changing the mean and standard deviation of the populations of errors in a reach).

We agree and we reworked our methodology in the revised manuscript accordingly. Details of our new methodological approach is illustrated in supplement A, the latter being incorporated as a supplementary figure in the revised manuscript (either in the main text or as supplementary material). The part 3.4.1 in the current manuscript has been rewritten accordingly. It is attached as Supplement B.

Hypotheses 2 and 3 have also been redesigned:

1. Orthophotos are affected by a local significant SV-error;
2. SV-error highly affects variability of MC simulated measurements of eroded and/or deposited surfaces;
3. Uncertainty of surficial changes depends on their magnitude

Page 3 Line 8: “the higher the SV-error is, the less significant the measured changes are.” More description is needed for the word “higher”. Do you mean the larger the mean of the SV-error, the larger the standard deviation of the SV-error, or a combination of both?

We actually meant “the higher the LSE (Figure 5 in the first version of the manuscript), the less significant the measured changes are”.
The LSE was however removed as it consisted in uniformizing the error over the sub-reaches. We now use a node-specific error, extracted from a normal distribution in the local node neighborhood (5m buffer). See our new formulated hypotheses above as well as supplement A and B for the new methodological approach.

Page 3 Line 29: What was the discharge on the day each image was collected?

Unfortunately the river wasn’t gauged before 1965. Nevertheless, as we strictly delineated the channels by referring to the active channel concept, we believe that differences in discharge do not have any impact on our methodology. Moreover, according to the observation of both orthophotos, the Bruche river wasn't at bankfull stage at these dates.

We added the following sentence: *“Despite the lack of hydrological data in the lower Bruche before 1965, we assume surveys were conducted during moderate-low water, according to the period of the year during which the photos were taken (09/13/50; 04/17/64) and the observation of the orthophotos. Active channel is a widely used concept to objectively identify channel boundaries on aerial photographs, regardless of the river discharge.”* (Page 3 Line 28)

Page 4 Line 10: Note that the RMSE of a single GCP is the Euclidean distance between the two points. See equation 1 verses 2 in Lea and Legleiter (2016).

Thank you for this precision. We propose to supplement the sentence by some precisions as following: "*Local Root Square Error (RSE) is then measured for each of the 18 GCPs, on both orthophotos. Error in x or y corresponds to the euclidean distance between the two points for x and y coordinates, respectively. SV-error is calculated by interpolating local RSE on our whole study area with an Inverse Distance Weighting (IDW) technique at the original spatial resolution (Fig. 3).*" (Page 4 Line 10)

Page 4 Line 14: The sentence starting with "First, Lea and Legleiter (2016) showed" is incorrect. Lea and Legleiter (2016) simply stated that linear and nearest neighbor reduced the spatial extent of large co-registration errors. The authors did not evaluate which interpolation method should be used.

We thank the reviewer for this comment. We modified our sentence by : "*First, based on a comparison of five interpolation methods, Lea and Legleiter (2016) showed that linear and nearest neighbour methods reduce the areal extent of large co-registration errors. These methods are thus discarded as they can strongly limit the influence of large co-registrations errors on the estimations of surficial changes. Then, in a comparative study of spatial interpolation methods to produce a Digital Elevation Model from a small set of points that were not spatially uniform, Tan and Xu (2014) showed that IDW provided better results than Spline or Kriging. Because of the difficulties of selecting a high number of independent control points spatially uniform over time in ancient remotely-sensed data, we argue that IDW is a reliable method to interpolate the registration error in our case.*" (Page 4 Line 14)

Page 4 Line 21: What is the length of each sub-reach?

Length of each sub-reach are added in the revised-manuscript, as following: "*Their mean talweg lengths amount to 530, 380, 700 and 890 meters long (upstream-downstream order).*" (Page 4 Line 21)

Page 4 Line 25: The method to determine the LSE needs to be more clearly stated. Is the LSE calculated using the SV-errors extracted from each channel boundary vertex or all SV-errors within the sub-reach?

LSE is not used anymore in our revised methodology, which now takes into account node specific error. Please see Supplement A and B for more details.

Page 5 Lines 4-6: These sentences seem to contradict one another. In one sentence the authors state that MC simulations are useful because the method assumes "spatial continuity and a relatively spatial homogeneity of the error", while in the second sentence the authors note that the method can improve the "generalization of methods for calculating planform changes and spatially variable uncertainty. . .". This is a major problem with the proposed method. Lea and Legleiter (2016) and Donovan et al. (2019) demonstrated the importance of using a spatially varying co-registration error to estimate uncertainty at individual points; however, the authors use the SV error to estimate the mean and standard deviation of the co-registration error population in each sub-reach.

Thanks for your comment, we agree it was contradictory in the first version since uniform mean and standard deviation were assigned to all nodes of one sub-reach. In the revised manuscript, we have calibrated one normal distribution for each node from the local neighborhood. Thus, we consider that the mentioned sentences can be held in the old form. A relative spatial homogeneity of error is assumed in the local neighbourhood of each node and we argue that our proposal can improve the "*generalization of methods for calculating planform changes and spatially variable uncertainty*. " (Page 5 Line 4)

Page 5 Line 8: Have you tested whether the distribution of raw LSE values is normal? Would another distribution better model these values?

LSE is not used anymore in our revised methodology. We thus tested the normal distribution of SV-error in a 5m buffer around 10 channel nodes randomly selected along the 1950 and the 1964 channels, with the Shapiro test. Please check Supplement D for details (histograms and test results).
The shapiro test is now mentioned in the revised manuscript as following: "*A check of the local distributions of error (Shapiro test) showed a normal distribution for a vast majority of them.*" (Page 5 Line 14 of the revised manuscript)

Page 5 Line 30: Note that the metric "erosion/deposition", as shown in Figure 1, does not always required erosion and deposition (e.g., channel avulsion or meander cutoff).

Thanks for this thoughtful comment; this short complementary text in the revised manuscript now specifies it : "*Note that the metric "erosion then deposition" measured in the area located between the former channel (T1) and the new one (T2) does not always imply continuous lateral channel migration followed by deposition. Sudden lateral shifts of meanders (e.g. through meander cutoff) or meander belts (e.g. through channel avulsion) may be involved as well and require specific geomorphological attention.*" (Page 5 Line 30)

Page 6 Section 3.4.3: Virtual Surface of Detection (SoD) is not an appropriate description and this is NOT equivalent to the LoD in Lea and Legleiter (2016). In my opinion, the SoD cannot be used to distinguish significant from non-significant changes. The SoD is simply a statistical description of the MC results. Because the authors adjust the channel delineations by the registration and digitization error for each MC iteration (equations 1 and 2), the individual iterations already take into account uncertainty and therefore should be significant. The SoD simply shows the variability of channel changes based on the distributions of error in the x and y directions for each image.

We believe that comparing our SoD to Lea and Legleiter's (2016) LoD was a mistake. As the SoD is technically not comparable to the LoD, we agree with reviewer 2. We therefore left the term SoD, as it might be confusing for readers. For these reasons, we chose instead to focus on the relative percentage of uncertainty associated with the variability of the measured changes through the MC runs in the revised manuscript. Because it is a simple and well-known indicator of variability, we believe it might simplify the interpretation and comparison of our results. The percentage of (total) uncertainty is calculated as following: 0.5x(max-min)x100/mean
Then, the (conservative) significance threshold becomes: percentage of uncertainty > 50%. Indeed, if the percentage of uncertainty exceeds 50%, the mean value is then necessarily lower than the total range of measured value (max-min), which leads to the

assumption that the uncertainty is too high to consider the change (mean value) as significant.
Part 3.4.3 of the revised manuscript has been rewritten accordingly.

Page 6 Line 24 to page 7 Line 2: It is not appropriate to directly compare results from each sub-reach without a normalization, such as by sub-reach length. The difference between sub-reaches could be caused by reaches being smaller or larger.

We agree. New results have been normalized by sub-reach length in Figure 7 (first version of the manuscript) which displays the mean surficial changes.

Page 7 section 4.3: The method cannot show the percentage of individual measurements of erosion or deposition retained because each MC iterations is treated as a single value, so sentences like: ": : :significant change globally increases from 17% using the raw-SoD to 37% using the 95-SoD" are incorrect.

We agree. Our methodology unfortunately does not allow dealing with a percentage of significance on surficial measurements. We therefore describe our new results using the relative percentage of uncertainty, which we believe to be a more appropriate indicator of the variability (and so uncertainty) of the results.
As our methodology and our results have changed, 4.2 and 4.3 have been re-written accordingly.

Page 7 Line 20: The authors state, "This emphasizes the need to take the SV-error into account: : :", yet their method does not include a SV-error.

We agree. Our new methodology now takes the real SV-error (node specific) into account. Please see supplements A and B for details.

Page 7 Line 25-31: The authors were not able to test their second hypothesis because the error ultimately did not vary spatially.

We agree, see our newly formulated hypotheses above.

In addition, the authors cannot identify the number of channel change measurements statistically retained and the results are not comparable to Lea and Legleiter (2016) or Donovan (2019).

We agree. Unfortunately, because (1) our surficial metric differs from the linear one used by Lea and Legleiter (2016) and Donovan et al. (2019) and (2) the way we deal with significance necessarily differs from the one proposed by Lea and Legleiter (2016), it is not possible to directly compare our results nor their significance to Lea and Legleiter's (2016) and Donovan et al.'s (2019) results.
As our results have changed since the first version of the manuscript, part 5 has been rewritten accordingly.

Page 8 Line 1-10: I do not believe that the authors successfully tested the third hypothesis because they did not directly include the SV-error nor was the significance of channel change measurements accurately determined.

We agree. Node specific SV-error is now actually included in our new methodology. Concerning the significance of channel change measurements, we now propose the relative percentage of uncertainty as a threshold. See comments above. See supplements A and B.

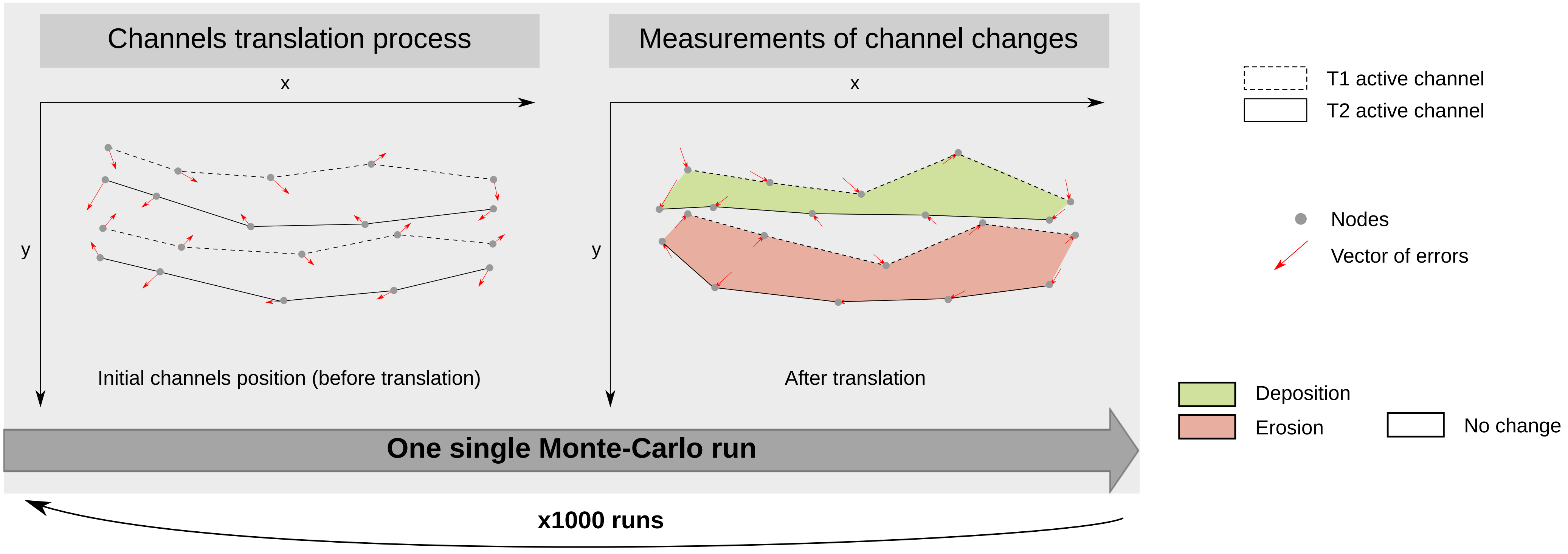
Page 9 Line 1: What is the appropriate sub-reach size and how sensitive are the results to the sub-reach size? How do you recommend users delineate sub-reaches for different channel types?

In our opinion, the suitable sub-reach size is dependent on the way the user intends to quantify planform changes. Our first thought was to focus on independent morphological units, such as meanders. We think it would be appropriate to decrease the sub-reach size when planform changes are more complex or channel pattern complexifies. On the contrary, a straight channel does not necessarily need to be divided into many sub-reaches. It would also be interesting to increase the size of the documented sub-reach, to check how sensitive the results would be. We propose to add the following sentence: “As for the size/length of the sub-reaches, we recommend adapting it according to the complexity of the planform changes and/or the channel pattern (e.g. anastomosing and anabranching channel patterns)” (Page 9 Line 2)

General editorial comment: The manuscript has numerous sentences that are awkwardly worded and could benefit from line-by-line edits to improve the readability. In addition, citations need to be checked (e.g., Wesley Lauer et al. (2017) should be Lauer et al. (2017)).

Proofreading of the revised manuscript was carried out and improved its formal quality. Citations have been checked too.

SUPPLEMENT A



Channels translation process

Measurements of channel changes

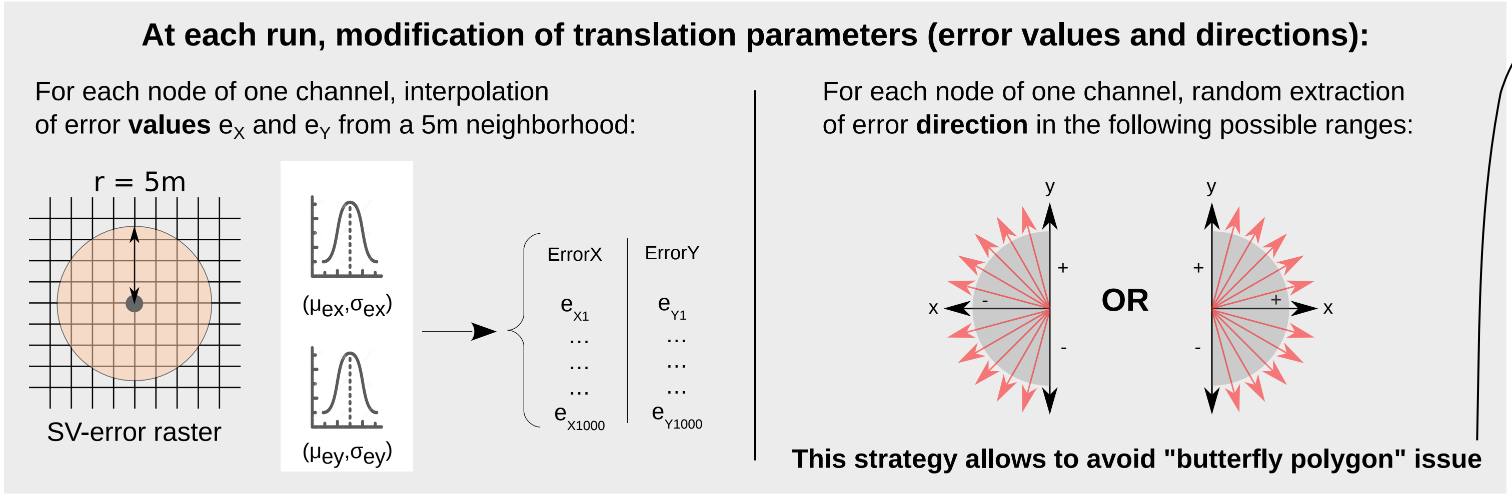
Initial channels position (before translation)

After translation

One single Monte-Carlo run

x1000 runs

At each run, modification of translation parameters (error values and directions):



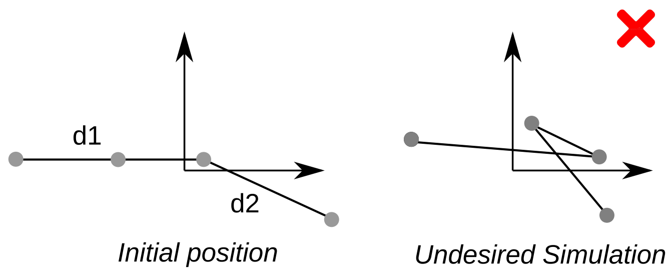
For each node of one channel, interpolation of error **values** e_X and e_Y from a 5m neighborhood:

For each node of one channel, random extraction of error **direction** in the following possible ranges:

This strategy allows to avoid "butterfly polygon" issue

"Butterfly polygon" issue

Conditions: If d < μ_{eX} or μ_{eY} with displacement in any positive/negative x and y directions for each node



SUPPLEMENT B

(Replaces part 3.4.1) Channel boundaries simulation method

MC simulations as statistical methods are generally used in cases where processes are random or when assumptions in the theoretical mathematics are badly known (Brown and Duh, 2004; Openshaw et al., 1991). Applying MC simulations in this research context is the main novelty of this study. This approach has two main advantages. Firstly, MC simulations are particularly well suited to our problem because of the difficulty of distinguishing between inherent and processing errors in the measured RMSE over the whole area. Secondly, MC simulations assume a spatial continuity and a relative spatial homogeneity of the error, which is consistent with resulting spatial patterns of errors observed after the coregistration or digitising process. MC simulations are also relatively easy to perform and applicable in very different cases. This approach could thus improve the generalisation of methods for calculating planform changes and spatially variable uncertainty in a fluvial context, as suggested by Donovan et al. (2019).

The approach used in this study followed the rules of boundary simulations (Burrough et al., 2015). A sketch illustrating this part of our methodology is available in Appendix B. As described in the previous section, SV-error has been interpolated over the whole study area. For each channel node, all pixels in a 5 m buffer were first selected. A check of the local distributions of error (Shapiro test) showed a normal distribution for a vast majority of them. The normal distribution of error was then calculated by averaging the mean local error and by calculating the standard deviation for each node, in each sub-reach. Hence, for each run (1000 runs in total), a specific value of error in x (e_x [i = 1, ..., 1000]) and y (e_y [i = 1, ..., 1000]) was randomly extracted from the respective normal distribution in order to shift each node from its original position.

Furthermore, in accordance with the results from Podobnikar (2008), the shape of a particular channel is assumed to remain coherent after simulation. In this study, as the distance between nodes is significantly higher than the local registration error, it is possible to move nodes of each sub-reach in any x and y directions without significantly impacting the shape. However, when this condition above is violated (in historical maps for instance, see Herrault et al. (2013)), the operation can potentially lead to strong geometrical errors such as “butterfly polygon” or excessive geometric distortions (Appendix A). These errors might be partially corrected (via e.g. the moving average algorithm or Douglas Peucker filtering) but can result in erroneous modifications of the original channel shape. Thus, we proposed an hybrid solution to simulate the node shifting in space: (1) nodes from one sub-reach can move in any y directions (i.e. positive or negative) at each run; (2) nodes from one sub-reach can move in only one x direction at each run. This last operation allows (i) avoiding topological errors while simulating the most probable displacements of channel polygons, and (ii) probably enhancing the transferability of our method to other fluvial settings. The direction of errors in x and y were randomly selected at each MC simulation with equal probability weights (i.e. 50 % each).

Last, as mentioned by Donovan et al. (2019), it is quite hard to distinguish between errors inherent to the coregistrating and digitising processes. For this reason, a digitising error (e_d) equal to 1 pixel was added as a reasonable constraint within the simulation process, considering the resolution of the orthophotos. This digitising error is assumed to be uniform over the entire area and does not fluctuate in different simulation runs (equations 1 and 2). Only the direction in x and y was randomly defined for each node of one sub-reach at each MC simulation. These directions may vary from one node to another for one given sub-reach.

The overall mathematical expression of the simulation process can be expressed as follows:

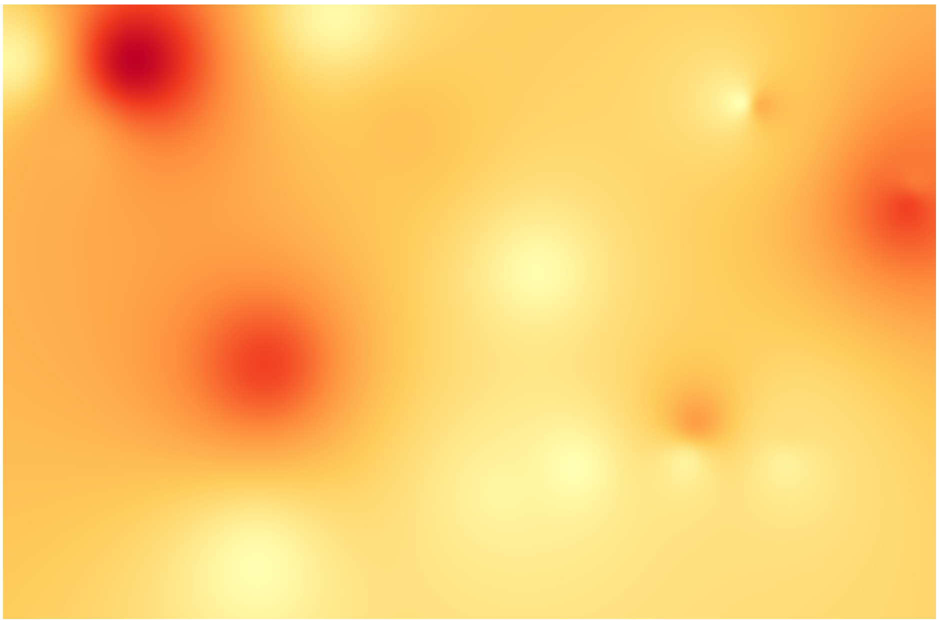
$x_{changed} = x_{original} + (|e_x| \times [-1;1]) + (|e_d| \times [-1;1])$

$y_{changed} = y_{original} + (|e_y| \times [-1;1]) + (|e_d| \times [-1;1])$

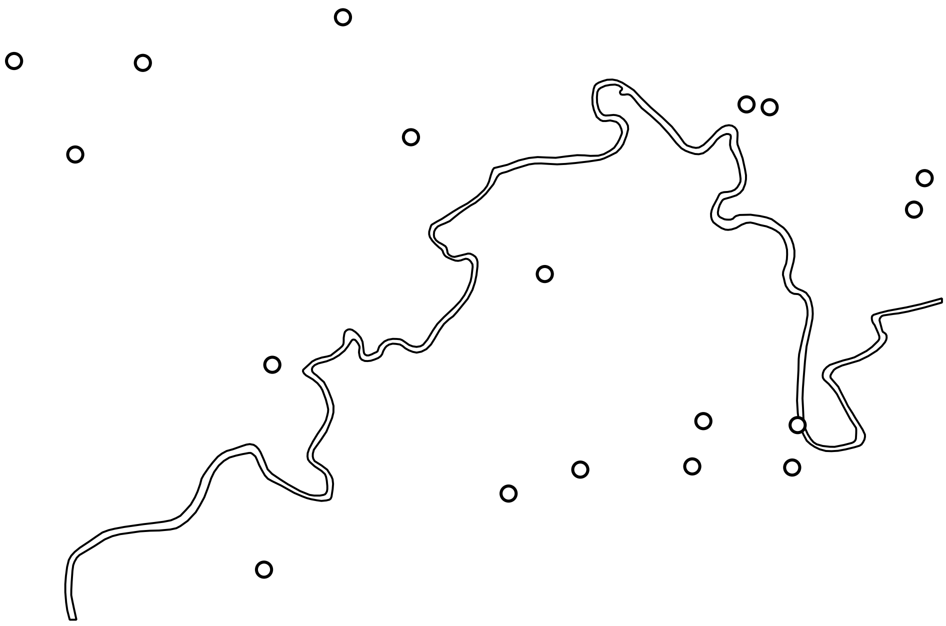
SUPPLEMENT C

SV-error in X (1964)

SV-error in Y (1964)



Total error (1964)



TotalError (m)

🟨 0.679502487182617

🟨 0.905932694673538

🟧 1.13236290216446

🟥 1.35879310965538

🟥 1.5852233171463

SUPPLEMENT D

Hereafter, we show statistical results verifying the normal distribution of errors in X and Y around nodes for 1950 and 1964. In tables, significant p-value mean that null hypothesis (H0 : the population is normally distributed) can be rejected. All histograms are also shown in Figure 3.

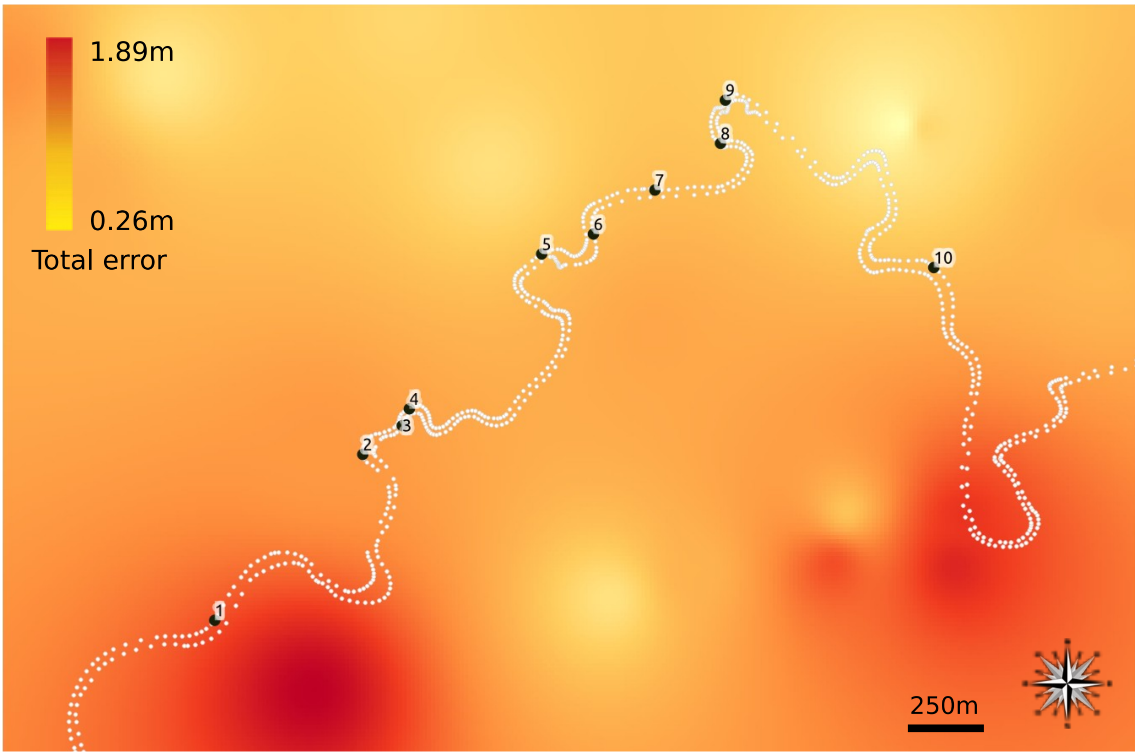


Figure 1 : 10 channel nodes randomly selected for the verification of the normal distribution of local errors in a 5m circular buffer zone in 1950.

Table 1 : Results of Shapiro-tests calculated from the local Error X distribution around nodes in 1950

Node	Shapiro test	p-value
Num 1	0,9734	0,1059
Num 2	0,9695	0,0668
Num 3	0,9600	0,0162
Num 4	0,9729	0,0992
Num 5	0,9751	0,1303
Num 6	0,9692	0,0584
Num 7	0,9713	0,0688
Num 8	0,9720	0,0875
Num 9	0,9730	0,0966
Num 10	0,9740	0,1154

Table 2 : Results Shapiro-tests calculated from the local Error Y distribution around nodes in 1950

Node	Shapiro test	p-value
Num 1	0,9761	0,1560
Num 2	0,9710	0,0825
Num 3	0,9718	0,0849
Num 4	0,9747	0,1282
Num 5	0,9657	0,0336
Num 6	0,9692	0,0587
Num 7	0,9723	0,0800
Num 8	0,9696	0,0621
Num 9	0,9751	0,1296
Num 10	0,9762	0,1567

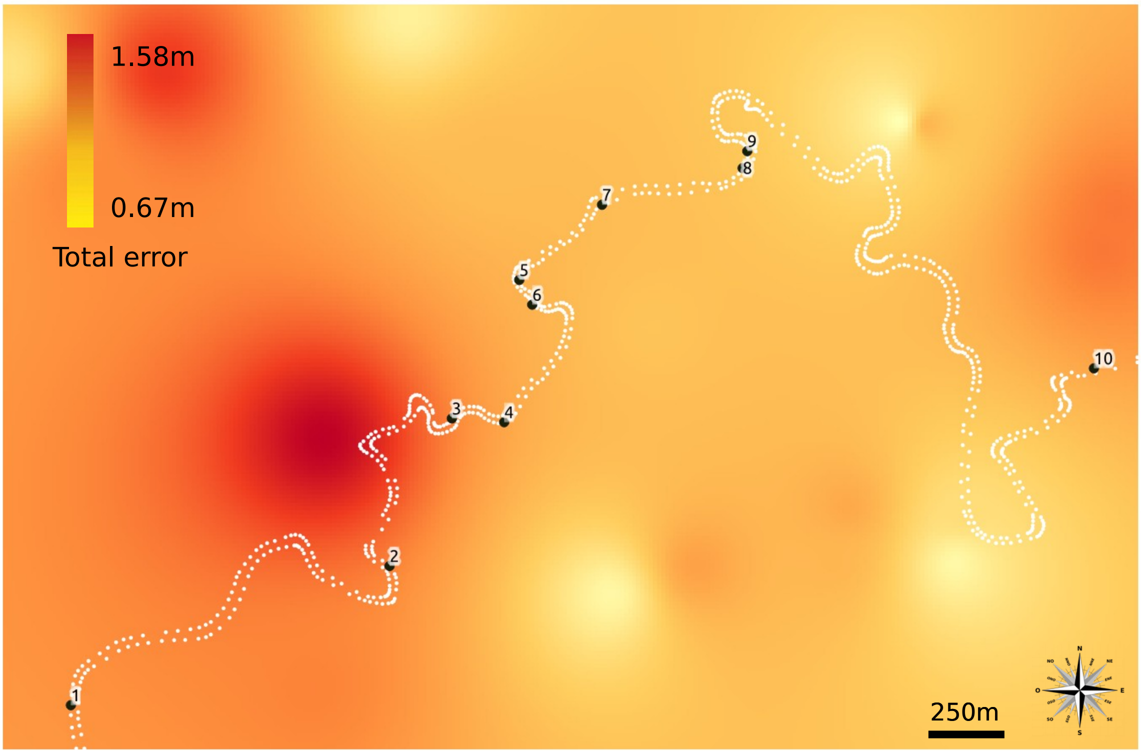


Figure 2 : 10 channel nodes randomly selected for the verification of the normal distribution of local errors in a 5m circular buffer zone in 1964

Table 3 : Results of Shapiro-tests calculated from the local Error X distribution around nodes in 1964

Node	Shapiro test	p-value
Num 1	0,9643	0,0275
Num 2	0,9764	0,1803
Num 3	0,9748	0,1199
Num 4	0,9742	0,1294
Num 5	0,9752	0,1372
Num 6	0,9721	0,0847
Num 7	0,9736	0,1048
Num 8	0,9763	0,1667
Num 9	0,9738	0,1080
Num 10	0,9760	0,1540

Table 4 : Results of Shapiro-tests calculated from the local Error Y distribution around nodes in 1964

Node	Shapiro test	p-value
Num 1	0,9709	0,0712
Num 2	0,9661	0,0442
Num 3	0,9757	0,1363
Num 4	0,9726	0,1033
Num 5	0,9743	0,1203
Num 6	0,9641	0,0271
Num 7	0,9735	0,1035
Num 8	0,9744	0,1270
Num 9	0,9712	0,0747
Num 10	0,9756	0,1439

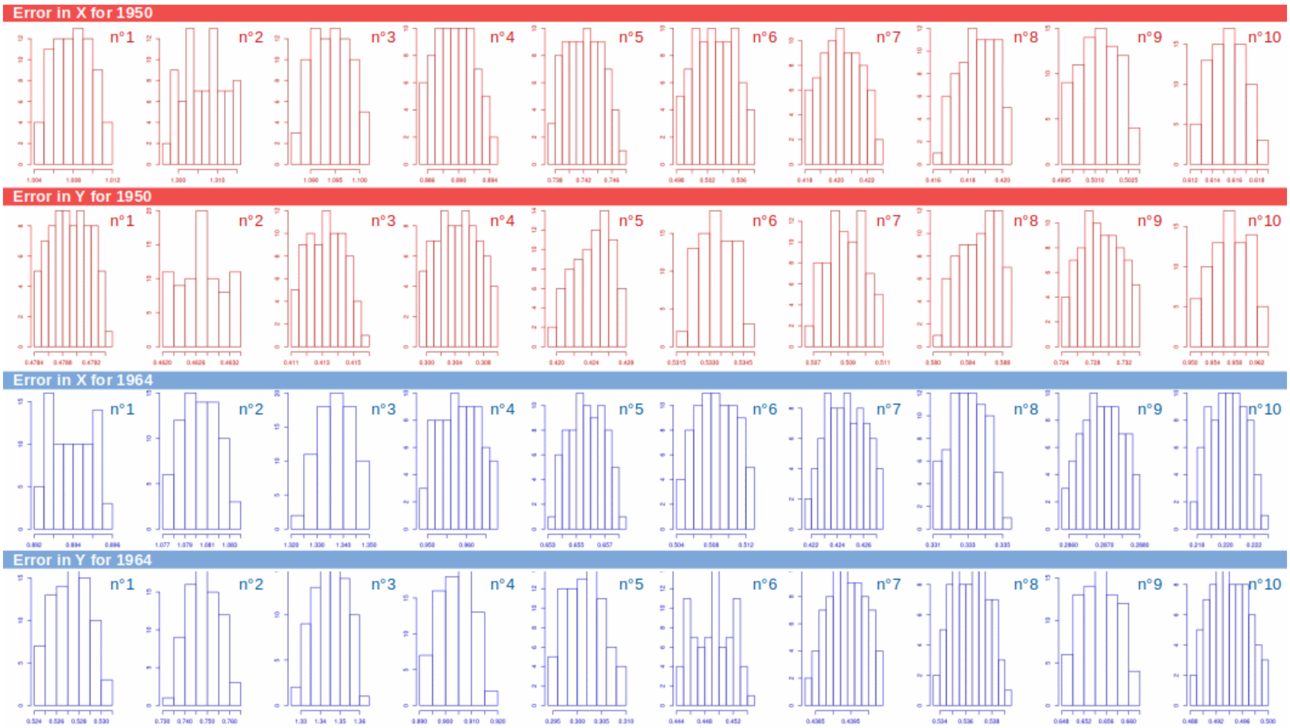


Figure 3 : Histogram distribution of local error in X and Y for 10 channel nodes randomly selected in 1950 and 1964 (see Figure 1 and 2 for visualizing the location of nodes).

Short communication: ~~Significance assessment of historical surfacic~~ Measuring river planform changes ~~of mid-sized rivers~~from remotely-sensed data: A Monte-Carlo ~~based~~ approach to assess the impact of spatially-variable error.

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[1]Laboratoire Image, Ville, Environnement (LIVE UMR 7362), Université de Strasbourg, CNRS, ENGEES, ZAEU LTER, 3 rue de l'Argonne, 67083 Strasbourg, France
[2]Laboratoire Image, Ville, Environnement (LIVE UMR 7362), ENGEES, CNRS, Université de Strasbourg, 1 quai Koch, 67070 Strasbourg, France
Correspondence: Timothée Jautzy (timothee.jautzy2@etu.unistra.fr)

Abstract.

~~Remote-sensed data in the fluvial context~~ Remotely-sensed data from fluvial systems are extensively used to document historical planform changes. However, geometric and delineation errors inherently associated with these data can result in poor or even misleading interpretation of measured changes, especially ~~(rates of)~~ rates of channel lateral migration. It is thus ~~fundamental to take~~ imperative to take into account a spatially-variable (SV) error affecting ~~remote-sensed datainto account~~the remotely-sensed data. In the wake of recent key studies using this SV-error as a level of detection, we introduce a new framework to evaluate the significance of measured channel migration. Going beyond ~~their linear metric~~ linear metrics (i.e. migration vectors between diachronic river centrelines), we assess this significance through the channel polygon method yielding a ~~surfacic~~ surficial metric (i.e. quantification of eroded, deposited, or eroded ~~/~~then deposited surfaces).

Our study area is an active wandering mid-sized river: the lower Bruche, a $\sim$20 m wide ~~sub-tributary~~ tributary of the Rhine in eastern France. Within our four test sub-reaches, the active channel is digitised using diachronic orthophotos (1950; 1964) and the ~~sub-reach specific~~ SV-error affecting the data is interpolated with an Inverse Distance Weighting (IDW) technique. ~~A main~~ The novelty of our approach ~~consists then in~~ arises from then running Monte-Carlo (MC) simulations to randomly translate active channels and propagate geometric and delineation errors according to the SV-error. This eventually leads to the ~~production of a Surface of Detection (SoD)~~computation of percentage of uncertainties associated with each of the measured planform changes, which allows ~~evaluating~~ to evaluate the significance of ~~measured surfacic changes. Putting the SoD into practice in~~ the planform changes. In the lower Bruche~~shows that only 37% of the total surfacic measured changes are significant. Our results suggest~~ , the uncertainty associated with the documented changes ranges from 15.8 to 52.9 %.

Our results show that (i) orthophotos are affected by a significant SV-error, (ii) the latter strongly affects the ~~significance~~ uncertainty of measured changes and (iii) the significance ~~is strongly dependent on the magnitude of surfacic~~ of changes is dependent on both the magnitude and the shapes of the surficial changes. Taking the SV-error into account is strongly recommended ~~, regardless of the remote-sensed data used (orthophotos or aerial photos)~~even on orthorectified aerial photos,

especially in the case of mid-sized rivers (<30 m width) and/or low amplitude river planform changes (<~~1000~~ 1 m^2/m/yr). ~~We finally insist on the transposability of our approach~~ In addition to allow detecting low-magnitude planform changes, our approach also is transferable as we use well-established tools (IDW, MC): this opens new perspectives in the fluvial context (e.g. multi-thread river channels) for robustly assessing ~~surfacic~~ surficial channel changes.

Copyright statement. TEXT

1 Introduction

In ~~the~~ a fluvial context, ~~remote-sensed data opportunely provides~~ remotely-sensed data provide spatial information on historical lateral dynamics of river channels ~~(Bollati et al., 2014; Cadol et al., 2010; Comiti et al., 2011; Gurnell et al., 1994; Hajdukiewicz and Wyż~~ This is of crucial importance for ~~e.g.~~ creating a scientific framework ~~transposable~~ applicable to sustainable management of hydrosystems, including river restoration (Biron et al., 2014; Piégay et al., 2005; Surian et al., 2009). Aerial photographs are thus commonly used to document and measure planform channel changes over a time period of at the most the last century ~~,~~ in a wide variety of fluvial settings. Requiring data coregistration and river bank digitisation, these planimetric studies ~~generally~~ often result in the ~~extraction of morphological metrics such as channel width (Gilvear, 2004; Werbylo et al., 2017; Winterbottom, 2000) or lateral migration (Hooke and Yorke, 2010; Janes et al., 2017; Mandarino et al., 2019; O'Connor et al., 2003) to characterise their evolution in time (e.g. rates of lateral migration)~~quantification of lateral migration rates (e.g., Hooke and Yorke, 2010; Janes et al., 2017; M

However, two major sources of spatial ~~uncertainties inherently question~~ uncertainty inherently compromise the robustness of these planimetric methods: the delineation error due to digitisation of river banks (Downward et al., 1994; Güneralp et al., 2014; Gurnell et al., 1994; Micheli and Kirchner, 2002; Werbylo et al., 2017) and the geometric error due to data coregistration (Gaeuman et al., 2005; Hughes et al., 2006; Liébault and Piégay, 2001; Payraudeau et al., 2010; Swanson et al., 2011). Whatever the scope of the study and the environmental context, these uncertainties ~~needs to~~ must be assessed as accurately as possible (De Rose and Basher, 2011; Donovan et al., 2019; Mount and Louis, 2005; Mount et al., 2003). ~~In that way, the~~ Root Mean Square Error (RMSE) has been frequently used ~~over the last decades to assess a~~ for this purpose over the past several decades to quantify the uniform geometric error affecting ~~coregistrated~~ co-registered planimetric data (Table 1). Lea and Legleiter (2016)~~however~~ , however, demonstrated that the RMSE approach was too simplistic because ~~coregistrated~~ co-registered data are affected by spatially-variable (SV) geometric error. To test ~~its impact~~ the impact of such error on the quantification of lateral migration, the SV-error was used as a SV Level of Detection (LoD): ~~it~~ this approach allowed detecting 33 % of statistically significant changes (migrations) instead of only 24 % with the RMSE/uniform error approach (Lea and Legleiter, 2016). The thorough review of Donovan et al. (2019) ~~lately~~ reached the same conclusion: they encouraged the generalisation of SV-error assessment and also ~~notified~~ noted the potential need ~~(for instance in the case of complex planforms such as braided rivers)~~ for testing SV-LoD on new metrics of lateral migration, such as ~~surfacic~~ surficial ones.

Both Lea and Legleiter (2016) and Donovan et al. (2019) developed a LoD ~~on~~ for a linear metric (Fig. 1a) implemented in the Planform Statistics Toolbox (Lauer, 2006), which reports fluvial planform changes as a linear adjustment. However, by conflating river banks onto ~~an~~ a unique centreline (Fig. 1a), ~~this last~~ a linear metric can oversimplify geomorphological changes. ~~It~~ This approach is prone to fail detecting observed lateral adjustments when, for instance, channel widening or narrowing occurs without any significant lateral migration of the centreline (Miller and Friedman, 2009; Rowland et al., 2016). This is all the more relevant for ~~the less investigated~~ mid-sized rivers (width<30 m; EPCEU, 2000; Table 1), which, despite their importance in terms of river geomorphological management (Marçal et al., 2017), might be more impacted by ~~the aforementioned issues (e.g.~~ delineation and geometric ~~error)~~errors.

This study aims ~~at completing~~ to advance the generalisation of SV-error assessment methods in fluvial settings by testing its impact on the quantification of lateral migration ~~, using a surfacic metric(Channel Polygon method ;~~ using a surficial metric: the channel polygon method (Fig. 1b). The latter consists in the extraction of eroded, deposited and eroded then deposited surfaces, from overlaid diachronic channels. SV-error is assessed on two diachronic orthophotos of the lower Bruche (i.e., a mid-sized ~~sub-tributary~~ tributary of the Rhine), by spatial interpolation (Lea and Legleiter, 2016) based on an independent set of ground control points (Hughes et al., 2006). ~~A~~ The main novelty of our approach is ~~to run~~ running Monte-Carlo (MC) simulations (Metropolis and Ulam, 1949) to propagate the geometric error in measurements of eroded and/or deposited surfaces~~and produce a Surface of Detection (SoD) which allows detecting significant~~. This eventually allows computing the uncertainty associated to each surficial changes, on which a threshold is applied to detect unsignificant planform changes.

More specifically, this study tests three hypotheses in the fluvial context: (1) orthophotos are affected by a local significant SV-error; (2) SV-error ~~significantly affects~~ highly affects the variability of MC simulated measurements of eroded and/or deposited surfaces; and (3) ~~the higher the SV-error is, the less significant the measured changes are~~uncertainty of surficial changes depends on their magnitude. This work also evaluates the effectiveness of MC simulations in ~~measurements of~~ measuring fluvially eroded and/or deposited surfaces and assessing their significance.

2 Study area

Located in the easternmost France (Alsace), the Bruche river is a western, mid-sized ~~sub-tributary~~ tributary of the Rhine with a drainage area of about 730 km². The 80 km long river firstly drains the eastern flank of the Vosges Massif before debouching into the Upper Rhine Graben (Fig. 2a). Although highly impacted by human activities (levee/canal construction, channelisation, artificial cut-offs), this alluvial river is known to have been laterally active over historical times (Maire, 1966; Payraudeau et al., 2010; Schmitt et al., 2007). This is especially true in its lowermost reach where it flows through the Strasbourg urban area (Fig. 2a), ~~thereby~~ raising important management issues (Payraudeau et al., 2008; Skupinski et al., 2009). Our test site is a 6 km long wandering reach located a few kilometres upstream of the Ill confluence: the river freely meanders within its Holocene floodplain and locally erodes Late Pleistocene terraces deposits of the lower Bruche about 2 km from its ~~outlet~~ confluence as well (Fig. 2a; Maire, 1966). In this reach, the Bruche ~~displays~~ has a 20 m wide mean active channel and a mean slope of 1‰. Elevation of the river banks decreases from 146 to 142 m above the sea level. The daily two-year (Q_2) and ten-year (Q_{10}) peak flow discharges amount to 71 m³/s and 126 m³/s, respectively~~(~~, for the period 1965-2018~~)~~. The specific stream power ~~amounts to~~ is estimated as 30-35 W/m².

3 Methodology

3.1 ~~Remote-sensed~~ Remotely-sensed data

To measure eroded and/or deposited surfaces on our study area, two orthophotos from 1950 and 1964 were used. They were produced by the French National Geographic Institute (IGN) and the Laboratoire Image Ville Environnement (LIVE) of the University of Strasbourg; they have a spatial resolution of 50 and 20 cm, respectively. Both are projected in RGF93/CC48 CRS (EPSG: 3948), which is the most accurate projection in this area. ~~Surveys~~ Despite the lack of hydrological data in the lower Bruche before 1965, we assume surveys were conducted during moderate-low water, according to the period of the year during which the photos were taken (09/13/50; 04/17/64) and the observation of the orthophotos.

Active channel is a widely used concept to objectively identify channel boundaries on aerial photographs, regardless of the river discharge. It basically refers to the unvegetated area (Liébault and Piégay, 2001; Liro, 2015; Mandarino et al., 2019; Surian et al., 2009; Winterbottom, 2000). Here, active channel boundaries have been digitised by a single user in QGIS at a 1/300 scale. To reliably assess the SV-error, we used a 2015 orthophoto as the base image; it was produced by the IGN with a resolution of 20 cm.

3.2 SV-error assessment

On both orthophotos (1950; 1964) of our study area, spatial variations of geometric error are assessed by an approach similar to that used by Lea and Legleiter (2016). However, because we use orthophotos (which are already coregistered), we must rely on an independent set of GCPs, as suggested ~~such~~ by Hughes et al. (2006). We selected a total of 18 GCPs, including both hard (buildings, canal) and soft (~~pathways~~ pathway intersections, trees) ~~edges~~ features (Fig. ~~??~~2a). After identification and manual plotting on the 2015 orthophoto, they are incorporated to both older orthophotos at a 1/200 computer-screen scale. The spatial distribution of GCPs in the study area is rather uniform, though hard edges are restricted to the northern sector (Fig. ~~??~~2a).

Local ~~RMSE~~ Root Square Error (RSE) is then measured for each of the 18 GCPs, on both orthophotos. Error in x or y corresponds to the euclidean distance between the two points for x and y coordinates, respectively. SV-error is calculated by interpolating local ~~RMSE~~ RSE on our whole study area with an Inverse Distance Weighting (IDW) technique at the original spatial resolution (Fig. 3). IDW uses a linear combination of values at specific sampled points. It allocated weights ~~proportionally~~ proportional to the proximity of the sampled points to estimate values of the unknown locations (Ikechukwu et al., 2017). We used the IDW interpolation method for two main reasons. First, ~~Lea and Legleiter (2016) showed the necessity to use interpolation methodsthat do not~~ based on a comparison of five interpolation methods, Lea and Legleiter (2016) showed that linear and nearest neighbour methods reduce the areal extent of ~~relatively large error, i. e cubic or spline compared to linear or natural neighbour interpolation methods~~ large co-registration errors. These methods are thus discarded as they can strongly limit the influence of large co-registrations errors on the estimations of surficial changes. Then, in a comparative study of spatial interpolation methods to produce a Digital Elevation Model from a small set of points that were not spatially uniform, Tan and Xu (2014) showed that IDW provided better results than Spline or Kriging. Because of the difficulties ~~to select~~ of selecting a high number of independent control points spatially uniform over time in ~~old spatial~~ ancient remotely-sensed data, we argue that ~~it is a crucial point to consider~~IDW is a reliable method to interpolate the registration error in our case.

3.3 Sub-reaches~~and local specific geometric error (LSE)~~

To ~~compare~~ examine the implications of SV-error on lateral migration measurements, we focus on four distinct ~~several hundred meters long~~ sub-reaches (Fig. 2). ~~They respectively~~ Their mean talweg lengths amount to 530, 380, 700 and 890 meters long (upstream-downstream order). They are (1) an extending and narrowing meander, (2) an almost straight (apparently inactive) sector, (3) two alternate meanders (the first one slightly extending ~~)~~ and the second one displaying a small cut-off), and (4) a long meander ~~slightly~~ extending at the downstream ~~curvature.~~

~~The SV-error allows determining a local specific geometric error (LSE) affecting the four sub-reaches. LSEs are sub-reach-specific: (i) they are a mean error calculated for each sub-reach, (ii) they are uniform within each sub-reach and (iii) they spatially and temporally differ from one sub-reach to one another~~end of the curve. We selected geomorphologically distinct sub-reaches to evaluate the effect of both different magnitude changes and types of geomorphic processes.

3.4 MC simulations

3.4.1 Channel boundaries simulation method

~~Monte Carlo (MC)~~ MC simulations as statistical methods are generally used in cases where processes are random or when assumptions in the theoretical mathematics are badly known (Brown and Duh, 2004; Openshaw et al., 1991). Applying MC simulations in this research context is ~~a~~ the main novelty of this study. ~~It results in~~ This approach has two main advantages. Firstly, MC simulations are particularly well suited to our problem because of the difficulty ~~to distinguish~~ of distinguishing between inherent and processing errors in the measured RMSE over the whole area. Secondly, ~~they~~ MC simulations assume a spatial continuity and a relative spatial homogeneity of the error, which is consistent with resulting spatial patterns of errors observed after ~~coregistrating~~ the coregistration or digitising process. MC simulations are also relatively easy to perform and applicable in very different cases. This ~~could~~ approach could thus improve the generalisation of methods for calculating planform changes and spatially variable uncertainty in a fluvial context, as suggested by Donovan et al. (2019).

The approach used in this study followed the rules of boundary simulations (Burrough et al., 2015). A sketch illustrating this part of our methodology is available in Appendix B. As described in the previous section, ~~LSEs were assigned to the channel boundaries for the two years in each sub-reach. Then,~~ SV-error has been interpolated over the whole study area. For each channel node, all pixels in a 5 m buffer were first selected. A check of the local distributions of error (Shapiro test) showed a normal distribution ~~of error (d_n) was~~ for a vast majority of them. The normal distribution of error was then calculated by averaging the ~~LSE of each node ($_n$) in each sub-reach~~ mean local error and by calculating the standard deviation ~~($_n$)~~for each node, in each sub-reach. Hence, ~~at~~ for each run (1000 runs in total), a specific value of error in x (~~$e_x[i=1,...,1000]$~~$e_x[i=1,...,1000]$) and y (~~$e_y[i=1,...,1000]$~~$e_y[i=1,...,1000]$) was randomly extracted from the respective normal distribution in order to shift each node from its original position~~(see equation 1 and 2). Furthermore, similarly to~~ .

Furthermore, in accordance with the results from Podobnikar (2008), the shape of a particular channel is assumed to remain ~~similar~~ coherent after simulation. ~~Indeed, the simulation process of error must not alter the manual digitisation of the producer. Respecting that condition, it must exist a correlation between nodes within the simulation of one channel. The correlation coefficient (CORR)depends on correlation between generalisation of the vector lines and/or the ratio between the absolute and the relative accuracy. To simplify this point, CORR was assumed equal to~~ In this study, as the distance between nodes is significantly higher than the local registration error, it is possible to move nodes of each sub-reach in any x and y directions without significantly impacting the shape. However, when this condition above is violated (in historical maps for instance, see Herrault et al. (2013)), the operation can potentially lead to strong geometrical errors such as "butterfly polygon" or excessive geometric distortions (Appendix A). These errors might be partially corrected (via e.g. the moving average algorithm or Douglas Peucker filtering) but can result in erroneous modifications of the original channel shape. Thus, we proposed an hybrid solution to simulate the node shifting in space : (1~~for every node of the channel boundary so each of them were shifted to a similar distance in x and y~~) nodes from one sub-reach can move in any y directions (i.e. ~~e_x and e_y) at a simulation run. From a similar way, the~~ positive or negative) at each run; (2) nodes from one sub-reach can move in only one x direction at each run. This last operation allows (i) avoiding topological errors while simulating the most probable displacements of channel polygons, and (ii) probably enhancing the transferability of our method to other fluvial settings. The direction of errors in x and y ~~, i.e. negative or positive, was~~ were randomly selected at each MC ~~run and applied uniformly for every node of the river channel~~simulation with equal probability weights (i.e. 50 % each).

Last, as mentioned by Donovan et al. (2019), it is quite hard to distinguish between errors inherent to the coregistrating and digitising ~~process~~processes. For this reason, a digitising error (e_d) equal to 1 pixel was added as a reasonable constraint within the simulation process, considering the resolution of the orthophotos. This digitising error is assumed to be uniform over the entire area and does not fluctuate in different simulation runs (equations 1 and 2). Only the direction in x and y was randomly defined for each node of one sub-reach at each MC simulation. These directions may vary from one node to another for one given sub-reach.

The overall mathematical expression of the simulation process can be expressed as follows:

$$x_{changed} = x_{original} + (|e_x \underline{\times CORR}| \times [-1;1]) + (|e_d| \times [-1;1]) \tag{1}$$

$$y_{changed} = y_{original} + (|e_y \underline{\times CORR}| \times [-1;1]) + (|e_d| \times [-1;1]) \tag{2}$$

3.4.2 Lateral migration measurements

Lateral migration of the river channel between 1950 and 1964 is calculated through three standard ~~surfacic~~ surficial morphological metrics (erosion, deposition, both erosion ~~/~~then deposition) illustrated in ~~figure~~ Fig. 1b. Note that the metric "erosion then deposition" measured in the area located between the former channel (T1) and the new one (T2) does not always imply continuous lateral channel migration followed by deposition. Sudden lateral shifts of meanders (e.g. through meander cutoff) or meander belts (e.g. through channel avulsion) may be involved as well and require specific geomorphological attention. Therefore, at each MC run, new values of metrics are derived for each sub-reach in order to estimate fluctuations induced by coregistrating and digitising errors.

3.4.3 ~~Assessment~~ Impact of ~~the statistical significance~~ SV-error on uncertainty of ~~the~~ lateral migration measurements

To ~~determine if lateral migration measured in~~ evaluate the uncertainty associated to lateral migration measurements within each sub-reach ~~is significant or not, a virtual Surface of Detection (SoD)was estimated. The SoD refers to a virtual surface which allows us to distinguish significant measurements from the insignificant ones, for each sub-reach. It can be considered as the surfacic equivalent of the linear LoD introduced by Lea and Legleiter (2016) and corresponds to the~~ and to allow comparison between the four sub-reaches, two types of relative uncertainty were calculated for each morphological metric (erosion, deposition, erosion then deposition). The first one (equation 3) corresponds to the total percentage of uncertainty and involves the total range of measured ~~surfaces (erosion, deposition, erosion/deposition) through the MC simulations. Two types of SoD are used: (1) The raw-SoD is calculated by subtracting the very maximum measured value by the very minimum measured value and (2) the 95-SoD, calculated by subtracting the maximum measured value by the minimum value, inside the~~ values (max-min) through MC simulation. The second one (equation 4) corresponds to the 95 ~~% confidence interval. We finally considered that significant lateral migrationmeasurements corresponds to the average measured values minus the SoD~~% uncertainty percentage and involves the 95 % confidence interval. Their mathematical expressions are, respectively:

$$Total\ uncertainty = \frac{\frac{1}{2} \times (max - min)}{mean} \times 100 \tag{3}$$

$$95\%\ uncertainty = \frac{\frac{1}{2} \times 95\%\ confidence\ interval\ width}{mean} \times 100 \tag{4}$$

Relative percentages of uncertainty inform about the variability of measurements induced by the SV-error through MC simulation, observed each sub-reach and for each morphological metric. We thus use these relative percentages of uncertainty to set a threshold above which the uncertainty is considered too high to yield a reliable measurement, i.e. a significant change in channel migration. Two thresholds are proposed here: a less conservative (i.e. 95 % uncertainty > 50 %) and a more conservative one (i.e. total uncertainty > 50 %). While the former does not include outliers, the latter, which corresponds to a measurement whose mean value is lower than the total range of measured values (max-min), does.

4 Results

4.1 SV-error~~and LSEs~~

~~Fig. 4 displays the LSE calculated for each sub-reach and year, from interpolated~~ Figure 3 shows the interpolated SV-error in x, y and the total SV-error ($\sqrt{e_x^2+e_y^2}$), for the year 1950. The mean value of total SV-error in each sub-reach for both years (Fig. ~~3) . Sub-reach~~ 4) indicates that sub-reach 4 is ~~respectively~~ affected by the highest (1.32 m) and the lowest (0.61 m) ~~LSE~~ error in 1950 and in ~~1964. These values~~ 1964, respectively. These values approximately corresponds to the range of ~~LSEs~~ total SV-error reached by the four sub-reaches. ~~Sub-reach 1,~~ Whereas the total SV-error was divided by a factor 2 ~~and 3 have a similar LSE~~ between 1950 and 1964 ~~, while the LSE for~~ in the sub-reach 4~~is divided by two between 1950 and 1964. LSE decreases from about 1.2 to~~ , it remained fairly stable in the three other ones, ranging from 0.6 ~~m, from~~ (sub-reach ~~1 to~~ 3) to 1.2 m (sub-reach ~~3.~~ 4).

4.2 MC simulations

An example of variations in measurements of eroded surface through MC simulations ~~are~~ is presented for sub-reach 1 in ~~figure~~ Fig. 5. The entirety of MC results are available in ~~appendix~~ Appendix A. A large majority of the measurements ~~appears~~ appear to be randomly varying around and close to the mean value, inside the 95 % confidence interval. Note that few outliers sometimes largely extends the maximum range ~~(raw-SoD)~~ compared to the 95 % confidence interval~~(95-SoD). It is especially the case~~ , especially when very low values ~~of measurements occurs~~occur. For instance, MC simulations for deposited surfaces in sub-reach 1 ~~let appears three outliers with values (2.9 $\cdot 10^3 m^2$~~include an outlier with a value ($2.5 \cdot 10^3 m^2$) corresponding to ~~56~~ 38 % of the mean measured value (~~$5.2 \cdot 10^3 m^2$~~$6.8 \cdot 10^3 m^2$).

Mean ~~surfacic~~ changes inferred from MC simulations between 1950 and 1964 are presented in ~~figure~~ Fig. 6a. Comparison between sub-reaches is allowed by the normalisation of the surficial changes by the respective talweg lengths of each sub-reach (expressed thus in m²/m). Whatever the sub-reach, changes in eroded or deposited surfaces are much larger than those associated to erosion/deposition. The latter are either negligible (sub-reaches 1 and 3) or not recorded (sub-reaches 2 and 4). ~~Sub-reaches~~ Sub-reach 1 shows the largest migration: eroded and deposited surfaces amount to $9.1 \pm 4.9\%$ and $12.8 \pm 3.5\%$ m^2/m, respectively. By contrast, sub-reach 2 ~~show the largest and lowest surfacic changes, respectively: $5.1 \cdot 10^3 m^2$ and $7.2 \cdot 10^3 m^2$ of~~ shows the lowest migration: eroded and deposited surfaces ~~(sub-reach 1) vs $0.9 \cdot 10^3 m^2$ for both (sub-reach 2). Intermediate surfacic changes~~ amount to $2.1 \pm 24.7\%$ and $1.8 \pm 30.8\%$ m^2/m, respectively. Intermediate measurements are reported in sub-reaches 3 and 4 where they range between ~~$1.3 - 1.6 \cdot 10^3 m^2$ (deposition) and $3.1 - 4.2 \cdot 10^3 m^2$ (erosion~~$1.4 \pm 25.3\%$ (deposition; sub-reach 4) and $4.5 \pm 8.5\%$ m^2/m (erosion; sub-reach 4). Note that, in these two last sub-reaches, changes in eroded surfaces are at least twice higher than those in deposited surfaces. ~~A coefficient of variation (CV), calculated as the ratio between 95-SoD and mean measured changes (Fig. 6a), allows visualising the variability in measurements of surfacic changes through MC simulations. CV lower than 1 means that the mean surfacic change is greater than the 95-SoD, leading to the assumption that changes are significant.~~

4.3 ~~Migration significance~~Uncertainty in lateral migration measurements

The ~~statistical significance of the measurements in surfacic~~ relative percentage of measurement uncertainty in surficial changes is presented ~~with both the raw-SoD and the 95-SoD (~~both in the 95 % confidence interval (95 % uncertainty; Fig. 6b) and in the whole range of measured values (Total uncertainty; Fig. 6~~b). The total percentage of significant changes globally increases from 17 % using the raw-SoD to 37 % using the 95-SoD. Whilst this increase of significance with the 95-SoD is the highest for sub-reach 1 (from 48 % to 86 % for eroded surfaces; from 35 % to 90 %for deposited surfaces), we also observe the outbreak of significant changes~~ c). As a reminder, the 95 % uncertainty does not take into account the presence of outliers, while the total uncertainty does. The 95 % uncertainty varies from 3.5 to 43.4 %. These extreme values both occur in sub-reach ~~3 (from 24 % to 66 % for eroded surfaces; from 0 % to 25 %for deposited surfaces) as well as~~ 1, for the deposited and the eroded then deposited surfaces, respectively. The total uncertainty varies from 15.8 to 52.9 %. These extreme values both occur in sub-reach 4 ~~(from 59 % to 75 % for eroded surfaces; from 0 % to 24 % for deposited surfaces; Fig. 6b). Regardless of the SoD used,~~ and 1, for the eroded and the eroded then deposited surfaces, respectively. Sub-reaches 2 and 4 both display the same pattern between the 95 % and the total uncertainty, with the uncertainty related to the deposited surface being higher than that related to the ~~eroded/deposited surfaces appears to be insignificant. Appliance of the 95-SoD let emerged respectively 2.6 and 0.5 % of apparently significant eroded and deposited surfaces in~~ eroded one. In contrast, sub-reaches 1 and 3 do not display the same pattern between the 95 % and the total uncertainty. For sub-reach ~~2. The relatively strong increase in measurements significance from raw-SoD to 95-SoD, common to any sub-reach, is explained by~~ 1 and relatively to the uncertainty of the eroded surface, the uncertainty of the deposited surface is higher than the latter only when taking into account the presence of outliers (~~Fig. 5), largely extending the raw-SoD in almost any sub-reach (Appendix A~~total uncertainty). For sub-reach 3 and relatively to the uncertainty of the eroded/deposited surface, the uncertainty of the eroded surface is higher than the latter only when taking into account the presence of outliers (total uncertainty).

5 Discussion and research perspectives

~~At~~ In the light of these new results, we first discuss the three hypotheses underlying this study. In a second step, we propose some methodological guidelines together with promising further implications of this study.

5.1 SV-error implications on ~~surfacic~~ uncertainty of surficial planform changes~~significance~~

Our results validate the first hypothesis: they confirm that orthophotos are affected by a local significant SV-error. Within our relatively small ($\sim$6 km^2) and flat study area, we ~~interpolate a~~ interpolated a total SV-error ranging from 0.26 to 1.89 m ~~while LSE values~~ (Fig. 3) while mean values of total SV-error range from 0.61 to 1.32 m for the four sub-reaches (Fig. 4). This emphasises the need to take the SV-error into account and, importantly, to assess ~~it~~ its impact on the uncertainty of the measured changes (Lea and Legleiter, 2016; Donovan et al., 2019), even if the characteristics of the studied reach may appear unproblematic at first glance. Moreover, as orthophotos are used in this study, we draw particular attention on the relevance of this statement in the case of studies using ~~coregistrated~~ co-registered aerial photographs for similar purposes (e.g., Cadol et al., 2010; Hooke and Yorke, 2010; Sanchis-Ibor et al., 2019).

Our results also validate the second hypothesis~~too~~: the SV-error ~~strongly affects significance of measured~~ highly affects the variability of MC simulated measurements of eroded and/or deposited surfaces. ~~Whereas the most conservative raw-SoD reduces the significance of the measured changes to only 17 %, the latter amounts to 37 % with~~ Variability of the surficial measurements has been assessed by calculating the relative percentages of uncertainty induced by the SV-error through the MC simulations. Whereas the more conservative percentage of uncertainty (total uncertainty) ranges from 15.8 to 52.9 %, depending on the metric and the sub-reach, the less conservative ~~95-SoD. Although this last value may appear low, it falls into the same range as the value (33 %) proposed by Lea and Legleiter (2016), who interestingly studied channels of similar width (∼15 m). On threefold larger river systems (widths ∼45 m), Donovan et al. (2019) found a total of 62 % of significant migration vectors (Table 1). Corroborating these authors outcomes, our study surely demonstrates the need for distinguishing between significant and unsignificant changes, whatever the size of the fluvial system considered~~percentage of uncertainty (95 % uncertainty) still ranges from 3.5 to 43.4 %. These results highlight the potentially high impact that SV-error can have on variability of surficial measurements and consequently on their uncertainty.

When applying the more conservative threshold of significance (50 % of total uncertainty; cf part 3.4.3), it appears that only one surficial change has to be considered unsignificant (eroded/deposited surface in sub-reach 1; Fig. 6c). However, the latter can be considered significant when applying the less conservative threshold of significance (Fig. 6b), because its uncertainty does not reach the 50 % threshold. Whilst this contrast may call into question whether or not the presence of outliers should be taken into account, visual comparison of specific situations may help unravelling this issue. As illustrated in Fig. 7, only subtle areal and shape differences may be observed between an inlier and an outlier, the latter likely representing a geomorphologically plausible situation. When using MC simulations in this context, we thus strongly suggest checking how outliers look like and not systematically rejecting them.

Our results partly ~~refute~~ validate the third hypothesis: the ~~significance of measured changes does not only depend on SV-error magnitude. Indeed, the first sub-reach simultaneously displays the largest amount of significant changes in eroded and deposited surfaces~~ uncertainty of surficial changes depends on their magnitude, but also possibly on their respective shapes. A contrasted pattern of uncertainty is observed between the sub-reaches 2 and 4 versus sub-reaches 1 and 3. Whereas the former seemingly display uncertainties solely related to the magnitude of changes (i.e ~~. 86-90 % with the 95-SoD) and high LSEs (1.15 m for 1950; 1.20 m for 1964). On the other hand, the third sub-reach, though characterised by low LSEs (0.65 m on both orthophotos), does not exhibit any significant change for the very low amount of eroded/deposited surfaces.Based on these both observations, we can suggest instead that the significance of measured planform changes may primarily depend on the magnitude of changes. A corollary is that the lower the measured changes are, the more the SV-error should be taken into account. As for the magnitude of planform changes, the annual rates in the lower Bruche amounting to ∼350 m^2/yr (according to the eroded surfaces~~ higher uncertainties for lower surficial changes), the latter don't (i.e. in some cases, higher uncertainties for higher surficial changes; see part 4.3; Fig. 6). It is the case for instance in sub-reach 3, which displays a higher total uncertainty for the eroded surface than for the eroded then deposited surface. Yet, as sub-reaches 1 ~~) contrast with those reported by Hooke and Yorke (2010) in a~~

~~similar context (i.e. one order of magnitude more for the 15 m wide River Dane in the UK; Table 1). In those kind of settings, leaving aside the assessment of the SV-error, such as Hooke and Yorke (2010) did, might be more acceptable, provided that the magnitude of changes largely exceeds a certain threshold (e.g. 1000 m²/yr, though this value has to be better defined by further research)~~and 3 displays the most complex geomorphological shapes and channel evolution compared to sub-reaches 2 and 4 (Fig. 2b), we suggest that uncertainty of surficial measurements might also be strongly influenced by channel morphology and its evolution through time.

5.2 Methodological guidelines and potential applications

In order to improve the generalisation of tools documenting fluvial planform changes and facilitate the implementation of our new methodological framework, we can summarise the complete workflow as follows (see Fig. 8 for more details): (1) interpolate the SV-error on the study area (as recommended in Lea and Legleiter, 2016), (2) ~~compute the LSEs affecting each sub-reach~~calibrate a normal distribution around nodes to randomly translate these (see Appendix B for more details), (3) ~~assess the SoDs affecting sub-reaches and~~ choose a significance threshold and visually check the outliers to eventually (4) assess the significance of the measured ~~surfacic~~ surficial planform changes. The key step (~~3~~2) is achieved ~~thanks to MC simulations (Fig. 8)~~via MC simulation, which is well-known for its simplicity, reliability and ~~transposability (Brown and Duh, 2004; Openshaw et al., 1991). Simulations~~ transferability (Brown and Duh, 2004; Openshaw et al., 1991). Simulation outputs allow assessing both the ~~raw and 95-SoDs~~ total and the 95 % uncertainties (Fig. 8).

We suggest a few practical recommendations when applying ~~our~~ the proposed methodological framework. If orthophotos are employed, we strongly ~~advice~~ advise using an independent set of GCPs for coregistration and bearing in mind that orthophotos are affected by a significant SV-error (see 5.1). As for GCPs, their amount must be high enough and their distribution over the entire study area as homogeneous as possible. As pointed out by Hughes et al. (2006), a location of these GCPs close to the river system is highly beneficial. As for the ~~SoD~~50 % significance threshold, we recommend ~~using the 95-SoD as it refers to the most probable results and greatly improve the significance of the results. Nevertheless, the conservative raw-SoD might also be considered as it refers to situations which are (very)rare but possible. In this respect~~applying it on the total uncertainty, as outliers might represent geomorphologically plausible situations (Fig. 7). Nevertheless, the few outliers (Fig. 5) should still be treated in an empirical manner by visually determining if they ~~match geomorphologically plausible situations. This could be achieved for instance by visualising the two randomly translated overlaid river channels~~should be rejected or not. Further work is required in a near future to deal with this issue in a more automatic way. More generally, when studying historical lateral migration of mid-sized rivers (active channel width <30 m) and/or low magnitude changes (<~~1000~~ 1 m²/m/y) with the ~~Channel Polygon~~ channel polygon method, we ~~suggest a systematical assessment of~~ emphasise on the systematic need of assessing both SV-error and ~~SoD as a majority of~~ uncertainty, as some of the measured changes might be ~~insignificant (see 4.3~~unsignificant (see 5.1).

This study, though focusing on short sub-reaches of a mid-sized (∼20 m), meandering (single-thread) channel using specific ~~remote-sensed~~ remotely-sensed data over a short timescale (~~ancient~~ archival orthophotos), has a strong potential ~~of transposability~~for transferability. Firstly, we assume that our methodological framework could be applied to any fluvial system, regardless of its size. Secondly, we likewise argue that it could be relatively easily extended onto an entire river reach by increasing the sub-reach database and/or onto a longer temporal scale by increasing the historical river channel database (Fig. 8). As for the ~~latter, other remote-sensed~~ size/length of the sub-reaches, we recommend adapting it according to the complexity of the planform changes and/or the channel pattern (e.g. anastomosing and anabranching channel patterns). As for the river channel database, other remotely-sensed data, such as ~~coregistrated~~ co-registered aerial photographs and satellite imagery, or traditional planimetric data (maps) can be easily integrated as well. Thirdly, ~~transposing~~ transferring this framework to other channel patterns ~~, in particular multi-thread river systems (e.g., Rowland et al., 2016),~~ represents a promising future ~~perspective. By~~ research topic. In contrast to the ~~Centreline~~ centreline approach (e.g., Lea and Legleiter, 2016), the ~~Channel Polygon~~ channel polygon method would actually suit the study of lateral mobility of ~~braided channels~~ multi-threaded channels (including anastomosing rivers which usually are characterised by a low lateral mobility), with a robust assessment of the SV-error. Unlike this present study where planimetric changes associated to erosion/deposition are negligible, we might expect a ~~much~~ higher proportion of these changes in this kind of ~~dynamic fluvial settings~~fluvial setting. Overall, long-term landscape reconstruction studies could also largely benefit from the methodology we proposes. In particular, works combining multiple diachronic spatial sources (e.g. old aerial photographs, historical and cadaster maps, satellite images) should draw particular attention because of the possible propagation of uncertainty in the assessment of landscape changes.

We conclude by stating that this study offers promising research ~~perspectives~~prospects. Firstly, a key outcome is the ability of MC simulations to actually detect low-magnitude planform changes in mid-sized river channels. This positive achievement thus overcomes the main difficulty related to the use of classic planimetric methods in such settings (Piégay et al., 2005), as recently highlighted by ~~?~~Lauer et al. (2017), who failed ~~detecting~~ to detect noticeable changes in mid-sized active channels (width<25 m). Secondly, as for river restoration, our methodological framework should help constructing robust scenarios of future river management, especially those based on past planform changes (e.g., Marçal et al., 2017). Thirdly, significance assessment of planform changes can strengthen the studies using surfaces of active channel as input for sediment budgeting (Wheaton et al., 2009). Finally, whilst this study, together with Lea and Legleiter (2016) and Donovan et al. (2019), ~~contributes drawing~~ draws a specific attention ~~to assess~~ the SV-error and, more globally, uncertainties in planimetric studies in a wide range of fluvial settings, the proposed propagation of geometric error via MC simulations could be extended to other geomorphological contexts where surface extraction from ~~remote-sensed~~ remotely-sensed data is involved.

Author contributions. All authors contributed to the conception of this study and manuscript writing. TJ wrote most of the manuscript, produced the initial data and figures; TJ and PAH conceptualised the global processing chain and performed Monte-Carlo simulations; VC contributed to result interpretation; LS and GR provided a complete review of the manuscript; GR supervised the text harmonisation.

Competing interests. The authors declare that they have no conflict of interest.

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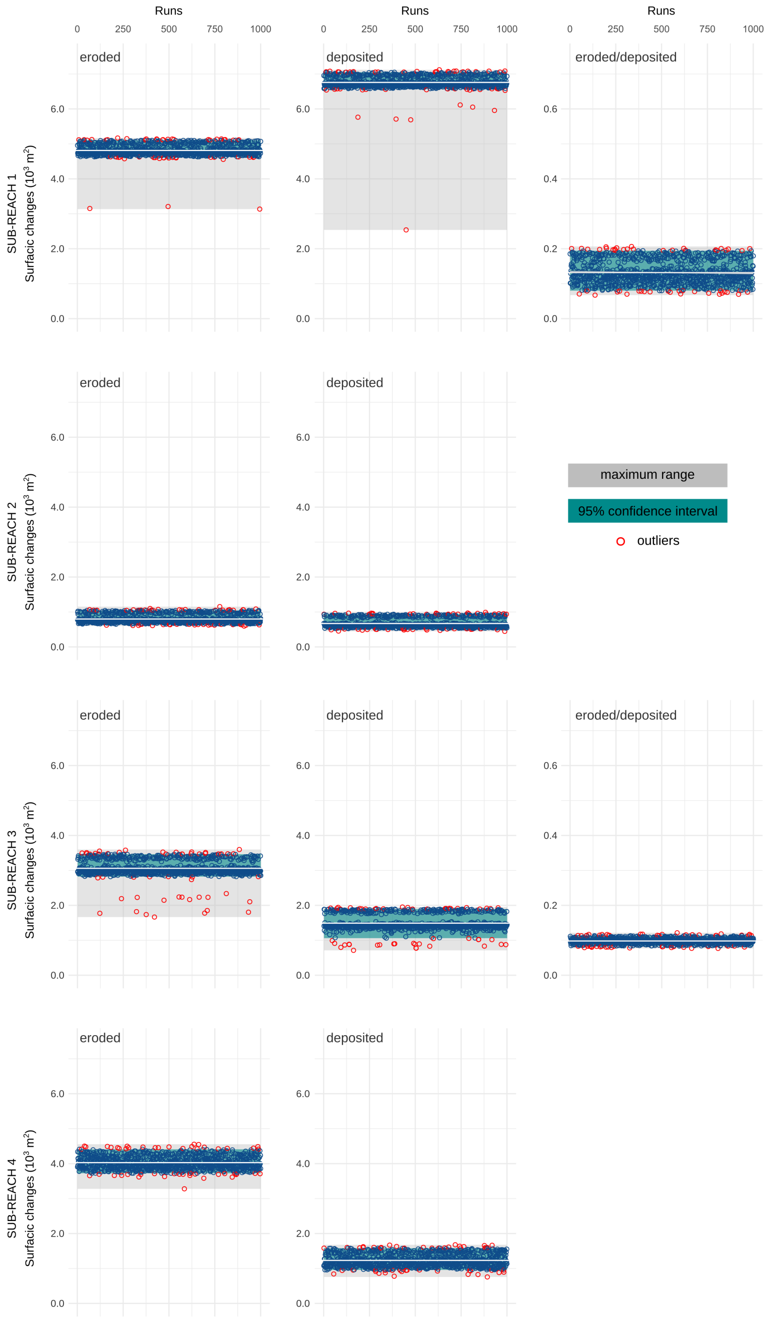
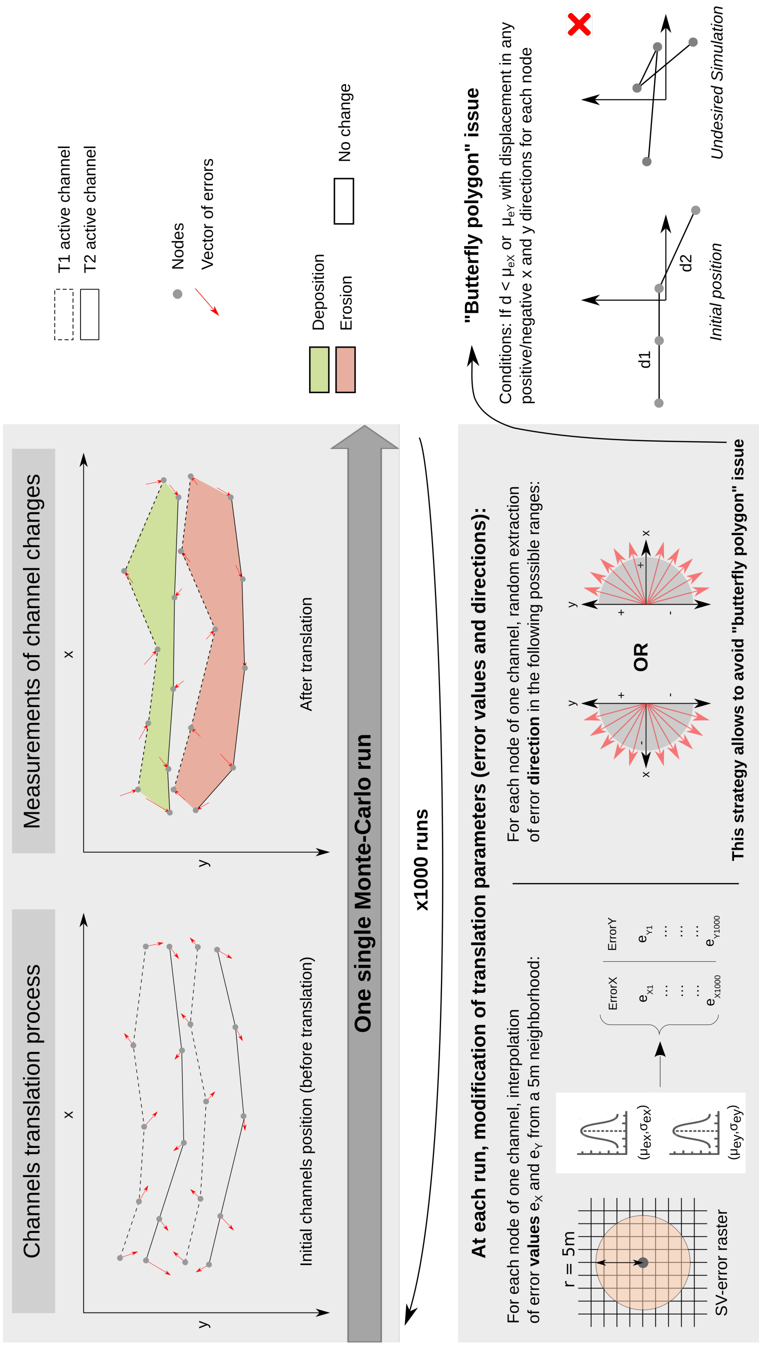


Appendix A: Monte-Carlo simulation results for every sub-reach.



Appendix B: Detailed workflow of the Monte-Carlo translation process used in this study.

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Table 1. Literature review of recent studies quantifying channel lateral migration using P: Channel Polygon method and/or T: Centreline Trajectory method. ~~X~~x: error not assessed. U: use of an uniform error. SV: use of a spatially-variable error. The table is sorted by the mean width of the channel(s) studied.

Authors (year)	Lateral migration metric	Delineation error (m)	Geometric error (m)	Channel width (m)	Erosion order of magnitude (m²/m/yr)
Donovan et al. (2015)	P/T	x	U: 1.0	1-12	/
Hooke and Yorke (2010)	P	U: 1.0	x	15	~~3230~~ 4.4
Legleiter (2015)	P/T	x	U: 0.8-1.8	10-20	/
Lea and Legleiter (2016)	T	U: 2.0	SV: 0-5	15	/
this study	**P**	**U: 0.5**	**SV: 0.3-1.9**	**20**	**~~360~~0.6**
Sanchis-Ibor et al. (2019)	P	x	U: 1.5	7-40	/
Gurnell et al. (1994)	P	U: 2.0	U: 1.4-4.5	30	~~500~~ 0.03
Rhoades et al. (2009)	P	x	U: <1.0	30	~~1375~~ 0.03
Janes et al. (2017)	P	x	U: 3.5	35	/
Donovan et al. (2019)	T	U: 1.4	SV: 0-10	45	/
Schook et al. (2017)	T	x	U: <1.6	50	/
Morais et al. (2016)	P	x	U: 0.9-3.6	30-80	~~760~~ 0.02
~~?~~ Lauer et al. (2017)	T	x	U: 2.3	11.5-107.3	/
Lauer and Parker (2008)	T	x	U: 2.3-6.6	150;50;50;15	/
Lovric and Tosic (2016)	P	x	x	130	~~151 000~~ 5.4
O’Connor et al. (2003)	P/T	x	x	90-240	/

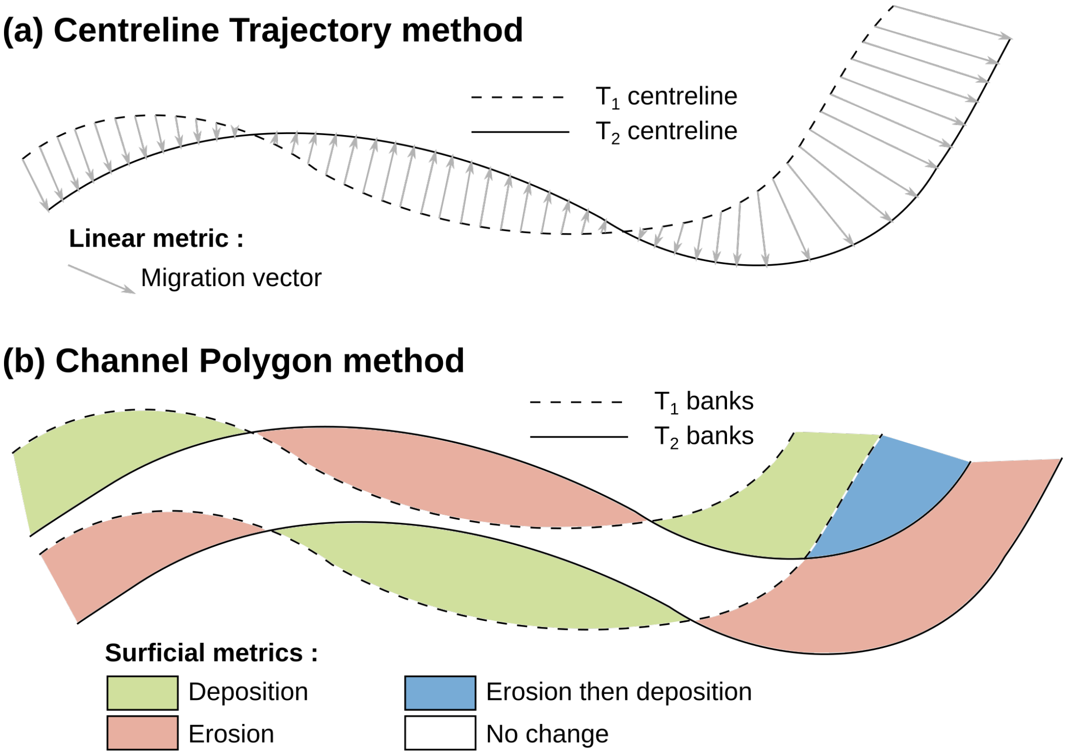


Figure 1. Illustration of the lateral migration metric used (a) by Lea and Legleiter (2016) and Donovan et al. (2019) and (b) in this study.

~~The independent set of GCPs used to assess SV-error on the study area. Background corresponds to a Sky View Factor visualisation of a 2015 LiDAR derived MNT.~~

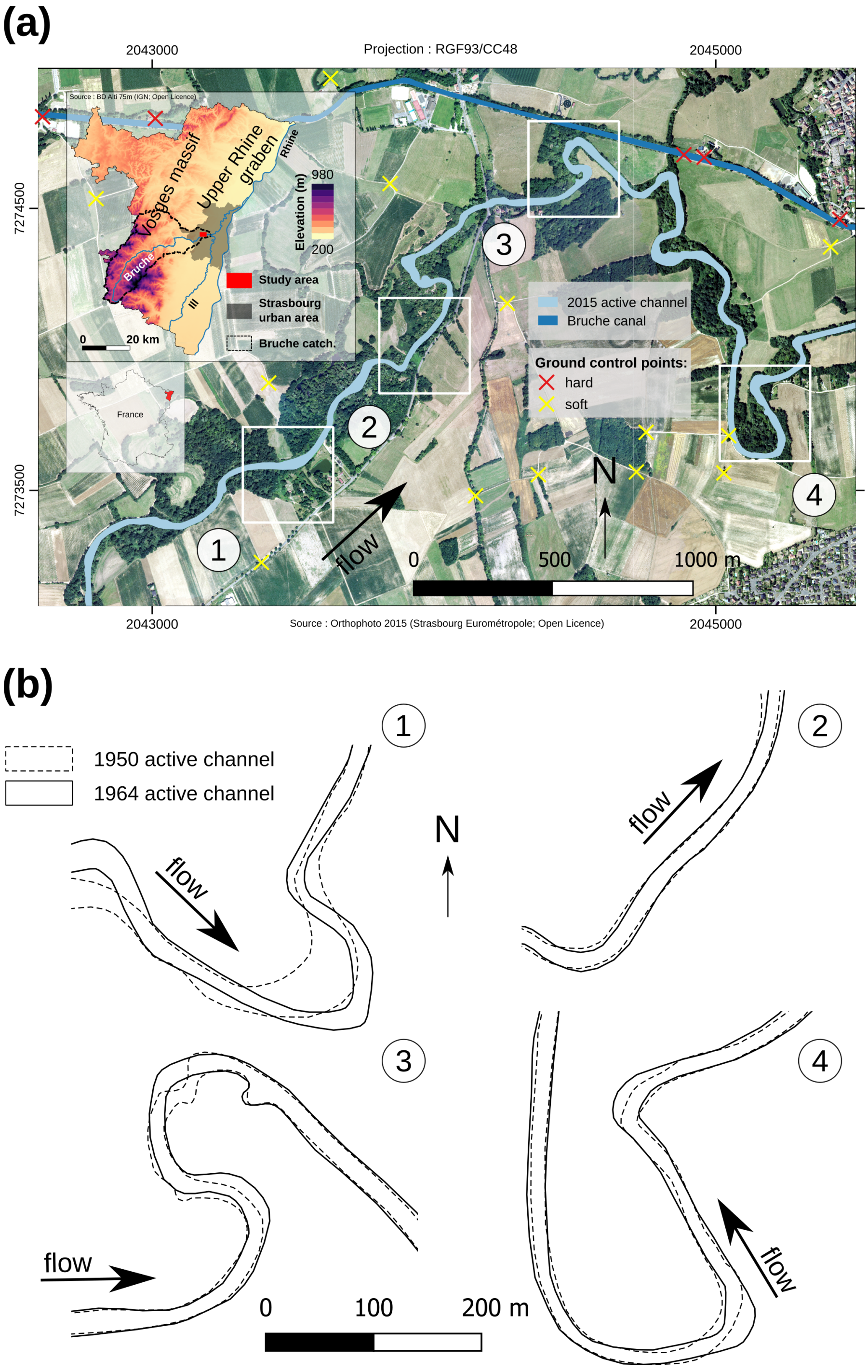


Figure 2. (a) Study area. Localisation of the four sub-reaches in the lowermost Bruche course. Red and yellow crosses indicates the position of the independent set of GCPs used to assess the SV-error over the study area. (b) Planimetric evolution of each sub-reach from 1950 to 1964 based on the two orthophotos.

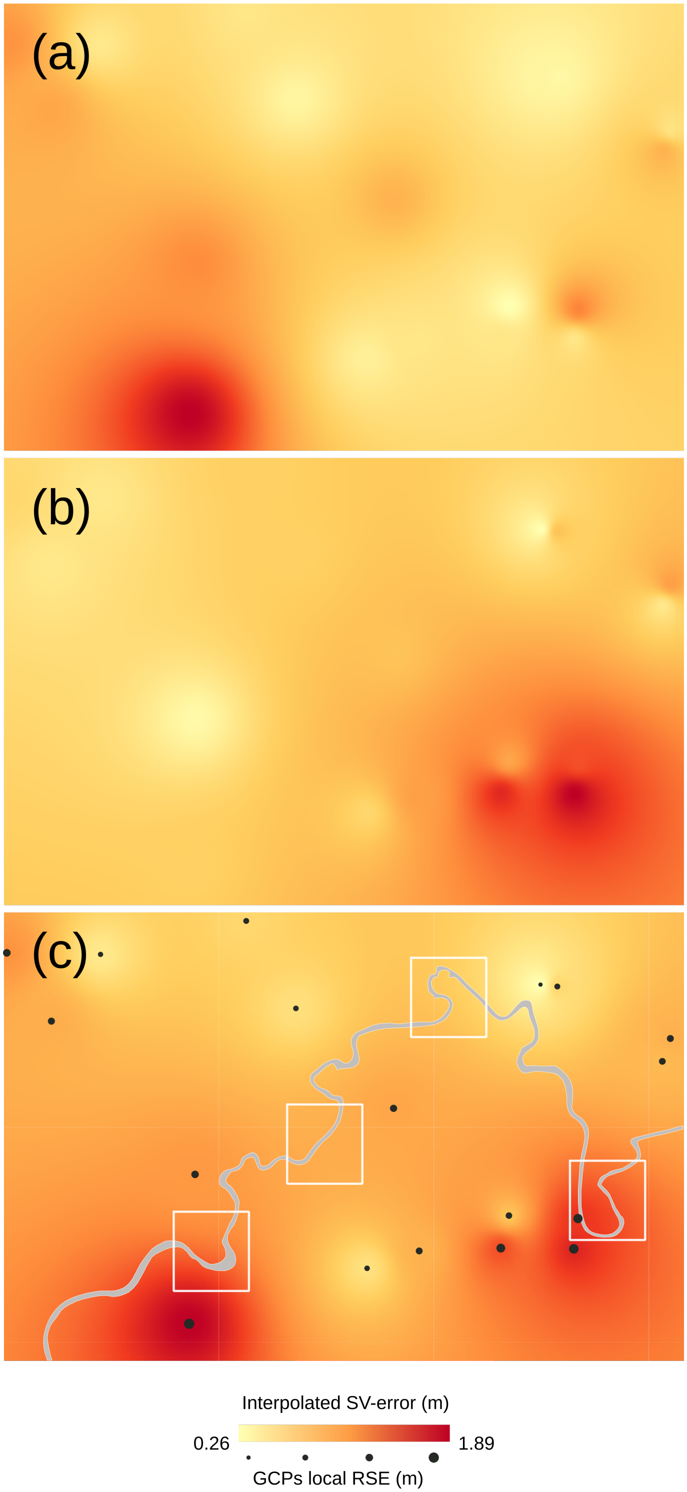


Figure 3. SV-error interpolation between GCPs from local ~~RMSEs~~RSEs, by IDW method. Year 1950. (a) Error in x. (b) Error in y. (c) Total error.

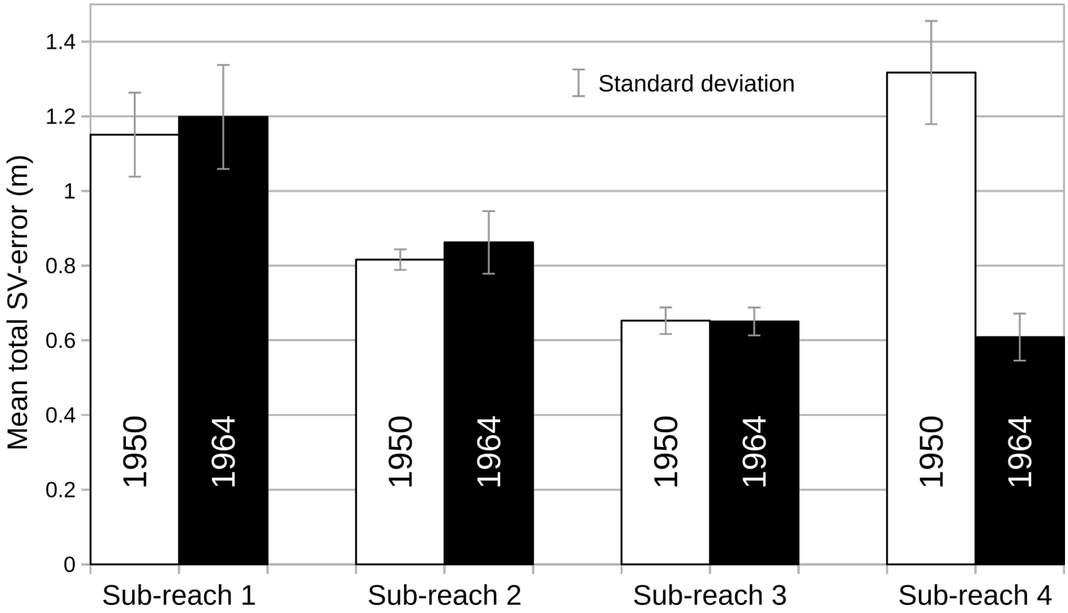


Figure 4. ~~Local specific error calculated~~ Mean total SV-error for each sub-reach, on both dates.

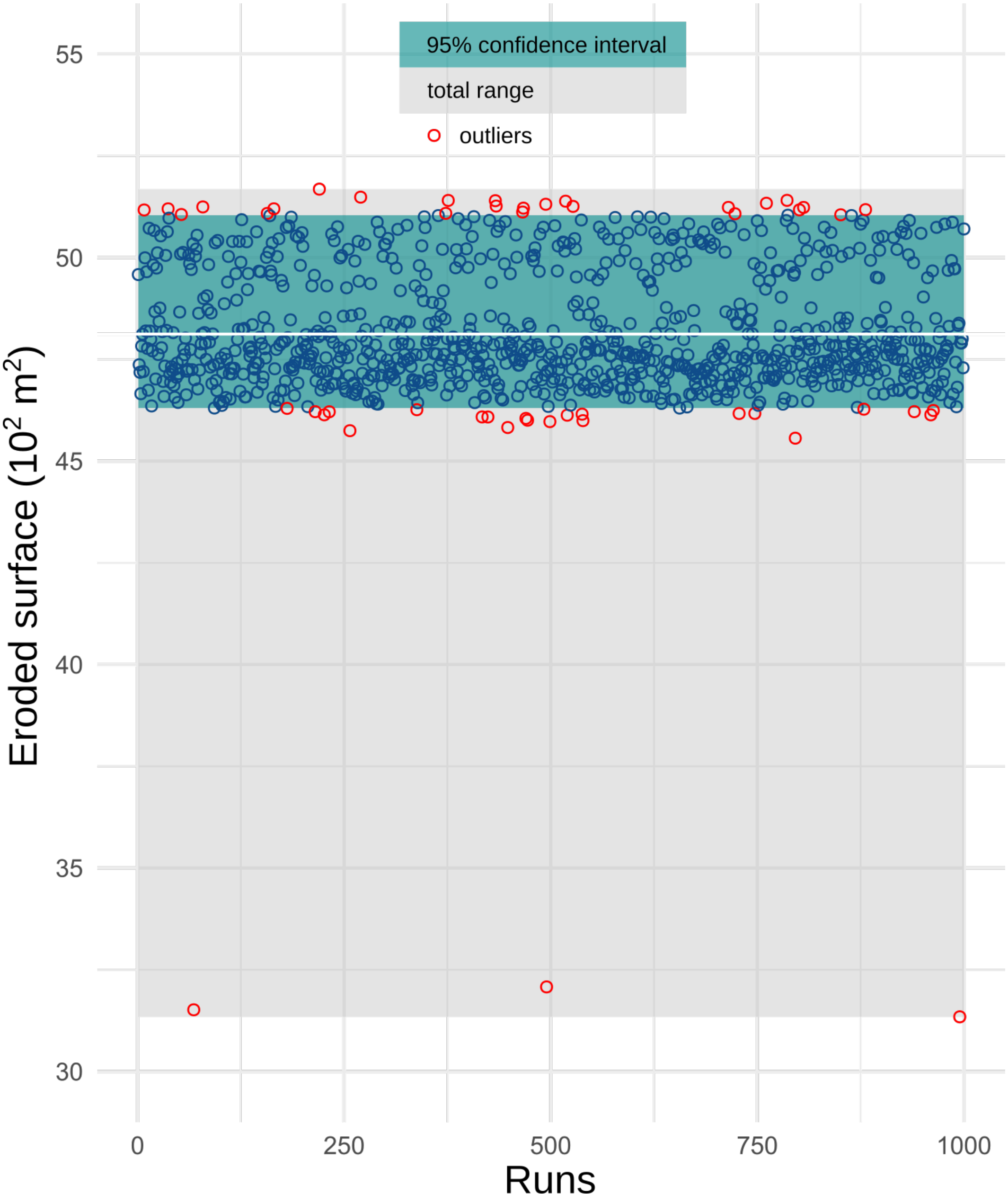


Figure 5. Measurements of eroded surface in sub-reach 1, through 1000 MC simulations. Gray horizontal line corresponds to the mean value.

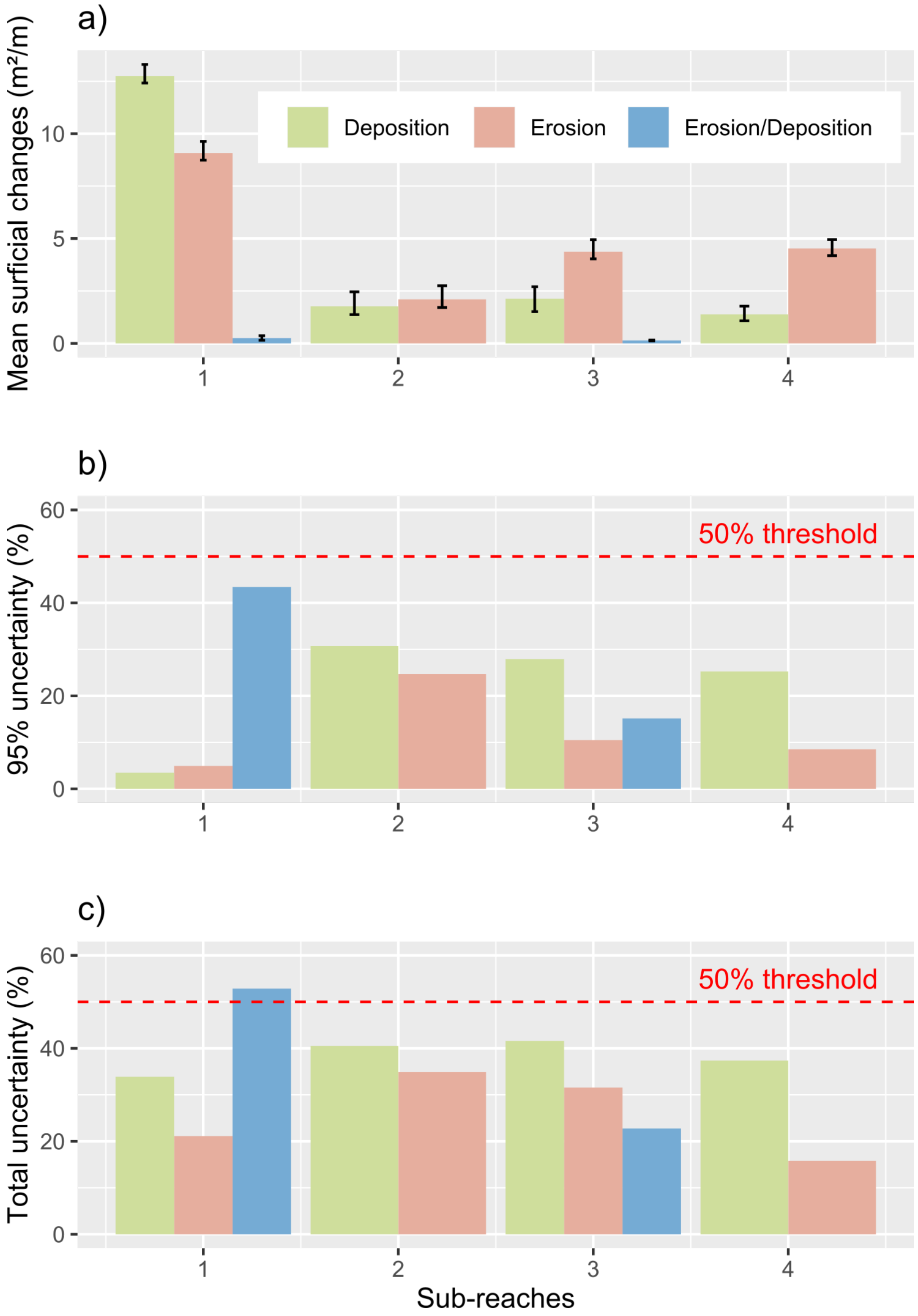
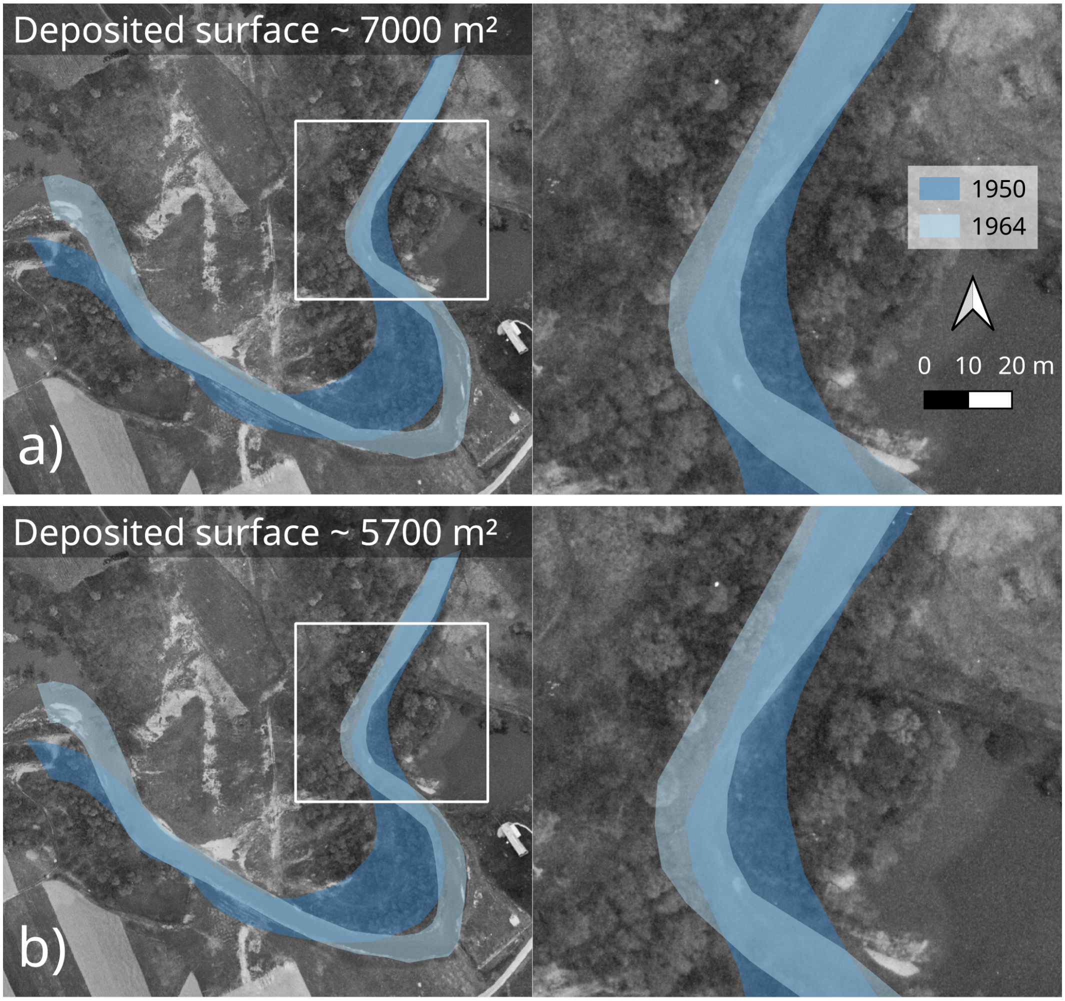


Figure 6. ~~(~~a) Mean ~~surfacic~~ surficial changes ~~and associated values~~ normalised by the length of ~~95-SoD, for~~ each sub-reach~~through Monte-Carlo simulation~~. ~~CV: Coefficient of variation equal~~ Error bars correspond to the ~~ratio 95-SoD/mean measured changes~~95 % confidence interval. ~~(~~b) ~~Significance of surfacic changes measurements when applying raw-SoD or 95-SoD~~95 % uncertainty percentage (without outliers). c) Total uncertainty percentage (with outliers). The red dashed line corresponds to the 50 % proposed threshold.



Source: Orthophoto 1964 (Strasbourg Eurométropole; Open Licence)

Figure 7. Example of translated channels for sub-reach 1, resulting from two different MC runs. Distinction between an a) inlier and an b) outlier according to the simulated deposited surface. Background corresponds to the 1964 orthophoto.

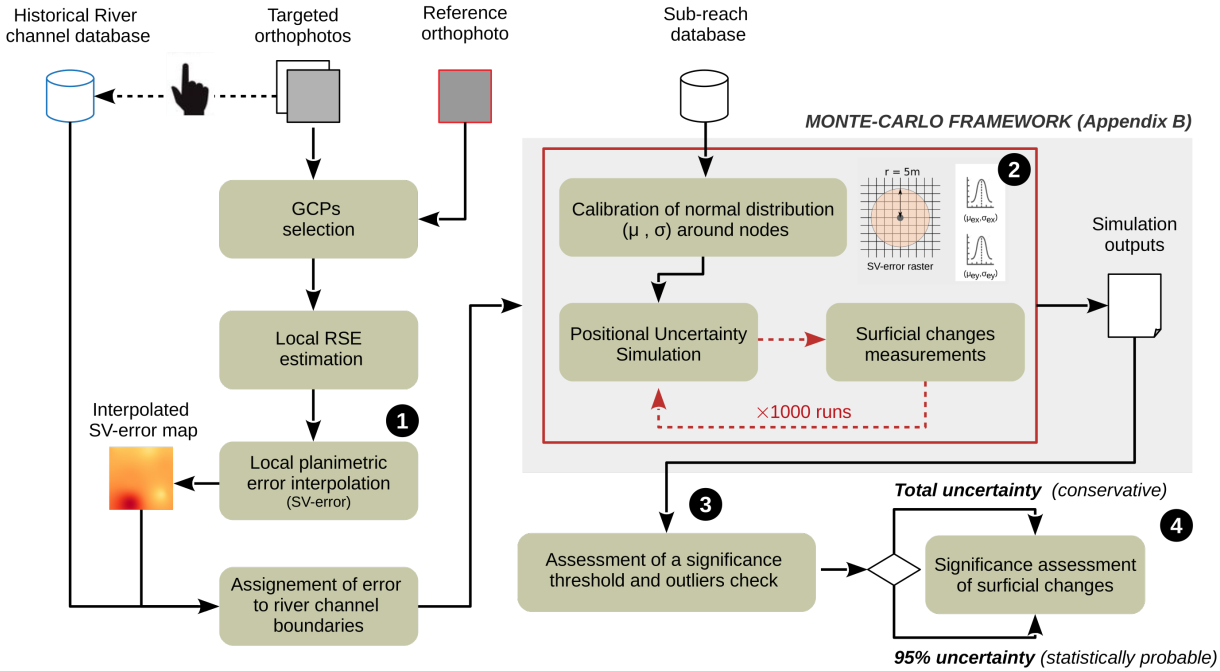


Figure 8. Detailed flow chart of the methodology applied in this study, allowing to assess ~~significance~~ uncertainty of eroded and/or deposited surfaces using SV-error.