Modelling Tributary Reforestation Effects on Downstream Main Channel Fluvial Geomorphology

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1. Introduction

1.1 Land use change and reforestation

Land-use change has remarkable impacts on the hydrological and geomorphic characteristics of a catchment. Removal of woodland can lead to heightened water flow and increased flood risk (Sokolova et al. 2019; Acreman et al. 2021), nutrient depletion (Lenhart et al. 2003), increased soil erosion activities with consequently increased sediment yield (Simon and Darby 2002), increased channel widths (Kondolf et al. 2002), decreased soil stability and thus degradation of the catchment (Liébault et al. 2005; Asfaha et al. 2016). With diminishing agricultural activities and the urgency of adaptation to climate change, reforestation, as one of the Nature-based Solutions (NbS), is considered globally as an indispensable approach to catchment sustainable management, flood mitigation, and biodiversity enhancement (Acreman et al. 2021; Nadal-Romero et al. 2023; Aghaloo et al. 2024; Lalonde et al. 2024). However, there is a risk that the expected benefits will not be achieved and that there will be unanticipated negative consequences on hydrological processes and ecosystems (Chappell et al. 2007; Trabucco et al. 2008). In order to successfully implement this land management measure, the hydrological impacts of reforestation on the entire catchment need to be understood from a long-term perspective (Hawtree et al. 2015; Buechel et al. 2022).

1.2 Reforestation catchment-based effects on geomorphic stability

Global monitoring and analytical studies of the response of river channels and floodplain geomorphology to human interventions such as reforestation can not only help to inform decision-makers about the impact of hydro-ecological interactions but also optimise sustainable land management strategies (Kondolf et al. 2002; Keesstra et al. 2009). Among these, concerns have been raised about the impact of forest-hydrological interactions on catchment erosion and deposition reduction and flood risk mitigation (Ballesteros Cánovas et al., 2017; Marden et al., 2014). Reforestation has been demonstrated to reduce sediment yield and deposition by around 50 per cent over 50 years (Piégay et al. 2004; Stott and

Mount 2004; Boix-Fayos et al. 2007; Keesstra et al. 2009; Phillips et al. 2018). In addition, as a consequence of reforestation, the river channel evolves in its physical morphology, with a changed width, changing patterns from braided to meandering and incision inducing a deeper riverbed (Rinaldi 2003; McBride et al. 2008, 2010; Scorpio and Piégay 2021). This change will undoubtedly affect the hydrological and ecological impacts of e.g. hydro-aquatic habitats in the catchment (Keesstra et al. 2009; McBride et al. 2010; Piégay et al. 2023). Much of the research on the impacts of reforestation on geomorphology at the catchment scale has focused on the observation and monitoring of existing projects (Boix-Fayos et al. 2007; McBride et al. 2008, 2010; Bunce et al. 2014; Marden et al. 2014; Ballesteros Cánovas et al. 2017). However, there are situations where decision-makers want to understand and compare the expected benefits of multiple decision options and make choices and preparatory measures prior to project implementation. This study contributes to the field of fluvial geomorphology by quantifying the decadal-scale geomorphic response of a main river channel to tributary reforestation. It focuses on sediment connectivity, channel evolution, and planform dynamics in response to land use interventions.

1.3 Effects of projects' location and size on geomorphic stability

More specifically, the location and scale of reforestation can have varying degrees of impact on the hydrology and geomorphology of the catchment. Soil and hydrological conditions, topographic and climatic constraints, persistence of woodland communities, and adaptability of species are important prerequisites to be considered when determining the location of reforestation sites (Zhou et al. 2002; van Dijk et al. 2007; Mosner et al. 2011; Cunningham et al. 2015; Rasiah and Florentine 2018). However, it is also worthwhile to explore the selection of sites for reforestation from the perspective of their benefits in terms of geomorphic impacts (Castillo-Reyes et al., 2023; Phillips et al., 2013; Trabucco et al., 2008). Existing research indicates that, compared to upslope zones, reforestation in channel riparian areas can reduce stream flow and improve biodiversity to a greater degree (Scott 1999; Cunningham et al. 2015). Reforestation of areas further downstream with high localised depositional activity can result in greater reductions in sediment yield (Castillo-Reyes et al., 2023; Coulthard & Van De Wiel, 2017). In addition, the cumulative effect of multiple projects is not equivalent to the sum of the impact of each project since there is not a linear relationship between the degree of impact on the geomorphology and the intensity of land use change (Hemond & Benoit, 1988; Phillips, 2003). Therefore, considering limited resources and financial provisions for reforestation, determining the optimal location and scale of projects from the perspective of the triggered geomorphic response is essential to optimising resources and minimising negative impacts.

1.4 Caesar-lisflood application and performance

Computational modelling provides the opportunity for geomorphic evolution simulation to predict the catchment responses to reforestation. A well-known model among them is CAESAR-Lisflood (CL), which can measure the processes of sediment deposition and suspension in restored and regulated catchments (Coulthard et al., 2013; Coulthard & Van De Wiel, 2017; Meadows, 2014). CL is a combination of two models: Caesar, a mesh-based Landscape Evolution Model (LEM) that models erosion and deposition over various time intervals, and Lisflood-FP, a two-dimensional flow model that follows the paths of water between individual cells (Coulthard et al., 2002; Coulthard et al., 2013). By continuously adjusting the elevation of each cell and updating the flow dynamics, the water flow that is generated by CL controls the transport and deposition of sediment (Van De Wiel et al. 2007). It is through this iterative process that zones of erosion and deposition within the catchment are adequately defined by this elevation change, so as to simulate the evolution of the physical geomorphology. The adaptability of CL has made it possible for it to be utilised in a variety of contexts. It has previously been employed for the purpose of evaluating the effects of landform and land use modification in terms of check dam construction or removal (Poeppl et al. 2019; Ramirez et al. 2020, 2022), and testing the efficacy of nature-based solutions, such as leaky barriers installation and reforestation, on erosion, deposition, and landscape trajectory along river channels (Coulthard & Van De Wiel, 2017; Na & Yoo, 2022; Walsh et al., 2020). CL has shown great accuracy and a low rate of error in the comparison of results between modelled scenarios and historical observations (Feeney et al. 2020; Walsh et al. 2020).

Existing research is still lacking in modelling the long-term impacts of reforestation location and allocation on the geomorphology, and in providing recommendations for reforestation in terms of geomorphic response. Drawing on prior research, this study aims to use CL to explore how land use changes in terms of reforestation projects in the catchment's higher-up tributaries impact the downstream main channel's geomorphology. Specific research questions are (Fig. 1):

1) In terms of long-term effects on geomorphic stability, what are the consistent advantages of reforestation downstream from the locations of implementation?

2) How will the relative location of reforestation projects, higher up in the catchment versus in the centre of the tributary, in the riparian buffer zone versus the upland of the channel, influence the long-term geomorphic stability of the main channel?

3) How will the major channel's geomorphic stability be affected in the long run by the distribution of projects in the tributary channels, specifically whether they are consolidated, large projects or numerous smaller ones?

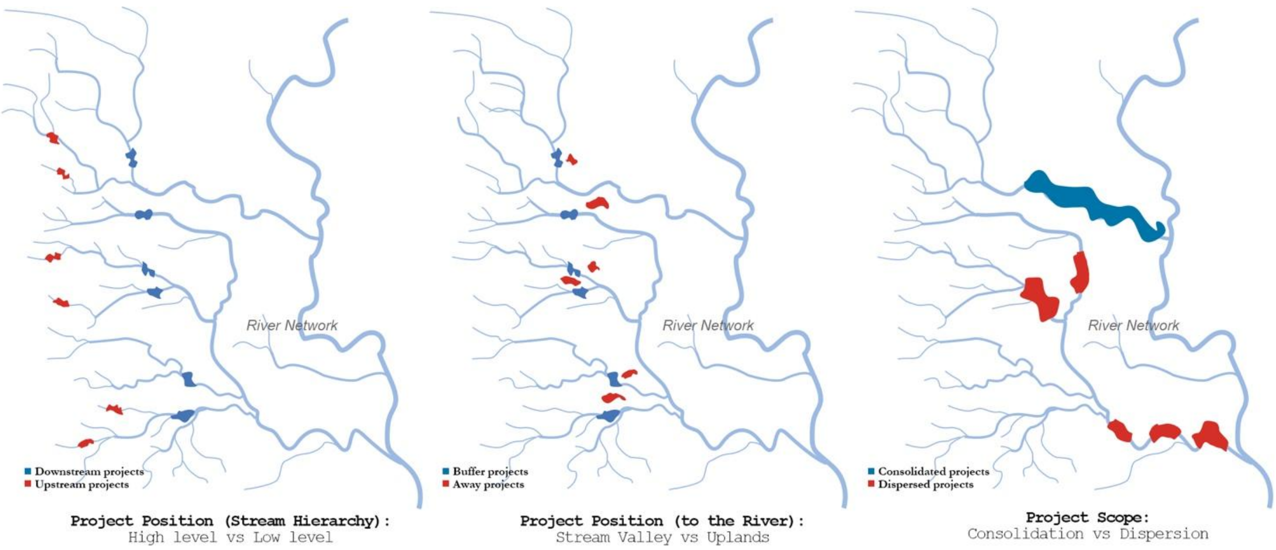


Fig. 1. Comparison of reforestation allocation scenarios in research questions. The cumulative project area remains equal in all scenarios (i.e. the sum of red areas = the sum of blue areas)

2. Methods

2.1 Study area

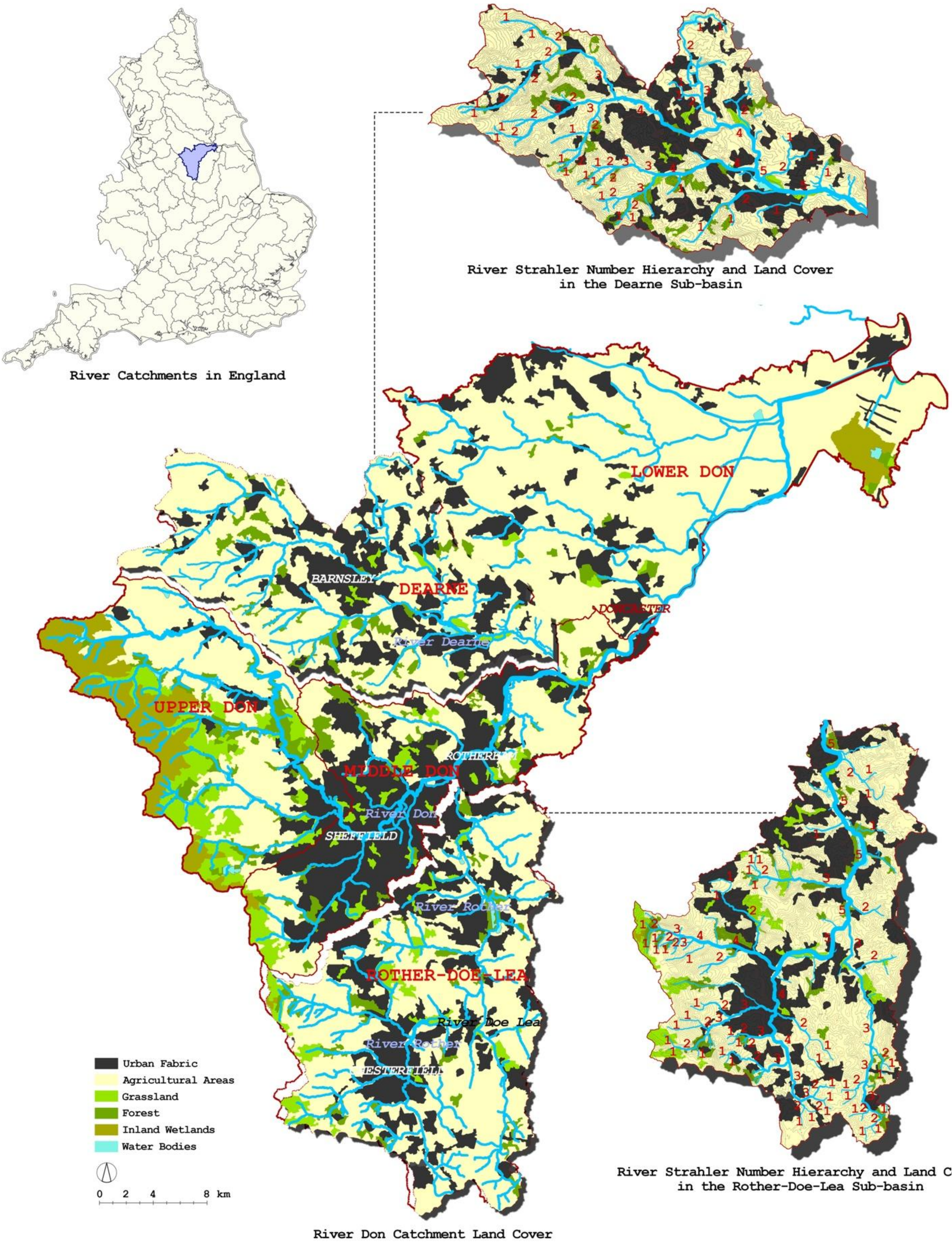


Fig. 2. The River Don Catchment land cover and Dearne and Rother-Doe-Lea sub-basins

Positioned in northern England, the River Don basin covers an area of almost 1,700 km² (Fig. 2). The River Don spans a total length of 80 km and functions as the principal river channel. The highest parts of the catchment and the source of the Don itself are located in the eastern Pennine hills of the Peak District National Park. Following its course through Sheffield, the most populous urban region in the catchment area, the river afterwards traverses Rotherham and Doncaster before joining with the River Ouse immediately upstream of the Humber Estuary, ultimately emptying into the North Sea. Two prominent tributaries, the River Rother and the River Dearne, converge with the River Don in its middle section. The Rother-Doe-Lea and Dearne sub-basins, with respective areas of 397 km² and 328 km², are drained by these rivers. Although both tributaries form part of the River Don system, they differ in several basic characteristics. The Rother–Doe Lea sub-basin is slightly larger and exhibits a higher mean and peak discharge. Terrain Ruggedness Index (TRI) classifications also show a greater proportion of moderately and intermediately rugged terrain in the Rother–Doe Lea, whereas the Dearne sub-basin contains a higher percentage of level areas. Land cover also varies, with the Rother–Doe Lea having a larger urban extent and slightly less woodland than the Dearne.

Additionally, in order to utilise the resources in this area effectively for various socioeconomic advantages, the river system has been historically regulated for different purposes such as water provision, mining, establishment of grazing land and farming, flood mitigation, waterpower generation, and navigation. These changes have impacted the ecological and hydrological processes of the river system. After experiencing a devastating flood in 2019, a catchment-scale Natural Flood Management (NFM) programme for the Don catchment produced by Environment Agency (EA) named ‘Source to the Sea’ in South Yorkshire, aimed to deliver nature-based approaches, including wetland and forest creation and floodplain and river channel re-naturalisation and reconnection, for constant climate resilience over a 12-year period from 2019 to 2031 (Shaw et al. 2021).

2.2 Technical procedure

This study utilised the CAESAR-Lisflood (CL) model to simulate the temporal changes in the catchment geomorphology. In order to accommodate the software's limit of processing up to 2 million grid cells in a single simulation, the modelling process was carried out in two phases (Fig. 3). The model computed water flow and sediment transport in the Dearne, Rother, and Upper Don sub-basins in Phase 1. The model simulated a base scenario in all three sub-basins with no land-use changes, along with several design scenarios representing different distributions of reforestation projects within the Rother and Dearne sub-basins only. This is due to an early judgement that the potential for reforestation in the Upper Don (but not in the Upper Rother nor Upper Dearne) was rather limited due to the large area of preserved moorland. Then, the hydrodynamical outputs from Phase 1 were integrated into Phase 2, as illustrated in Fig. 3. The water and sediment flow coming from the three upper sub-basins were set as inputs together with the precipitation in the Middle Don to simulate the Middle Don sub-basin’s evolution. After data collection and preparation using ArcGIS, the processed data were utilised as inputs for the CL model in each phase. Ultimately, the scenario results were examined using ArcGIS and SPSS software to evaluate the various reforestation approaches.

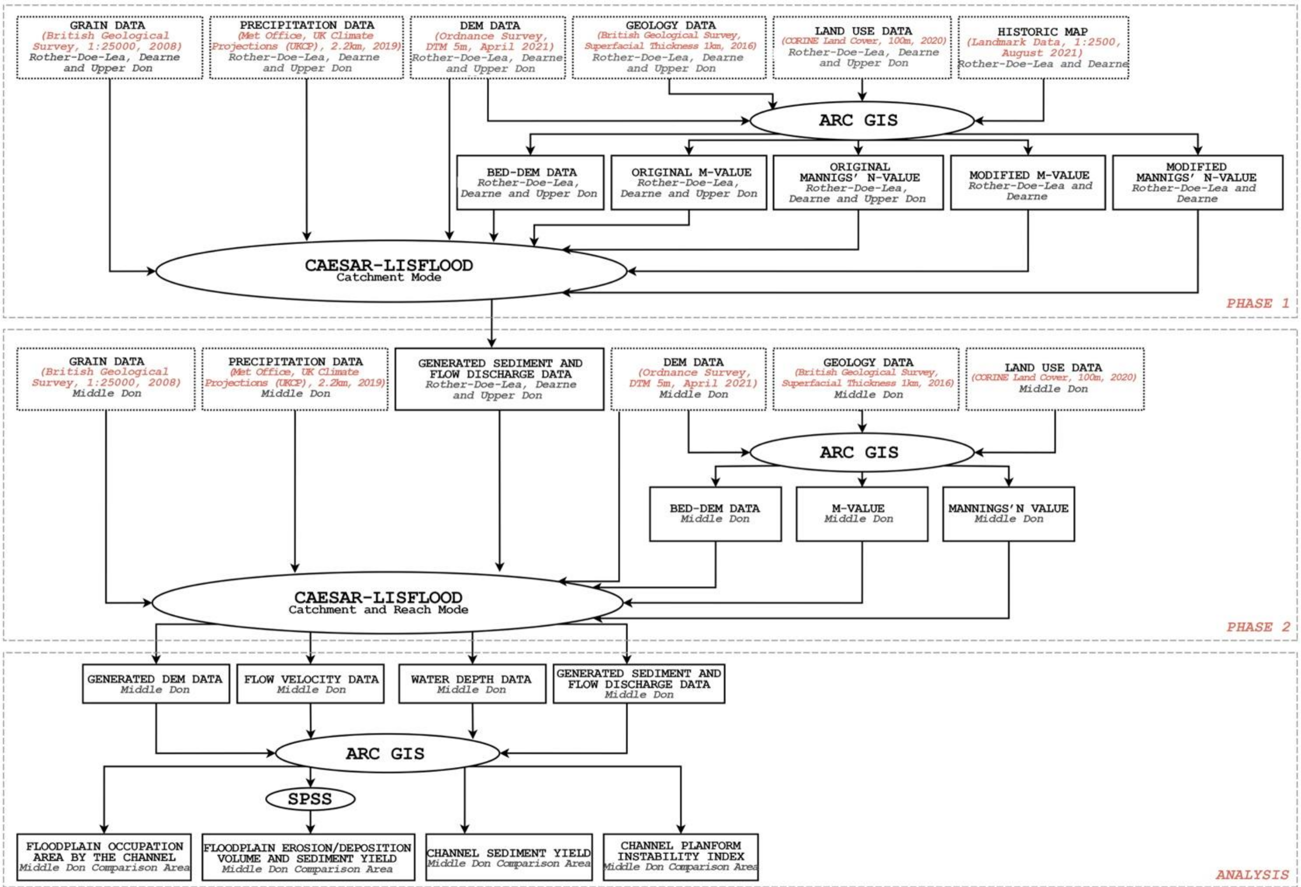


Fig. 3. Modelling simulation flow diagram

a. Model inputs, parameters and calibration

The CAESAR-Lisflood model is primarily set upon four main types of inputs to reflect the catchment characteristics: a Digital Elevation Model (DEM), sediment data, rainfall data, and land cover data. Other major associated parameters are shown in Table 1. A 5 m-resolution Digital Elevation Model (DEM) obtained from the Ordnance Survey (2021) is resampled to 50 m in ArcGIS to account for the cell limit of the CL. A 'bedrock DEM' is also required as a representation of the underlying layer that is resistant to rapid erosion by water, thereby preventing simulated erosion from exceeding a specific threshold in chosen regions (Poeppl et al. 2019). This bedrock DEM was derived by deducting 0 to 8 metres from the baseline DEM, based on the surface layer thickness values provided by the British Geological Survey (2016).

Accurate determination of the direction and volume of sediment flow requires meticulous analysis of sediment data, related to the size and distribution of up to 9 different particle kinds. Given the extensive size of the catchment, it is not practicable to collect representative soil particle data by individual soil sampling throughout the whole region in this study. Previous investigations on sediment in the River Don have utilised particle size data (Woodward and Walling 2007) and data on silt, clay, and loam proportions obtained from Soil Parent Material, sourced from the British Geological Survey (2018), to inform the creation of sediment behaviour models. Following an analysis and comparison of particle parameters from previous research, namely those carried out in North England's Swale catchment using the CL model (Coulthard & Van De Wiel, 2017; Walsh et al., 2020; Xie et al., 2018), which were shown to be achievable by Feeney et al. (2020), a suitable set of values for the sediment data in the Don catchment was established by calibrating the model.

Table 1 Key parameters of CL

Parameters	Values
Grain sizes (m)	0.000001, 0.0000015, 0.000002, 0.00001, 0.00002, 0.00005, 0.000625, 0.002
Grain size proportion (total 1)	0.08, 0.15, 0.265, 0.225, 0.125, 0.035, 0.065, 0.055
m' value	0.005 (urbanized) -0.02 (forested) based on land cover
Mannings' n	0.015 (urbanized) -0.15 (forested) based on land cover
Sediment transport equation	Wilcock & Crowe Formula
Lateral erosion rate	0.000001
Max erode limit (m)	0.02
Courant number	0.7
Froude flow limit	0.8
Soil creep value	0.0025
Slope failure threshold	45°

All simulations were driven by hourly precipitation data from the UKCP18 local climate projections under the RCP 8.5 emissions scenario for 2021–2070. Extreme-event and calibration rainfall inputs were taken from the MIDAS hourly observational dataset. An hourly timestep was adopted to balance computational efficiency and model stability, as increasing temporal resolution does not improve CL performance (Coulthard & Van De Wiel, 2017; Ramirez et al., 2022). The same climate forcing was applied across all scenarios to ensure that variations in model outcomes reflect land-cover change rather than climatic variability.

Manning’s roughness coefficient (Manning’s n) and the 'm' value are crucial parameters in this study for quantifying land use and plant density in a catchment area. These indicators have a direct influence on flow depth and the hydrograph, especially in relation to peak flow and flow duration. This research employed the Corine 2018 land cover data (European

Environment Agency, 2020). Building upon prior research with the CL model and calibration efforts (Wang et al. 2025a, b), this work utilises Manning's n values ranging from 0.015 to 0.15, together with 'm' values ranging from 0.005 to 0.02. The values represent varying degrees of plant density, ranging from scant to abundant, and surface types, ranging from hard-paved surfaces, which are urbanised areas, to extensively vegetated landscapes, which are woodland or forest (Li et al. 2020; Walsh et al. 2020; Na and Yoo 2022). In the setting of CL, the vegetation parameters are accessible but have limited configurable parameters that represent conditions in terms of grass maturity, critical vegetation shear, and the percentage of mature vegetation that is susceptible to erosion. These parameters are set for the entire modelled area and cannot be customised according to the area. The characteristics in this study were chosen based on prior research to replicate a catchment with stable banks and well-developed vegetation, therefore accurately representing the present vegetation condition in the catchment area (Saynor et al. 2019; Walsh et al. 2020). Therefore, the simulation scenarios in this study referred to a reforestation area where the trees were already mature and had skipped their growth process.

Model calibration was undertaken by comparing simulated discharge with observations from a lower-catchment gauging station between December 2012 and May 2013. Although this represents only a six-month window, the period includes both low flows and a pronounced high-flow event (>40 m^3/s), offering a suitable range of hydrological conditions for tuning peak response and hydrograph recession. Calibration rainfall inputs were taken from the MIDAS hourly dataset, and model agreement with observed discharge reached a Nash–Sutcliffe Efficiency of 0.71, classified as ‘good’ (Moriasi et al. 2015; Walsh et al. 2020). Short validation intervals have been effectively used in long-term geomorphic simulations elsewhere; for example, Meadows (2014) validated a 200-year sediment-yield model using one year of observations. In this study, the six-month period represents approximately 1% of the simulation length, which is within precedent. Spatially distributed m-values were calibrated following Ramirez et al. (2022), enhancing the model’s ability to reproduce realistic hydraulic behaviour. Additionally, comparison of simulated lateral migration with documented historical adjustments in the Don catchment indicates that the magnitude and pattern of channel change produced by the model are geomorphologically comparable over longer timescales (Appendix A). Additionally, before the real simulation, there is a period of five years, which is designated as the "model spin-up" phase. This interval is essential to enhance the synchronisation of the model's behaviour with real-world conditions, by considering variations across datasets (Feeney et al. 2020). The duration of the spin-up phase was verified by analysing sediment and water discharge metrics over many years, with rainfall data that was replicated ten times within the same year. During the fifth year, the findings reached a point of convergence towards consistent values, which was also validated by a prior study conducted by Feeney et al. (2020).

2.4 Simulation scenarios

A map of possible reforestation sites is created by identifying regions currently used as pasture or arable land with historically recent deforestation, transitioning from woodland or plantation to agricultural land from the 1840s onwards, using historical Ordnance Survey maps (Landmark Data, 2021) (Fig. 4). Utilising this data, the land use map in ArcGIS is adjusted to create inputs for the m-value and Manning's n parameter, which are derived from these historical changes.

Subsequently, the Rother and Dearne sub-basins were modelled with m- and n-values corresponding with the baseline conditions and the changes in values aligned with the eight different reforestation scenarios. Three fundamental characteristics distinguish the eight scenarios from each other: a) the relative placement of projects within the stream hierarchy, b) their closeness to the channel (either in the valley buffer zone or in the surrounding uplands), and c) whether the projects are consolidated or dispersed. The Strahler hierarchy was employed to describe the position of streams within the catchment hierarchy. A stream without tributaries is categorised as Strahler Number 1 (SN1), whereas SN2 streams are created by merging two SN1 streams, and so forth, with SN3 streams resulting from the merging of two SN2 streams (Strahler 1957). This paper utilised the Average Strahler Number (ASN) to aggregate and characterise the Strahler number of multiple projects. In this study, upstream reforestation scenarios had a lower ASN than downstream scenarios, however this comparison was relative rather than absolute. The upstream scenarios in the Rother and Dearne sub-basins varied between ASN 1.3-1.5, whereas the downstream scenarios ranged from ASN 3.2-3.6.

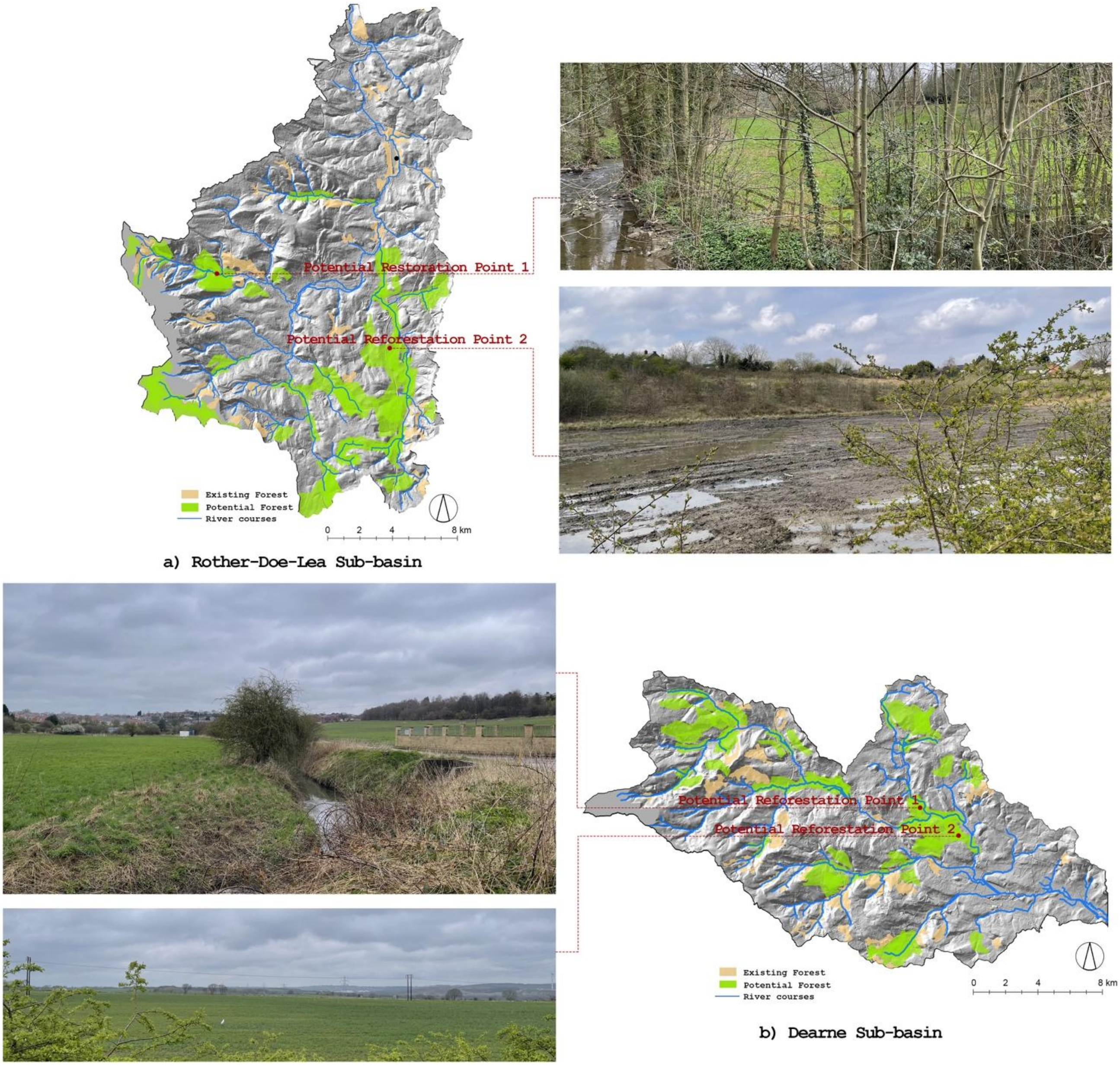
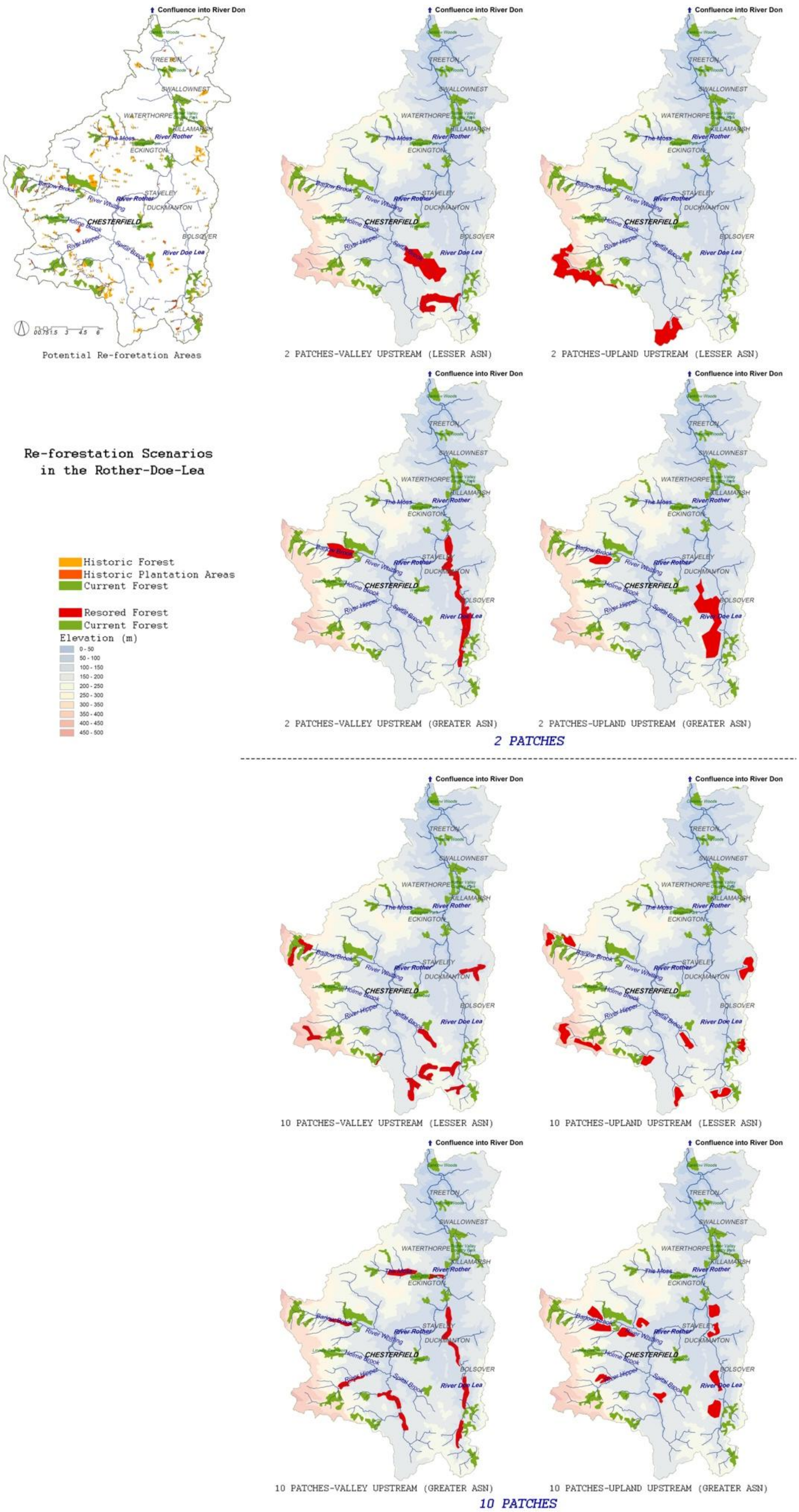
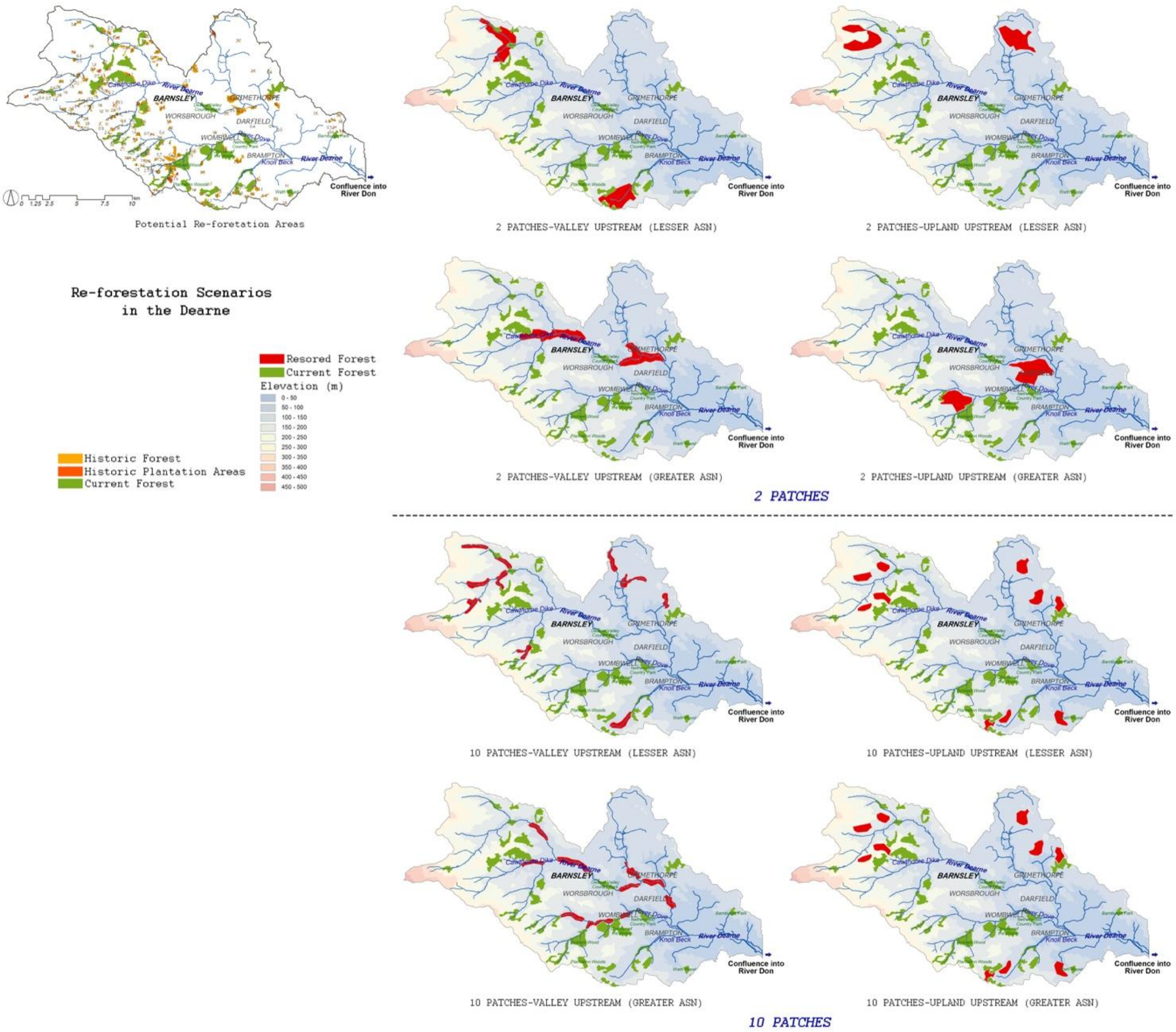


Fig. 4. The photographs of potential reforestation areas in the a) Rother-Doe-Lea and b) Dearne sub-basins

When evaluating the effectiveness of consolidated reforestation projects compared to dispersed forests, each upstream and downstream scenario considered four project distribution possibilities: two large projects or ten smaller ones. Both scenarios maintain the same total area in each sub-basin, which was equivalent to 2.5% of the entire Rother sub-basin (1000 ha) and Dearne sub-basin (820 ha) (Fig. 5). To maintain an equal total cumulative area, the location of each project in the scenarios was determined based on the map of potential reforestation sites.


Re-forestation Scenarios
in the Rother-Doe-Lea
Confluence into River Don
Potential Re-foretation Areas
Historic Forest
Historic Plantation Areas
Current Forest
Resored Forest
Current Forest
Elevation (m)
0 - 50
50 - 100
100 - 150
150 - 200
200 - 250
250 - 300
300 - 350
350 - 400
400 - 450
450 - 500
TREETON
SWALLOWNEST
WATERTHORPE
KILLAMARSH
The Moss
River Rother
ECKINGTON
STAVELEY
DUCKMANTON
CHESTERFIELD
BOLSOVER
River Doe Lea
River Whitting
River Hipper
2 PATCHES-VALLEY UPSTREAM (LESSER ASN)
2 PATCHES-UPLAND UPSTREAM (LESSER ASN)
2 PATCHES-VALLEY UPSTREAM (GREATER ASN)
2 PATCHES-UPLAND UPSTREAM (GREATER ASN)
2 PATCHES
10 PATCHES-VALLEY UPSTREAM (LESSER ASN)
10 PATCHES-UPLAND UPSTREAM (LESSER ASN)
10 PATCHES-VALLEY UPSTREAM (GREATER ASN)
10 PATCHES-UPLAND UPSTREAM (GREATER ASN)
10 PATCHES

a)



b)

Fig. 5. Simulation scenarios in the a) Rother-Doe-Lea and b) Dearne sub-basins

2.5 Outputs processing and analysis

The impacts of the reforestation projects on erosion processes, channel migration, sediment yield and channel planform dynamics were assessed downstream of all woodland initiatives after the convergence of each tributary (River Dearne and Rother) with the River Don rather than inside the sub-basins themselves. A comprehensive analysis of the floodplain of the River Don was conducted, beginning 2 km upstream and extending 10 km downstream from the confluence of the Rother and Dearne rivers with the Don (Fig. 6).

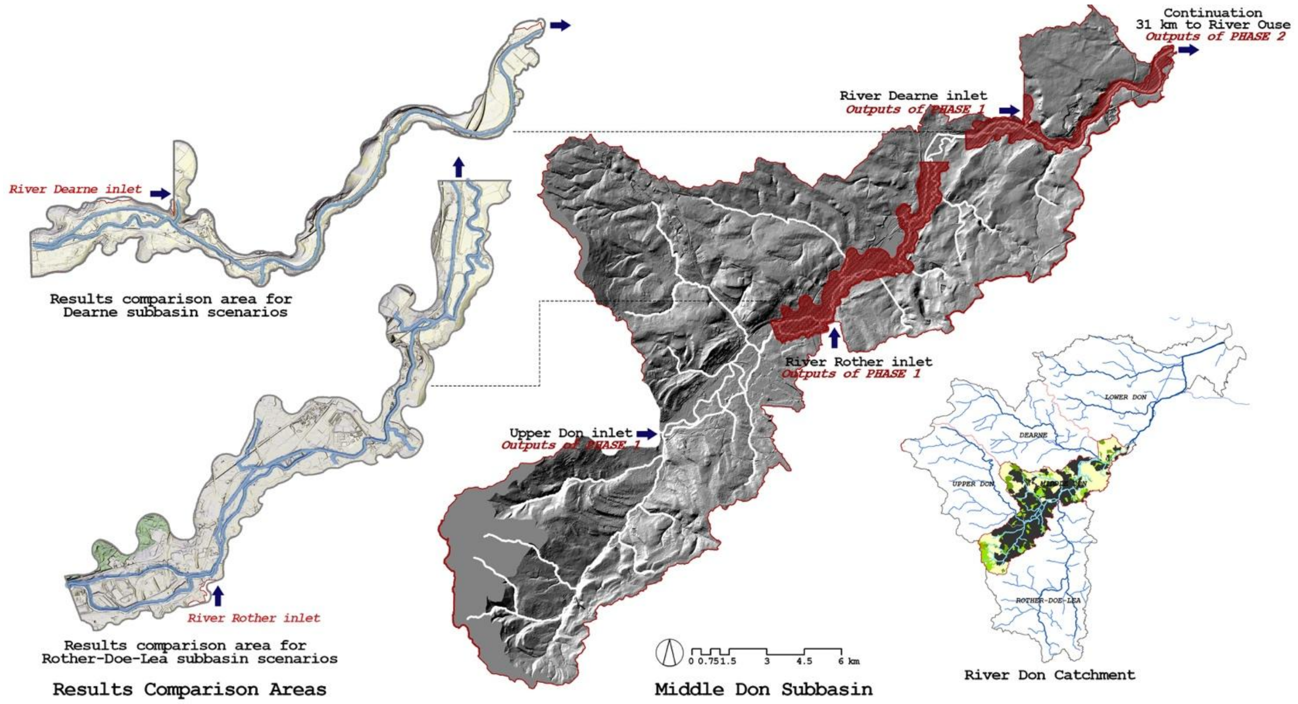


Fig. 6. Comparison area in the Middle Don sub-basin for Rother-Doe-Lea and Dearne reforestation scenarios

This study collected data using CAESAR-Lisflood (CL) simulations at regular intervals, every year from 2020 to 2070. The main outputs were Digital Elevation Models (DEMs), water depth, and flow velocities. After the acquisition of the modelled DEMs, the annual erosion and deposition volumes in the Middle Don sub-basin were calculated. There was a distinction between areas that were rising in elevation and those that were falling; the former was defined as "erosion", while the latter was defined as "deposition". The erosion and deposition amount for each year was computed as a cumulative sum over 50 years, yielding an average yearly cumulative quantity that was utilised to compare the effects of the reforestation scenarios. The monitoring of the evolving river channel involved the analysis of flow velocity and water depth. Subsequently, the cumulative lateral migration areas, regarded as the active occupation areas of the channel, were obtained by measuring the crossed area between the newly formed and previous main channels of the River Don. Thereafter, the study assessed the stability of the floodplain in the middle part of the River Don by employing two main methods: a) computing the overall amounts of erosion and deposition caused by bank and thalweg incision (Coulthard & Van De Wiel, 2017; Gioia & Schiattarella, 2020), and b) measuring the extent to which the channel is occupied, which indicates the intersection between past and current channel centrelines resulting from lateral erosion (Feeney et al. 2020).

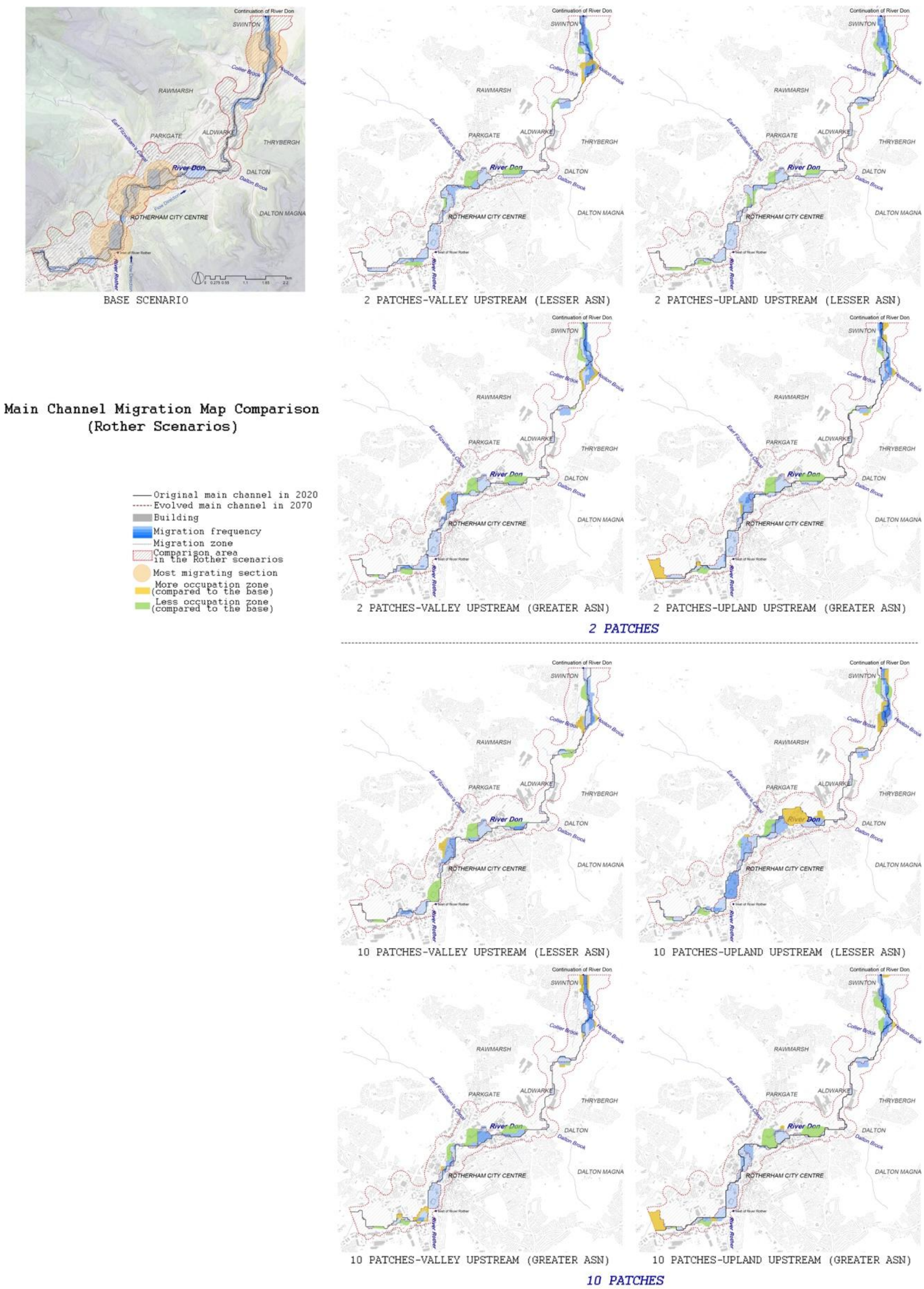
Annual assessments of the channel migration were conducted every five years during the 50-year analysis period. To assess the extent of channel incision, the variations in cumulative erosion and deposition volumes during each decade (2020-2070) to the initial conditions as well as the sediment yield were assessed.

To analyse the channel planform and determine how various reforestation projects affected the river's spatial form, fundamental geomorphic evaluations like the Sinuosity Index (SI) and Braid Index (BI) were employed. It is possible to monitor the SI over time by comparing the developed channel length to the valley length and the BI over time by comparing the total length of all subsidiary and major channels to the main channel length (Brice 1964; Mueller 1968; Mosley 1981). The stability of both indices was assessed by analysing the coefficients of variation (CV) for both indices under different reforestation scenarios (Kuo et al. 2017). A composite measure of channel stability, the Planform Instability Index (PII), was derived using the combined coefficients of variation (CVs) of SI and BI.

A comparative analysis of several morphological stability indicators was used to assess the efficacy of reforestation project sites. Assessment of the effects of project distribution on river morphology was based on differences in average channel migration area, erosion and deposition volumes, sediment discharge, and PII between upstream and downstream sections, compared to baseline scenarios, which represent the original conditions without any land cover change. Morpho-dynamic changes were assessed using spatial overlay analysis in ArcGIS 10.6 and statistical comparisons in SPSS v.26. This approach allowed interpretation of long-term geomorphic impacts of reforestation under different spatial configurations.

3. Results

3.1 Floodplain occupation area by the channel



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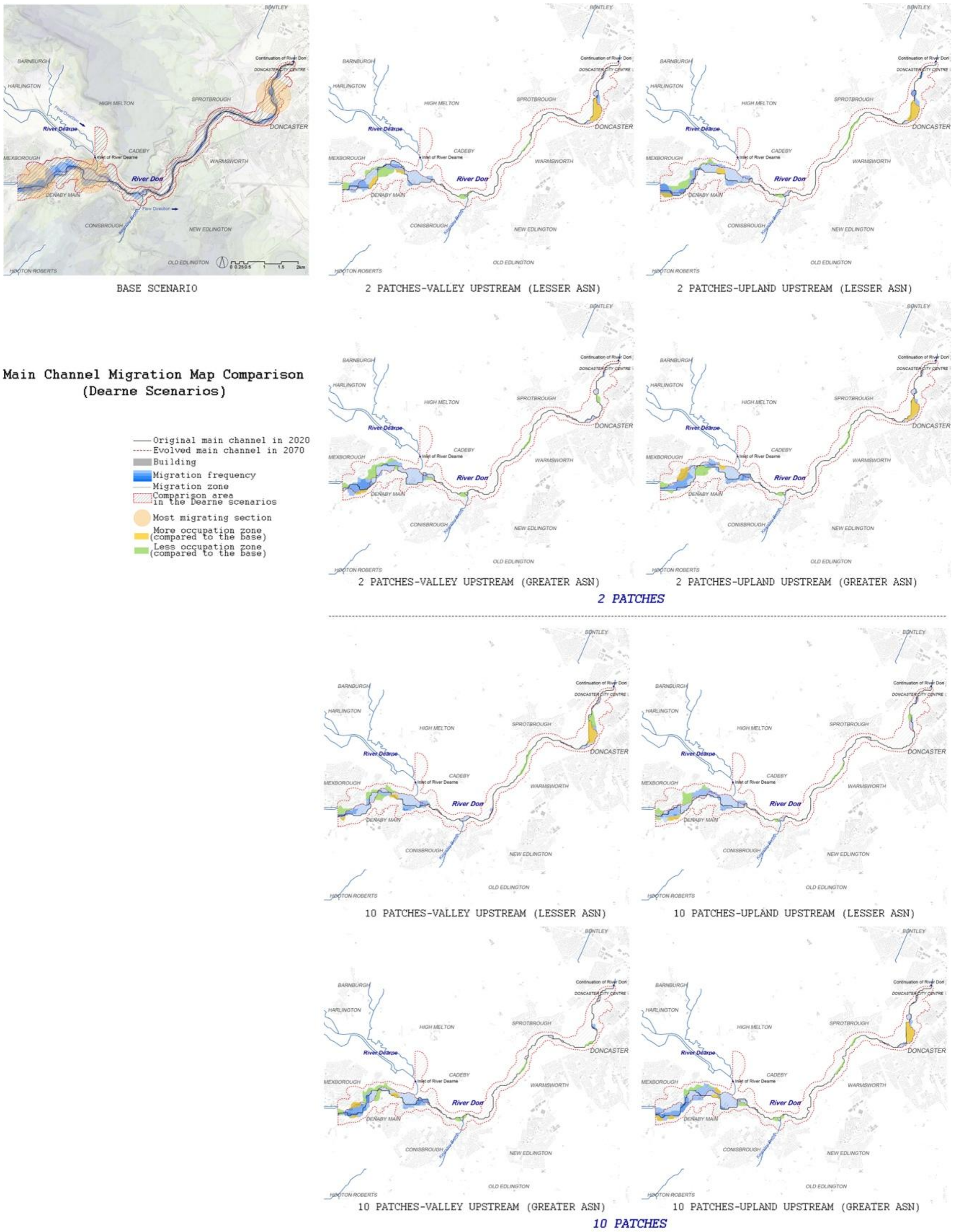
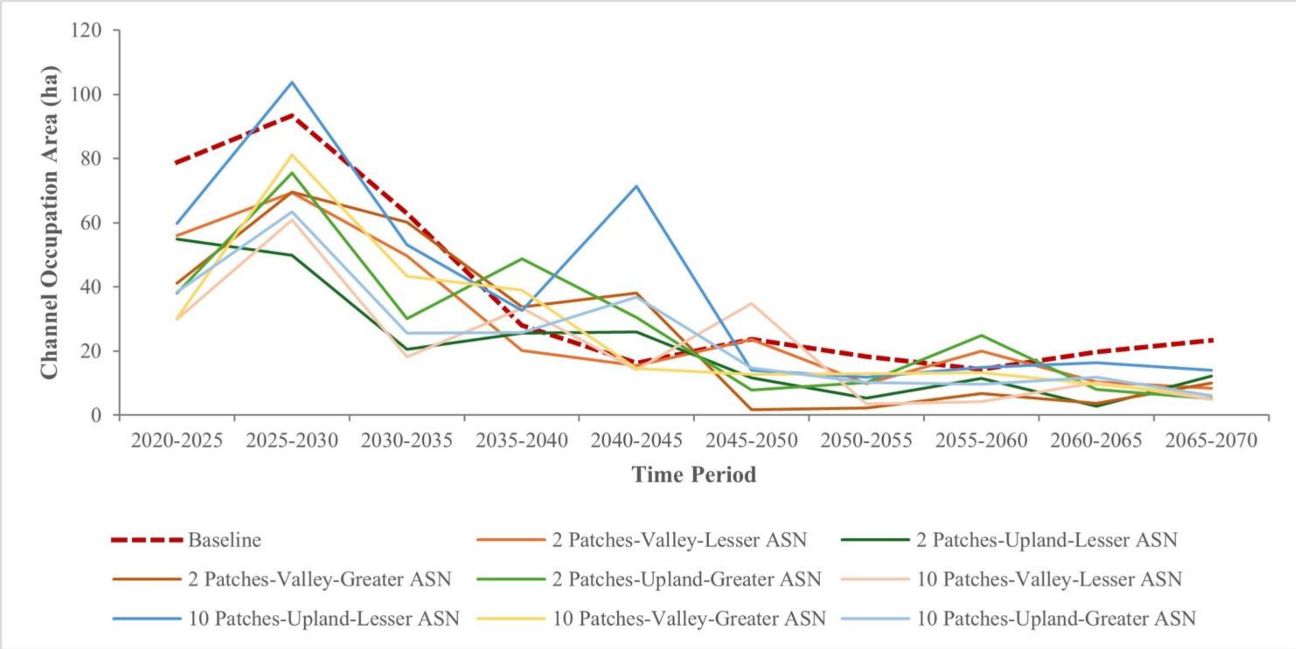


b)

Fig. 7. River Don Channel migration in the 50-year simulation period for the a) Rother-Doe-Lea and b) Dearne sub-basins reforestation scenarios

The map of the active area delineated by the former and reshaped channel of the simulated 50 years in all scenarios has been illustrated in Fig. 7. In the assessment, both the Rother-Doe-Lea and Dearne sub-basins exhibited designs for reforestation that consistently resulted in a decrease in the area occupied by channels, as compared to the baseline scenario (Fig. 8). Although both sub-basins experienced considerable fluctuations throughout the first time periods (2020–2045), the projected scenarios ultimately resulted in reduced channel-occupied areas compared to the baseline as time passed by, especially after 2045. Within both sub-basins, the baseline scenario maintained a somewhat consistent level across the whole timeframe, whereas the designed scenarios exhibited more significant variations, particularly in the early decades. Over time, the designed scenarios consistently stabilised, gradually approaching or even decreasing below the initial occupied area. Such evidence may suggest that the reforestation efforts, however initially inconsistent, resulted in long-term advantages by diminishing and stabilising the area occupied by channels. Through the second half of the simulated period, the scenarios transition towards dynamic equilibrium, leading to more consistent channel-occupied regions compared to the baseline, characterised by reduced fluctuation and lower total values. Nevertheless, disparities existed between the two sub-basins. According to Fig. 8 a, the channel occupation area in the Rother-Doe-Lea sub-basin experienced an early surge in most scenarios, especially between 2025 and 2045, before gradually stabilising after 2045. While also exhibiting variability, the Dearne sub-basin (Fig. 8 b) had lower peak values and sustained larger oscillations across the timeframe, with dynamic equilibrium coming significantly later, around 2060-2065. It is also noted that in both sub-basins, the scenarios with greater patches reforested in the downstream upland area generally lead to more stability and less channel migration, showing a clear benefit in limiting lateral erosion.



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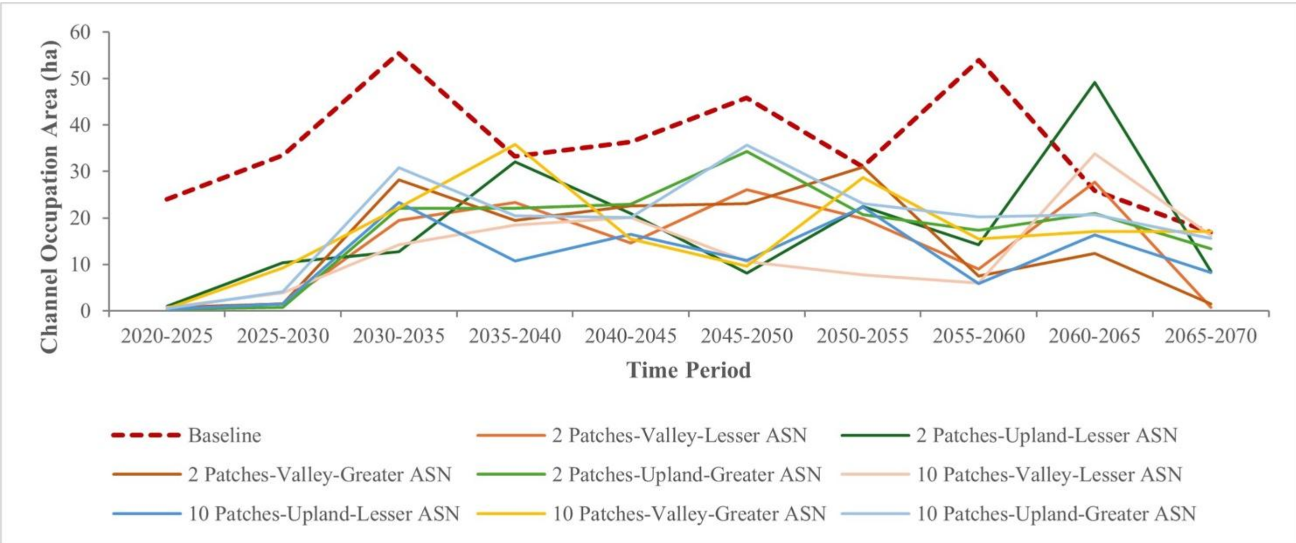
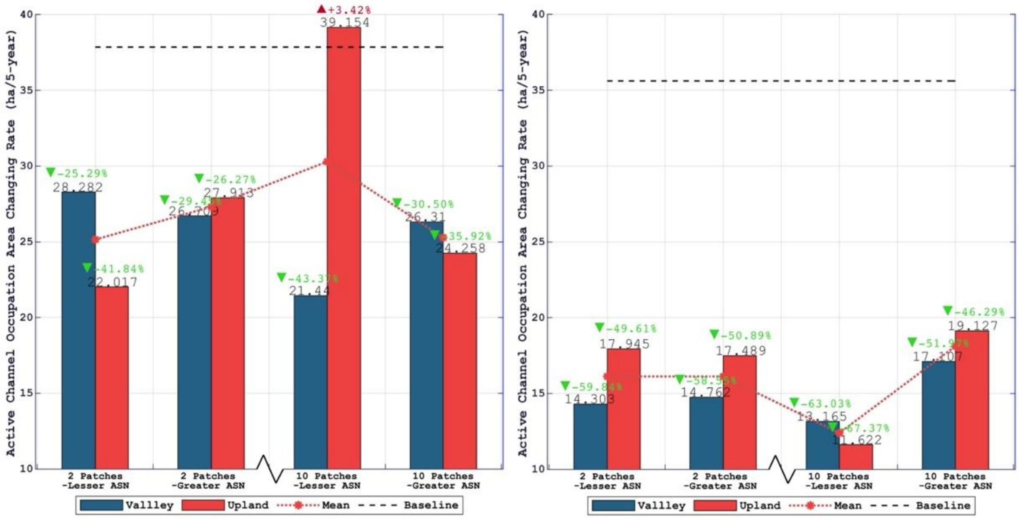


b)

Fig. 8. Occupation area by the channel every 5 years from 2020 to 2070 in the a) Rother-Doe-Lea and b) Dearne sub-basins reforestation scenarios

In both the Rother-Doe-Lea and Dearne sub-basins, the evaluation of the rate at which the active channel occupation area changes consistently revealed that nearly all designed reforestation scenarios resulted in a decrease compared to the baseline scenario, with some scenarios being particularly beneficial (Fig.9). Specifically, upstream and valley interventions showed relatively more reductions in the channel occupation rate than downstream or upland scenarios. There was not a consistent trend in comparing the distribution of smaller reforested areas and fewer, larger ones.

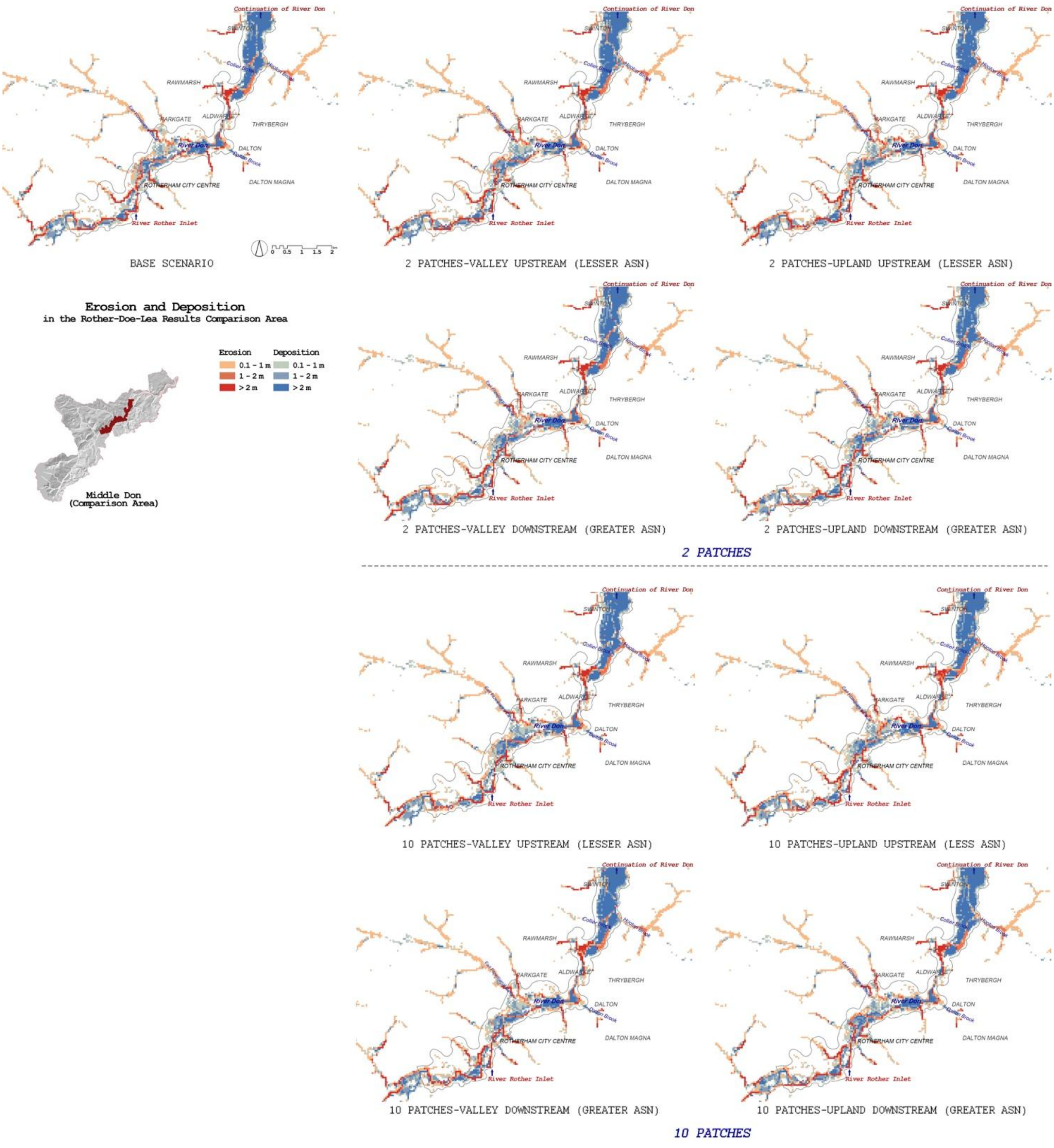


a) b)

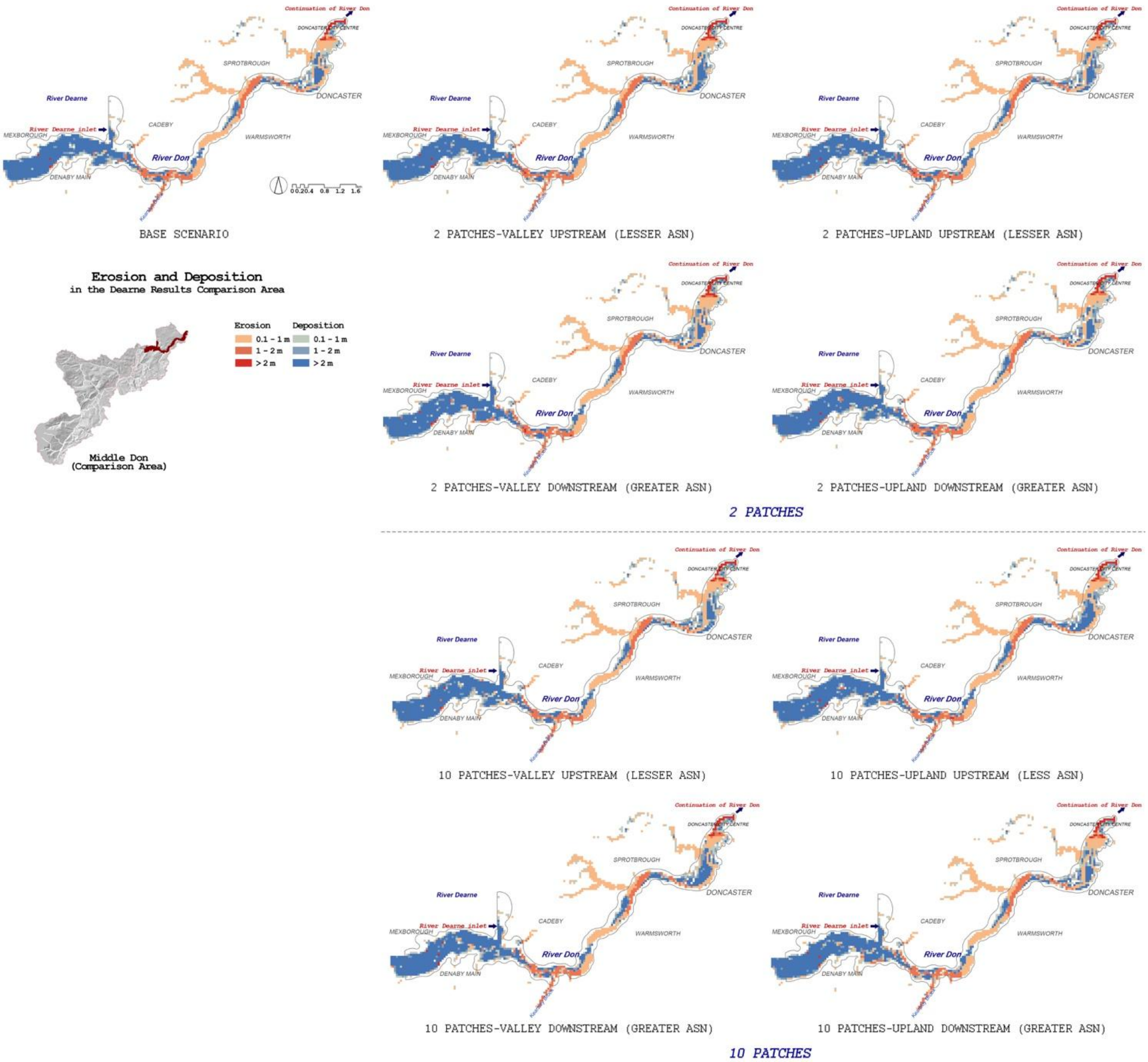
Fig. 9. Comparison of the rate of change in active channel occupation area between 2020 and 2070 under the a) Rother-Doe-Lea and b) Dearne reforestation scenarios

When comparing upstream (lesser ASN) and downstream (greater ASN) scenarios, most upstream scenarios typically had lower channel change rates than downstream scenarios, indicating better lateral migration control in the lower catchment. This trend holds in both the Rother-Doe-Lea (Fig. 9 a) and Dearne (Fig. 9 b) sub-basins, with buffer zone patches upstream yielding the lower occupation area change rates, particularly in the highly dispersed scenarios (10 patches). Regarding the buffer zone (valley) versus upland interventions, in both sub-basins, buffer zone interventions (blue bars) mostly achieved lower rates than upland interventions (red bars), particularly in downstream locations. Discrepancies between the two sub-basins still existed especially in examining the effects of varying levels of project dispersal. Moreover, the Rother-Doe-Lea sub-basin (Fig. 9 a) exhibited more extreme variations, particularly in valley intervention. In contrast, the Dearne sub-basin (Fig. 9 b) showed more moderate fluctuations across all scenarios, with fewer pronounced differences between the valley and upland interventions.

3.2 Erosion and deposition volume



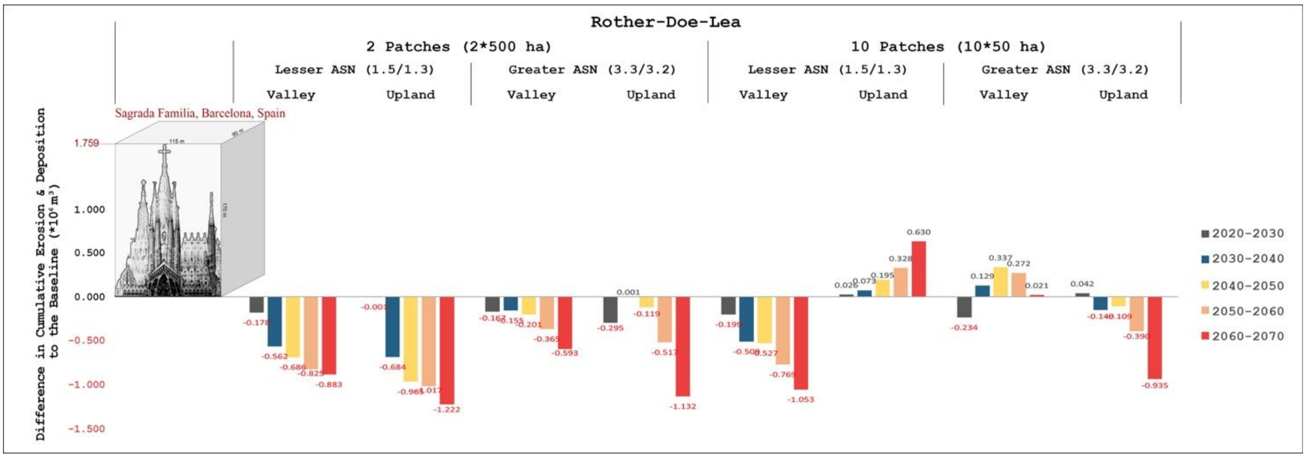
a)



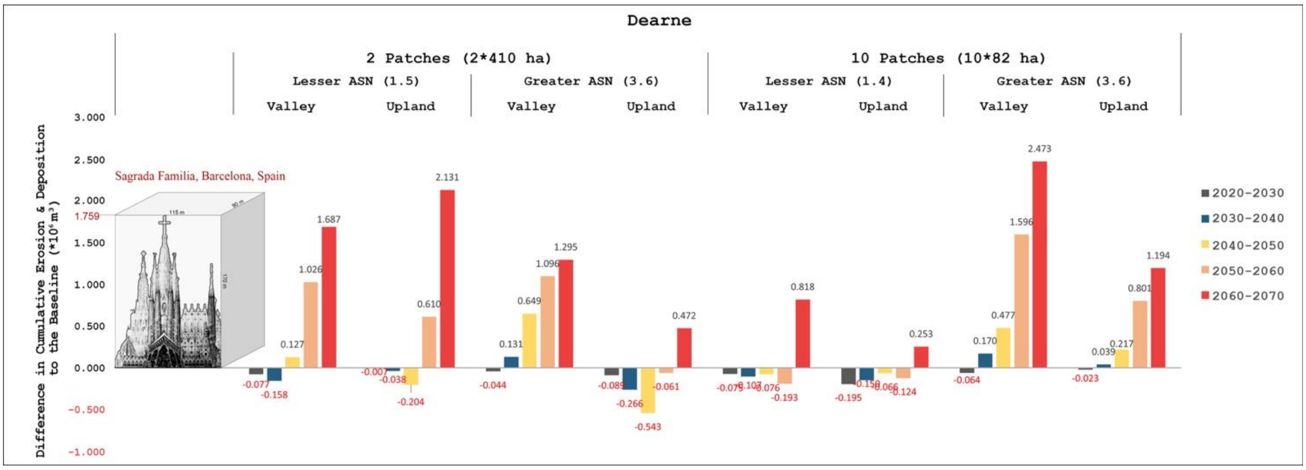
b)

Fig. 10. Erosion and Deposition n 2070 with respect to 2020 for the scenarios in the a) Rother-Doe-Lea and b) Dearne sub-basins

Deposition and erosion maps of the varied reforestation scenarios are shown in Fig. 10 as areas with higher and lower elevations, respectively. The consistent trend across both the Rother-Doe-Lea (Fig. 11 a) and Dearne (Fig. 11 b) sub-basins highlighted the greater effectiveness of reforestation interventions in upland areas, particularly downstream locations with a higher ASN. These scenarios induced significant decreases in erosion and deposition in comparison to valley regions, which were in closer proximity to the channel. A smaller number of more consolidated (2 patches) reforestation projects, were more successful in managing erosion and deposition compared to more dispersed projects. The Rother-Doe-Lea scenarios had a more noticeable trend as all 2-patch reforestation initiatives continuously maintained lower levels than the baseline for nearly the entire duration of the 50-year testing period. Furthermore, the temporal dynamics in the Rother-Doe-Lea region demonstrated a gradual enhancement of the scenarios in reducing erosion and deposition as time progressed, whereas the Dearne scenarios revealed a more rapid development.



a)



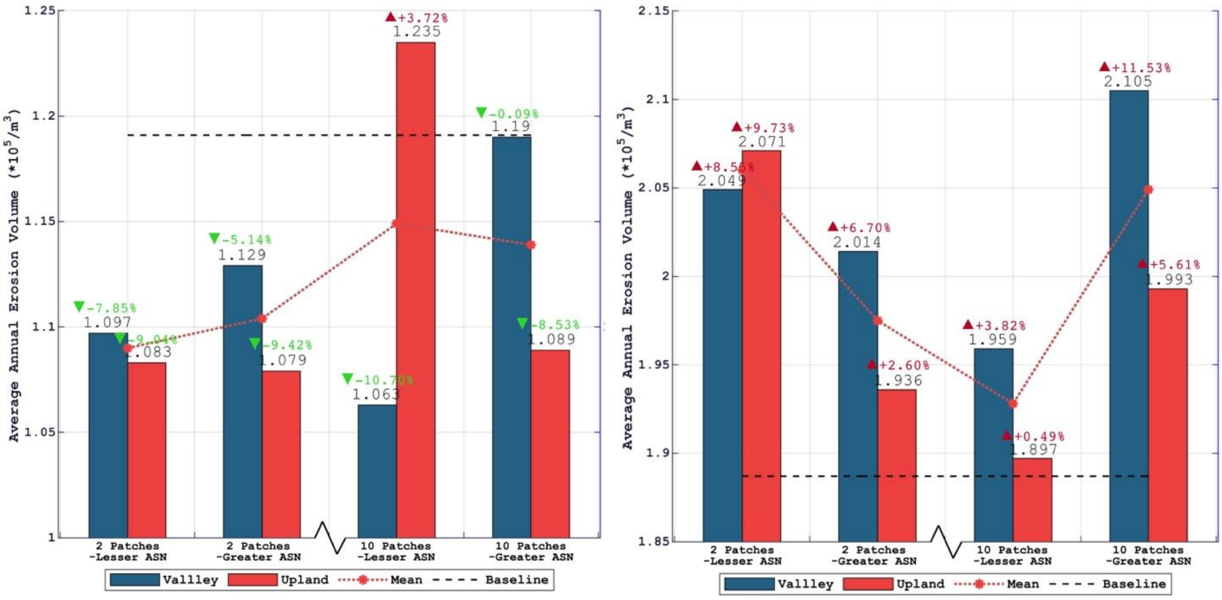
b)

Fig. 11. A comparison of the cumulative erosion and deposition volume difference of the a) Rother-Doe-Lea and b) Dearne reforestation scenarios to the baseline from 2020 to 2070. Under the baseline scenario, the overall erosion of sediment is comparable to a cube of earth that is as tall as the Sagrada Familia Basilica in Barcelona, Spain, which stands at 175m

The figures illustrate the average annual erosion volumes from 2020 to 2070 under different reforestation scenarios in the Rother-Doe-Lea (Fig. 12 a) and Dearne (Fig. 12 b) sub-basins, compared to the baseline. The deposition comparison results showed a similar trend to the erosion comparison and were illustrated in Appendix B In both sub-basins, the general trend indicated that scenarios with projects located in the upland were more effective at limiting erosion and deposition activities in most but not all cases.

Neither the upstream nor downstream set of project scenarios exhibited a consistent trend in across the two sub-basins. A comparison between valley and upland reforestation revealed that, in most cases, upland regions located farther from the stream channel exhibited lower average erosion and deposition volumes than valley regions, as shown by the red bars. This was particularly evident in the downstream scenarios with greater ASN in both sub-basins. In comparing project dispersion, 2-patch scenarios typically resulted in more erosion and deposition reduction than the 10-patch reforestation, especially when reforested downstream. In the Rother-Doe-Lea sub-basin (Fig. 12 a), the 2-patch, lesser ASN valley scenario resulted in the most significant reduction in erosion and deposition. These findings suggested that lesser dispersal of lager patches, especially in downstream valley locations, provided the best erosion and deposition control.

Although the overall trends were consistent between the sub-basins, some discrepancies exist. Notably, the Rother-Doe-Lea sub-basin (Fig. 12 a) showed more pronounced erosion reduction in upstream areas when reforesting consolidated larger projects but downstream when reforesting multiple dispersed projects, whereas the Dearne sub-basin (Fig. 2) exhibited the opposite trend.

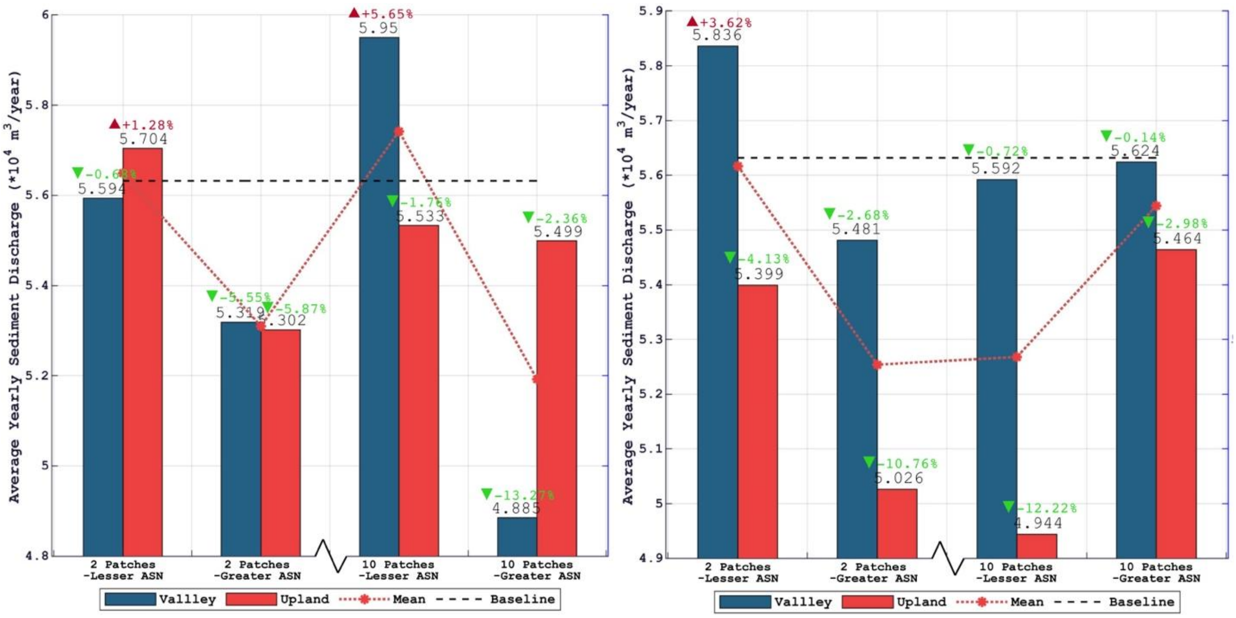


a) b)

Fig. 12. Average yearly erosion volume in a) Rother-Doe-Lea, b) Dearne reforestation scenarios from 2020 to 2070

a. Sediment yield

The two figures exhibited important findings on the average yearly sediment discharge under various reforestation scenarios in the Rother-Doe-Lea (Fig. 13 a) and Dearne (Fig. 13 b) sub-basins from 2020 to 2070. Across both sub-basins, almost all proposed reforestation scenarios generally showed reductions in sediment discharge compared to the baseline, notably in upland and downstream locations. Nevertheless, there existed significant differences in the effectiveness of various types of geographical arrangements of interventions.



a) b)

Fig. 13. Average yearly sediment yield of simulated Middle Don from 2020 to 2070 in a) Rother-Doe-Lea and b) Dearne reforestation scenarios

The upstream versus downstream comparison shows a clear pattern across both sub-basins. Downstream interventions with greater ASN showed significantly lower sediment discharge rates than upstream interventions, especially for large patches reforestation. This may imply that focusing on reforestation in sections located downstream is more efficient in decreasing the movement of sediment. When comparing buffer zones (valley) to upland initiatives, the upland interventions generally presented more favourable results. The Dearne reforestation scenarios showed this phenomenon prominently, as 10 patches that were reforested in the upstream upland area produced the most significant decreases. Both sub-basins exhibited limited efficacy in valley reforestation, as evidenced by two scenarios where sediment discharge rates were greater than the baseline in both sub-basins. The results emphasised the need for implementing reforestation initiatives at greater distances from the stream channel in order to attain more effective sediment management. Furthermore, the dispersion of projects also has a vital impact on the efficiency of reducing sediment discharge. Analysis of upland reforestation scenarios revealed that scenarios including 10 smaller patches have a greater efficacy in reducing sediment discharge compared to scenarios with 2 larger patches in the upstream region. Nevertheless, the consolidated lager projects consistently maintained reduced rates of sediment flow when in downstream tributaries.

Additionally, there were differences between the two sub-basins in the assessment. The Rother-Doe-Lea sub-basin (Fig. 13 a) exhibited greater levels of variation among several scenarios, notably in valley environments where sediment flow rates were elevated, particularly in the interventions that were more widely spread out. However, all scenarios in the Dearne sub-basin (Fig. 13 b) produced less sediment discharge, with upland interventions consistently exhibiting better results than valley projects. Though disparities exist, the general pattern in both sub-basins emphasized the efficacy of downstream and upland reforestation projects in decreasing sediment yield.

3.4 Channel planform morphology

The comparison of the Planform Instability Index (PII) in the various Rother-Doe-Lea and Dearne sub-basin reforestation scenarios is shown in Table 2. Overall, the designed reforestation scenarios resulted in increased channel instability in the Rother-Doe-Lea but a more stable channel planform in the Dearne as compared with the baseline. Nevertheless, projects in upland and upstream regions usually contributed to lower PII values, indicating improved management of channel planform stability in terms of sinuosity and braiding levels. Moreover, more consolidated projects (2 larger patches) exhibited more reduced PII values in comparison to dispersed, smaller patch interventions, suggesting consolidation had a positive impact on channel stability, particularly in managing sinuosity stability.

An analysis of upstream (lesser ASN) and downstream (higher ASN) scenarios revealed that upstream interventions consistently resulted in lower PII values in both sub-basins, suggesting greater stability in planform morphology. The analysis of buffer zone (valley) vs. upland interventions demonstrated that upland situations typically result in reduced PII values, implying higher planform stability. This trend was consistent across both sub-basins, though it was more significant in the Rother-Doe-Lea sub-basin, where upland interventions in upstream areas exhibited significantly lower PII values than valley reforestation. Furthermore, when comparing the effects of project dispersion, the 2-patch scenarios demonstrated more effects than the 10-patch scenarios in stabilising the channel planform, particularly in upland and upstream areas. This trend was more evident in the Rother-Doe-Lea sub-basin. There were still discrepancies between the two sub-basins observed, with the Dearne sub-basin showing more significant instability in some upland scenarios, especially in larger patch configurations.

Table 2 The middle Don's planform instability index over the simulated 50 years for the base and designed scenarios in the two sub-basins (a darker shade indicates a more unstable planform).

Sub-basin	Project Size	Project Location		Sinuosity Index CV	Braid Index CV	Planform Instability Index	Percentage Change Relative to Baseline (%)
Rother	**Base (no modification)**			7.82%	39.45%	47.28%	0.00%
	2 PATCHES	Lesser ASN	Valley	7.79%	68.63%	76.42%	61.64%
			Upland	9.52%	32.22%	41.73%	-11.73%
		Greater ASN	Valley	9.52%	59.35%	68.86%	45.65%
			Upland	12.80%	54.02%	66.82%	41.34%
	10 PATCHES	Lesser ASN	Valley	6.85%	58.85%	65.70%	38.96%
			Upland	14.34%	43.66%	58.00%	22.68%
		Greater ASN	Valley	8.06%	58.18%	66.24%	40.11%
			Upland	13.44%	58.23%	71.67%	51.59%
Dearne	**Base (no modification)**			5.80%	72.72%	78.53%	0.00%
	2 PATCHES	Lesser ASN	Valley	7.95%	30.41%	38.36%	-51.16%
			Upland	10.61%	25.99%	36.60%	-53.39%
		Greater ASN	Valley	10.30%	19.04%	29.34%	-62.64%
			Upland	36.27%	42.24%	78.52%	-0.02%
	10 PATCHES	Lesser ASN	Valley	8.22%	23.72%	31.94%	-59.32%
			Upland	8.85%	34.54%	43.39%	-44.75%
		Greater ASN	Valley	7.19%	35.01%	42.19%	-46.27%
			Upland	10.55%	26.18%	36.73%	-53.23%

4. Discussion

4.1 Consistent geomorphic trends

This study demonstrates that reforestation can significantly influence the long-term geomorphic evolution of river systems, with notable reductions in erosion activities, channel lateral migration, sediment yield, and planform stability. These results provide quantitative support for the hypothesis that the NbS, when strategically implemented, can enhance geomorphic stability at the catchment scale.

Table 3 Consistent trends and discrepancies in the two sub-basins according to the research questions.

		Rother-Doe-Lea	Dearne
Channel Active Occupation Area	Better than baseline	Almost all	All
	Upstream (lesser ASN) vs Downstream (greater ASN)	Half upstream is better than downstream	Upstream is better than downstream
	Valley vs Upland	Half valley is better than the upland	Valley is better than the upland
	Consolidated vs. Dispersed	Mixed	Mixed
Erosion and deposition	Better than baseline	Almost all	None
	Upstream (lesser ASN) vs Downstream (greater ASN)	Upstream in the valley is better than the downstream	Half upstream in the valley is better than the downstream
	Valley vs Upland	Upland, especially in downstream is better than valley	Upland especially in downstream is better than the valley
	Consolidated vs. Dispersed	Consolidated is better than dispersed	Consolidated is better than dispersed
Sediment discharge	Better than baseline	Almost all	Almost all
	Upstream (lesser ASN) vs Downstream (greater ASN)	Downstream is better than upstream	Half downstream is better than upstream
	Valley vs Upland	Half upland is better than valley	Upland is better than valley
	Consolidated vs. Dispersed	Mixed	Mixed
PII	Better than baseline	Almost None	All
	Upstream (lesser ASN) vs Downstream (greater ASN)	Upstream is better than downstream	Upstream is better than downstream
	Valley vs Upland	Upland is better than valley	Half upland is better than valley
	Consolidated vs. Dispersed	Consolidated is better than dispersed	Half consolidated is better than dispersed

Consistent tendencies in response to reforestation scenarios are revealed when comparing the Dearne sub-basin with the Rother-Doe-Lea sub-basin, which provides insights into the stability of the geomorphology in the long term (Table 3). Large-scale reforestation in both sub-basins improved a number of important indicators when compared to the baseline condition. For example, in terms of sediment discharge and channel active occupation area, both sub-basins had improved conditions in comparison with the baseline; in fact, nearly every scenario in the Dearne and Rother-Doe-Lea sub-basins showed improvement. By reducing sediment production and minimising channel lateral migration activities, these improvements indicate that reforestation greatly improves geomorphic stability. This result is comparable to the monitoring values for catchments where land-use change has occurred (Keesstra et al. 2009; Buendia et al. 2016; Quiñonero-Rubio et al. 2016). This may be due to the fact that the reduction in the area of agricultural land has been simultaneously accompanied by an increase in the area covered by forests, where water flows and sediments are retained or infiltrated during transport (Boix-Fayos et al. 2007; Buendia et al. 2016). In addition, existing research indicates that the contribution of forests is significant in flood events and the benefits of reduced peak flows are significant (De Roo et al. 2003). The reduced peak flows simultaneously result in lower amounts of sediment being transported. Reduced peak flows contribute to a reduction in the intensity of lateral erosion activity on the riverbanks, therefore, a reduction in channel migration activity.

Across both sub-basins, upstream projects performed noticeably better in reducing channel migration, channel planform instability regarding sinuosity and braiding degree and erosion and deposition. Existing research indicates that variations in the effectiveness of reforestation are highly contextualised by location-specific environmental features (Trabucco et al. 2008). Upstream regions generally exhibit steeper gradients, resulting in accelerated water flow and a greater vulnerability of channels to incision and lateral migration (Keesstra et al. 2009). It is possible that reforestation in these upstream regions decelerates runoff, reduces peak flow rates, and eliminates the energy responsible for channel instability, erosion, and migration. Furthermore, stabilizing upstream tributaries can also prevent downstream sediment accumulation, helping maintain downstream planform integrity (Phillips et al. 2013). This strategy successfully facilitates the prevention of increased sediment deposition and widening of the channel at lower areas within the catchment. Nevertheless, downstream reforestation appeared to provide consistent advantages in reducing sediment discharge. This finding is also supported by previous research conducted by Castillo-Reyes et al. (2023) and Coulthard & Van De Wiel (2017). One possible reason for this phenomenon is the increasing frequency of sediment movement and deposition over erosion in the downstream areas. In such cases, reforestation can serve as a natural buffer that effectively catches and retains material. As the river's lower parts see a progressive reduction in flow, the reforested areas can serve as sediment reserves, allowing material to settle and be conserved rather than being carried further downstream.

The relative location of reforestation in relation to the channel is also critical. Upland reforestation was consistently more effective in stabilizing the geomorphology in terms of reducing erosion and deposition, sediment discharge and channel planform instability, compared to valley (buffer zone) reforestation. Both sub-basins showed that reforestation in upland regions, especially in downstream areas, saw greater improvements in erosion and deposition control. The reasons behind this might be similar to the significant effectiveness of upstream interventions in intensifying the geomorphic responses. Reforestation of uplands improves infiltration and reduces the speed and volume of surface runoff, significantly limiting erosion and sediment transport because of the steep terrain and runoff characteristics of upland areas (Keesstra et al. 2009). While reforestation in the stream valley limits channel lateral migration more than uplands. This may be due to the fact that riparian reforestation reduces to a greater extent the high velocities of water flow (Scott 1999; Cunningham et al. 2015), which contribute substantially to lateral erosion of riverbanks (Stark 2006), thus more effectively limiting the lateral migration of the river channel.

Finally, the dispersion of reforestation efforts is another key factor. The data presents a mixed view, but the scenarios studied in this research tend to favour larger, consolidated projects over numerous smaller ones. In both sub-basins, consolidated efforts in terms of erosion control and channel planform stability enhancement tend to deliver more consistent benefits. The consolidation of projects results in the creation of larger, continuous regions of stabilised geomorphology, so offering more significant ecosystem services such as interception throughout a wider geographical area. It is possible that these larger projects will also enable more efficient hydrological and geomorphic modifications, such as reducing peak flow and enhancing overall sediment retention. Smaller, dispersed initiatives, while advantageous, may not have the necessary magnitude to generate substantial long-term effects throughout the whole catchment area.

4.2 Possible reasons for inconsistency

While similar scenarios examined in the two sub-basins demonstrated an overall consistency in channel lateral migration and sediment discharge findings, there are variations in the consequences of erosion and deposition processes and the stability of the channel planform (Table 3).

In the erosion and deposition improvements comparison, the Rother-Doe-Lea sub-basin shows "better than baseline" performance, with almost all scenarios showing improvement, suggesting that reforestation efforts have largely succeeded in stabilizing the geomorphology by reducing erosion and deposition volumes, with half of the upstream reforestation scenarios performing better controlling especially in the valley. In contrast, the Dearne sub-basin shows no improvement from the baseline in erosion and deposition control, but upstream reforestation consistently reveals less erosion and deposition than downstream projects. These differences may relate to the physical setting of the tributaries. The Rother–

Doe Lea exhibits higher peak discharges and a larger proportion of rugged terrain, suggesting stronger erosive forces during high flows. In contrast, the Dearne contains a greater area of level terrain and is located further downstream in the Don system, where depositional processes tend to dominate. These characteristics help explain why erosion-related metrics respond less uniformly to reforestation in the Dearne.

In the channel Planform Instability Index comparison, the trend is the opposite. In the Dearne sub-basin, PII consistently shows "better than baseline" improvement, with half of the upland and half of the consolidated projects performing particularly well. However, the Rother-Doe-Lea sub-basin shows a different trend, with PII improving across "almost none" of the scenarios compared to baseline conditions but all upland and consolidated projects induced a more stable channel planform than riparian and dispersed ones. A similar explanation may apply to the differences in planform stability. The Rother–Doe Lea has steeper areas and higher peak discharges, producing short, energetic flow events that are not easily moderated by changes in vegetation. The Dearne, with a larger proportion of level terrain and more attenuated downstream flows, appears more responsive to the increased bank strength and roughness introduced by reforestation, leading to more consistent improvements in planform stability.

It is also important to acknowledge that some inconsistencies between the two sub-basins may stem from limitations inherent to CL rather than from physical catchment differences alone. For example, the model represents vegetation effects through fixed Manning's n and m values, without simulating forest growth or seasonal changes in surface conditions. This simplification can influence how roughness evolves over time and may affect the magnitude of geomorphic adjustment in each sub-basin. In addition, the required coarsening of the DEM to 50 m, together with uncertainties in historical channel morphology and limited availability of long-term migration data, reduces the model's sensitivity to finer-scale hydrological and morphological contrasts between the Dearne and Rother. The model also applies sediment transport and erosion thresholds uniformly across space, which may under-represent localised erosion pressures or spatial heterogeneity in channel stability. Together, these constraints may partly contribute to the differences observed in scenario performance across the two sub-basins and should be considered when interpreting the results.

It is also worth noting that the Dearne's reforestation scenario provides better control of lateral channel migration and stabilises channel morphology, despite increasing total erosion and sedimentation. This suggests that the Dearne sub-basin is most likely inducing the increased incision of the river valley and, thus, deeper and narrower channels. This is consistent with the findings of existing research (Kondolf et al. 2002; Piégay et al. 2004; Boix-Fayos et al. 2007).

4.3 Implications and limitations

Sustainable river management actions, such as reforestation, still require considering the responses in river hydrological and geomorphic conditions caused by interventions in determining the optimal location and circumstances for implementation, despite substantial studies demonstrating the benefits they provide. This study provides new evidence that tributary reforestation, when strategically located, can be a viable tool for enhancing geomorphic resilience in large river systems.

From a management perspective, prioritizing reforestation in upland and upstream areas offers robust control over sediment connectivity, erosion, and channel planform morphology. Meanwhile, valley interventions, particularly when placed downstream, may enhance sediment retention and reduce lateral instability. An integrated strategy for stabilising the channel planform can be achieved by combining upland reforestation with riparian woodland creation. Upland regions manage erosion and sediment movement more effectively, while riparian zones significantly strengthen the riverbanks, decreasing the probability of channel lateral migration. Another point is that compared to smaller, dispersed initiatives, larger, consolidated reforestation projects offer more consistent advantages by establishing a stable channel planform more efficiently. In addition to the location and dispersion of replanting forests, other aspects, such as the selection of tree species (Zhou et al. 2002), can also contribute to increasing the stability of catchments and river channels. Integrating geomorphic process understanding into the planning of NbS can improve the efficiency and longevity of restoration strategies. This includes accounting for the catchment's gradient, hydrological regime, and sediment budget when selecting reforestation sites. Geomorphic modelling frameworks such as CAESAR-Lisflood provide valuable predictive tools to evaluate these interventions prior to implementation.

This study provides insights into the geomorphic consequences of tributary reforestation, yet several constraints should be acknowledged. The modelling framework treats forested areas as fully established throughout the simulation and therefore does not capture gradual changes in vegetation structure or roughness. Similarly, potential seasonal differences in surface conditions are not incorporated, which may influence erosion and deposition processes in regions with marked winter–summer contrasts e.g. the North of England. At the spatial scale adopted here, the model is unable to reflect the effects of specific tree species or woodland mixes, nor can it fully represent fine-scale interactions between local topography and land cover. In addition, complete alignment of project areas with identical ASN values is not always possible due to existing morphology, historical land use, and terrain configuration, introducing some unavoidable variation across scenarios. These considerations do not undermine the comparative value of the model results but indicate that findings should be interpreted as representations of broader geomorphic tendencies rather than precise predictions of absolute change.

5. Conclusions

This study evaluated the long-term geomorphic impacts of tributary-scale reforestation on the downstream main channel, using the CAESAR-Lisflood landscape evolution model applied to the River Don catchment in northern England. A series of alternative reforestation scenarios were simulated over a 50-year period, allowing for the systematic investigation of spatial variation in intervention location (upstream vs downstream, valley vs upland) and configuration (dispersed vs consolidated). The model examined channel later migration, erosion and deposition volumes, sediment discharge, and channel planform stability.

Key findings indicate that:

1) Reforestation can effectively reduce sediment yield and limit channel lateral migration. However, under certain conditions, some interventions may have negligible or even adverse effects on specific geomorphic metrics.;

2) Reforestation in upstream areas appears to be more effective in controlling channel migration, stabilizing the planform (reducing sinuosity and braiding), and minimizing erosion and deposition compared to downstream interventions;

3) Reforestation of upland areas tends to result in greater reductions in erosion and sediment yield and contributes to a more stable channel planform;

4) Consolidated, larger reforestation projects (fewer but larger patches) generally tend to outperform numerous smaller, dispersed ones in improving overall geomorphic stability and mitigating sediment connectivity.

These findings contribute to advancing geomorphic theory by offering model-based evidence of how nature-based land use changes influence multi-decadal fluvial evolution at the catchment scale. They also provide applied insights for sustainable river catchment management, supporting the targeted implementation of reforestation based on geomorphic sensitivity and network positioning. Future work can explore the integration of vegetation dynamics, climate extremes, and feedback mechanisms to further improve the realism and applicability of predictive modelling tools. Nonetheless, this study demonstrates the value of coupling spatially explicit modelling of fluvial systems with geomorphic assessment frameworks to inform the strategic design of reforestation and NbS.

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