Reviewer 1

My major concerns are related to the analysis of environmental variables:

I do not think the current Table 1 and Figure 7 provide sufficiently clear evidence to support the conclusions. I suspect that the associations with these environmental variables may not be very strong, and these variables may not be expected to provide substantial predictive skill. Nevertheless, it would be useful to illustrate the regression results more explicitly, for example by showing the fitted relationships and/or predicted probabilities.

Response: We thank the reviewer for this suggestion. To better assess and illustrate the relationships between environmental variables and bank pull/bar push occurrence, we have implemented a Random Forest model and produced an entirely new Figure 8 illustrating the findings. The new figure presents SHAP values, showing both the direction and magnitude of each variable's contribution to model predictions (Fig. 8a), alongside their relative importance (Fig. 8b). This approach allows us to identify which environmental variables contribute most strongly to distinguishing between the two migration mechanisms, while also accounting for potentially nonlinear relationships. We have substantially revised the Results and Discussion sections to reflect this new analysis.

New L 446 – 474 – "We employed a Random Forest classifier to investigate the relative contribution of environmental, hydrological, and geomorphological variables to the distinction between Bank Pull and Bar Push mechanisms. The model was evaluated across 30 spatially structured training and testing splits (70% and 30%, respectively), performed within each river to increase spatial separation between training and testing bends and reduce spatial dependence. The model achieved a mean accuracy of 0.599 ± 0.024, balanced accuracy of 0.595 ± 0.022, and ROC-AUC of 0.635 ± 0.031. All performance metrics are dimensionless, and values are reported as mean ± standard deviation across the 30 repetitions. These results indicate modest discriminatory performance, with relatively limited variation across repetitions. 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.

However, our primary objective was not to predict whether individual river bends are dominated by Bank Pull or Bar Push, but rather to understand which variables contribute to their differentiation. For this purpose, we applied SHapley Additive exPlanations (SHAP), a model interpretation method based on cooperative game theory that quantifies the contribution of each variable to individual model predictions (Lundberg & Lee, 2017). SHAP

values indicate both the magnitude and direction of each variable's contribution relative to the model's baseline prediction. Values close to zero indicate little influence on a particular prediction, whereas larger absolute values indicate stronger contributions. Positive and negative SHAP values indicate contributions towards different predicted classes, depending on the model output being explained. In our binary classification, where Bank Pull was coded as 0 and Bar Push as 1, positive SHAP values favour predictions of Bar Push, whereas negative values favour Bank Pull, assuming SHAP values are calculated for the Bar Push class. Thus, the Random Forest was used primarily as an exploratory framework for investigating relationships between environmental variables and Bank Pull and Bar Push mechanisms, rather than as an operational predictive tool. Figure 8 presents the contribution of environmental, hydrological, and geomorphological variables to the Random Forest classification of Bank Pull and Bar Push."

Two additional variables that I think could potentially be useful for the pull/push analysis are flow variability (e.g., coefficient of variation) and bend angle. These should be relatively straightforward to derive from the existing data.

Response: We thank the reviewer for this helpful suggestion and have expanded our analysis to include discharge variability, sinuosity, and channel curvature as additional predictors in the Random Forest model. Discharge variability was obtained from Ouellet Dallaire et al. (2019) and was defined as the ratio between the maximum long-term average monthly discharge and the long-term mean discharge, rather than the coefficient of variation (CV). These variables contributed to distinguishing between bank pull and bar push, although their relative importance varied. Discharge variability was the fourth most important predictor, with higher values associated with bank pull. Higher sinuosity and curvature also contributed to bank pull predictions, although their predictive importance was lower. These relationships are now presented in the revised Figure 8 and discussed in the manuscript.

How does river width change over time for the investigated rivers? This point is mentioned in the Introduction but is not analysed in the Results or Discussion.

Response: We have expanded the Introduction and Discussion to clarify why changes in river width were not used in our analysis. Although river width reflects the balance between erosion and sedimentation, it does not indicate which process precedes the other, which is the central distinction between bank pull and bar push. Furthermore, width measurements derived from 30 m Landsat imagery are sensitive to water-level fluctuations and uncertainties in bankline delineation, particularly along shallow inner banks. We therefore focused on separately quantifying erosion and sedimentation and examining their temporal relationships, rather than using changes in river width as an indicator of the dominant migration mechanism.

New L 120 – 134: "However, in natural environments, river width varies with water levels, which fluctuate due to changing hydrological conditions (Feng et al., 2022; Phillips et al., 2024). This issue is particularly evident on the shallower inner bank, where even minor

fluctuations in water level can cause substantial advance or retreat of the water-defined bankline. These changes can obscure bank pull and bar push signals, a challenge further amplified by the spatial resolution of satellite imagery. For example, when using 30 m Landsat imagery (as is the case here), small changes in bank position may remain undetected or be affected by mixed pixels and uncertainties in water boundary delineation, introducing additional noise into the estimation of river width. For these reasons, we do not use changes in river width to distinguish between bank pull and bar push mechanisms. Besides being sensitive to water-level fluctuations and uncertainties associated with the 30 m spatial resolution of Landsat imagery, changes in river width also reflect the net balance between erosion and deposition rather than indicating which process drives channel migration. Instead, we adopt a pixel-based approach to separately track outer-bank erosion and inner-bank sedimentation over time, allowing us to investigate their temporal sequence rather than assuming that greater erosion or deposition rates necessarily indicate the dominance of one mechanism."

New L 646 – 655: "An important methodological consideration is that changes in river width were not used to distinguish between bank pull and bar push. Although channel width reflects the balance between outer-bank erosion and inner-bank sedimentation, it does not reveal which process precedes the other. Furthermore, width estimates derived from Landsat imagery are subject to uncertainties associated with its 30 m spatial resolution, particularly in narrower channels, as well as variations in water level that can affect the apparent position of the bankline, especially along shallow inner banks. Consequently, width changes may obscure the temporal relationship between erosion and sedimentation that defines the two mechanisms. Our pixel-based approach instead examines these processes separately, allowing their temporal sequence to be assessed without assuming that erosion and deposition occur at equivalent rates or that channel width remains constant".

It would also be interesting to investigate whether there are systematic differences in migration rates among different regions and climatic settings, or between pull-dominated and bar-dominated rivers.

Response: We have expanded our analysis to compare erosion, sedimentation, and total mobility between bank pull and bar push, as well as total mobility across individual rivers. The results show that bank pull bends exhibit significantly higher erosion, sedimentation, and total mobility than bar push bends ($p < 0.001$), although substantial variability exists among rivers. These findings are now presented in the revised Figure 7 and discussed in the Results section.

New L 429 – 438: "Figure 7 compares the magnitude of erosion, sedimentation, and total mobility between Bank Pull and Bar Push mechanisms, as well as the variability in total mobility across rivers. Overall, bends classified as Bank Pull exhibit higher erosion, sedimentation, and total mobility than those classified as Bar Push, with statistically significant differences ($p < 0.001$). Erosion also tends to exceed sedimentation, although this pattern is not consistent across all bends. Considerable variability is observed among rivers,

with some systems exhibiting substantially greater mobility than others. Rivers such as the Beni, Khan, and Guaviare show relatively high total mobility, illustrating that intense morphological activity can occur under both Bank Pull and Bar Push mechanisms. These results suggest that, although the two mechanisms differ in their overall mobility distributions, the magnitude of riverbank erosion and sediment deposition varies considerably across river systems."

Regarding the water-index method, how is pixel connectivity considered? From the presented plots, the classified water pixels appear to be nicely connected and adjacent to the channels. However, if pixel-scale NDWI is being tracked, I would expect some pixels to be classified as water without being directly connected to the channel. If this occurs, how are such pixels handled? Some clarification of the procedure is needed.

Response: Potential interference from disconnected water bodies was addressed primarily through the manual delineation of river bend polygons using the Water Transition Dataset (Nagel et al., 2025). Lakes and other nearby water bodies exhibiting temporal changes were identified and excluded from the analysis boundaries. In addition, multiple mNDWI thresholds were applied to reduce spurious detections associated with isolated pixels and other sources of noise. We have clarified these procedures in the revised Methods section.

Included L 149 – 157: "River bends were selected and delineated using the Water Transition Dataset developed by (Nagel et al., 2025), which maps historical patterns of erosion and sedimentation. We selected bends with clearly identifiable erosion and sedimentation areas and well-defined inflection points, allowing individual bends to be consistently delineated (Fig. 1). A polygon was manually drawn for each selected bend, with its boundaries defined by the inflection points. The Water Transition Dataset was also used to identify nearby lakes and other water bodies exhibiting changes over time that could interfere with the detection of riverbank erosion and sedimentation. This spatial delineation restricted the analysis to the river bend and its immediate migration zone, reducing the likelihood that changes in disconnected water bodies would be incorrectly classified as riverbank erosion or sedimentation."

From the text in L 209 – 2012: "To account for varying migration rates, we applied additional thresholds, including 0.06 ΔmNDWI for erosion and -0.06 ΔmNDWI for sedimentation, along with values of ±0.08, ±0.1, ±0.12, and ±0.14 ΔmNDWI. The final erosion and sedimentation rates were determined by calculating the median of all thresholds where more than half of the values were greater than zero."

We included in L 212 - 214: "By retaining thresholds that consistently identify river movement, this approach reduces the influence of spurious detections while balancing migration sensitivity and data quality."

I have the following minor comments:

I wonder how sensitive the reported ratio is to the selection of the 4,923 river bends.

Response: We included all river bends that could be reliably identified and delineated according to our methodological criteria, rather than selecting a predetermined sample. Nevertheless, we acknowledge that the observed proportions of bank pull and bar push may be sensitive to the inclusion of additional rivers and bends. We have therefore added a discussion of this limitation to the revised manuscript, clarifying that the reported proportions should not be interpreted as being representative of all meandering rivers globally.

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 necessarily be interpreted as being representative of all meandering rivers. Including additional rivers, particularly those not meeting our delineation criteria, could alter these proportions."

Lines 69–77: This text duplicates the material presented in Lines 42–49. A similar duplication appears in Lines 88–92. These points have already been described in the Introduction and could be shortened or removed.

Thank you for spotting this. We have corrected accordingly.

Lines 105–106: Equilibrium is mentioned here for the first time. It is not clear whether equilibrium is expected or required for an effective analysis of the bank-pull and bar-push effects. Some clarification would be helpful.

Response: We have clarified that equilibrium between erosion and sedimentation is not a prerequisite for identifying bank pull and bar push. These mechanisms are distinguished by the temporal relationship between outer-bank erosion and inner-bank sedimentation, rather than by equivalent erosion and deposition rates or constant channel width. We have expanded the Introduction to make this distinction explicit.

New L 101 – 115: "Therefore, while the study by Martin et al. (2024) was spatially constrained to a single bend, Mason and Mohrig (2018) did not resolve the temporal sequence of outer-bank erosion and inner-bank sedimentation to examine which process preceded the other. We argue that neither changes in river width nor the relative magnitude of erosion and deposition necessarily indicate which mechanism drives channel migration. Bank pull and bar push describe the relationship between outer-bank erosion and inner-bank sedimentation, rather than simply which process occurs at a higher rate. For example, relatively limited outer-bank erosion may drive more extensive deposition along the inner bank, while still representing a bank pull mechanism. Similarly, width equilibrium is not a prerequisite for identifying these mechanisms, since erosion and deposition do not necessarily occur at equivalent rates. Changes in river width therefore reflect the net balance between erosion and deposition, rather than revealing which process drives channel migration. Identifying bank pull and bar push requires examining the spatial and temporal relationships between outer-bank erosion and inner-bank sedimentation, particularly whether one process systematically precedes the other. Remote sensing time

series offer an opportunity to investigate these relationships across a large number of river bends and diverse river systems."

Lines 139–140: I wonder how the 4,923 bends are selected, are those from the global rivers after applying the criteria outlined here (e.g., channel width, migration rate, and dams)?

Response: The 4,923 bends were identified from the selected rivers using the Water Transition Dataset (Nagel et al., 2025). We included all bends with clearly identifiable erosion and sedimentation areas and well-defined inflection points, allowing consistent manual delineation. We have revised the Methods section to clarify the bend selection and delineation procedures.

New L 149 – 157: "River bends were selected and delineated using the Water Transition Dataset developed by Nagel et al. (2025), which maps historical patterns of erosion and sedimentation. We selected all bends with clearly identifiable erosion and sedimentation areas and well-defined inflection points, allowing individual bends to be consistently delineated (Fig. 1). A polygon was manually drawn for each selected bend, with its boundaries defined by the inflection points. The Water Transition Dataset was also used to identify nearby lakes and other water bodies exhibiting changes over time that could interfere with the detection of riverbank erosion and sedimentation. This spatial delineation restricted the analysis to the river bend and its immediate migration zone, reducing the likelihood that changes in disconnected water bodies would be incorrectly classified as riverbank erosion or sedimentation."

Lines 144–145: Does the filtering consider dams/reservoirs upstream of the river reach as well, or only those within the investigated reach? Please clarify how this filtering was performed.

Response: The absence of dams was not an explicit selection criterion. During the selection process, we avoided river reaches directly affected by reservoir backwater conditions. However, the presence of dams further upstream was not systematically assessed and was therefore not used as an exclusion criterion. Consequently, although the investigated reaches were not directly affected by reservoir backwater conditions, we cannot rule out potential downstream influences of upstream dams on sediment transport and flow regimes. We have clarified this distinction in the revised manuscript.

We included L 143 – 148: "River reaches directly affected by reservoir backwater conditions were excluded from the analysis. However, the presence of dams further upstream was not systematically assessed. 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."

Figure 1: It is difficult to differentiate between streams and sedimentation, and between bend polygons and erosion. Different colours or other visual distinctions should be used to make these features easier to distinguish. I also suggest explaining how the watershed is selected in the first paragraph of the Methods section.

Thank you for spotting this. We have corrected accordingly.

Figure 2, panels a and b: It would be better to place the index name alongside the colour bar rather than using it as the panel title.

Thank you for spotting this. We have corrected accordingly.

Figures 2 and 3: It would be helpful to annotate the river location (longitude and latitude), perhaps also on the satellite imagery, to provide better geographical context.

Thank you for spotting this. We have corrected accordingly.

Lines 271–273: I wonder why MODIS is used instead of Landsat, given that Landsat is already used for the pull/push analysis and provides substantially higher spatial resolution. For rivers approximately 55 m wide, is the 500 m spatial resolution of MODIS sufficient to support the vegetation analysis?

Response: We agree that the 500 m spatial resolution of MODIS may be insufficient to adequately characterize vegetation conditions around relatively narrow rivers. In response to this concern, we revised our methodology and replaced MODIS-derived EVI with Landsat-derived EVI at 30 m spatial resolution. This change provides a more detailed characterization of vegetation surrounding individual river bends and improves the spatial consistency between the vegetation data and the satellite observations used to identify bank pull and bar push mechanisms. The Methods section has been updated accordingly.

New L 291 – 293: "Vegetation conditions surrounding each river bend were characterized using the Enhanced Vegetation Index (EVI) derived from Landsat imagery at 30 m spatial resolution".

Section 3.3, Table 1: I notice that mean and median values are used for environmental variables that have temporal variation. How robust is the correlation when temporal changes in these variables are not considered, particularly for vegetation?

Response: Our objective was to identify broad environmental characteristics associated with bank pull and bar push across 4,923 river bends worldwide, rather than to investigate the temporal effects of individual variables. We therefore used summary statistics to characterize environmental conditions consistently across the study sites. To assess temporal variability in vegetation, we examined EVI statistics for all the river bends. The median temporal standard deviation was 0.052, with 75% of bends exhibiting values below 0.068, suggesting relatively limited temporal variability. Nevertheless, we acknowledge that summary statistics do not fully capture temporal changes in vegetation and other environmental conditions that may influence riverbank dynamics. Investigating these temporal relationships would require a different analytical framework and represents an important direction for future research. Investigating these relationships would require a different analytical framework and represents an important direction for future research.

We included L 293 – 296: “Vegetation cover exhibited relatively limited temporal variability across the analyzed bends. The median temporal EVI standard deviation was 0.052, with 75% of bends exhibiting values below 0.068, suggesting that vegetation conditions remained relatively consistent throughout the observation period”

We included L 298 – 301: “Given the global scope of the analysis, environmental variables were summarized to characterize the prevailing conditions at each river bend, rather than their temporal dynamics. Consequently, the analysis focuses on broad spatial associations, without explicitly accounting for temporal variations in variables such as vegetation.”

Figure 5: It would be helpful to include the river name and acquisition date on the images.

Thank you for spotting this. We have corrected accordingly.

Figure 6: The legend for the black-and-white background images is missing. Do these images represent NDWI values? Please clarify.

They represent the Google Basemap on a gray scale. We have added an explanation on the figure accordingly.

Figure 7: I am not sure that the bar plots provide the clearest evidence for the analysis of the environmental variables. What do the results from the multivariable logistic regression look like? I think some figures illustrating the regression results would be useful to support the analysis. The table may contain the relevant information, but the results are currently less intuitive to interpret.

Response: As mentioned above, we have replaced the multivariable logistic regression with a Random Forest classification model and revised Figure 8 accordingly. The new figure presents SHAP values and variable importance, allowing a clearer interpretation of the magnitude and direction of each environmental variable's contribution to bank pull and bar push predictions. The Results and Discussion sections have also been updated to reflect this new analysis.

Please provide the code and data outputs associated with the analysis as supplementary material or in an appropriate public repository.

Response: Thank you for the suggestion. We have made the dataset and analysis code publicly available on Zenodo. The repository includes the GeoJSON dataset containing bank pull and bar push classifications and their associated environmental variables, along with the Python code used for the Random Forest analysis.

New 704 – 705: “

Data availability

The dataset and code used in this study are publicly available on Zenodo at https://doi.org/10.5281/zenodo.23540949. The repository includes a GeoJSON file containing the bank pull and bar push classifications and associated environmental

variables for the analyzed river bends, as well as the Python code used to perform the Random Forest analysis."