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Modelling the Long-term, Cumulative Impacts of Upstream Meander Restoration on the Downstream Channel's Geomorphology

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Abstract: Meander restoration contributes to the flow energy reduction, the river systems' overall stability enhancement and a number of ecological services production. The spatial and temporal impacts of this technique on the river's flow and sediment behaviour are critical topics that practitioners should respond to. Because of the scale and cost of such projects, it is difficult to make informed decisions about the optimal siting, scale, and linked-up benefits of restoration projects based solely on real-world case studies. Digital models such as landscape evolution models, on the other hand, can be used to test numerous alternate futures to make more informed decisions concerning the allocation of scarce resources in landscape planning contexts, revealing a range of potential outcomes of anthropogenic interventions within dynamic river systems. This can provide proper technical support for restoration proposals. This study utilises CAESAR-Lisflood to simulate the impact of various meander reconstruction scenarios on the downstream geomorphology in terms of erosion, deposition, channel migration patterns and sinuosity and braiding variations. Moreover, project size and location in the catchment are used to determine the most effective investment of limited resources by analysing the long-term, cumulative impacts of the scenarios. The initial results suggest that restorations in the lower reach of the channel would be more beneficial to the downstream channel's stability than in the upper reach of the channel. Furthermore, multiple smaller restoration projects benefit more than fewer, larger projects of equivalent length. These findings derived from digital experimentation could help decision-makers and practitioners implement plans to optimise project scoping and placement in the catchment-scale planning phase to conduct meander restoration, in particular, where there are cost limitations and property ownership issues.

Keywords: Meander restoration, cumulative effects, geomorphology changes, CAESAR-Lisflood simulation

1 Introduction

Meander restoration and reconnection are widely used re-naturalisation tools for channelised and urbanised rivers which were historically sinuous. Substantial research indicates this technique could: (1) alleviate the excessive incision effect on stream beds, subsequently decreasing sediment yield downstream (KONDOLF 2006), (2) reduce channel instability by dissipating water unit power and potentially adding storage area (BROOKES 1990) and (3) create various instream and riparian habitats (LORENZ et al. 2016). Moreover, the geomorphology of the fluvial system plays an indispensable role in restoration success because of a river's dynamically changing nature (SEAR 1994). SEAR (1994) illustrated that, within a long-term scale, a more sustainable and idealistic restoration approach that allows the river system to evolve spontaneously into a more stable form needs to accommodate the catchment-scaled geomorphological dynamics (SOAR & THORNE 2001). Therefore, how the detailed planform and reconstructed morphology should be designed in terms of its geometry and how the

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river's flow and sediment will react to the proposed measures both spatially and temporally are crucial questions that need to be answered by practitioners.

Cases exist where several restoration projects funded by unrelated organisations were individually implemented in river systems with little consideration regarding their cumulative effects on the catchment. Existing studies have emphasised the cumulative benefits and demonstrated its evaluation method in wetland restoration, wherein the differences between its cumulative effects and the sum of independent projects on water quality have been indicated (BECK et al. 2019). Furthermore, the cumulative effects of river-channel modification through time and specific measures on channel and floodplain morphology have been evaluated in both empirical and model-based studies (TENA et al. 2020). Thus, considering cumulative effects from a catchment view is a critical aspect of fluvial system restoration.

Considering their huge cost, potentially unpredictable outcomes, especially when multiple projects are linked up, and the complexity of implementing projects in real-world contexts with a host of stakeholders, it is essential to know in the early stage what kinds of projects are worth pursuing further. Digital simulations are one way of testing project feasibility. Substantial studies have used landscape evolution models (LEMs) for quantifying and predicting the sediment and flow responses which subsequently alter the downstream morphology. Among these, CAESAR-Lisflood is one of the models which can elaborate sediment deposition and suspension conditions in the restored basin (HANCOCK & COULTHARD 2012). Simulations themselves can prove quite costly, however, and might only be feasible once significant resources have already been invested. Can they be used to identify generalisable patterns to help guide decision making at the earliest possible stage?

This study aims to use LEM simulations to model the consequences not of a specific project itself, but to model the cumulative geomorphological effects of multiple meander restoration project scenarios to help decision-makers and practitioners to discover generalisable practices that promote relative channel stability in order to better allocate scarce resources. CAESAR-Lisflood has been applied to forecast the long-term geomorphological impacts. More specifically, this study has used a digital simulation to answer the following questions:

1) Which is a more effective approach on the downstream channel's stability, one single large project or multiple smaller restoration projects of equal cumulative length when implemented in the upstream channel?
2) How will the relative placement of restoration projects upstream, whether higher up in the catchment versus in the middle of the catchment, affect the long-term morphological development of the channel downstream?

2 Methods

2.1 Study Area

The study area is located in the Don Catchment in the northeast of England, UK (Fig. 1). The River Don is the main channel with several major tributaries including the Dearne and the Rother, joining it in the middle part. The river flow rate can change considerably since the catchment is comparatively thin, daily rainfall fluctuates markedly and the rivers are supplied mainly by runoff (SHAW et al. 2016). This study selected two sub-catchments – the Dearne

(328 km^2) and the Rother-Doe-Lea (397 km^2) – to test the effects of meander restoration projects on the downstream parts of the two sub-catchments as the area whose simulated geomorphological evolution has been compared (Fig. 1).

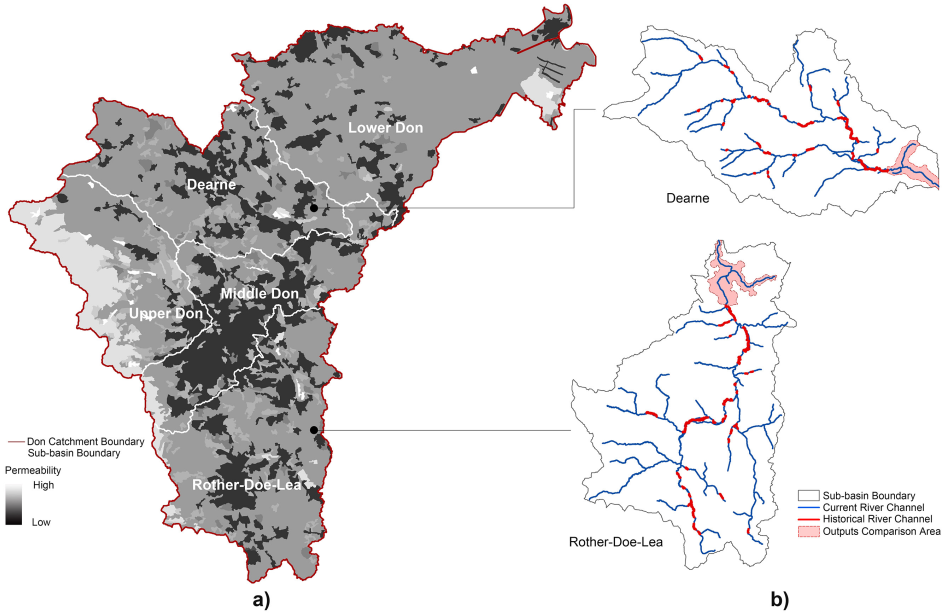


Fig. 1: a) The Don Catchment Permeability and b) selected sub-catchments the Dearne and the Rother-Doe-Lea and corresponding outputs comparison areas

2.2 CAESAR-Lisflood Model Description and Simulation Scenarios

CAESAR as a cellular landscape evolution model (COULTHARD & WIEL 2006) and LISFLOOD-FP a 2D hydraulic model (BATES et al. 2000) have been integrated into a new hydro-landscape evolution model 'CAESAR-Lisflood' that can simulate in a more physics-based and realistic way. It has been frequently used in simulating flood control measures, with recent research quantitatively evaluating CAESAR-Lisflood's capability and accuracy (PASCULLI & AUDISIO 2015). It was demonstrated that CAESAR-Lisflood shows good performance with low error in the test of historical landscape replication (FEENEY et al. 2020).

After comparing the current and theoretical river network, which is generated from hydrologic analysis using ArcMap, sites with significant differences between the two were identified. Considering the practicalities of interventions, the sites with soft land cover were further considered for potential meander restoration. According to Brookes and Rosgen, there are two approaches to implement river morphology restoration: (1) historic replication based on 'carbon copying' (BROOKES & SHIELDS 1996) and (2) similar reach reference (ROSGEN 1998). The first of these two approaches are tested with restored river channels in the high potential areas drawn based on historical maps to maintain consistency. Ultimately, the possible points map for meander reconstruction projects provides suggestions on its specific location and shape for the simulation scenarios.

Table 1: Meander restoration plan for scenarios simulation in the Dearne

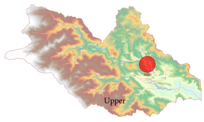
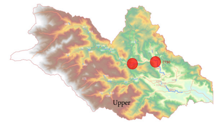
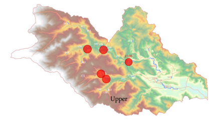
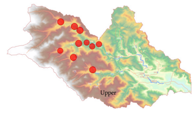
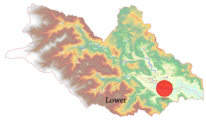
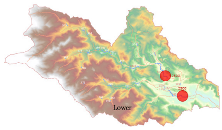
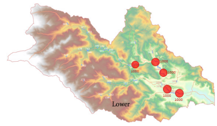
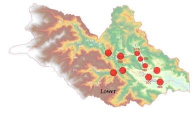
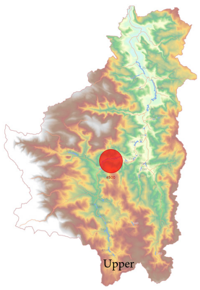
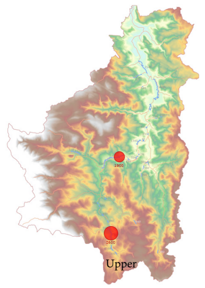
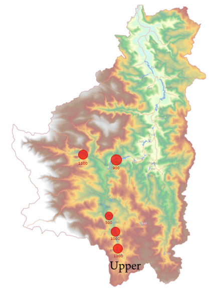
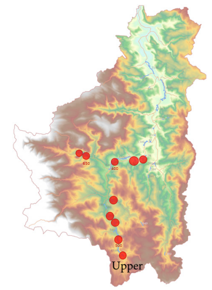
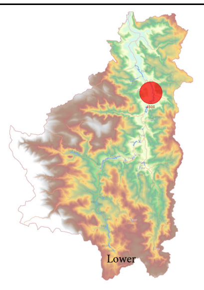
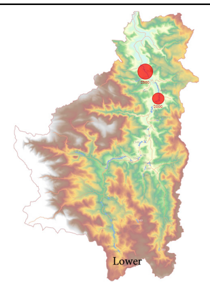
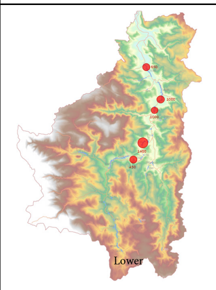
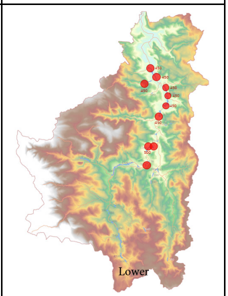
	1 (5 km) section	**2 (2 * 2.5 km) sections**	**5 (5 * 1 km) sections**	**10 (0. 5 km) sections**
Series 1 – Upper place-ment				
Series 2 – Lower place-ment				

Table 2: Meander restoration plan for scenarios simulation in the Rother-Doe-Lea

	1 (4.5 km) section	**2 (2 + 2.5 km) sections**	**5 (4 * 1 + 0.5 km) sections**	**10 (0.45 km) sections**
Series 1 – Upper place-ment				
Series 2 – Lower place-ment				

The total lengths of simulated meander restoration projects are determined to be 5 km in the Dearne and 4.5 km in the Rother-Doe-Lea. From this, two potential approaches with projects clustered in 1) the upper reaches versus 2) the lower reaches are tested to compare the performance of project spatial placement. Then the simulation is tested by changing the division plan of the meander restoration projects. In each sub-catchment, the cumulative project length is maintained in each scenario, which is tested as either 1 large project or 2, 5, or 10 smaller projects. The specific meander restoration plans (Table 1 and 2) for a total of 8 scenarios are based on the restoration potential points map.

2.3 Model Set Up

The operational data inputs for this study contain a digital elevation model (DEM), data on sediment including grain size and proportion, and rainfall intensity (mm/h) (Table 3). Restricted by the total cells of this model, a 50 m resolution DEM of current topography is resampled from the Ordnance Survey (OS) 5 m resolution (2019) DTM product using ArcMap. DEMs representing meander-restored scenarios were modified by applying the 'Rasteredit' tool (available at http://www.coulthard.org.uk/downloads/downloads.htm). The grain size and proportion data are derived from the geological map data and a rough proportion of the 3 grain classes: clay (0-0.002mm), silt (0.002-0.06mm) and sand (0.06-2.0mm) are used. The 20-year (2021-2040) hourly rainfall input for the two sub-catchments is obtained from the UKCP 18 local climate projection database.

Table 3: The input values of CAESAR-Lisflood

Tabs	Parameters	Values	Data source
DEM	–	Resolution 50 m	resampled from the OS Terrain 5 (2019) DTM
Sediment	Grain sizes (mm)	0.001, 0.0015, 0.002, 0.01, 0.02, 0.05, 0.625, 2	Geological Map Data BGS
	Grain size proportions	0.08, 0.15, 0.265, 0.225, 0.125, 0.035, 0.065, 0.055	Geological Map Data BGS
	Sediment transport law	Wilcock & Crowe Formula	Based on field and laboratory data from a coarser bed gravel/sand mix
	Lateral erosion rate	0.000001	
Hydrology	'm' value	0.015	Typically range from 0.005-0.02 so will use 0.015 to represent farmland.
	Rainfall	Hourly	UKCP 18 local climate projection
	Slope failure threshold	50°	
Flow model	Min Q for depth calculation	0.5	Min Q 05 for DEM cell size 50 m.
	Mannings' n	0.04	According to reference tables for Manning's n values for Channels.

2.4 Simulation Outputs Analysis

For the CAESAR-Lisflood simulations, output files can be saved regularly by time. In this study, DEMs, water depth and flow velocity are set to be collected every 200 days for the 20 years corresponding to 2021-2040. Simulated DEM results are used to calculate the volume of erosion and deposition. Pixels with decreased elevation are labelled 'erosion,' while pixels' with increased elevation are labelled 'deposition.' Flow velocity and water depth – are dually converted to shapefiles representing the evolved river channel based on tracing the line with the highest flow velocity as well as the deepest water. Cumulative lateral migration areas are subsequently calculated from the measured area formed by the evolved and the current main river channel intersection. On the other hand, the Sinuosity Index (SI) and Braid Index (BI) are significant indices for describing channel planform and can be used to study and analyse the river's spatial activity patterns, and thus can be used in this study to assess the geomorphic impacts of different meander restoration deployment strategies on the downstream river. According to BRICE (1964) and MULLER (1968), SI can be calculated by dividing the evolved channel's length by the valley's length. Where this ratio is between 1 and 1.05, the channel is called straight, between 1.05 and 1.3 is described as sinuous, and greater than 1.3 is defined as meandering. Finally, BI can be derived by calculating the ratio of the length of all included secondary and main channel to the length of the main channel (MOSLEY 1981), which is applied to define the braiding intensity of the river.

3 Results

3.1 Erosion and Deposition

Analysis of the erosion and deposition in the Dearne sub-catchment indicates that erosion volume increases linearly with time for the eight scenarios and base, while deposition volume tends to fluctuate and decrease with time with an insignificant linear relationship. However, since erosion activity is far more intense than deposition activity, the sum of erosion and deposition exhibits the same tendency as erosion. Moreover, both the daily erosion and deposition rates converge to two constant values respectively as time passes.

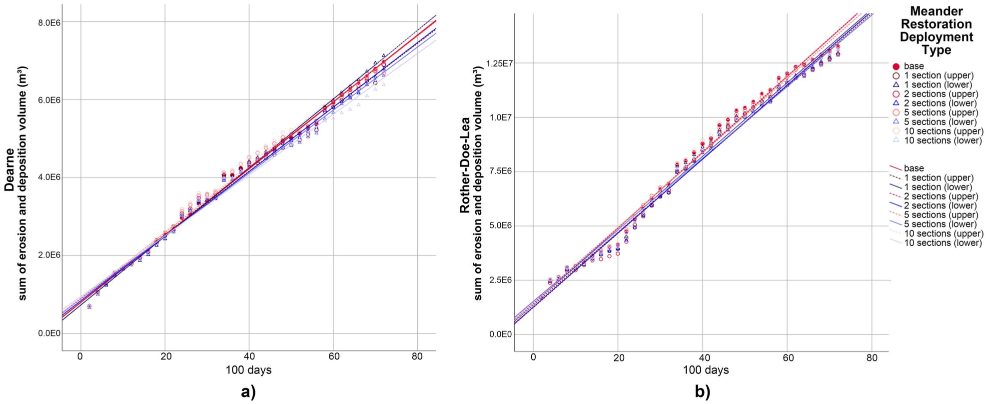


Fig. 2: Changes in the sum of stream erosion and deposition soil volumes over time (every 100 days) for the base and 8 restoration scenarios in a) the Dearne and b) the Rother-Doe-Lea sub-catchments between 2021 and 2040

In the Dearne sub-catchment, in general, meander restoration in the lower reaches is a better option than in the upper if erosion and deposition activity is to be mitigated, with 10 small projects in the lower reaches performing best (Fig. 2). More specifically, if meander restoration is carried out in the upper reaches, multiple small projects lead to more erosion and deposition in total than one large project. However, in the lower reaches, the more projects, the less erosion and deposition activity and the more stable the landscape. Notably, the total amount of erosion and deposition in all but two scenarios are less than the base group, which implies almost all options are contributing to the stability of the river geomorphology.

Compared to the Dearne, the Rother-Doe-Lea sub-catchment follows similar patterns (Fig. 2). In general, meander restoration in the lower reaches has a slightly lighter degree of erosion and deposition activity than in the upper reaches. The higher the number of modification projects in the upper reaches, the greater the total erosion and deposition, which is the exact opposite of when the projects are implemented in the lower reaches.

3.2 Channel Trajectory Lateral Migration

As the cumulative area of the channel's migration does not show a significant linear relationship with time, the mean and median values of the channel's active area at four time-points, 2025, 2030, 2035 and 2040, are selected for analysis and comparison in this study. Overall, in both cases, at the same project scale, there is a 62.5% probability that the restoration scenarios in the lower reaches perform better than in the upper reaches (the Dearne 100% and the Rother-Doe-Lea 50%) in the median values' comparison.

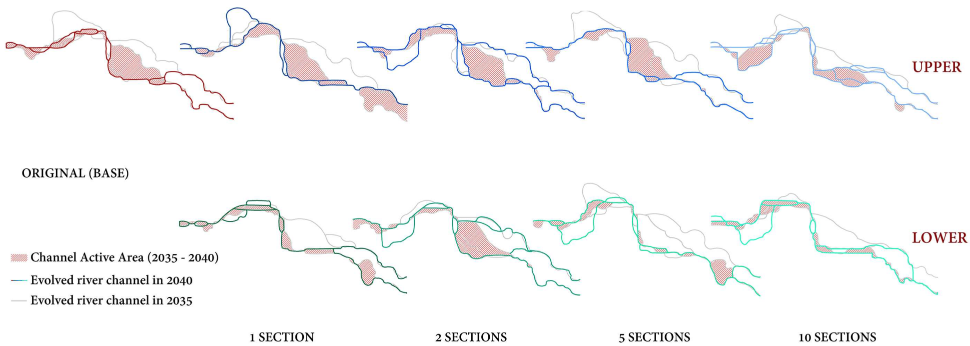


Fig. 3: Migration of the evolved channels of the base and 8 scenarios in the Dearne sub-catchment restoration from 2035 to 2040

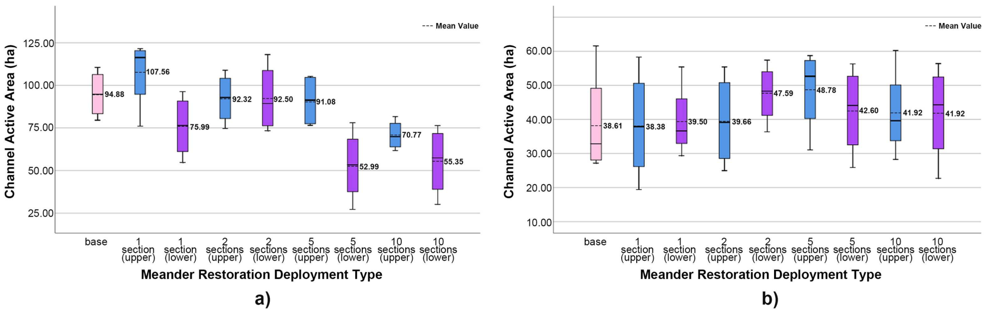


Fig. 4: The mean and median values of cumulative channel migration active areas of the base and 8 scenarios at four time-points, 2025, 2030, 2035 and 2040 in a) the Dearne and b) the Rother-Doe-Lea sub-catchments

In the Dearne, all modifications in the lower reaches results in less lateral river migration than in the upper reaches (Fig. 3 and Fig. 4). Except for the 1 large, all deployments in the upper have fewer mean cumulative active areas than in the base, with 10 small having by far the fewest active areas followed by 5 medium and 2 medium projects. However, in the lower reaches' restoration, the cumulative mean migration active areas are all less than in the base condition, especially the 10 small and 5 medium projects.

In the Rother-Doe-Lea sub-catchment, 8 meander restoration scenarios result in more complicated lateral migration (Fig. 4). In the upper area's restoration, the mean cumulative active areas are slightly greater than the base value, except for 1 large project, which is slightly smaller than the base, with 2 medium greater than 5 medium greater than 10 small projects. In the lower reaches, the mean area for the 2 medium projects is dramatically larger than the base, to which the values for the other three get close, with 5 medium larger than 10 small larger than 1 large larger than the base 10.33%, 8.57% and 2.3% respectively.

3.3 Sinuosity Index and Braid Index

In this study, four years (2025, 2030, 2035 and 2040) are selected in the period 2021-2040 to evaluate the stability of the downstream channel by comparing the changes in SI and BI in the corresponding scenarios in the two sub-catchments. The coefficient of variance (CV) can be used to compare the dispersion of the data obtained in different dimensions (Kuo et al. 2013) and thus measure the stability of the SI and BI over time in the different restoration

Table 4: The Planform Instability Index of the base and 8 scenarios in the two sub-catchments in the 4 years (the darker, the higher)

Sub-catchment	Project Size	Project Location	Sinuosity Index			Braid Index			Planform Instability Index
			M_{SI}	SD_{SI}	CV_{SI}	M_{BI}	SD_{SI}	CV_{SI}	
Dearne	base (no modification)		1.33	0.06	4.42%	1.7	0.48	28.04%	32.46%
	1 large	upper	1.33	0.08	6.17%	1.7	0.46	27.16%	33.34%
		lower	1.33	0.06	4.69%	1.56	0.36	22.81%	27.49%
	2 medium	upper	1.31	0.03	2.60%	1.82	0.41	22.55%	25.15%
		lower	1.32	0.06	4.73%	1.86	0.43	22.92%	27.56%
	5 medium	upper	1.31	0.05	3.92%	1.6	0.05	25.32%	29.25%
		lower	1.33	0.02	1.66%	1.77	0.37	20.84%	22.50%
	10 small	upper	1.36	0.04	2.94%	1.66	0.35	20.78%	23.73%
		lower	1.3	0.04	3.34%	1.74	0.34	19.30%	22.64%
Rother-Doe-Lea	base (no modification)		1.57	0.04	2.57%	1.44	0.26	17.81%	20.38%
	1 large	upper	1.53	0.05	2.95%	1.4	0.14	10.23%	13.18%
		lower	1.55	0.06	3.93%	1.51	0.1	6.40%	10.32%
	2 medium	upper	1.54	0.03	2.16%	1.43	0.32	22.54%	24.69%
		lower	1.59	0.1	6.24%	1.41	0.24	17.27%	23.52%
	5 medium	upper	1.61	0.07	4.04%	1.36	0.25	18.37%	22.40%
		lower	1.5	0.08	5.35%	1.42	0.23	15.90%	21.24%
	10 small	upper	1.55	0.03	1.65%	1.53	0.19	12.73%	14.39%
		lower	1.54	0.04	2.40%	1.49	0.47	31.14%	33.54%

scenarios in this study. The CV of SI and BI (CV_{SI} and CV_{BI}) are obtained by dividing the standard deviation (SD) of the four years obtained (SD_{SI} and SD_{BI}) by their mean (M) values (M_{SI} and M_{BI}), respectively. Finally, the planform instability index (PII) of the river in the sinuosity and braid profile defined in this study is obtained by summing the CV_{SI} and CV_{BI}, with larger numbers representing a more unstable channel ($PII=CV_{SI}+CV_{BI}$) (Table 4).

In the Dearne sub-catchment, the downstream reaches of the selected areas have SI values between 1.24 and 1.42 in all cases and around 1.3 in most cases, between sinuous and meandering. The M_{BI} values, on the other hand, suggested that the channel is the least braided (1.56) in the scenario of 1 large in the lower and the most braided (1.86) for 2 mediums in the lower. Finally, a comparison of the calculated PII shows that, in general, the downstream channel is more stable in the lower than in the upper restoration scenarios.

In the Rother-Doe-Lea sub-catchment, the SI values for the channel are generally greater than those for the Dearne sub-catchment, ranging between 1.36 and 1.71, all of which are sinuous. Although there are existing significant discrepancies in the comparison of its calculated PII and results of the Dearne, a common trend is that except 10 small projects, lower reaches' restoration result in more stable downstream than in the upper reaches. However, the 10 small and 1 large project downstream that performs the best and the second worst respectively in the Dearne performs the worst and the best here.

4 Discussion

This study compares the stability of downstream channels in two sub-catchments of Don, Dearne and Rother, in terms of different meander restoration scenarios in the upstreams. The comparisons are based on total channel erosion and deposition, cumulative channel migration distances and the degree of change in channel planform SI and BI in the period of 2021-2040, using simulations with CAESAR-Lisflood. Notably, the results of all three types of the analysis show that the restoration scenarios exceeding 60% contribute more to the constancy of the downstream river landscape than the base group without modification. More specifically, it suggests that conducting meander restoration in the middle reaches, rather than higher up, is more effective in enhancing the downstream channel's stability. Furthermore, in the middle reaches' restoration of the catchment, multiple small projects perform better than one single large project of equivalent overall length. Whether this pattern holds in other catchments of similar scale and geomorphology should be a question for further research, the answer to which should help planners and agencies in the early stages of project planning gauge the potential benefits of possible interventions.

The model uses the same precipitation and geological data in the same sub-catchments, but only because the different modified DEMs results in different geomorphological outputs for the river over time. As a result, the various landforms are formed in the scenarios primarily because of fluctuations in water discharge and sediment yield triggered by the modified topography (LANE et al. 1996). The multiple changes affect the downstream erosion and sedimentation activities, causing feedback in their morphology, which also causes the area further downstream to be subject to a dual effect of the initial topographic changes and the morphological feedback in its upper section. On the other hand, despite the discrepancies in the results of the three analyses, the exploration of the total volume of erosion and deposition is an exploration of three-dimensional properties, whereas the latter two are based on two- dimensional planform characteristics, and therefore the former has more credibility than the latter two to describe the extent of channel alteration.

CAESAR-Lisflood was applied to explore the hydrologic and sediment activities when given specific parameters such as rainfall or discharge, DEM standing for topography, grain size and proportion for sediment information, 'm' value representing catchment vegetation cover types, manning's n value for channel types and so on. In this study, hydrology, sediment and resistance-related parameters were not discussed, except for the DEM, which represents topographic changes. This enables the effects caused by terrain modification solely to be effectively identified. In the simulations, due to a large number of cells, the 20-year simulation for each scenario took several tens of hours, depending on the computing power of the equipment's processor. In addition, in the catchment and river studies, both at small scales with high resolution and large scales with low accuracy, the effects of changes in vegetation type, climate change, and the addition or removal of specific channel regulation facilities such as dams and large woods are also important issues and can be simulated using this model. These are perhaps the questions that future landscape researchers will need to address in the field of fluvial landscape using digital technology.

5 Conclusion

The upstream interventions undeniably impact the downstream's landscape stability, which is an essential concern in river management and a critical factor in landscape planning. The modelling approach can be applied to predict and visualise the morphological changes of the catchment thus helping landscape practitioners determine the optimal plan before it is conducted. This study investigates the long-term responses of downstream geomorphology to upstream's meander restoration at catchment scale and gives an example of the landscape evolution model's application in catchment planning which could contribute to downstream's stability thus the sustainable catchment management. It is also hoped that the findings can be used to assess river landscape modifications from the perspective of catchment morphology.

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