Reviewer 2

Overall, this is a strong contribution that adds a new dimension to the bank pull/bar push debate. The authors demonstrate the value of using a large-sample satellite remote sensing approach (n = 4,923 river bends, sampled from 64 global rivers), in combination with other relevant environmental datasets, to explore factors that influence bank pull/bar push. The satellite remote sensing methodology is rigorously designed/developed and clearly explained. My general reading of the manuscript is positive.

My main comments are:

Section 4.1 – I was confused about how the benchmark datasets were compared. It is my understanding that the authors provide a sum of erosion/sedimentation pixels per polygon; the Langhorst and Pavelsky (2023) data provide a rate of erosion/accretion per node (approx. 200 m spacing). Are nodes paired within each bend polygon (if so, how many nodes are included per bend?). The caption states that 2,000 bends are compared – this is an important point and should be included in the main body text (i.e., only 40% of the sample – which rivers cannot be included, does that bias the comparison in any way?). Around L309-314, it could be more clearly stated that the rates of erosion/accretion are drawn from the Langhorst and Pavelsky (2023) data, not calculated from the sums of erosion/sedimentation pixels? I think lots of the key information is included in the figure/caption, but it could be more clearly explained in the main body text.

Response: We agree that the comparison between the two datasets requires further clarification. We have now revised Section 4.1 and Figure 4 to explain how the datasets were spatially matched. Specifically, erosion and accretion rates from Langhorst and Pavelsky (2023) were aggregated from individual river nodes within each bend polygon, while the maximum node migration rate was used for the threshold analysis in Figure 4b. Of the 4,923 bends, 2,632 (53.5%) had data available for comparison, with approximately 12 nodes per bend on average. We have added Figure 4c to illustrate this distribution. Although the independent dataset has limited spatial coverage, it was used exclusively to assess our erosion and sedimentation detection method and did not influence the selection or classification of bends in the main analysis. These distinctions have been clarified in the revised manuscript.

New L 336 – 360: "To lend confidence to our analysis, we initially benchmark our estimates of erosion and sedimentation against the independent channel migration dataset of Langhorst and Pavelsky (2023). Our method quantifies erosion and sedimentation through the annual number of affected pixels within each bend polygon, accumulated over the period 1984–2023. In contrast, Langhorst and Pavelsky (2023) provide erosion and accretion rates at individual river nodes, spaced approximately 200 m apart. To compare the two datasets, we spatially matched these nodes to our bend polygons and summed their erosion and accretion rates within each polygon. This comparison was possible for 2,632 bends, containing approximately 12 nodes per bend on average (Fig. 4c). Although this represents only a subset of the analysed bends, the comparison serves exclusively as an independent assessment of our method's ability to detect erosion and sedimentation. The Langhorst and

Pavelsky (2023) data are not used in the identification or subsequent analysis of Bank Pull and Bar Push mechanisms.

The total number of erosion and sedimentation pixels detected by our method shows a strong relationship with the corresponding aggregated migration rates from Langhorst and Pavelsky (2023). Both relationships follow a power law, becoming approximately linear after log–log transformation (R^2 = 0.71 for erosion and R^2 = 0.64 for sedimentation; Fig. 4a). Although the two datasets represent different measures of river migration, their correspondence provides independent support for our method's ability to capture spatial variations in erosion and sedimentation activity. To further examine the sensitivity of our adaptive threshold approach, we compared the maximum erosion and accretion rates recorded among the nodes within each bend polygon with the highest ΔmNDWI thresholds required to detect erosion and sedimentation (Fig. 4b). As migration rates increase, higher positive thresholds for erosion and more negative thresholds for sedimentation are required to detect rapid channel changes. For instance, at an erosion migration rate of 1.74 m/yr, the maximum required threshold is typically 0.04 ΔmNDWI, whereas at 10.9 m/yr it increases to 0.14 ΔmNDWI. Above 20 m/yr, the highest tested threshold of 0.14 ΔmNDWI predominates. A similar pattern is observed for sedimentation. These results illustrate the ability of the adaptive threshold approach to capture river migration across a broad range of intensities."

(2) The majority of the bends (63.5%) show no clear signal of bank pull/bar push, so they cannot be classified. This is an important result that warrants some further discussion. These bends are referred to in L346-347, but we do not learn about their geographical location (i.e., not shown in Figure 6) or the local factors that could be influencing this behaviour (i.e. not explained in Section 4.3). The results/discussion sections could say more about the environmental conditions where bank pull/bar push is not observed (are there typical characteristics that inhibit either process?).

Response: We have revised Figure 6 to show the geographical distribution of unclassified bends, which were distributed across the sampled rivers without an apparent geographical concentration. We also tested the inclusion of these bends as a third category in the Random Forest model, but this substantially reduced model performance. This result may reflect the heterogeneous nature of the unclassified category, potentially including bends that alternate between Bank Pull and Bar Push over time, as well as cases affected by uncertainties in satellite observations. Consequently, we restricted the environmental analysis to bends with identifiable Bank Pull or Bar Push signals. We have clarified these points in the revised manuscript.

New L 391 – 392: "Undefined bends were evenly distributed across the sampled river bends (Figure 6.a)"

New L 453 – 459: "We also tested the inclusion of Undefined bends as a third category in the Random Forest classification, but this resulted in substantially lower model performance. This may reflect the heterogeneous nature of this category, which potentially includes bends experiencing shifts between Bank Pull and Bar Push over time, as well as cases affected by uncertainties in satellite observations, including sensor noise, atmospheric effects, and

errors in water classification. Given these limitations, we restricted the main analysis to bends classified as Bank Pull or Bar Push."

New L 545 – 548: "To investigate whether bends without a persistent signal were associated with particular environmental conditions, we also applied a Random Forest model to distinguish these bends from those exhibiting a clear migration mechanism. However, the model showed limited discriminatory ability (ROC-AUC = 0.572), and no consistent environmental patterns emerged "

Line-specific comments:

L19: Are these "river characteristics", elsewhere referred to as environmental conditions/characteristics?

Thank you for spotting this. We have corrected accordingly.

L22: Are velocities known/calculated, elsewhere refers to unit discharge?

Response: The velocities are not known, but we have a proxy by dividing discharge by the river width. We changed the name of the unit discharge to Discharge per river width (Discharge / Width) in order to make it clearer, since we have now included more variables to the model. Higher flow in narrower rivers tends to increase the velocity of the water. But this is proxy, not a direct measurement of speed.

L50: Replace "other" with "another".

Thank you for spotting this. We have corrected accordingly.

L59: Conceptually, how is a pulse being defined? How does this differ from gradual change?

Response: We thank the reviewer for this comment. The term "pulses" was used to describe increases in erosion and sedimentation relative to their long-term trends, rather than necessarily abrupt or discrete events. In our methodology, we apply detrending to the annual erosion and sedimentation time series to remove long-term trends and focus on temporal variations around them. We agree that the term "pulses" may suggest abrupt events, which are not explicitly identified in our analysis. Therefore, we have revised the terminology to improve clarity, replacing "pulses" with "increases" and clarifying their interpretation in the methodology.

New L 61 – 63: "whether increases in outer-bank erosion precede increases in inner-bank sedimentation (indicating bank pull), or vice versa (indicating bar push)"

L88: Represent rather than capture.

Thank you for spotting this. We have corrected accordingly.

L127: Bankline rather than shoreline?

Thank you for spotting this. We have corrected accordingly.

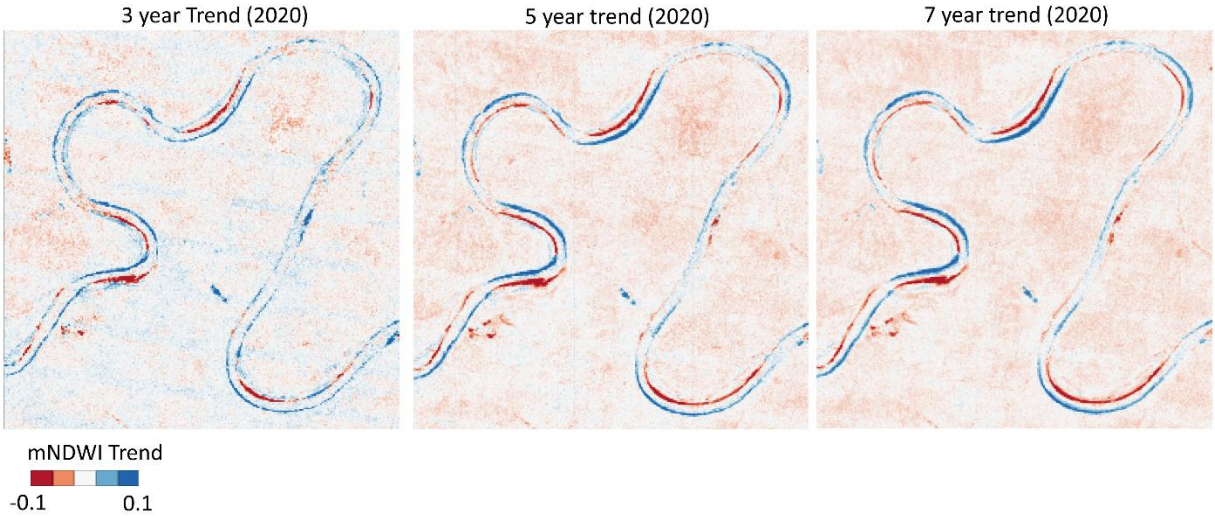
L138-155: Could provide a little more rationale for how the rivers were selected/sampled. How representative are the selected rivers in terms of global river migration rates? Are there any biases in the selection/sampling?

L165: Could add “cloud-masked” yearly median composites to make clear that cloud masking has been applied.

Thank you for spotting this. We have corrected accordingly.

L176-178: Some further justification needed for the 5-year moving window – how does this relate to bankfull conditions; why not 3, or 7 years? Were any other windows tested, and did they impact the results?

Response: We thank the reviewer for this comment. The ±5-year median moving window was adopted following Nagel et al. (2025), who evaluated this approach using 1,200 randomly selected locations. The choice of window length is not directly related to bankfull conditions, but rather aims to reduce short-term fluctuations in water extent and observational noise. To further evaluate this choice, we conducted an additional sensitivity analysis of mNDWI trends using ±3-, ±5-, and ±7-year moving windows. As shown in the figure below, the 3-year window resulted in substantially noisier spatial patterns, including artifacts associated with Landsat 7 sensor limitations. In contrast, the 5- and 7-year windows produced similar, more spatially coherent trends. We therefore retained the 5-year window, which provided an effective balance between noise reduction and preservation of temporal variability.



Included L 182 – 189: “To address this, we applied a ±5-year median moving window, following the methodology developed by Nagel et al. (2025), to fill data gaps and smooth the time series. This approach was previously evaluated using 1,200 randomly selected locations, demonstrating its ability to reduce short-term variability while preserving overall temporal patterns. The moving window mitigates temporary fluctuations in river area associated with changing water levels, as well as image imperfections caused by

undetected clouds, while maintaining long-term trends associated with erosion and sedimentation (Fig. 2a). Due to the application of the moving window and data gaps in certain regions, the first five years of analysis were excluded, resulting in a 34-year analysis period.

Figure 3 – Some "noise" is visible on land in the background of the mNDWI tendency images; is that filtered out or included in the number of pixel counts? Does it have any impact on the results?

Response: We thank the reviewer for this observation. The background noise visible in the mNDWI tendency images is excluded by applying the detection thresholds and therefore does not contribute to the erosion and sedimentation pixel counts. We have revised Figure 3 to include the corresponding erosion and sedimentation detection maps using the least restrictive threshold (0.04), illustrating how this noise is filtered out.

Included L 235 – 244: "Figure 3 illustrates the detection of erosion and sedimentation from mNDWI tendency images using the least restrictive threshold (0.04), which effectively removes background noise. It also presents the resulting annual time series of erosion and sedimentation pixel counts and their detrended patterns. Although the workflow involves several processing steps, the underlying principle is relatively simple. First, we use satellite imagery to estimate the areas of erosion and sedimentation for each river bend on an annual basis, expressed as the number of pixels classified as erosion or sedimentation. We then detrend both time series to remove long-term trends, as our interest lies not in the magnitude of erosion or sedimentation, but in how these processes vary in relation to each other over time. Finally, we analyse the temporal relationship between the detrended curves to determine whether changes in outer-bank erosion tend to precede changes in inner-bank sedimentation, indicating bank pull, or whether the opposite occurs, indicating bar push."

Figure 3 – maps have different years (1989, 2005, 2010) than the caption (1991, 2005, 2019).

Thank you for spotting this. We have corrected accordingly.

L232: Add "annual" before "rates of erosion and deposition".

Thank you for spotting this. We have corrected accordingly.

Figure 4: Tamlin not needed in 4a and 4b.

Thank you for spotting this. We have corrected accordingly.

L478-484: Agree these are likely to be important, but would these processes be captured by the 5-year moving window for the analysis? This relates to the earlier comment on selection of the moving window timeframe.

Response: The mechanisms discussed here are hypotheses based on previous studies, proposed to explain the observed association between vegetation and bar push. Our analysis considers the presence (or absence) of vegetation rather than its temporal dynamics, and therefore does not directly capture processes such flow redirection, or tree

falls. These mechanisms are discussed as possible explanations for our findings, rather than processes directly measured by the 5-year moving window.

New L 593 – 595: "Although these processes provide plausible explanations for the observed relationships, our analysis considers vegetation conditions rather than their temporal dynamics and does not directly capture the individual physical mechanisms involved."

L516–519: Some further reflection is needed on how globally representative the results are. If more rivers were sampled, would the pull/push dominance change?

Response: Our study included all river bends that could be reliably identified and delineated using the Water Transition Dataset (Nagel et al., 2025), based on clearly identifiable erosion and sedimentation areas and well-defined inflection points. Therefore, the sample was not restricted to a predetermined number of bends or rivers.

To further assess the representativeness of our dataset, we compared the erosion and accretion rates of the riverbank nodes included in our sample with those of the global Pavelsky dataset. This comparison revealed that our sample covers nearly the full range of observed rates, extending from the 0.03rd to the 99.99th percentile for erosion and from the 0.03rd to the 99.93rd percentile for accretion. However, the sampled nodes are more concentrated at higher erosion and accretion rates.

These findings indicate that our dataset encompasses a broad range of riverbank migration rates, although its distribution is not identical to that of the global reference dataset. Moreover, we acknowledge that the selection criteria may limit the representativeness of the observed proportions of bank pull and bar push. Including additional rivers, particularly those with bends that could not be reliably delineated, could potentially change these proportions, although the direction and magnitude of such changes remain uncertain.

New L 145 – 148: "The dataset covers nearly the full range of erosion and accretion rates observed in the global Pavelsky dataset, spanning the 0.03rd to 99.99th percentiles for erosion and the 0.03rd to 99.93rd percentiles for accretion. However, the sampled riverbank nodes are more concentrated at higher rates of erosion and accretion."

New L 655 – 659: "Although our analysis encompasses a large number of river bends distributed worldwide, the sample is limited to bends with clearly identifiable erosion and sedimentation areas and well-defined inflection points. Consequently, the observed proportions of bank pull and bar push should not be interpreted as globally representative of all meandering rivers. Including additional rivers, particularly those not meeting our delineation criteria, could alter these proportions."