Article:

Wang, M. orcid.org/0009-0007-5251-5857, Claghorn, J. orcid.org/0000-0002-9389-4159 and Zhuo, L. orcid.org/0000-0002-5719-5342 (2025) Assessing the efficacy of tributary upstream meander restoration on downstream landscape stability through computational modelling. Landscape and Urban Planning, 254. 105232. ISSN 0169-2046

https://doi.org/10.1016/j.landurbplan.2024.105232

Landscape and Urban Planning 254 (2025) 105232

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

Assessing the efficacy of tributary upstream meander restoration on downstream landscape stability through computational modelling

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HIGHLIGHTS

- Re-meandering projects effectively limit channel migration and sediment yield.
- Re-meandering projects higher reduce sediment load more effectively than lower.
- Consolidated projects limit more bank erosion and sediment load than dispersed.

ARTICLE INFO

Keywords:
Nature-based Solutions (NBS)
Meander restoration
Landscape evolution models
Catchment landscape stability
CAESAR-Lisflood simulation

ABSTRACT

Meander restoration has become a commonly advocated solution in flood-prone or ecologically degraded river networks. The long-term impact of such measures on the stability of the landscape at the catchment scale beyond the implementation site itself is critical to project success and for sustainable catchment management and needs to be considered by all stakeholders. It is challenging, however, to predict the overall contribution of meander restoration in stabilising the lower catchment and to make reasoned assumptions about the optimal placement, scale, and interconnected benefits of restoration projects based on an analysis of real-life cases due to the complexity and uniqueness of each catchment's hydrology and the size and cost of such projects. Meanwhile, digital models can be utilised to test a wide variety of hypothetical futures so that the potential impacts of meander restoration can be understood in advance and limited resources can be better allocated to promote effective kinds of projects. In this study, computational modelling is employed to model the impacts of various upstream meander restoration scenarios on the downstream landscape due to erosion and deposition activities in northern England's River Don catchment. The results indicate that compared to a baseline scenario, river restoration in tributaries effectively reduces downstream main channel sediment discharge and lateral migration activities. Upstream restoration projects prevent watershed deterioration more effectively than downstream projects. Clustering projects close to one other is more effective in reducing valley lateral erosion and deposition, as well as channel loading, compared to having projects dispersed across multiple tributaries.

1. Introduction

The increased occurrence of flooding resulting from climate change and urbanization has prompted the recognition that conventional flood defences are insufficient and that a broader range of approaches to river and flood management should be explored (Cuny, 1991; Kalantari et al., 2017). In recent years, there has been a growing interest and broad implementation of nature-based solutions (NBS) in flood management due to their ability to improve urban resilience and offer a wide range of ecosystem services, as well as social and economic advantages (Brillinger et al., 2021; Short et al., 2019). Therefore, quantifying the effectiveness and limitations of NBS is an urgent and pressing issue for policymakers. Another aspect is that rivers have been straightened historically to facilitate more efficient land use, promote navigation, and locally control floods. This trend has been challenged or even reversed in recent decades, however, with meander restoration as one of the NBS being promoted to increase overall river system stability and to enhance ecosystem services, with meander restoration projects being considered and put into practice worldwide in river flood mitigation and ecological renewal projects (Nakamura et al., 2014; The river restoration center,

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https://doi.org/10.1016/j.landurbplan.2024.105232
Received 27 February 2024; Received in revised form 8 August 2024; Accepted 12 October 2024

2021). In some instances of river restoration, multiple project initiatives funded by different organisations are executed independently in a single river system with little regard for their aggregate effects on the entire catchment. In these cases, the linked effects of the restoration projects and their distributed deployment need to be more fully taken into account. Both empirical and model-based research have analysed the cumulative impacts of time-varying and specialised river regulations on the geomorphology of the channel and floodplain (Gao et al., 2019; Tena et al., 2020). Research has also emphasized that the cumulative effects of restoration projects on the hydrological regime cannot be determined by summing the individual parts, such as efficacy in improving water quality (Hemond & Benoit, 1988). If meander restoration is to be adopted more widely, it is essential to understand how the spatial arrangement of multiple meander reconstructions generates various long-term, cumulative effects. Such evidence can support the identification of river sections in a catchment where restoration can be most beneficial when the project's objective is to reduce flow incision and improve channel stability. The purpose of this study is to demonstrate the cumulative geomorphological responses of the main channel as a consequence of meander restoration projects higher up in the catchment's tributaries. The aim of this study is to assist decision-makers and practitioners in locating sites for potential restoration where the channel and floodplain are relatively stable before embarking on costly feasibility studies or even project implementation.

The geomorphology of the fluvial system plays an indispensable role in restoration success. (Sear, 1994; Soar & Thorne, 2001; Vietz et al., 2016). Inadequate accounting for a project's impact on downstream sedimentation and erosion occasionally induces the project's failure (Rinaldi & Johnson, 1997). In a study by Sear (1994), two different river restoration cases were compared, one of which was unsuccessful because of an increase in sediment load causing an unexpected meander migration downstream, while the other was successful due to the proper accounting for sediment and flow transport. These cases imply that not all restoration projects will have long-term, positive benefits, and that the catchment-scaled geomorphological dynamics need to be accounted for to prioritise projects that allow the overall river system to evolve into a more stable form over time (Soar & Thorne, 2001). A clear recognition of the drivers of change in river geomorphology through disturbance or restoration can contribute to sound policy development and river management (Tranmer et al., 2018). It is important then for governments, practitioners and other stakeholders to more fully consider catchment morphology features by projecting how the river's flow and sediment as well as the floodplain geomorphology will react spatially and temporally over the long term before implementing projects (Hancock et al., 2015).

A study of post-restoration monitoring data in one instance in Hokkaido Japan revealed that meander restoration significantly reduced flood-related suspended loads in the stream by over 80 % and greatly increased groundwater levels in the floodplain (Nakamura et al., 2014). An increase in width and depth may occur in the restored meanders, and a reduction in flow velocity often leads to accretion in the area (Eekhout et al., 2015). Physical laboratory experiments have shown that the extent and spatial distribution of alluvial activity in meanders is more stable and predictable than in straight channels (Welber et al., 2020) and results in an average 33 % reduction in bank erosion in restored reaches and an average 85 % increase in bank sedimentation (Han et al., 2015; Rachelly et al., 2021). On a larger scale, the planform migration of the channel can be influenced by upstream and downstream morphological changes (Seminara, 2010), which are spatially extended and decay in magnitude with increasing distance in the flow direction (Güeneralp & Marston, 2009, 2012). From a catchment management perspective, NBS impacts are comprehensive and can have project synergistic benefits (Liu et al., 2023). Nevertheless, there is limited research on the extended effects of meander restoration projects on areas further away from the modified reaches resulting in limited understanding of the holistic impacts on the river continuum. This is especially the case in terms of erosion and sedimentation activity and morphological evolution.

From a practical standpoint, river restoration projects in urban areas face higher financial costs and social consequences due to increased development densities, land prices, and the need for public support (Chen et al., 2022; Guimarães et al., 2021). Urbanisation in tributary sub-basins of upper catchment areas tends to be less intense than in the plains near the mainstream confluence. This difference is influenced by landform, geology, and evolutionary processes affecting water supply and navigation (Pattacini, 2021; Yesilnacar & Cetin, 2008). Furthermore, the river network, viewed as a continuum, exhibits dynamic flow interactions impacting species distribution, hydrological regimes, and geomorphological evolution (Doretto et al., 2020; Phillips et al., 2022). This interconnectedness is largely controlled by the river's topology and network embeddedness (White et al., 2018). Empirical studies have shown that tributary confluences influence channel width, valley slope, shape ratio, and load grain size in different sections of the mainstream. Larger tributaries have a more significant impact due to diverse flow and sediment discharge mechanisms (Benda et al., 2003; Benda et al., 2004). Additionally, most research has focused on small-scale responses within 100 m-1 km of the confluence (Benda et al., 2004; Hellmann et al., 2014). Consequently, upstream restoration efforts will affect downstream areas, necessitating an investigation of river system responses to modifications. Moreover, tributary floodplains offer potential for restoration initiatives, emphasizing the importance of studying river connectivity on a large scale before implementation (Hancock et al., 2015).

Landscape evolution models (LEMs) can aid in forecasting and examining the transformation of Earth's surface in meandering river-floodplain systems caused by human intervention or shifts in environmental conditions. CAESAR-Lisflood (CL) is one of the widely used LEMs used to quantify sediment deposition and suspension conditions (Coulthard & Van De Wiel, 2017) within the catchment that has experienced regulation and restoration (Meadows, 2014). CL is an integration of Caesar, a mesh-based LEM simulating erosion and deposition activities during various timescales, with Lisflood-FP, a 2-D flow model which traces water directions between cells (Coulthard & Van De Wiel, 2017). The generated water flow governs sediment transport or deposition, iteratively changing the elevation of each cell while updating the flow dynamics (Van De Wiel et al., 2007). As a result, it defines the zones of erosion and deposition in the basin, imitating landscape evolution. This model has also been utilised to demonstrate the effects of engineering works (Ramirez et al., 2020) and nature-based interventions including log-jams (Walsh et al., 2020), dam removal (Poeppl et al., 2019; Ramirez et al., 2022) and reforestation (Coulthard & Van De Wiel, 2017; Na & Yoo, 2022) along river channels on erosion and deposition conditions and trajectory evolution. Scenarios can also anticipate the effects of natural disasters and the amplified impact of climate change on drainage basin sediment yield using the UKCP 09 probabilistic scenarios (Li et al., 2020; Xie et al., 2018). When modelled scenarios are compared with real-world fluvial evolution through historic records, CL exhibits high performance and minimal error (Feeney et al., 2020; Walsh et al., 2020).

CL was used to predict the cumulative long-term effects of various scenarios. Specifically, this research employed this model to address the following questions (Fig. 1):

1) Is there a downstream landscape stability benefit from meander restoration?

2) Is there a benefit to favouring meander restoration projects 'higher' in the catchment versus those 'lower' in the catchment in terms of the floodplain's long-term geomorphological development?

3) Is there a benefit to favouring consolidated meander restoration projects over dispersed meander restoration projects, of equivalent cumulative length, in terms of the stability of the downstream mainstream and floodplain?

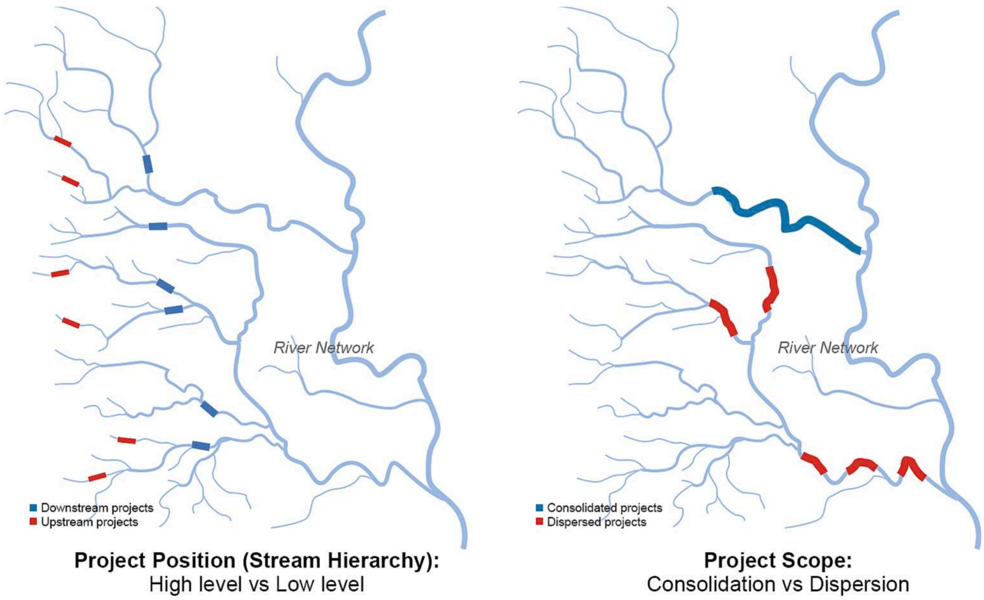


Fig. 1. Comparison of meander restoration projects allocation.

2. Methods

2.1. Study area

The study area is located in the Don Catchment in north England, UK (Fig. 2). The primary stem of the River Don has a length of more than 80 km and is fed along its length by several significant tributaries, most notably the Rother and the Dearne, which pass through the most urbanised regions in this catchment. The highest elevations exceed 500 m in the west with much of the uplands enjoying a degree of protection within the Peak District National Park on account of the value of the peat bog and conservation of certain key species. Since the catchment is relatively narrow, daily precipitation is highly variable, and rivers are fed mostly by runoff, the river flow rate can fluctuate substantially and consequently, the catchment has a long history of flooding caused by extreme rainfall.

Historically, the river system has been highly regulated, with numerous weirs built for mills and industry, upstream reservoirs to provide drinking water for burgeoning industrial populations, canal excavations to move the goods of industry, and channelization and straightening of the river to maximise land use for large industrial buildings or agriculture and to locally alleviate floods. In the lower catchment large drainage works have been developed for agriculture. In recent years, several river restoration projects, such as sinuous low-flow channel restoration in the River Dearne, have already been undertaken to reverse some of negative anthropogenic effects (The river restoration center, 2021). Additionally, after devastating flood events in 2007, 2019 and 2023, numerous proposals aiming to deliver nature-based approaches for climate resilience have emerged. Due to the rapidly changing nature this post-industrial region's catchment, the political

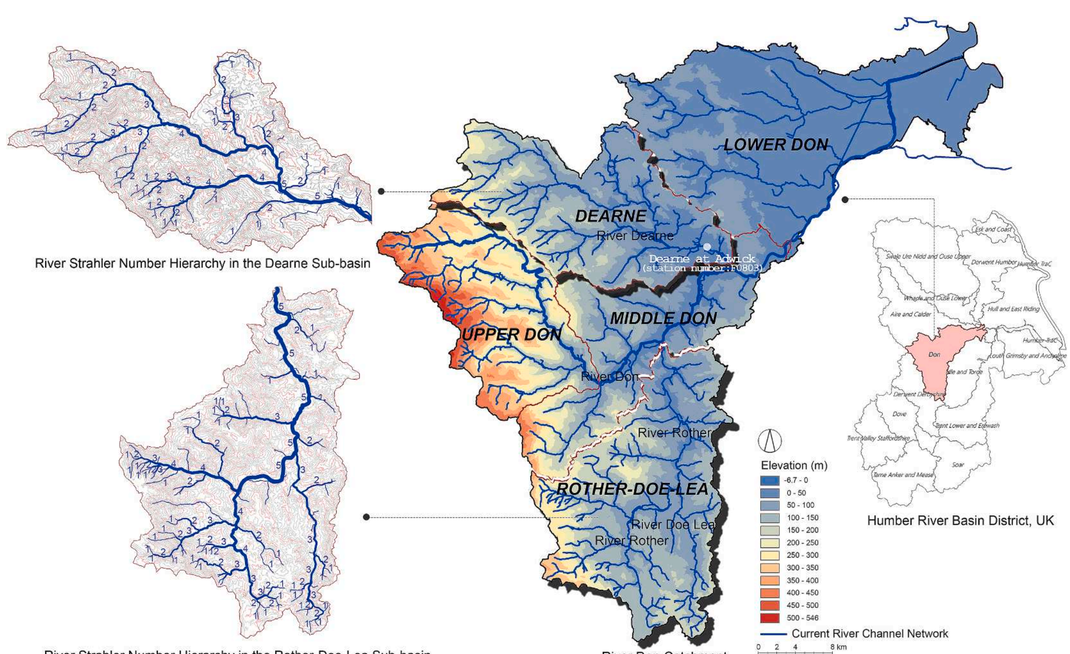


Fig. 2. River Don catchment and river Strahler Number hierarchy in the Dearne and Rother-Doe-Lea subbasins.

and social will to implement positive changes, and its similarities to other catchments in northern England grappling with issues of sustainable catchment management, but also due to its relatively small size, the Don River catchment is an ideal candidate for studying restoration dynamics at the catchment scale. In this particular study, based on the land cover and degree of historical modification, the focus is on the subbasins of the Don's two major tributaries which have the greatest potential for meander restoration, the Rother-Doe-Lea (henceforth simplified to Rother) and Dearne (Fig. 3), to test the geomorphological effects of meander restoration projects locally and on the main channel and floodplain of the River Don below their confluence. The draft analysis for determining the potential subbasins can be found in Appendix A. Table 1 shows the physical characteristics of the two subbasins.

3. Technical steps

In this study, CAESAR-Lisflood (CL) is employed to simulate the evolution of the catchment landscape through time. The model uses water flow and sediment transport calculations in a base scenario considering no modifications in the Dearne, Rother, and Upper Don subbasins and a suite of potential design scenarios representing various distributions of restoration projects in the Dearne and Rother sub-basins. River dynamics and evolution in the Upper Don subbasin are also modelled but restoration scenarios are not tested here due to its limited

Table 1
Subbasin information of Rother-Doe-Lea and Dearne in the Don catchment.

Subbasin information	Rother-Doe-Lea	Dearne
Area (km2)	397	328
Mean flow discharge (m3/s) (1963–2022)	4.264	3.435
Historical max peak discharge (m3/s) (1956–2022)	123.117	76.98
Landcover (UKCEH, 2021)	Woodland 11.36 %, Arable-land 29.46 %, Grassland 30.24 %, Urban extent 27.74 %	Woodland 15.77 %, Arable-land 32.66 %, Grassland 28.03 %, Urban extent 22.29 %
Terrain Ruggedness Index (TRI)	Level 72.15 %, Nearly level 15.12 %, Slightly rugged 6.92 %, Intermediately rugged 3.87 %, Moderately rugged 1.87 %, Highly rugged 0.06 %	Level 78.90 %, Nearly level 12.73 %, Slightly rugged 5.19 %, Intermediately rugged 2.35 %, Moderately rugged 0.80 %, Highly rugged 0.03 %
Ecological status (surface water) (EA, 2019)	Bad 5.26 %, Poor 26.32 %, Moderate 63.16 %, Good 5.26 %	Bad 0 %, Poor 13.33 %, Moderate 80 %, Good 6.67 %
Modification status (EA, 2019)	Natural 44.44 %, Heavily modified 55.56 %	Natural 26.67 %, Heavily modified 73.33 %

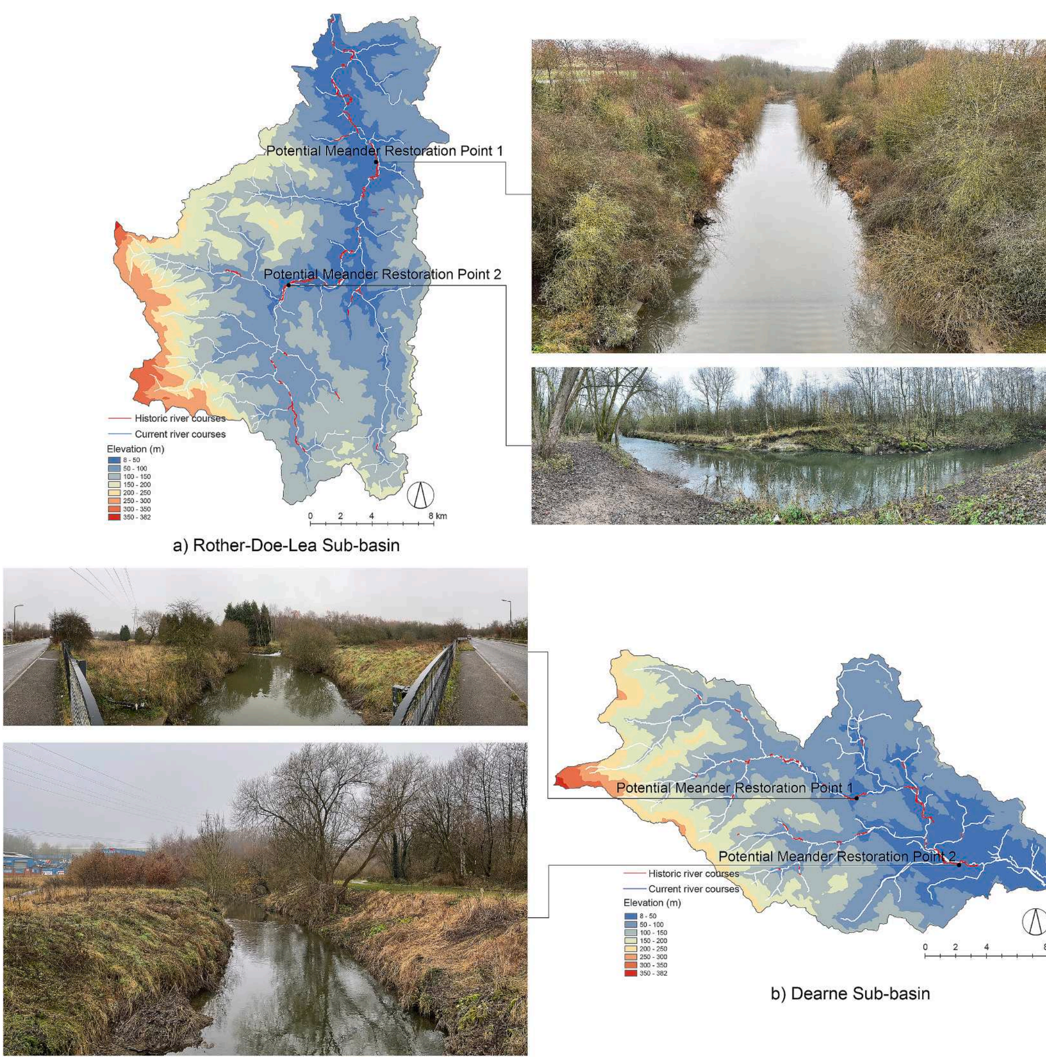


Fig. 3. The a) Rother-Doe-Lea and b) Dearne subbasins and photographs of channels that are candidates for meander restoration.

potential for river restoration. Due to the software's cell limitation of 2 million grid cells in a single simulation, the overall modelling is done in two phases, with outputs of phase 1 'stitched' into phase 2 as shown in Fig. 4. Each phase contains data collection and pre-processing using RasterEdit and ArcGIS, with the processed data then used as inputs into CL. Finally, the outputs are analysed using ArcGIS and SPSS to compare different scenarios (as shown in Fig. 4). A more detailed explanation of the technical steps can be found in Appendix B.

3.1. Model set-up and parameters

The four types of key inputs representing the features of the

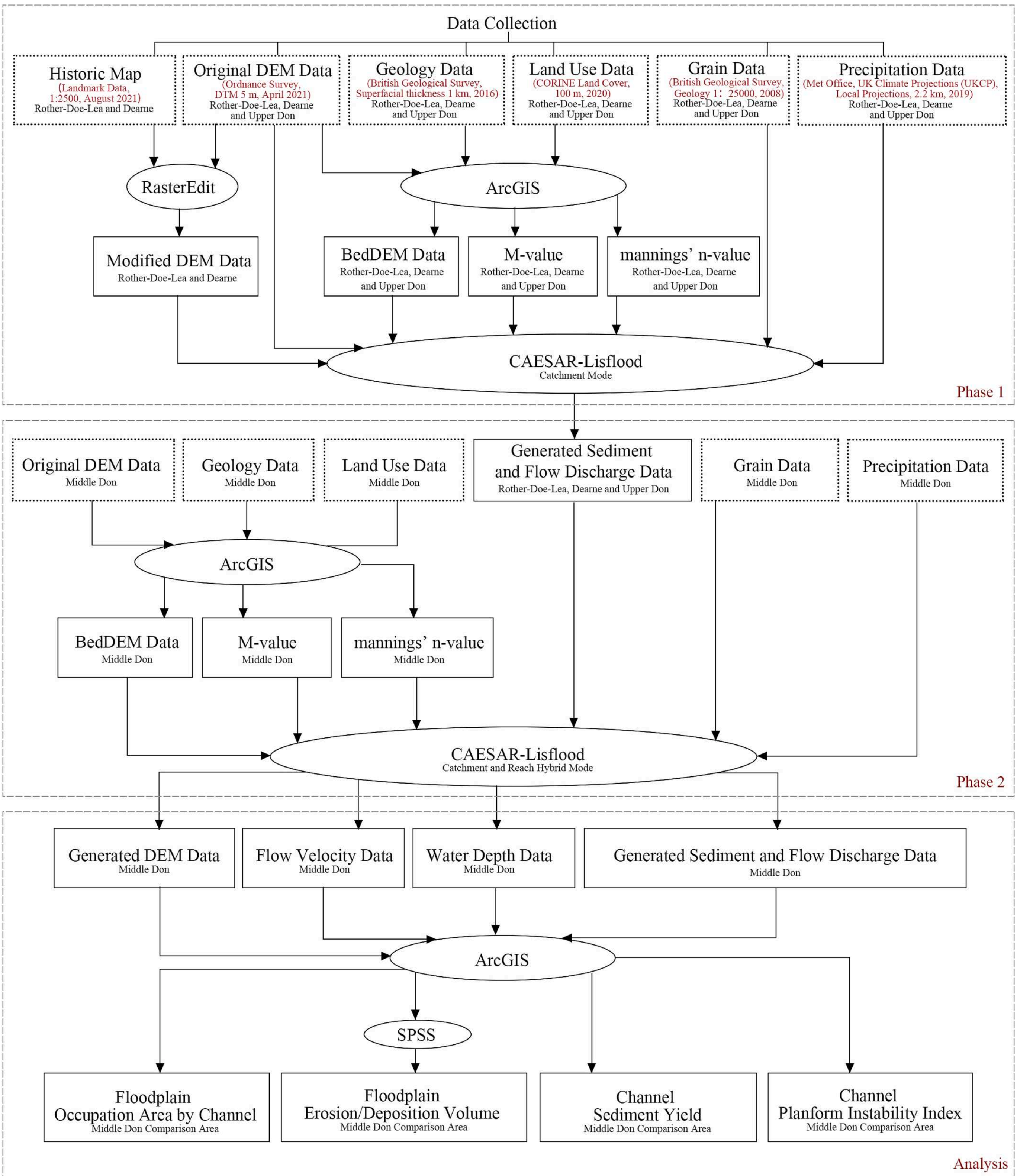


Fig. 4. Flow chart of technical steps.

catchment in this study include a digital elevation model (DEM), grain size and proportion data, precipitation data, and land cover data. Model inputs and parameters are summarised in Table 2.

3.1.1. Topography and bedrock

The base catchment is derived from 5 m-resolution DEM data from Ordnance Survey (2021), resampled to 50 m in ArcGIS due to the limitation of cell amount of CL. For each of the simulated restoration scenario, the tool RasterEdit is used to adjust cell elevation values in the original 5 m-DEM corresponding to the area assumingly conducting the various restoration projects, which in turn are resampled and mosaiced into the raster for the overall sub-basin.

A 'bedrock DEM' is used to represent the subsurface layer that is impervious to rapid erosion by water, effectively preventing the simulated erosion from passing a certain threshold in certain areas (Poeppl et al., 2019). This bedrock DEM is obtained by subtracting 0 to 8 m from the corresponding surface layer thickness from the initial DEM, using data from the British Geological Survey (2016).

3.1.2. Grain-size distribution and hydrology

Grain size and proportion data are used to compute sediment activity direction and volume. In this study, due to the large size of the study area, it is challenging to obtain data to represent soil particles throughout the whole catchment by collecting soil samples individually. However a previous survey on particles in River Don indicating particle size (Woodward & Walling, 2007) and the representation of the three particle diameters and proportions of silt, clay and loam derived from Soil Parent Material data taken from the British Geological Survey (2018) can give the directions. After comparing the particle parameters employed in previous studies, originally in England's Swale catchment, utilising CL (Coulthard & Van De Wiel, 2017; Walsh et al., 2020; Xie et al., 2018), which can be evidenced to be feasible in Feeney et al.'s research (2020) and conducting model calibration work, a reasonable value for the grain data in the Don catchment was fixed. Based on the experimental studies associated with the model, most of the lateral erosion rate values were set in the range of 0.0000005–0.00001 and needed to be calibrated, with relatively large values being more suitable for braided channels and smaller values for meandering channels with less lateral erosion (Coulthard & Van De Wiel, 2017; Na & Yoo, 2022; Van De Wiel et al., 2007). Therefore, within the range of available values used, the calibrated lateral erosion rate value was set at 0.000001 in this study.

Table 2
Caesar-Lisflood parameters used in this study.

Tabs	Parameters	Values
DEM	–	Resolution 50 m (resampled from *Ordnance Survey Terrain 5*)
Bedrock	–	Spatially Variable (1–8 m) based on the superficial thickness database (*British Geological Survey*)
Sediment	Grain sizes (m)	0.000001, 0.0000015, 0.000002, 0.00001, 0.00002, 0.00005, 0.000625, 0.002
	Grain size proportions	0.08, 0.15, 0.265, 0.225, 0.125, 0.035, 0.065, 0.055
	Sediment transport law	Wilcock & Crowe Formula
	Max erode limit (m)	0.02 (default)
	Active Layer thickness (m)	0.1 (default)
	Lateral edge smoothing passes	30
	Lateral erosion rate	0.000001
Hydrology	'm' value	Spatially Variable (0.005–0.02) based on land cover (*Corine*) Construction(0.005); Marshes(0.007); Grassland(0.008), Arable land and Pasture (0.013); Urban green area(0.015); Forest (0.02)
	Rainfall	Hourly (2021–2070)
Vegetation	Grass maturity (years)	0
	Vegetation crit shear	100 (new model)
Slope processes	Soil creep/diffusion value	0.0025 (default)
	Slope failure threshold	45°
Flow model	Min Q for depth calculation	0.5
	Evaporation rate	0.001 m/day
	Courant number	0.7 (default)
	Frounde number flow limit	0.8 (default)
	Mannings' n	Spatially Variable (0.015–0.15) based on land cover (*Corine*) Construction(0.015); Sports and leisure (0.03); Arable land and Natural grassland (0.045); Pastures and Urban green(0.05); Water bodies (0.06); Moors, Heathland and Wetland (0.1); Coniferous forest(0.12); Broad-leaved/Mixed forest(0.15)

Projected precipitation levels between the years 2021–2080 for the three sub-basins provided by Met Office are used in Phase 1 to generate water flow data used in Phase 2. (Met Office, 2019) Although CL allows the time step of the rainfall data to iterate in minutes, a more computationally economical interval of one hour is used in the present research as more time precision does not necessarily generate better results (Coulthard & Van De Wiel, 2017; Ramirez et al., 2022; Xie et al., 2018).

The Mannings' n, also known as Manning's roughness coefficient, and the 'm' value reflect the catchment land cover and vegetation density condition, which directly determine the flow depth and hydrograph in terms of peak flow and duration, respectively. Based on the previous research that applied CL and this study's calibration, the Mannings' n ranging from 0.015 to 0.15 and 'm' value from 0.005 to 0.02 represents a progression of vegetation density from sparse to dense and surfaces from hard-paved to highly vegetated (Li et al., 2020; Na & Yoo, 2022; Walsh et al., 2020). There are relatively limited vegetation parameters in CL, including grass maturity, vegetation crit shear, and the proportion of vegetation that is likely to erode at maturity. Based on existing research, the parameters used in this study were chosen to simulate a channel with mature riparian vegetation and stable banks to replicate the current state of vegetation in the catchment (Saynor et al., 2019; Walsh et al., 2020).

3.2. Model calibration

In this study, the results of the simulation are only considered after the simulated five-year mark as a period known as 'model spin up' is typically used to more closely align model dynamics with reality due to inevitable misalignments between datasets (Feeney et al., 2020). The duration of the spin-up is verified comparing the sediment and water discharge outcomes of each year using repeated 10 times rainfall data of the same year. The results converge to almost the same value from the fifth year onwards, which is also evidenced by other research (Feeney et al., 2020). The calibration is conducted by comparing the actual water discharge obtained in the lower catchment gauge station for the six-month period December 2012- May 2013 with the simulated model predictions (Fig. 5). The precipitation data used was the MIDAS UK Hourly Rainfall Data provided by Met Office (2006), which was collected by observation stations throughout the UK and covered the period from 1915 to the present. The Nash Sutcliffe Model Efficiency (NSE) test is then used to assess the consistency of the simulation with the observation (Meadows, 2014; Walsh et al., 2020), with the value for this study of 0.71 being described as 'good' in the criteria (Moriasi et al., 2015). The calibration was conducted in the Dearne sub-basin and the calibrated parameters were used in the Rother-Doe-Lea, Upper Don and Middle Don because of the similar precipitation patterns, land use, soil types, and topographical features.

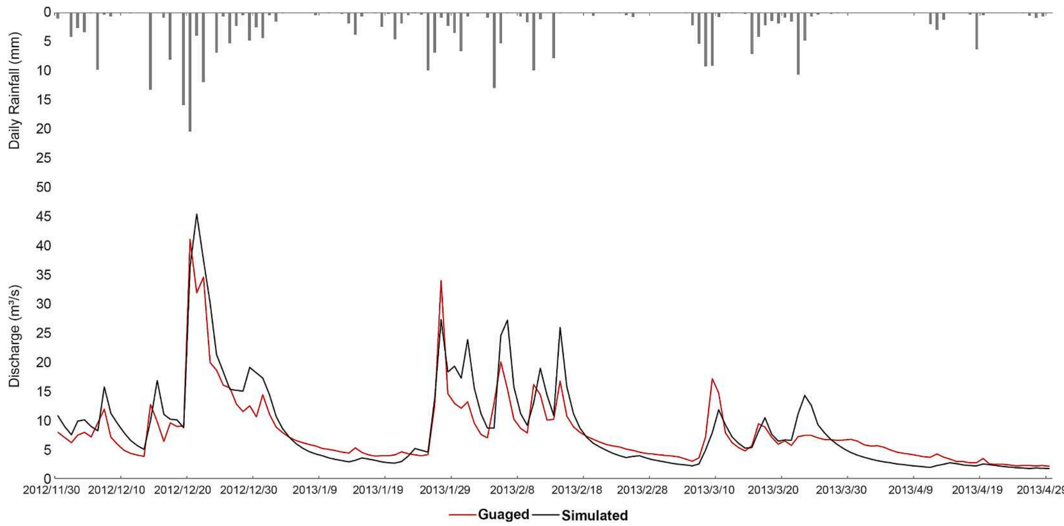


Fig. 5. Calibration result.

3.3. Simulation scenarios and outputs analysis

A map of sites for potential restoration is created by finding areas with notable variations between the 'observed' and 'predicted' river networks using ArcMap's hydrologic analysis. The processing maps are in Appendix C. Sites with a soft land cover (i.e. not urbanised) are prioritised for intervention feasibility. Recreating the original riverbed using the approach called "carbon copying" (Brookes & Shields, 1996), which is trying to rebuild the historic pre-disturbance channel, is applied with potential restoration scenarios based on the river geomorphology indicated on historic maps produced by Ordnance Survey starting in the 1840 s (Landmark Information Group, 2021). Then the 5 m DEM is modified in RasterEdit based on the historical river course.

Next, the baseline and eight distinct meander restoration scenarios are simulated in the Rother and Dearne sub-basins, with differences between scenarios examining 1) relative positioning of projects in the stream hierarchy and 2) relative consolidation or dispersal of projects. For each set of scenarios, the Strahler order of each stream being restored is applied to describe its placement in the hierarchy, with Strahler Number 1 (SN1) describing a stream with no tributaries, an SN2 stream formed by the confluence of two SN1 streams, SN3 formed by the confluence of two SN2 streams (but not SN2 with SN1), etc. (Strahler, 1957). In this study, the Average Strahler Number (ASN) is used to describe the Strahler number of multiple projects together, hence the series of 'upstream' restoration scenarios has a smaller ASN than the series of 'downstream' scenarios in the same comparison, although distinctions are drawn only in relative terms and not in absolute terms. In the two sub-basins, the 'upstream' scenario series ranges from ASN2.5–4.5 and the 'downstream' scenario series ranges from ASN3.5–5. For testing the efficacy of consolidated vs. dispersed projects, each series of upstream vs. downstream scenarios contains four restoration project plan distribution possibilities—one large project, two medium size projects, five small projects, or ten very small projects, maintaining the same cumulative overall length in each of the sub-basins—4.5 km for the Rother and 5 km total of restoration for the Dearne (Table 3 and 4). Then the position of each scenario's projects is determined by referencing the possible restoration points map, maintaining the cumulative length.

The effects of the restoration scenarios on erosion, deposition, and changes in planform are not tested in the sub-basins themselves, but only downstream from all interventions after each respective tributary joins up with the Don itself. These results are compared through detailed study of the floodplain of the River Don starting 2 km upstream and continuing 10 km downstream from each confluence of the River Rother and River Dearne respectively with the Don. (Fig. 6).

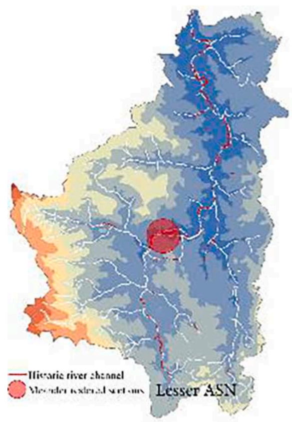
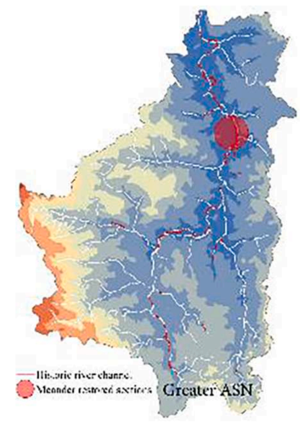
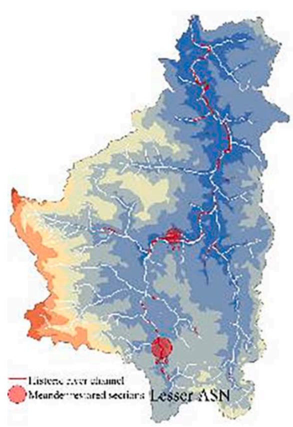
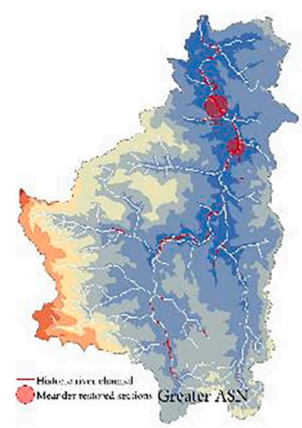
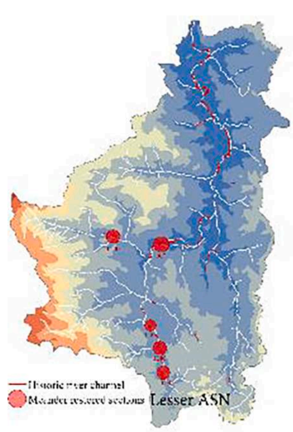
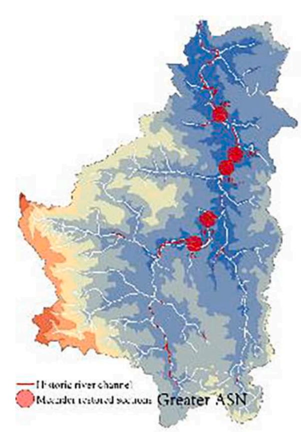
Outputs for CL simulations can be stored periodically by time. In this study, DEMs, water depth, and flow velocity are gathered annually from 2020 to 2070. Using simulated DEMs, the volume of erosion and deposition in the Middle Don subbasin for each year is calculated. Pixels with decreasing elevation are labelled as "erosion," with increasing height as "deposition." Flow velocity and water depth are used to tracing the river channel that reflects the evolved one. Subsequently, cumulative lateral migration areas are calculated from the area generated by the junction of the evolved and previous main channel of the River Don.

Additionally, the Sinuosity Index (SI) and Braid Index (BI) are significant indices for describing channel planform and can be used to analyse the river's spatial form. These are used to evaluate the geomorphic effects of various deployment strategies on the main channel. Brice (1964) and Mueller (1968) stated that SI is computed by dividing the length of the developed Channel by the length of the valley. The BI is determined by calculating the ratio of the length of all included subsidiary and major channels to the length of the main channel (Mosley, 1981). This study considers how well SI and BI hold up over time across the various restoration scenarios. This is achieved by comparing the dispersion of the data acquired in different dimensions using the sum of their coefficients of variation (CV) (Kuo et al., 2017).

The stability of the floodplain occupied by the middle section of the River Don is evaluated by 1) quantification of the channel occupation area, which is the crossing area formed by historic and evolved channel centrelines and triggered by channel lateral erosion (Feeney et al., 2020) and 2) by calculation of total erosion and deposition volumes caused by both bank and thalweg incision (Coulthard & Van De Wiel, 2017). These are compared every five years across the 50-year study time frame. The difference in every ten-year cumulative volume of erosion and deposition to the base group over the years 2020–2070 and the sediment yield amounts are duly compared to identify the intensity of channel incision activities. To assess the channel stability, the CV of both SI and BI are taken together to derive the Planform Instability Index (PII) ($PII = CV_{SI} + CV_{BI}$).

In addition, the effectiveness of project location can be determined by comparing the difference between the upstream and downstream results of each morphological stability indication. The difference between the means of upstream and downstream indicators in terms of average channel migration area, erosion and deposition volume, sediment discharge and PII, and the baseline can be employed to identify the impacts of project dispersion.

Table 3
M€eander restoration scenarios simulated in the Rother-Doe-Lea.

	Series 1 — Upstream placement (ASN 3.5–4.5)	**Series 2 – Downstream placement (ASN 4.6–5)**
1 (4.5 km) section	ASN = 4.5	ASN = 5
		
2 (2 + 2.5 km) sections	ASN = 3.8	ASN = 5
		
5 (4*1 + 0.5 km) sections	ASN = 3.8	ASN = 5
		
10 (10*0.45 km) sections	ASN = 3.5	ASN = 4.6

(*continued on next page*)

Table 3 (*continued*)

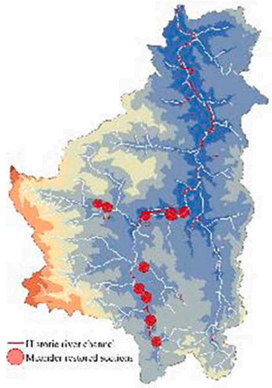
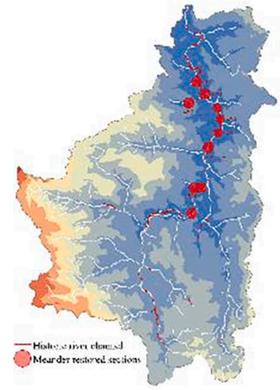
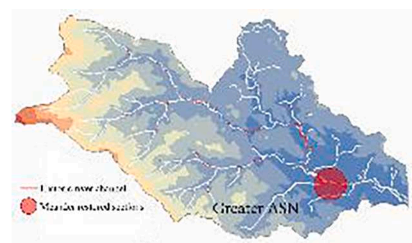
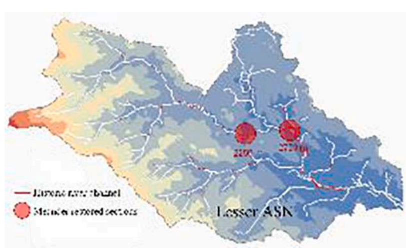
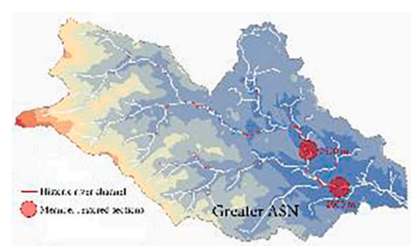
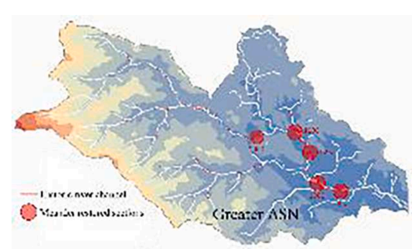
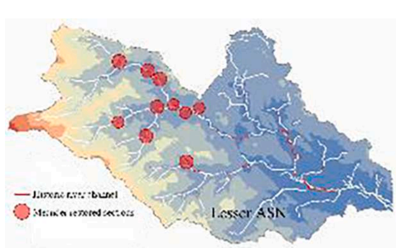
	Series 1 — Upstream placement (ASN 3.5–4.5)	Series 2 – Downstream placement (ASN 4.6–5)
		

Table 4
Meander restoration scenarios simulated in the Dearne.

	Series 1 — Upstream placement (ASN 2.8–4)	Series 2 – Downstream placement (ASN 3.9–5)
1 (5 km) section	ASN = 4	ASN = 5
		
2 (2 * 2.5 km) sections	ASN = 3.5	ASN = 4.5
		
5 (5 * 1 km) sections	ASN = 3	ASN = 4.5
		
10 (10*0. 5 km) sections	ASN = 2.8	ASN = 3.9
		

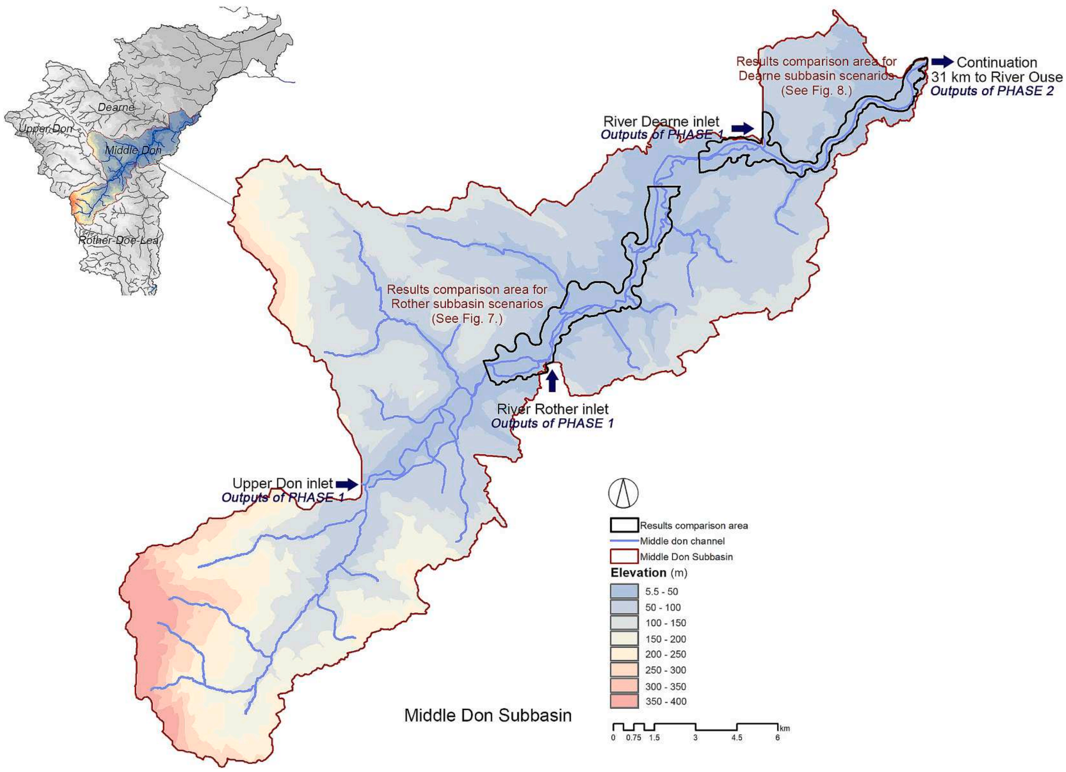


Fig. 6. Results comparison areas for meander restoration scenarios in the Rother-Doe-Lea and Dearne subbasins.

4. Results

4.1. Floodplain occupation area by the channel

The active area defined by the previous and evolved channel was shown in Figs. 7 and 8. In the active area assessment below the Rother confluence under the base scenario (Fig. 9), a significant decline in the active area emerged after 15–20 years, while in half of the restoration scenarios, this point of ‘dynamic equilibrium’ was reached earlier. It is worth noting that almost all modification scenarios had a consistently smaller channel occupation area than the baseline after reaching this point. In the mean value comparison, with one exception, all the scenarios positively affected the stabilisation of channel bank erosion as contrasted with the base group. In the Dearne’s comparison, though there was not a fixed time where dynamic equilibrium was achieved within the 50-year period, all restoration scenarios resulted in a significantly more stable active area lower in the catchment than under the baseline conditions (Fig. 10).

In the “higher” vs. “lower” comparison (Fig. 11a), the Rother’s scenarios showed a different pattern from the Dearne’s. In the Rother, the restoration of tributaries downstream in the stream hierarchy (greater ASN) was consistently more effective in promoting active area stability further downstream than the equivalent smaller ASN restoration scenarios. However, in the Dearne (Fig. 11b), excepting the ten very small project scenario, restoration in the lesser ASN reaches was more effective in reducing active area than in greater ASN scenarios.

In the project scope comparison (Fig. 11 a), however, there was not a consistent trend to indicate a relationship between changes in the degree of dispersal and the effectiveness of limiting channel migration. Five small upstream sections restoration in both subbasins had a relatively good performance in inducing a more stable mainstem. Furthermore, one large in the Rother and two medium projects in the Dearne (Fig. 11b) also significantly stabilised the downstream channel. The results showed that one large and five small sections restoration performed the best in limiting river migration.

4.2. Erosion and deposition volume

Fig. 12 indicates the area with higher and lower elevation representing deposition and erosion in the Middle Don. All the scenarios indicated erosion mostly happened higher in the comparison area of the Rother scenarios and lower in the area for the Dearne scenarios’ comparison, and areas of deposition were mostly located lower in the Dearne scenarios’ comparison area. The specific erosion and deposition comparison of all the scenarios can be found in Appendix D. Figs. 13 and 14 show the difference in volumes of the sum of erosion and deposition respectively in the 50 years for restoration scenarios compared with the base group. In the first ten years, 11 out of 16 (68.75 %), more specifically, four Rother-Doe-Lea and seven Dearne restoration scenarios effectively reduced the erosion and deposition volume. However, by the years between 2060–2070, only four of the Rother-Doe-Lea and one of the Dearne scenarios exhibited a volume below the base value. Notably, over the long-term, the Rother’s scenarios showed a significant trend in reducing erosion and deposition while modifications in the Dearne showed the opposite.

In the “higher” and “lower” comparison, with the exception of one large project, meandering restored in the greater ASN was proved to be more efficient in controlling the erosion and deposition activities in the Rother (Fig. 15). The deposition comparison is in Appendix E. Furthermore, in the long-term trend detection, restoration in the greater ASN illustrated more drastically reducing the erosion and deposition volume compared to the baseline (Fig. 13). However, projects restored in lesser ASN of the Dearne not only drastically induced less erosion and deposition than in greater ASN in the 50 years but also held this trend in the long-term detection (Fig. 14).

In the project scope comparison, both in the Rother and Dearne, the results showed that consolidated projects were more reliable than dispersed in restricting erosion and deposition activities (Fig. 15). In Rother’s average annual total volume comparison, one large, two medium and five small projects were lower than the control group. In the Dearne, except for two medium projects, the other three dispersion

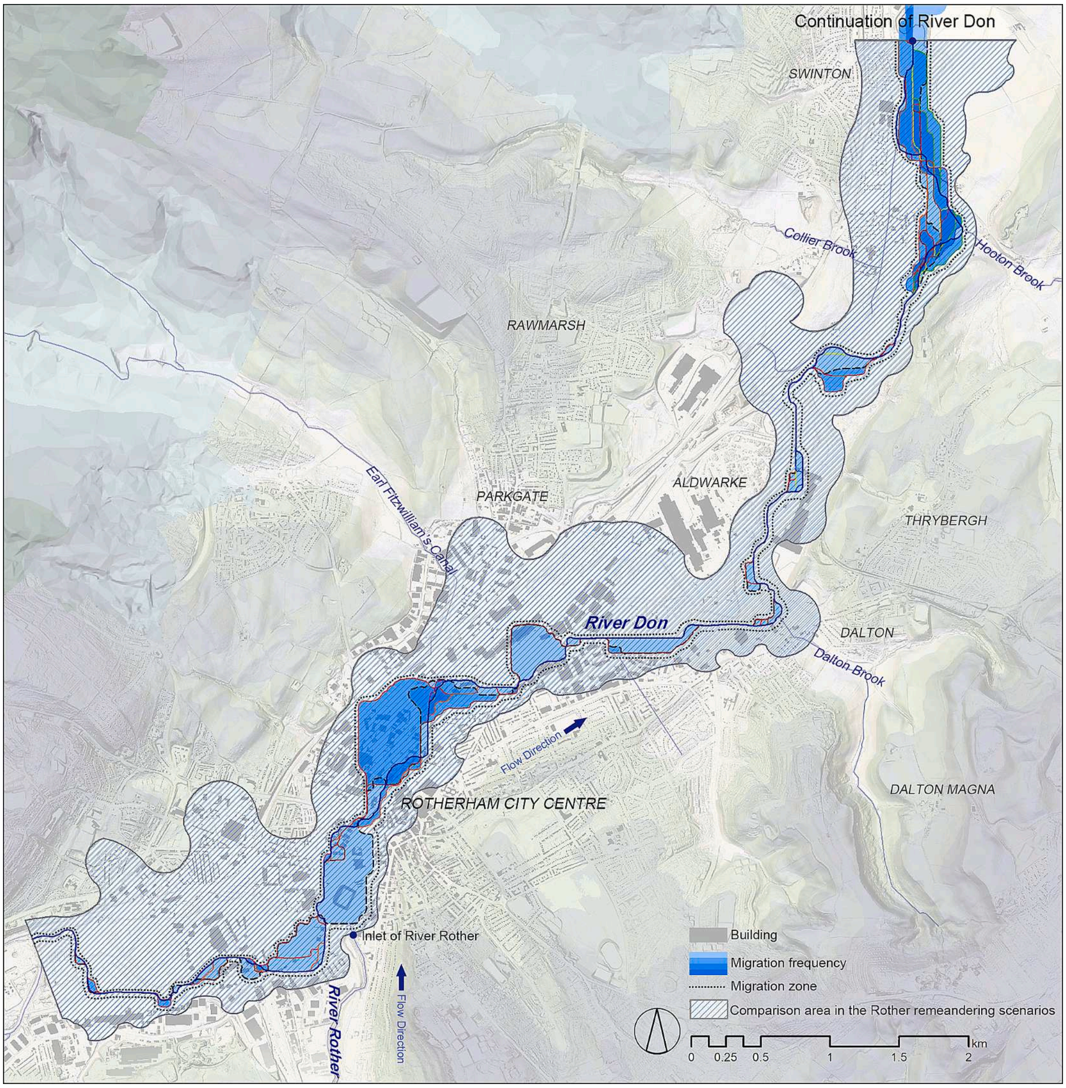


Fig. 7. The 5-year cumulative lateral migration from 2020 to 2070 in the comparison area along the Middle Don near the Rother confluence, under the conditions of the single upstream large project (4500 m) restoration scenario.

scenarios triggered more erosion and deposition than the baseline.

4.3. Sediment yield

15 of the 16 simulated scenarios in the two sub-basins would contribute to a reduction in average annual sediment yield discharge (Fig. 16).

In the "higher" vs, "lower" comparison, the Rother results (Fig. 16 a) indicated the lesser ASN reaches restoration projects reduced sediment yield more than those in greater ASN reaches. Dearne's scenario results (Fig. 16 b) generally showed a similar pattern to the Rother, i.e., there was a 75 % probability that restoration in lesser ASN reaches was more effective in reducing sediment discharge than in greater ASN reaches.

In the project scope comparison, though not a linear relationship, one notable trend emerging in both the Rother and Dearne restoration scenarios was that fewer large projects resulted in less sediment discharge than a larger number of small projects, specifically ten very small (Fig. 16). More explicitly, in the Rother lesser ASN restorations, one large project discharged less sediment than five small-sized projects less than two medium-sized projects less than ten very small projects while sediment discharge raised as project magnitude and number decreased in the downstream restoration scenarios (Fig. 16 a). In the Dearne, two projects in lesser ASN reaches and one project in both lesser and greater ASN reaches did the best performance with baseline reductions of 17.08 %, 11.33 %, and 9.00 %, respectively (Fig. 16 b).

4.4. Channel planform Instability Index (PII)

Table 5 shows the PII comparison in the baseline and simulated scenarios. Overall, in the Rother's results, all designed scenarios triggered more unpredictable planform of the main channel due to the instability significantly higher than the braid index of the base scenario. Conversely in the Dearne, all scenarios significantly stabilised the planform of the mainstream channel compared to the control group as a result of the control of the braid index. Consistent with the floodplain occupation area results, the most stable planform of the mainstream was found in five small projects in the Rother and one large project in the Dearne.

In the "higher" and "lower" comparison, there was no consistent trend in the Rother and Dearne results indicating whether upstream or downstream restoration was more effective in stabilising channel morphology. However, it is worth noting that the scenarios for both sub-basins indicated that if ten very small projects were to be employed, it was significantly preferable to restore in the upstream than in the downstream.

In the project scope comparison, the results of the Rother and

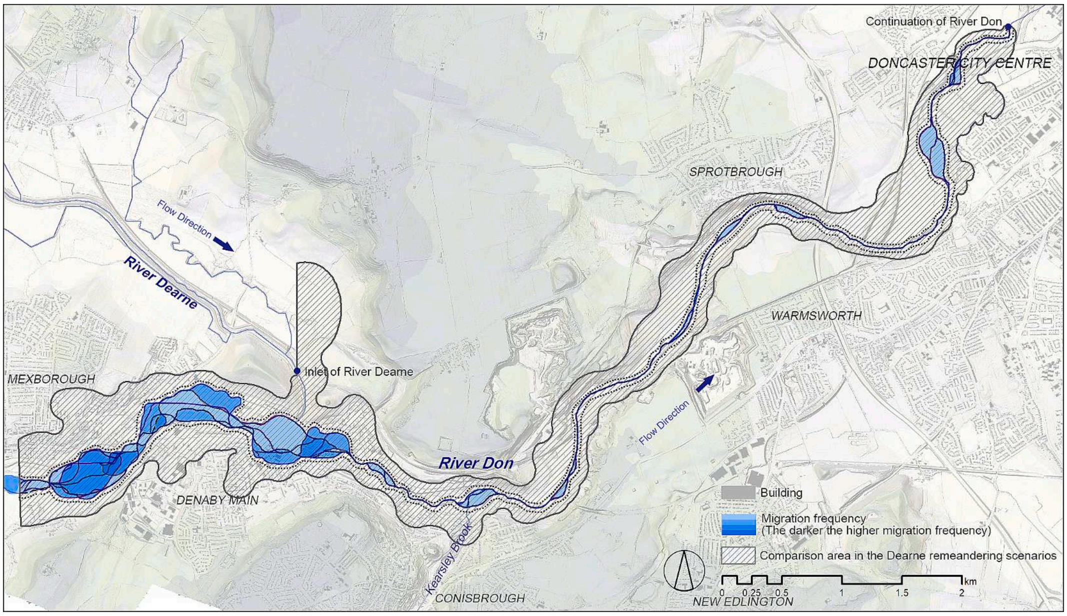


Fig. 8. The 5-year cumulative lateral migration in the comparison area along the Middle Don near the Dearne confluence from 2020 to 2070, under the single large project (5000 m) restoration scenario in the Dearne sub-basin.

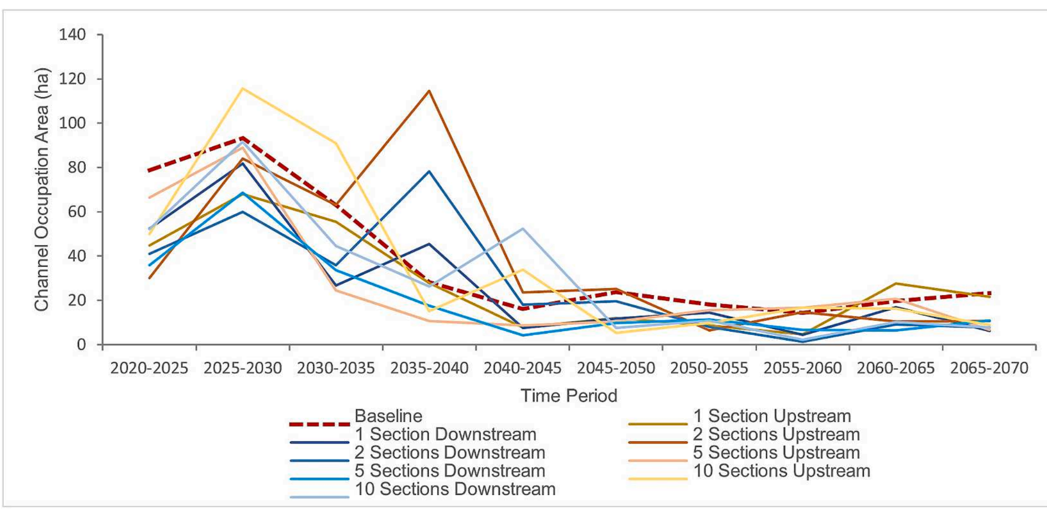


Fig. 9. Rother-Doe-Lea restoration scenarios' occupation area by the Channel every 5 years from 2020 to 2070.

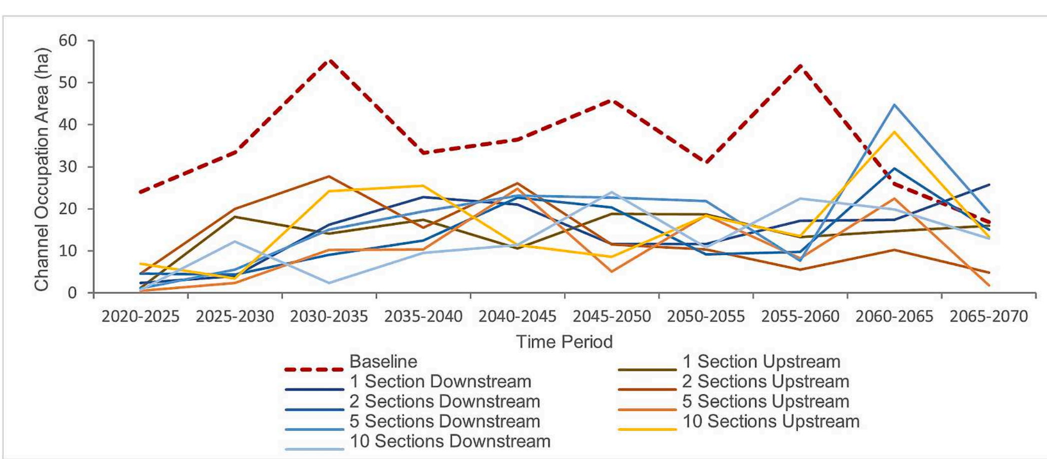


Fig. 10. Dearne restoration scenarios' occupation area by the Channel every 5 years from 2020 to 2070.

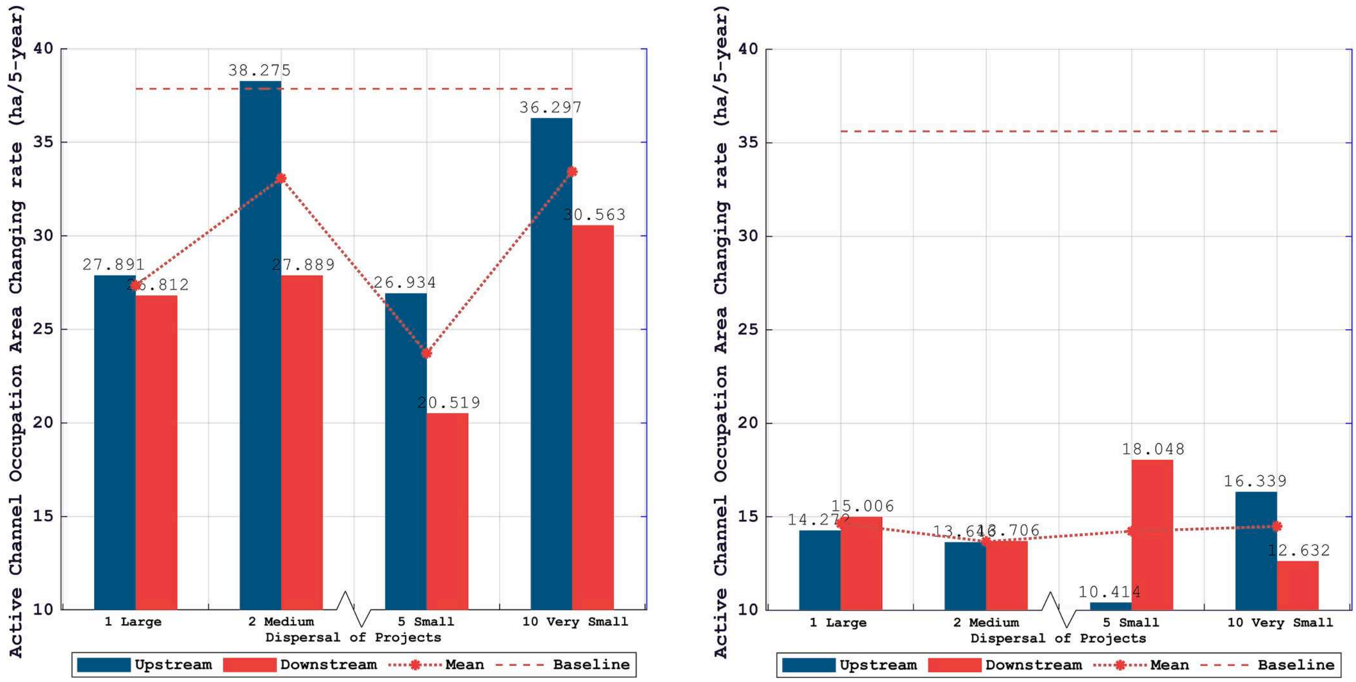


Fig. 11. Active channel occupation area changing rate from 2020 to 2070 in a) Rother-Doe-Lea and b) Dearne restoration scenarios.

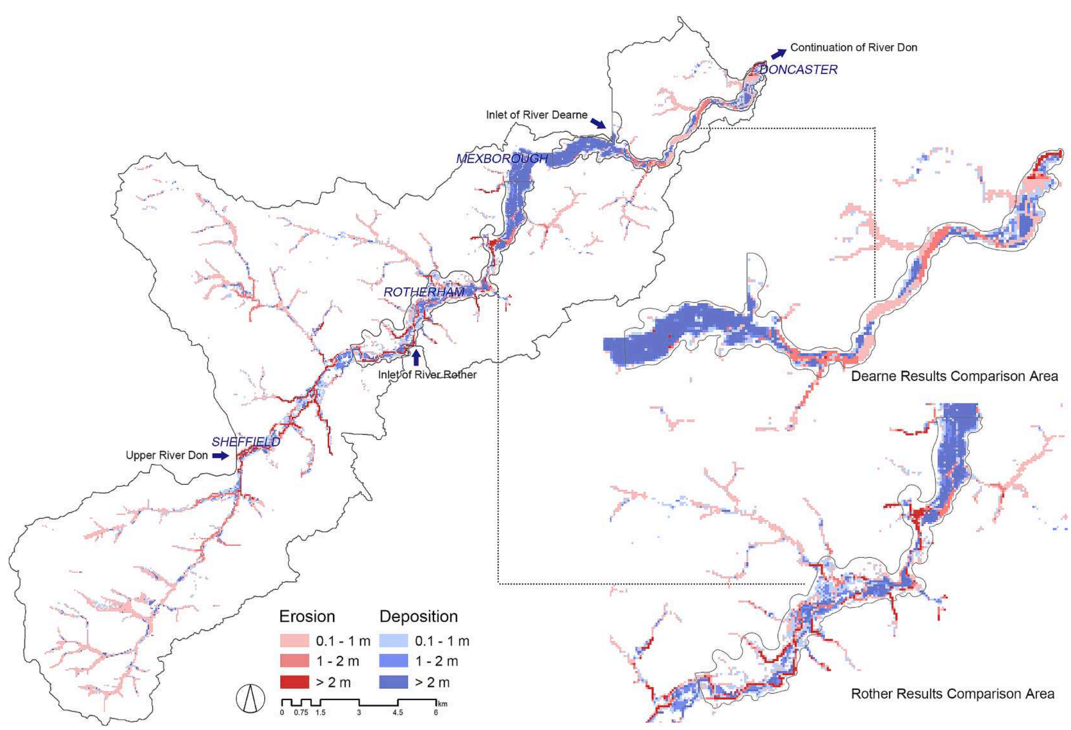


Fig. 12. Erosion and deposition in 2070 with respect to in 2020 for the scenario of one large project restored in the lesser ASN of Rother.

Dearne, however, have inconsistent indications. In the Rother, two medium and five small projects were more worthy of consideration in the combined SI and BI stability comparison. In the Dearne, one large and ten very small projects more effectively maintain the stability of the main channel.

5. Discussion

5.1. *Consistent trends in both subbasins*

Although the restoration scenarios in the two subbasins often exhibited divergent patterns, there were several instances where the results from both subbasins showed consistency. Meander restoration in tributaries was consistently effective in reducing lateral migration activity in the channel downstream of the mainstem and significantly

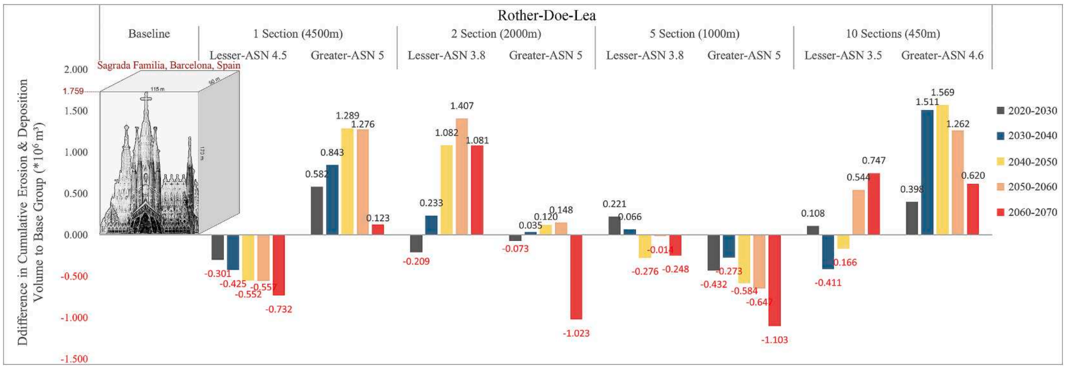


Fig. 13. Rother-Doe-Lea restoration scenarios' difference in cumulative erosion and deposition volume to the baseline from 2020 to 2070. In the baseline scenario, total sediment erosion is equivalent to a cube of earth as tall as the Sagrada Familia basilica in Barcelona Spain (175 m).

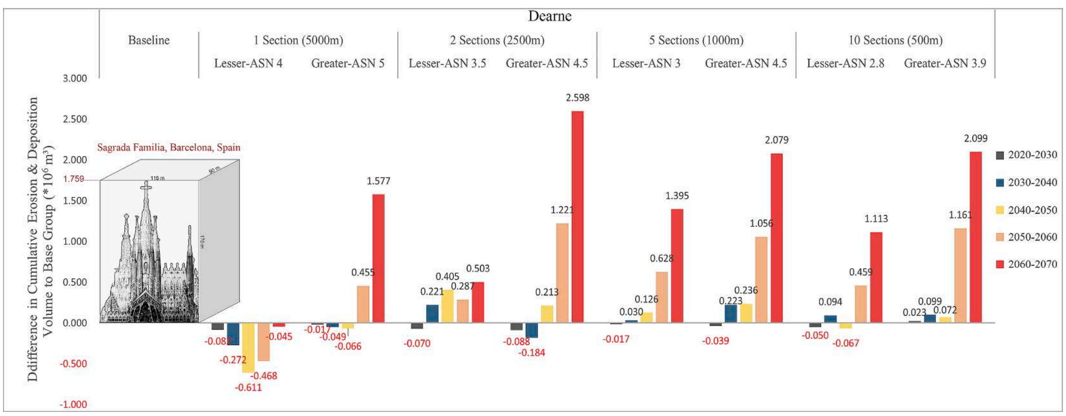


Fig. 14. Dearne restoration scenarios' difference in cumulative erosion and deposition volume to the baseline from 2020 to 2070.

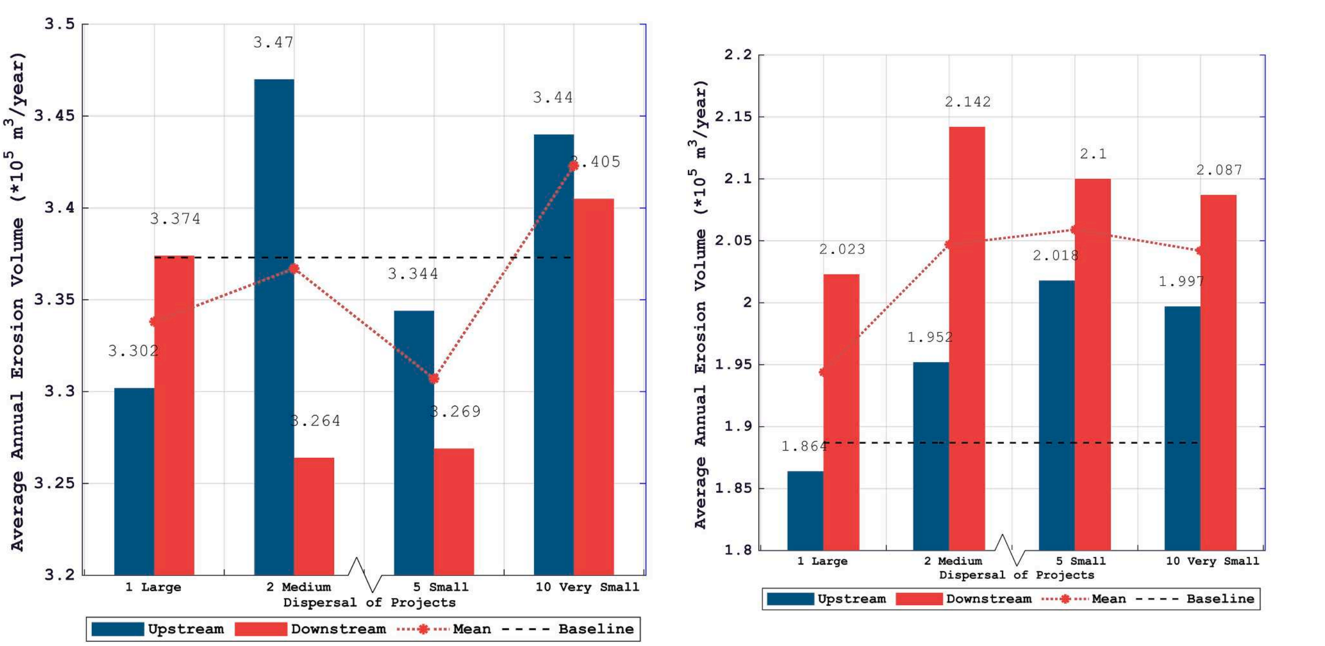
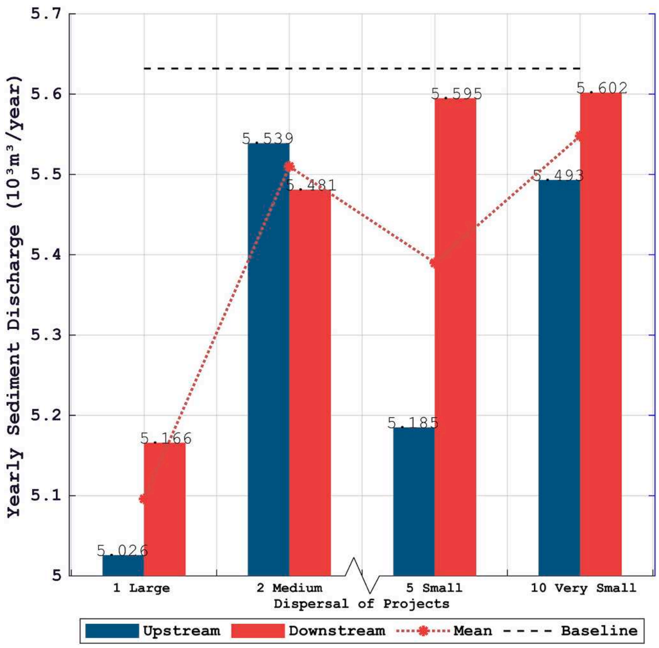


Fig. 15. Average annual erosion volume in a) Rother-Doe-Lea and b) Dearne restoration scenarios from 2020 to 2070.

reduced downstream sediment discharge (Table 6). This may be attributable to the fact that the assumed restoration scenarios are already strongly consistent with current hydrodynamic mechanisms and close to the natural steady state of the river in its initial stages (Soar & Thorne, 2001).

For the intervention's placement, with the same cumulative length of restoration measures, there are differences in the geomorphological impact of different meander restoration options on the catchment. This



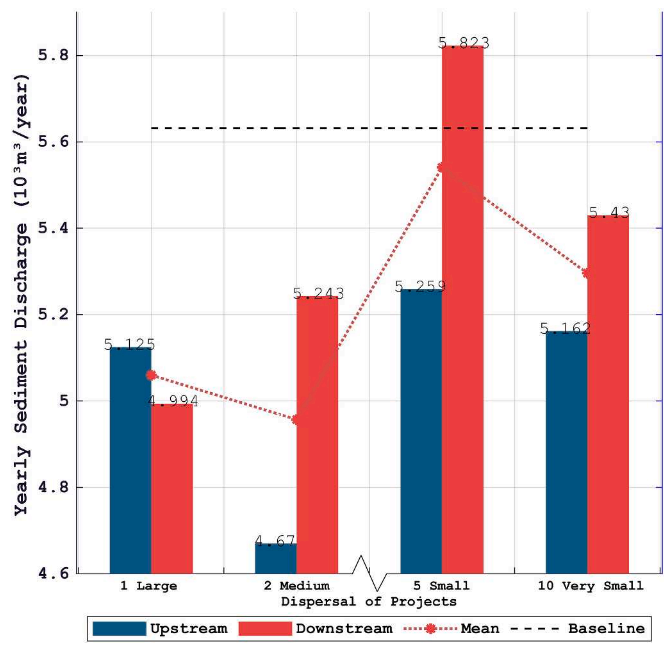


Fig. 16. Average annual sediment discharge of simulated middle Don from 2020 to 2070 in a) Rother-Doe-Lea and b) Dearne restoration scenarios.

Table 5
The Planform Instability Index of the middle Don in the base and modification scenarios in the two sub-basins in the 50 years (the darker colour, the higher value, the more unstable the planform).

Sub-basin	Project Size	Project Location	Sinuosity Index CV	Braid Index CV	Planform Instability Index
Rother	**Base (no modification)**		7.82 %	39.45 %	47.28 %
	1 large	Lesser ASN 4.5	7.88 %	75.04 %	82.93 %
		Greater ASN 5	27.97 %	71.78 %	99.75 %
	2 medium	Lesser ASN 3.8	11.79 %	70.04 %	81.83 %
		Greater ASN 5	9.74 %	62.55 %	72.30 %
	5 small	Lesser ASN 3.8	17.66 %	54.84 %	72.49 %
		Greater ASN 5	7.88 %	63.52 %	71.39 %
	10 very small	Lesser ASN 3.5	6.14 %	82.01 %	88.15 %
		Greater ASN 4.6	10.32 %	109.03 %	119.35 %
Dearne	**Base (no modification)**		5.80 %	72.72 %	78.53 %
	1 large	Lesser ASN 4	5.40 %	32.74 %	38.14 %
		Greater ASN 5	6.91 %	27.22 %	34.13 %
	2 medium	Lesser ASN 3.5	6.18 %	29.26 %	35.43 %
		Greater ASN 4.5	7.34 %	32.32 %	39.66 %
	5 small	Lesser ASN 3	8.56 %	33.52 %	42.08 %
		Greater ASN 4.5	10.51 %	27.30 %	37.81 %
	10 very small	Lesser ASN 2.8	6.00 %	24.18 %	30.18 %
		Greater ASN 3.9	4.79 %	34.41 %	39.20 %

Table 6
Consistent trend comparison of the two subbasins based on the research questions.

		Rother-Doe-Lea	Dearne
Channel Active Occupation Area	Better than baseline	Almost all	All
	Higher vs. Lower	Lower	Most higher
	Consolidated vs. Dispersed	Mixed	Mixed
Erosion and deposition	Better than baseline	Half	None
	Higher vs. Lower	Most lower	Higher
	Consolidated vs. Dispersed	Consolidated	Consolidated
Sediment discharge	Better than baseline	All	Almost all
	Higher vs. Lower	Most higher	Most higher
	Consolidated vs. Dispersed	Consolidated	Consolidated
PII	Better than baseline	None	All
	Higher vs. Lower	Mixed	Mixed
	Consolidated vs. Dispersed	Mixed	Mixed

result is supported by existing research indicating that optimally allocating intervention resources is more effective in reducing peak flows and sediment yield than with random allocation (Liu et al., 2016, 2017; Phillips et al., 2022).The two subbasins' results indicated restoration in lesser ASN reaches contributed more significantly than those in greater ASN reaches in reducing sediment yield (Table 6). In empirical experiments, the flow velocity is reduced as it passes through a sinuous reach, thereby attenuating the river shear stress, while the settling of suspended load leads to more significant channel deposition (Eekhout et al., 2015; Rachelly et al., 2021). Restoration in the zone of sediment transport in higher catchment enables more sediment to settle in the upper floodplain (Huggett & Shuttleworth, 2022).

For the optimal division plan, the effect of fewer consolidated projects in reducing river loading and limiting the channel lateral migration are more significant than a larger number of dispersed projects (Table 6). Typically, one large restoration project significantly reduced floodplain erosion deposition activity in the mainstream, despite its constrained role in controlling lateral erosion. Researchers have pointed to a correlation between the spatial distribution and sinuosity patterns of river erosion and flow discharge variability (Houser & Hamilton, 2009). More specifically, extreme flood events induce significant streambank erosion (Stark, 2006) and moderate flows are more likely to lead to valley bed erosion (Hartshorn et al., 2002). Additionally, meandering reaches can considerably reduce suspended loads during flash floods (Nakamura et al., 2014). The results of this study may therefore imply that the cumulative effect of more consolidated projects is more effective in controlling water flows in both flood events and moderate steady intensity than multiple dispersed projects. However, more subsequent research is required to support this inference.

5.2. Factors affecting discrepancies between two subbasins' results

Although similar scenarios tested in the two sub-basins showed relative consistency in sediment yield results overall, there were differences in the results of channel migration and erosion and deposition activities. For instance, the 50-year assessment of the stability of the floodplain below the confluence of the Rother and Don showed that the river would experience a significant decline in lateral migration after 20 years, implying that a dynamic equilibrium in planform could be reached. This is in line with the findings of Li et al. (2020) and Zhang and Zhang (2017) that rivers take about 27 years to evolve to an equilibrium state after disturbance. In the floodplain below the confluence with the Dearne, however, the designed modifications upstream did not significantly decrease the time towards reaching dynamic equilibrium since these scenarios significantly reduce channel migration intensity from the very beginning, the point at which the channel active occupation area dramatically decreases during this 50-year period is not evident.

Moreover, restoration in the greater ASN tributary reaches more effectively decreased channel lateral migration and reduced more total erosion and deposition activities especially in the long-term trend in the Rother. All scenarios in the Rother contributed more to an unstable channel planform of the mainstem from the perspective of BI and SI. The discrepancies, however, are that the scenarios in the lesser ASN reaches of the Dearne more significantly limited channel lateral migration and controlled erosion and deposition in both short- and long-term period. Furthermore, all the scenarios in Dearne induced a more stable mainstem planform. This is presumably due to the heterogeneity of the catchment environment (Liu et al., 2016).

The results imply the Rother's scenarios are more effective in reducing the vertical erosion while Dearne's scenarios more effectively control the channel lateral migration. The possible reason behind is the construction rate in the comparison areas which can be supported by Jarriel et al., (2021). In the Rother (Fig. 7), more constructed area limits the daily moderate flows thus the bed vertical erosion (Hartshorn et al., 2002). The Dearne, with a lower construction rate (Fig. 8) has more space to store the water during flood events, which is contributable in limiting bank erosion (Stark, 2006).

In addition, in this model, differences in the modified sub-basins' floodplain land cover (Table 1) affects the infiltration of surface water flows and the friction and resistance of the soil to scouring by water (Na & Yoo, 2022; Xie et al., 2018), which in turn affects the flow velocity and sediment discharge (Coulthard & Van De Wiel, 2017; Meadows, 2014). Slope also impacts the intensity of erosion and sedimentation activity (Williams et al., 2016), and the scale of tributaries influences the intensity of this conductive effect (L. E. E. Benda et al., 2004). Sites with different characteristics (Table 1) can reveal variable environmental responses to the same restoration scenario. Consequently, it is essential to select the most optimal modification allocation scheme based on the environmental expectations including flood risk control, catchment degradation reduction and habitat creation.

5.3. Implication to meander restoration projects and limitation

It is recommended that rivers should be given sufficient space to allow themselves to adjust in less urbanised areas (Henshaw & Booth, 2000). On the other hand, the reduction of river sediment discharge is an important attribute for maintaining soil and limiting river degradation (Deng et al., 2022). Therefore, a small number of consolidated projects restored in upper tributaries are likely to help the catchment to achieve sustainable development, in terms of restricting erosion and deposition activities and limiting degradation of the main channel floodplain. However, from a biodiversity enhancement perspective, such schemes may have limited effects since it is evidenced that the physical heterogeneity of the river channel caused by lateral erosion is essential for the creation of habitats (Williams et al., 2020).

In reality, rivers are constrained by levees in highly urbanised areas, which inhibit lateral migration. Thus, it is quite likely that river migration downstream of the main channel will not take place in this study. Nevertheless, the study's findings remain very useful, since they suggest that during severe flood occurrences, levees in channel active areas are particularly susceptible to failure, resulting in increased flood danger for nearby communities. Additionally, due to the topography, land cover and historical river morphology, it was not possible to ideally control the values of ASN to be precisely aligned when doing project scope comparisons, which is one of the limitations of this study. This could possibly be remedied in subsequent studies by a larger number of experiments in more catchments with similar characteristics. The intertwined root systems of riparian vegetation can undoubtedly reduce water velocity, reduce erosion and stabilise the riverbanks (Florsheim et al., 2008). However, this study solely considers changes in hydrological characteristics due to geomorphological changes, which subsequently affects erosion and deposition activities, excluding the impact on channel stability due to the response of the vegetation community as a result of meander restoration. This is limited by the model applied (Coulthard & Van De Wiel, 2017), which may lead to deviations between the river evolution in this study and the real river self-adjustment. In the future, other models could be used to assist in exploring the indirect effects on catchment geomorphology of vegetation changes caused by meander restoration.

6. Conclusion

This study applied Caesar-Lisflood to explore the long-term impacts of different tributary's meander restoration scenarios on mainstream's geomorphological stability. The scenarios varied in the scope and position. The results of the 50-year assessment of channel and floodplain stability illustrate that different meander restoration deployment scenarios for tributaries have different impacts on landscape stability in the mainstream subbasin, given the same cumulative length. More specifically,

1) overall, 93.75 % (15 out of 16) hypothetical restoration scenarios benefit from limiting lateral migration of the mainstream channel with less floodplain occupation area and 87.5 % (14 out of 16) scenarios successfully reduced sediment discharge.
2) In the project's placement exploration, upstream (lesser ASN) projects are more efficient in preventing watershed degradation because of the significantly reduced sediment discharge than the downstream.
3) In project's scope exploration, fewer consolidated projects are more effective in limiting lateral erosion and deposition in the valley and reducing channel loading than multiple dispersed projects.

Therefore, an appropriate restoration scheme needs to be adapted to the specific objectives and based on the specific topography. The more specific recommendations are made: 1) when aiming to reduce sediment discharge to downstream reaches and to thus prevent the mainstream watershed's degradation, the lesser ASN tributary restoration projects should be prioritised for further investigation; 2) when possible, consolidated meander restoration projects are worthy of primary consideration for controlling the overall mainstream erosion and deposition activities and reducing sediment yield downstream. These suggestions should provide scientific basis for practitioners, planners and policymakers to make early project assumptions regarding how meander restoration projects can be deployed to achieve sustainable development of catchments with similar physical characteristics to this study area, for instance the Humber river basin district, given the limited project resources available. Further study is needed to determine if these patterns will apply to similarly sized catchments in other parts of the world, or to catchments of significantly greater or smaller size.

The results indicate the significance of project placement and allocation in achieving landscape stability. This provides landscape planners and designers with a possible reference to prioritise restoration initiatives. An appropriate restoration scheme needs to be adapted to the specific objectives and based on the specific topography. The more specific recommendations are made: 1) when aiming to reduce sediment discharge to downstream reaches and to thus prevent the mainstream watershed's degradation, the lesser ASN tributary restoration projects should be prioritised for further investigation; 2) when possible, consolidated meander restoration projects are worthy of primary consideration for controlling the overall mainstream erosion and deposition activities and reducing sediment yield downstream. These suggestions should provide scientific basis for practitioners, planners and policymakers to make early project assumptions regarding how meander restoration projects can be deployed to achieve sustainable development of catchments with similar physical characteristics to this study area, for instance the Humber river basin district, given the limited project resources available. Further study is needed to determine if these patterns will apply to similarly sized catchments in other parts of the world, or to catchments of significantly greater or smaller size. Additionally, the utilisation of computational modelling to comprehend the interaction between hydrological processes and landscape morphology can equip planners with a technical perspective to achieve sustainable catchment management and resilience to climate change.

CRediT authorship contribution statement

Mincong Wang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joseph Claghorn:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Conceptualization. **Lu Zhuo:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2024.105232.

Data availability

Data will be made available on request.

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Data:

British Geological Survey (2016), Superficial Deposit Thickness (1Km Hex-Grid1Km Hex-Grid), https://www.bgs.ac.uk/geological-data/datasets/?tax_topic=geology&tax_purpose=all&tax_area=all&sterm=Superficial+thickness&order=asc#reset.

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