Climate Risk Management 36 (2022) 100439

Contents lists available at ScienceDirect

Climate Risk Management

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

Forecasting riverine erosion hazards to electricity transmission towers under increasing flow magnitudes

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ARTICLE INFO

Keywords:
Erosion hazard
Critical infrastructure
River channel change
Electricity transmission towers
Flow magnitude scenarios

ABSTRACT

Flooding and erosion will pose increasing challenges to urban settlements and critical infrastructure, such as roads and power grids in the future. Improved projections on the impact of climate change to critical infrastructure are essential to assist future planning. This paper uses hydro-sedimentary modelling to predict river erosion threats to electricity transmission infrastructure in an urbanised river valley under multiple increasing flow magnitude scenarios. We use a coupled hydrodynamic and landscape evolution model, CAESAR-Lisflood, to simulate river channel changes along a reach of the River Mersey, UK from the present day to 2050. A range of synthetic flow scenarios, based on recent hydrological records, was used in the model ranging from 'no change' up to a flow with 50% higher magnitude. The results revealed: (1) riverbank erosion will pose significant threats to several transmission towers located along the river, requiring intervention to avoid destabilisation by the moving channel; (2) the total area of floodplain erosion and deposition $\geq$ 0.5 m deep was positively related to increasing projected flow magnitudes. However, through running a 'low' and 'high' erosion version of the model, the simulations revealed these threats were most sensitive to the calibration of the erosion component of the model, illustrating the challenges and uncertainty in forecasting long-term river channel change; and (3) how long-term simulations can assist in adaptation planning for electricity transmission towers. Further reach- and catchment-scale modelling will be necessary to determine the timings of large floods more accurately, which produce the most significant erosion and deposition events, and to evaluate the efficacy of protections to transmission towers.

1. Introduction

Continuing encroachment of urban populations into river valleys has led to more human assets, like houses and utilities infrastructure, being sited on floodplains (da Luz et al., 2015). The Environment Agency's 2008 National Flood Risk Assessment estimates that around 2.4 million properties in England are at risk from coastal or river flooding (Environment Agency, 2009). This figure has likely increased as between 1990 and 2015, urban area grew by 3,376 km^2 in Great Britain (Rowland et al., 2020). Intensification of the hydrological cycle over the 20th Century and beyond will increase flood risk (Huntington, 2006). For example, the UK Climate

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https://doi.org/10.1016/j.crm.2022.100439
Received 24 October 2021; Received in revised form 30 March 2022; Accepted 16 May 2022
Available online 18 May 2022

Projections 2018 (UKCP18) and recent studies, project flood risk to increase over the next several decades. Average winter rainfall could increase by up to 35 % by 2070, as well as the frequency (3 ± 5%) and intensity (3 ± 1 %) of the most extreme storm events during the winter (Mizuta, 2012; Zappa et al., 2013). Combined, these urbanisation and climate change trends look set to expose more human assets to riverine flooding and erosion hazards (Milly et al., 2002).

Several advances have been made in predicting the impacts of natural hazards on human assets, including in coastal environments (e.g. Lyddon et al., 2020; Phillips et al., 2017; Prime et al., 2018), and in river catchments (e.g. Ekeu-Wei & Blackburn, 2020; Guan et al., 2016; Hajdukiewicz et al., 2016). Some studies have focussed on erosion scour that occurs under extreme flooding (Hajdukiewicz et al., 2016), while others have stressed the importance of channel morphology in driving hazards from flooding (Slater et al., 2015).

Fluvial processes, including riverbank erosion and point bar deposition, are important for continuously shaping channel position and form within the landscape. While these processes influence the passage of geomorphologically effective flows (flows which are strong enough to initiate sediment erosion and transport), this shaping of river channel morphology in turn affects the conveyance of stream flows in a complex feedback between process and form (Knighton, 1998). This feedback drives the magnitude and timing of 'erosion hazards', defined here as 'destructive geomorphological phenomena that may cause damage to property or loss of life' (adapted from the definition of 'natural hazards' by UNISDR, 2009). Erosion hazards pose a significant threat to 'critical infrastructure' – the network of inter-connected engineered systems and processes that produce and distribute essential goods and services (Wilson et al., 2014), including electricity supply networks (Rinaldi et al., 2001). In fluvial settings, much attention has focussed on erosion hazard impacts to roads and bridges (e.g. Batalla & Vericat, 2011; Hajdukiewicz et al., 2016). For example, 257 bridges in the UK were destroyed in the wake of Storm Desmond in December 2015, and erosion of the A591 main trunk road in the Lake District cost ~£1 million in economic losses per day (Joyce et al., 2018). Recent modelling applied different storm scenarios under future climate conditions to quantify economic costs of erosion to critical infrastructure in Cockermouth, NW England. This modelling revealed that the highest costs are likely to be associated with damage caused to bridges (£102-130 million), followed by sediment deposition in the urban fabric (£9-82 million), and erosion damage to agricultural land (£16-26 million), buildings (£0.4–18 million) and roads (£0.4-4million) (Li et al., 2021).

>7,000 electricity infrastructure assets are located on floodplains (Environment Agency, 2009). Electricity infrastructure includes three types of asset: 'Generation' (assets that generate electricity, such as gas and nuclear power stations), 'Transmission' (assets that take the high voltage electricity produced by generation assets and transmits it across the country for distribution to consumers), and 'Distribution' (assets where high voltage electricity is stepped down to a useable voltage for consumption). The impacts of flooding and erosion on electricity infrastructure have been modelled in coastal settings but not river catchments. Prime et al. (2018) modelled flood hazards under 16 storm surge probabilities to electricity infrastructure along the coast of northwest England. Fluvial erosion hazards to transmission assets – which are more spread out in the landscape than generation or distribution assets – are, well known however. For example, along the River Mersey, southwest Greater Manchester, UK, extensive riverbank erosion prompted National Grid, who own

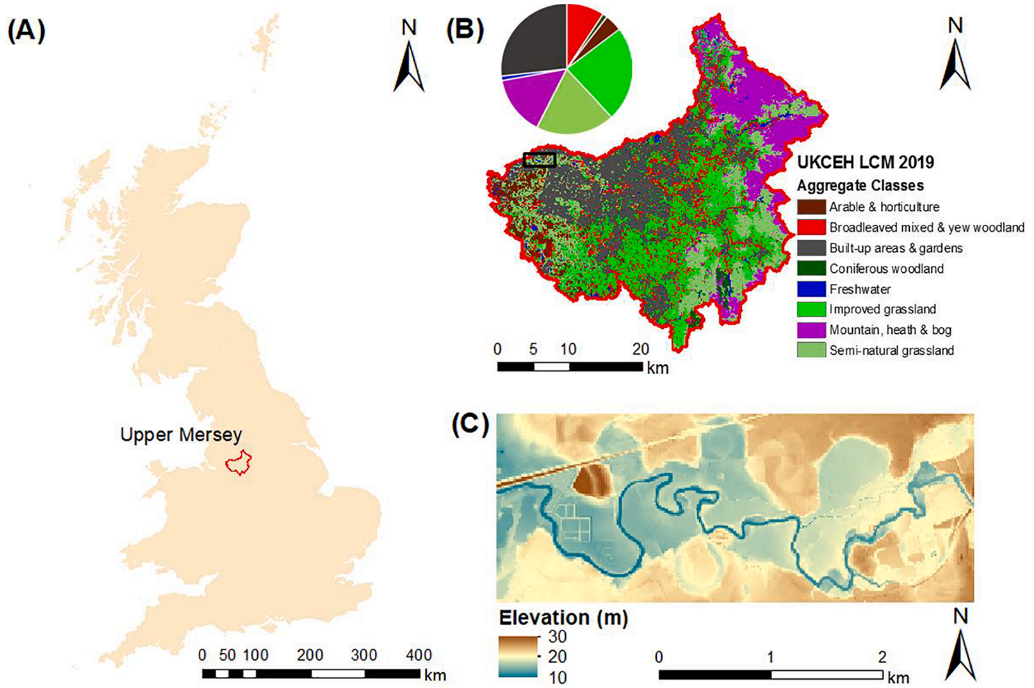

Fig. 1. (A) Location of the Upper Mersey river catchment; (B) Aggregate land cover classes in the catchment, according to the UKCEH Land Cover Map for 2019 (Morton et al., 2020) – the bounding box just below the pie chart shows the study reach location; (C) The study reach at Partington, south Manchester. Local topography (© Environment Agency) is from 2019.

and run the high-voltage electricity transmission network in England and Wales, to re-locate a local electricity transmission tower at a cost exceeding £0.5 million (da Luz et al., 2015). Despite this, no studies have attempted to forecast how river erosion hazards to towers will adjust with climate change. Thus, the electricity network sector cannot quantify the future erosion risk posed to towers, and the vulnerability and resilience of these assets to future changes in the frequency and severity of storms. For example, National Grid own 21,990 steel lattice towers that support 14,000 km of overhead power lines in England and Wales (National Grid, 2019). They inspect the condition of around 3,650 steel lattice towers each year, and invested £5.4 billion in their distribution network in 2019/20 (National Grid, 2020). Despite the monetary and operational importance of these towers, this lack of predictive capability poses enormous challenges to focussing monitoring, maintenance and protection towards the most vulnerable towers, and assessing when mitigation is likely required.

Here, we show how predictive capability can be improved through forecasting the magnitude and timing of erosion hazards to electricity transmission towers under climate change. We demonstrate this capability through modelling a reach of the River Mersey - along which 40 National Grid towers are located in close proximity to a channel that is prone to flooding and river channel change - highlighting our method's ability to determine which towers are at risk. We achieve this through three key objectives. First, by calibrating a 2-D hydro-sedimentary model capable of simulating river channel dynamics and evaluating the model performance by reconstructing past channel changes observed in the map record. Second, by forecasting future changes under several increased river flow magnitude scenarios. Third, by quantifying the severity of geomorphic changes to the site of each transmission tower and determining which are most at risk of erosion hazards. By providing the first quantification of these risks, we show that erosion hazards have critical implications for the climate resilience of floodplain-located towers. In so doing, this research demonstrates how the forecasting of river erosion hazards to electricity transmission towers under different hydro-climate scenarios assists the electricity network sector in optimising erosion mitigation strategies.

2. Case study

The site chosen for this study was a ~ 4.5 km-long reach of the River Mersey valley between the towns of Sale, Urmston and Partington in southwest Greater Manchester, UK (Fig. 1). This reach lies at the outlet of the Upper Mersey catchment (1,006 km^2) where the river joins with the Manchester Ship Canal. Standard average annual rainfall (from 1961 to 1990, which is the most recent period available on the NRFA website) exceeds 1,100 mm year^{-1} (NRFA, 2020 – see "Rainfall" under "Catchment Info": https://nrfa.ceh.ac.uk/data/station/spatial/69007) with little inter-annual, but high intra-annual variability which, together with the land cover composition of the catchment (dominated by urban areas and improved grassland), contributes to regular flash flooding (Daniels et al., 2008). The Rivers Goyt, Etherow and Tame join at Stockport (along with Lady Brook downstream) in the southeast of the catchment to form the River Mersey. These tributaries drain peat-covered Millstone Grit sandstone units and flow through the Cheshire Plain where highly erodible Pleistocene glacial deposits overlie Permian & Triassic sedimentary rocks (Johnson, 1985).

This particular reach was chosen for four reasons. First, it is one of the few reaches of the river that is laterally dynamic, with reconstructions from historical Ordnance Survey (OS) maps revealing how much the channel has changed its form and migrated its position over time (da Luz et al., 2015). The reach is a rare example of a laterally unconfined stretch of river found in such close proximity to a large urbanised area, and further study of this aspect may offer useful insight to geomorphologists and river restoration specialists who may be keen to 're-naturalise' urban rivers. Second, this stretch of river lies between channelization and flood controls upstream, and the Manchester Ship Canal downstream. Hence, there is a valuable opportunity to model a system whose flow regime and geomorphological processes have been heavily altered compared to more natural rivers nearby, such as the Bollin and Dane (Douglas, 1985; Leng, 1989). Third, there is abundant environmental data to facilitate the parameterisation of the hydraulic and erosion components of the model, including Environment Agency (EA) gauging stations at the reach inlet and outlet (Ashton Weir to the east and Irlam Weir to the west, respectively), EA airborne laser altimetry (LiDAR) and historical OS maps. Fourth and most importantly, river channel changes and erosion, may threaten a number of National Grid electricity transmission towers, though this has yet to be quantified. River erosion along this reach has already proven to cause costly damage to towers (da Luz et al., 2015) and based on a qualitative model of contemporary and anticipated long-term future processes (Fig. S1; Supplementary Materials), many local transmission towers are thought to be at serious risk. Significant efforts have been made to protect two transmission towers in this reach (see Text S1; Supplementary Materials). Our hypothesis is that in this area of the UK, river erosion hazards will worsen as, given 20th century trends, the intensification of the hydrological cycle due to climate change will lead to more frequent and higher magnitude flow events (Huntington, 2006). Thus, due to the severity of historical events and their occurrence, climate change projections are of strong interest to National Grid, helping to assist in optimising operational response to erosion hazards, ultimately leading to cost savings and constancy of supply.

3. Methods

3.1. The CAESAR-Lisflood model and its reach-scale application

CAESAR-Lisflood is a 2-D cellular automata model that integrates landscape evolution with hydrodynamic modelling (Coulthard et al., 2013). During simulation, water is routed across a regular grid of cells, and both convergent and divergent flows can be modelled. As a result of this model design, channels of variable width, plus single- and multi-thread patterns, can be simulated capturing a broad range of river channel adjustments to environmental drivers (Coulthard et al., 2002). CAESAR-Lisflood is also a reduced-complexity model, meaning a large number of Earth surface processes are represented by relatively few equations and parameters (Coulthard et al., 2002). This simplifies model set-up for the user while expediting simulation times compared to more computationally complex models. Thus, multi-decadal channel-floodplain dynamics can be simulated within tractable timeframes (Coulthard et al., 2013). Additionally, we chose this model because of its capabilities to: (1) simulate unsteady flows and their impacts on topographic change and sediment transport; (2) resolve asset-scale (i.e. at the location of individual transmission towers) hydraulics and geomorphological impacts; and (3) model reach-scale landscape evolution accurately, which has been quantitatively verified (e.g. Feeney et al., 2020; Pasculli & Audisio, 2015).

Although CAESAR-Lisflood can operate in either 'catchment' or 'reach' mode for simulating fluvial processes, for the purposes of this study, reach mode was used and only this capability will be discussed further. In reach mode, CAESAR-Lisflood requires a digital elevation model (DEM) of the valley floor, sediment grainsize information, a continuous river discharge time-series, and parameter settings for equations governing hydraulic roughness, vegetation conditions, flow conveyance and sediment transport dynamics that require calibration. Once all these are in place, the model reconstructions can be evaluated against observed channel-floodplain morphological changes.

3.2. Model parameterisation, calibration and evaluation

A 1-m resolution LiDAR digital terrain model from the EA from 2019 was used as the DEM input into version 1.9j of CAESAR-Lisflood (from https://sourceforge.net/projects/caesar-lisflood/files/) to represent the valley floor. The DEM was first clipped to a $\sim 7.25\ km^2$ area and resampled to 5 m spatial resolution, before the channel was 'smoothed out' by interpolating between floodplain cells adjacent to the channel in the 'RasterEdit' tool (from https://sourceforge.net/projects/caesar-lisflood/files/). Then, the old channel morphology and position from the year 1976, which was used for the start of the calibration run, was 'burned in' using the raster calculator tool in ArcMap. Following initial trials with a 5 m-resolution grid, the DEM was resampled using bilinear interpolation to 15 m as this spatial resolution offered the optimum compromise between landscape detail and simulation run times.

A daily river flow series from the National River Flow Archive gauge at Ashton Weir (https://nrfa.ceh.ac.uk/data/station/info/69007), spanning a record of 42 years (31/05/1976 – 31/05/2018) was used to drive the simulations during model calibration and evaluation (Fig. S2; Supplementary Materials). Hourly data can also be used, but this significantly increases model run times. As no historical sediment flux data were available, each simulation was run with sediment outputs re-circulated, acting as the sediment input for subsequent time steps. In so doing, both stream flows and sediment loads were passed through the reach. This type of substitution for measured sediment flux data has been applied successfully in previous CAESAR-Lisflood modelling (e.g. Pasculli & Audisio, 2015).

Nine sediment grain size classes were used as the basis for establishing separate grain size distributions for the channel and floodplain areas. Floodplain and channel environments in the reach exhibit distinct grain size compositions; the former being dominated by silts, clays and some sands, with a gravel layer at the base of riverbanks; the latter dominated by gravels, cobbles and coarse sands. The British Geological Survey soil texture map on the UK Soil Observatory website (http://mapapps2.bgs.ac.uk/ukso/home.html) reveals the reach is dominated by argillaceous (clayey) and arenaceous (sandy), with some rudaceous (gravelly) parent material deposits. We combined this information with the floodplain and channel sediment data to construct the grainsize distributions (Table S1; Supplementary Materials). Areas of the valley floor that contain large structures, such as buildings and the railway line to the northwest were set as fixed and unerodible in the model domain by incorporating an unerodible layer. Grid cells, where transmission towers are located, were not treated as fixed, so that their erosion hazard could be quantified.

CAESAR-Lisflood has a number of other parameters relating to sediment fluxes, flow routing, vegetation growth, slope processes and morphological evolution process rates (Table S1; Supplementary Materials). More information on these parameters can be found in the CAESAR-Lisflood wiki (https://sourceforge.net/p/caesar-lisflood/wiki/Home/) and Meadows (2014: Chapter 4). Two parameters governing river channel erosion required calibration: the lateral erosion rate parameter, θ, and the in-channel erosion rate parameter, λ. These are explained further in Text S2 (Supplementary Materials).

Calibration proceeded by trialling different combinations of θ and λ values, with no cross-parametrisation between simulations (only one parameter was altered at a time). Calibration simulations were run until at least two of the resulting modelled channel

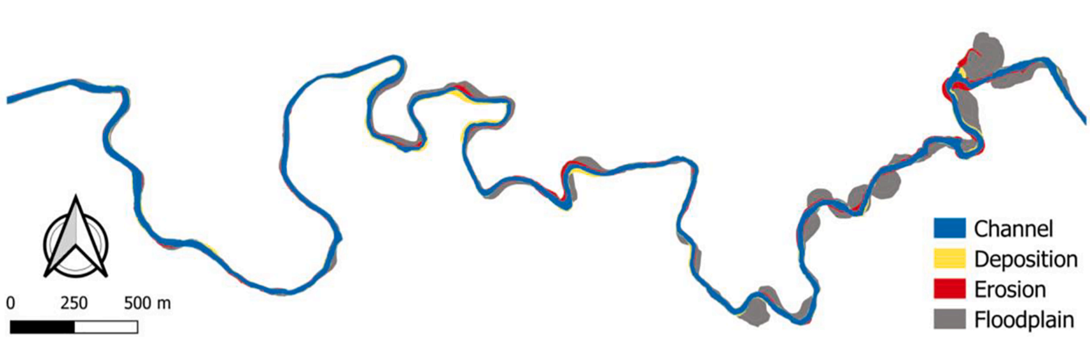

Fig. 2. Recent geomorphological changes along the River Mersey near Partington. 'Erosion' and 'Deposition' refer to floodplain removal and creation by lateral migration processes from 2005 to 2018. 'Floodplain' refers to older floodplain areas that formed between 1976, 1993 and 2005.

change time-series most closely matched observed river channel changes (reconstructed from historical maps from the years 1976, 1993, 2005 and 2018) in Fig. 2. Although calibration covered the full period from 1976 to 2018, the first river channel change time interval (1976–1993) was taken up by model spin-up: a period required for the model to develop a more 'natural' cross-sectional channel profile and successful dynamic armouring of the channel bed (Mao et al., 2011). Previous modelling has demonstrated that at reach-scale, spin-up is complete within ~ 10 years (Batz, 2010; Feeney et al., 2020; Meadows, 2014). Thus, model evaluation, in which we compared model outputs with mapped reconstructions, focussed on the latter two time intervals (1993–2005; 2005–2018). We adopt an approach of model evaluation over validation as evaluation implies not only that agreement between observation and prediction can be demonstrated, but also considers model shortcomings and uncertainties (Oreskes, 1998; Oreskes et al., 1994).

3.3. Quantifying river erosion threats to transmission towers

Following calibration, the two best performing model set-ups from the evaluation were used to predict future channel dynamics. River channel change is a deterministic but non-linear ('chaotic') process, sensitive to initial conditions and small disturbances such as meander bend cut-offs, the effects of which compound over time (Phillips, 2003). We therefore deemed it inappropriate to predict

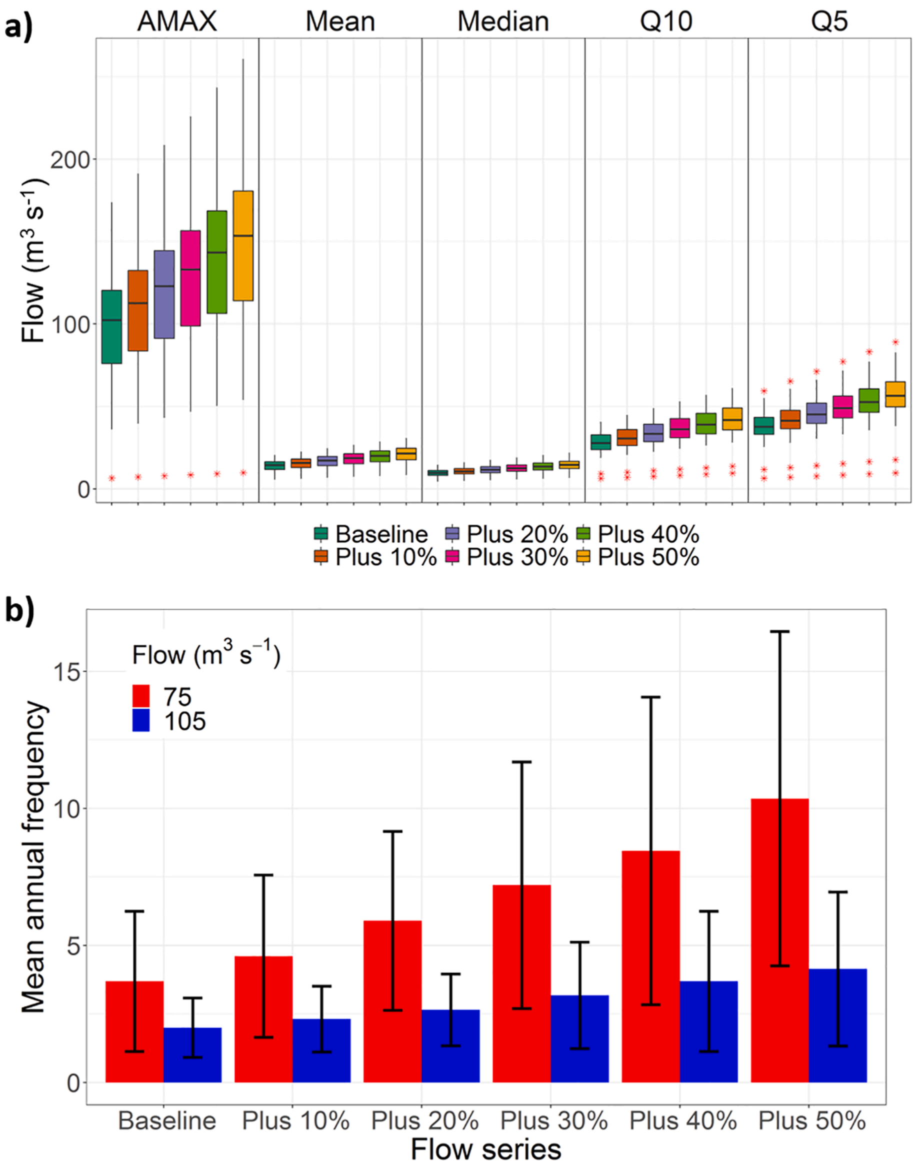

Fig. 3. a) Differences in the distributions of annual maximum (AMAX), median (Q50), and flows exceeded 5 and 10 % of the time (Q5 & Q10, respectively); b) Differences in the frequency of geomorphologically effective flows – between 75 & 105 $m^3 s^{-1}$ – between the six tested hydro-climate scenarios. Error bars represent one standard deviation.

future river channel change with just one model. By using two models we intended to maximise the chances of creating an envelope of possible futures within which the 'true' trajectory of river channel change would most likely occur.

We used 32 years of the historical flow record, 31/12/1985 – 31/12/2017 (Fig. S2; Supplementary Materials) as the basis for six synthetic hydro-climate scenarios spanning 01/01/2018 – 31/12/2049. The first of these scenarios was an unaltered baseline; the other five were designed to explore amplifications in flow discharge of 10, 20, 30, 40 or 50 % compared to the past 32 years. Hence all the values in the baseline gauged flow series were multiplied by factors of 1.1, 1.2, 1.3, 1.4 and 1.5, respectively. This amplification caused the high flows (AMAX, Q5 and Q10) to increase more than the median (Q50) (Fig. 3a). The result was an increase in the annual frequency of 'geomorphologically effective' flows, previously identified by JBA (2009) as being between 75 and 105 $m^3 s^{-1}$ for this reach (Fig. 3b).

The purpose of these projections was to encompass the range of possible discharge amplification scenarios predicted for the catchment by the UK Climate Change Projections 2018 (UKCP18; Kay et al., 2021; Lane et al., 2021). Thus, this approach enabled us to reveal the uncertainty in future channel change and the sensitivity of tower risk to hydro-climate scenarios. An alternative approach would have been to generate future flow and sediment flux predictions through catchment modelling, and feed these results into the reach-scale model. This is possible in principle, but was unnecessary, as it was not the focus of our work. The approach we have taken, which is based on amplifying magnitudes of historical flows, is attuned to user requirements (identifying which transmission towers are at risk in the near future) and is readily achievable given our data and resource constraints. Given the inherent complexity in modelling river channel change due to its chaotic behaviour, we restricted our simulations to the year 2050 and only considered changes in magnitude and not the timing or duration of flow events, limiting the scale of uncertainty that would compound over time.

Daily sediment fluxes simulated during the 32-year period of the calibration runs were combined with each scenario flow-series (Fig. S3; Supplementary Materials). For all but the baseline scenario, sediment flux input was multiplied by 1.1–1.5, depending on the percentage increase concerned, in the same way as for stream discharge values. This was to attempt to account for the fact that larger sediment loads will be transported with higher flow magnitudes. With model spin-up complete within ~ 10 years, using a flow record that began 9.5 years after the start of spin-up ensured this signal of augmented daily sediment fluxes, produced by the win-nowing of excess clays and silts, was minimised.

4. Modelling river channel change: results and discussion

The two models that most closely replicated observed channel changes (based on reconstructions from the historic map record) differ only in the chosen size of the parameter, θ (6×10^{-5} & 10×10^{-5}), and are referred to as the 'Low' and 'High' models, respectively (Table S1; Supplementary Materials). Both of these selected models over-estimate lateral erosion (Fig. 4). However, most of the

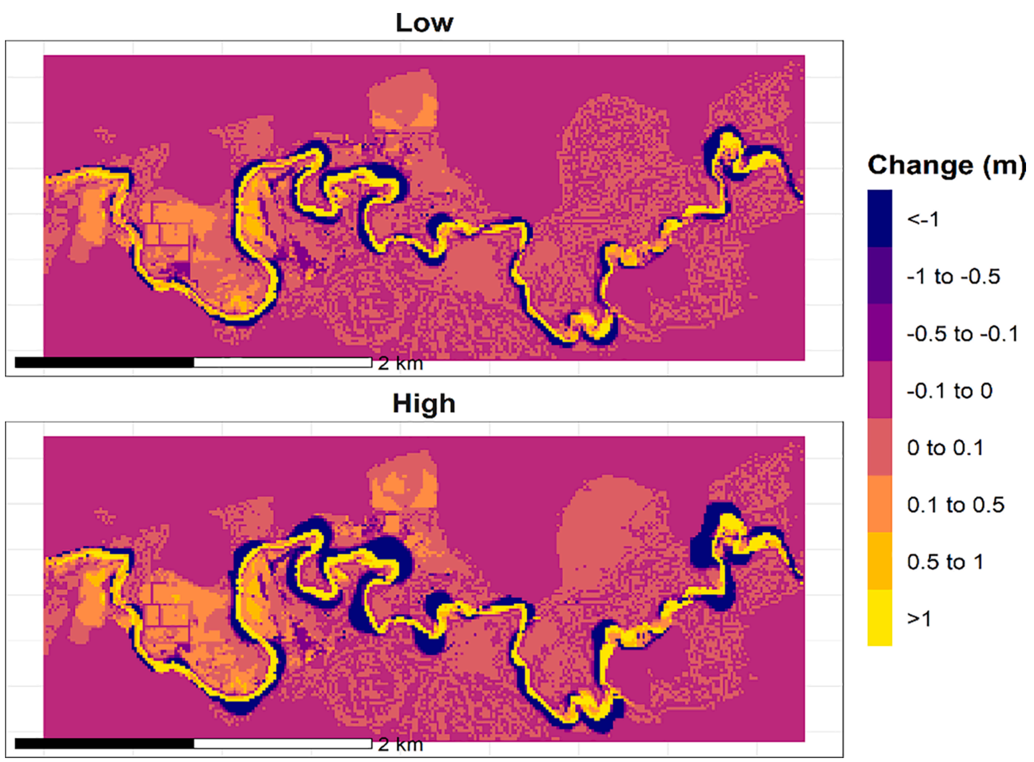

Fig. 4. Simulated river channel changes between 1976 and 2018 for the two selected models: Low and High (in reference to the relative sizes of θ-parameter settings). Erosion and deposition are indicated by negative and positive values, respectively.

alternative models trialled during calibration produced little, if any, detectable lateral erosion, and their results were very difficult to differentiate. This dichotomy of over- and under-predicted erosion extents between the selected and rejected models may have arisen from the coarse grid resolution; assuming that lateral erosion must cover a distance of at least 50 % of the length of a grid cell between time-step$_n$ and time-step$_{n+1}$, then for a 15 m grid resolution, a longer distance (at least 7.5 m) must be traversed by the channel to be detected in the DEM than for a 5 m grid resolution (at least 2.5 m).

No model calibration trial was able to recreate a channel cut-off near the reach inlet, even when lateral erosion extent was over-estimated reach-wide. This flaw has been identified with the model (Coulthard & Van De Wiel, 2006) and may have been exacerbated by our choice of a relatively low value for λ (Feeney et al., 2020), which could not have been changed without producing a channel that was too wide. While the High model over-estimates lateral erosion (Figs. 4 & 5), the choice of value for θ was the smallest out of all the simulations that did produce a channel cut-off. Thus, the Low model best captured lateral erosion, while the High model best captured the development of cut-offs – both processes that are expected to occur in the near future based on recent channel change trends.

Another potential issue is the effect of the Manchester Ship Canal, causing the lower third of the reach to be 'ponded', characterised by slower flows and lower lateral erosion rates than io the more active two thirds of the reach upstream (da Luz et al., 2015; JBA, 2009). Capturing this contrast in process rates was challenging, hence, modelled lateral erosion rates in the ponded reach may be somewhat higher than anticipated. In addition, the use of daily-averaged rather than hourly-averaged flows meant a greater number of geomorphologically effective flows were not modelled. While it would have been ideal to drive simulations with hourly flow data, model run times would have been intractable.

Both models over-estimated erosion extents in 1993–2005 and 2005–2018 relative to the mapped reconstructions (Fig. 5). The Low model over-estimated erosion by 27.6 % and 55.6 % during 1993–2005 and 2005–2018, respectively; the High model over-estimated by 119.7 % and 105.8 % for the same periods. Deposition was generally under-estimated, albeit to a lesser degree than erosion was over-estimated. For the Low model, deposition extents were under-estimated by 70.9 % and 6.8 % during 1993–2005 and 2005–2018, respectively; the High model by contrast over-estimated deposition by 16.4 % during 1993–2005 and under-estimated by 12.5 % during 2005–2018.

The EA maintains an archive of high resolution LiDAR-generated DEMs. Although less extensive than the combined overlapping flow and map archives, this record contains data for the Mersey reach from the early 2000 s which can be used to look at depths of erosion and deposition. A DEM from 2006 was subtracted from the DEM from 2019 to create a DEM of Difference (DOD). This DOD was resampled using bilinear interpolation from 2 m to 15 m resolution to compare with DODs from our simulations. DEMs saved by the Low and High model outputs for these years were subtracted from each other and compared with the EA DOD. Both models produced similar distributions of erosion and deposition depths to the EA data, though, as both models over-predicted lateral erosion extents, erosion and deposition depths are not all recorded in the same cells as the EA DOD (Fig. S4; Supplementary Materials).

Fig. 6 shows the geomorphic changes that occurred under all flow scenarios applied to the two calibrated models (Low and High). The majority of cells recorded 0.1–0.5 m of vertical erosion and deposition across all the simulations (Fig. 6). The highest levels of erosion and deposition were recorded for the two strongest flow magnitude scenarios (+40 % and + 50 %) across both the Low and High models. The greatest differences in erosion and deposition extents occurred between the two models, with more modest differences between the six flow scenarios (Fig. 6C). All the High model results showed a greater extent of lateral erosion and deposition compared with their Low model equivalents. Further, two large meander bend cut-offs occurred in all of the High model simulations – one near the reach inlet (right-hand edge of each map) and another in the ponded reach (centre-left of each map).

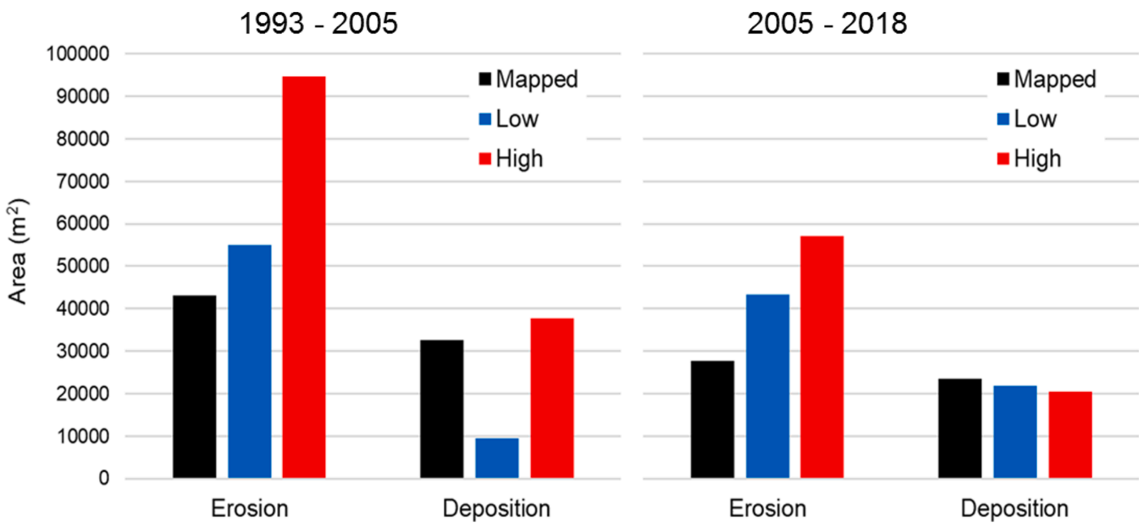

Fig. 5. Comparisons of erosion and deposition areal extents between mapped historical river channel changes and the two models: Low and High. Comparisons are made for 1993–2005 and 2005–2018.

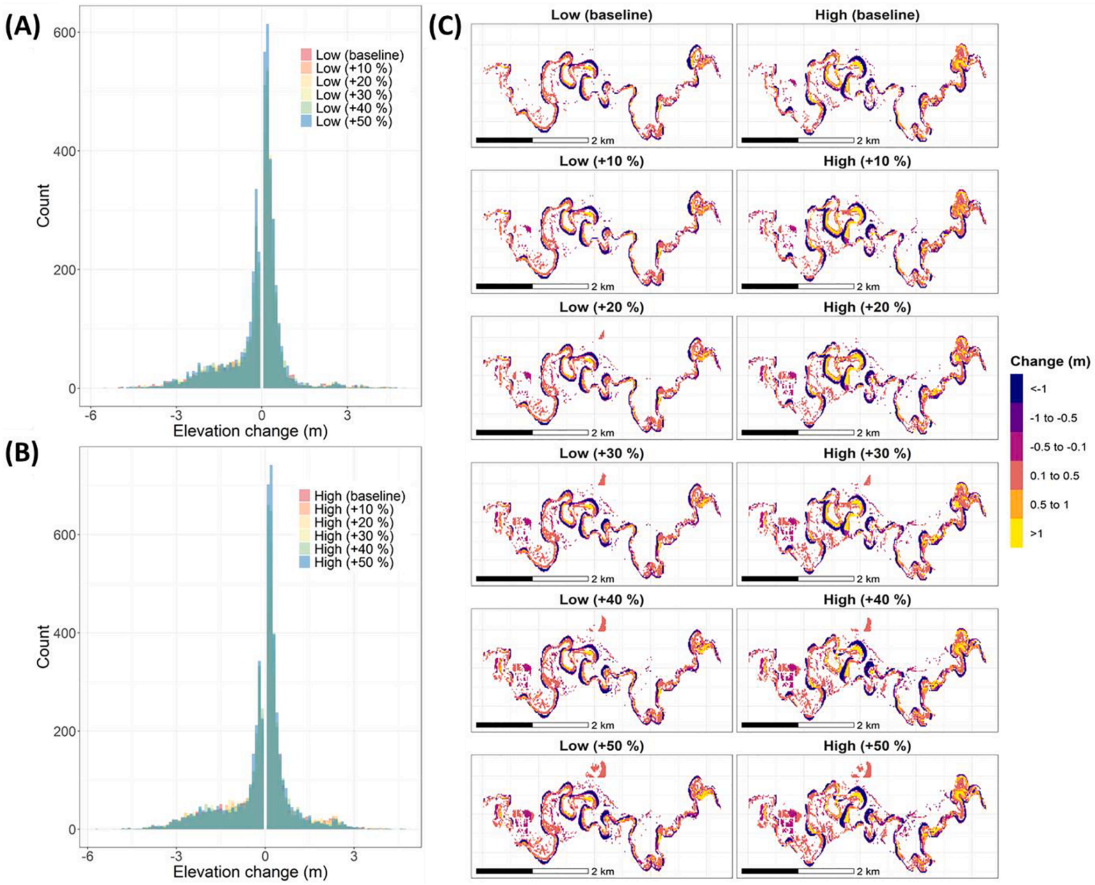

Fig. 6. Vertical erosion and deposition distributions from 2018 to 2050 for each simulated flow scenario and model, (A) Low and (B) High (bin width = 0.1 m). (C) Spatial distributions of elevation changes at the end of all simulations. Elevation changes of −0.1 to 0.1 m are excluded as we assume a minimum threshold of 0.1 m for recording of erosion or deposition. Erosion and deposition are indicated by negative and positive values, respectively.

5. Erosion threats to electricity transmission towers: Results and discussion

5.1. Threats to transmission towers from predicted river channel changes

Forty electricity transmission towers are located within the river reach, with ten of these located within 50 m of actively eroding riverbanks (Fig. S5; Supplementary Materials). Consequently, future channel changes are expected to threaten the structural integrity of the foundations of some of these towers. At the locations of most towers, virtually no erosion or deposition (0 ± 0.1 m) occurs between 2018 and 2050. The areas at the base of Towers, ZO005A and ZZN024, experience between slight (0.1–0.5 m) and severe (>1 m) erosion. The Low model predicts the onset of erosion for ZO005A at around the year 2035, with erosion depths steadily increasing to 2050 (Fig. 7). Under the High model predictions, this onset occurs about 10 years earlier (~2025) with erosion depths increasing steeply until the end of the decade, before stabilising (Fig. 8). Under the Low model, ZZN024 suffers erosion from the start of the simulation, which continues until stabilising in the early 2030 s (Fig. 7). Interestingly, the trajectory is very different under the High model, where this tower does not begin to experience erosion until the early 2040 s, and even then does not stray beyond slight erosion, and not under all scenarios (Fig. 8).

Towers, ZQ005 and ZZN018, experience significant amounts of overbank sediment deposition. While not as serious an issue as erosion for tower stability, deposition usefully indicates flooding and associated scour, causing cyclical patterns of erosion and deposition. This pattern is evident in the Low model predictions for ZZN018, which show jagged profiles in the predicted time-series of all scenarios. While the overall trend here is towards deposition, there are clear spikes of erosion that likely signal overbank flood scour (Fig. 7). Under the High model, the first few years of the simulation show erosion at this location, before a more pronounced deposition trend that continues until the early 2030s before stabilising (Fig. 8). The pattern of deposition at ZQ005 is broadly similar for both models.

While it is clear that four towers in particular are at risk from erosion hazards, there is considerable disagreement between the Low and High models on the timings of the onset of these hazards. Care should thus be taken with interpreting when towers will be

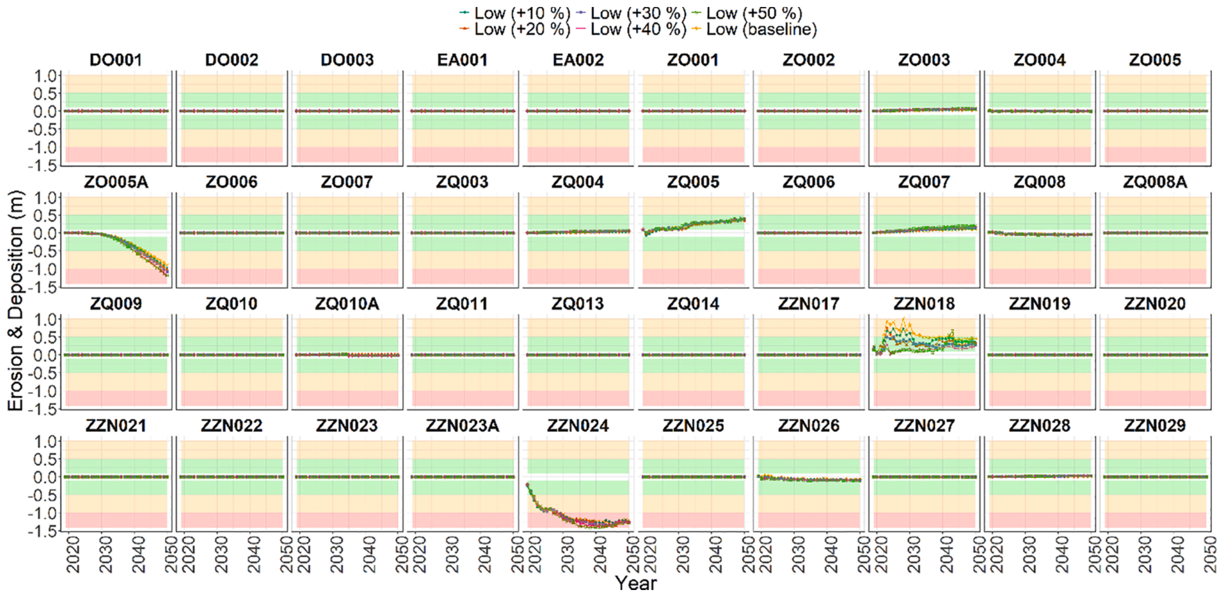

Fig. 7. Time-series of erosion (negative) and deposition (positive) predicted by the Low model to occur at each transmission tower (© National Grid UK). Colour-coded areas represent different severities: 0.1 to 0.5 m & −0.1 to −0.5 m (green) indicate slight deposition and erosion, respectively; 0.5 to 1 m & −0.5 to −1 m (orange) indicate moderate deposition and erosion; >1 m & <-1 m indicate severe deposition and erosion.

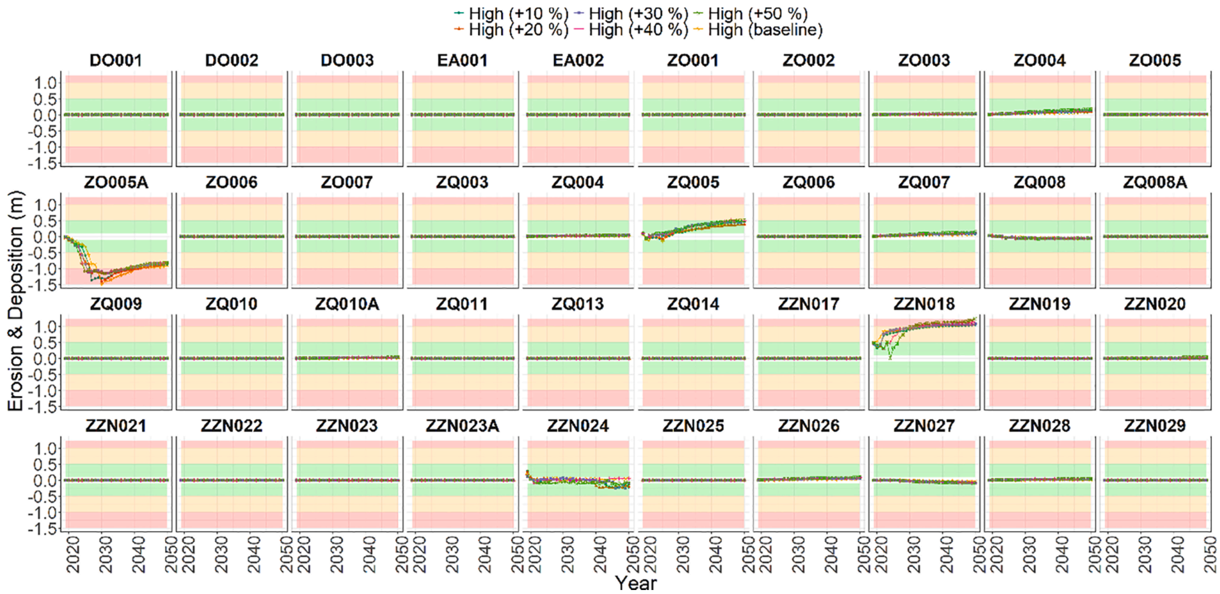

Fig. 8. Time-series of erosion (negative) and deposition (positive) predicted by the High model to occur at each transmission tower (© National Grid UK). Colour-coded areas represent different severities: 0.1 to 0.5 m & −0.1 to −0.5 m (green) indicate slight deposition and erosion, respectively; 0.5 to 1 m & −0.5 to −1 m (orange) indicate moderate deposition and erosion; >1 m & <-1 m indicate severe deposition and erosion.

destabilised by erosion.

5.2. A quantitative model of erosion hazards to transmission towers

In their analysis of the studied reach, JBA (2009) developed a ‘model of system function’ that integrates reconstructed channel changes from historical maps over the last ~ 150 years, with a walk-over survey which identified smaller-scale features such as riffle-pool sequences in the channel, and the condition of eroding riverbanks, including bank morphology and the presence of revetment works (Fig. S1; Supplementary Materials). To account for changes that have occurred over the last decade, we have adapted this qualitative model, updating it to reflect new, additional trends in erosion and channel morphological evolution. The purpose of this exercise was to communicate the locations and relative magnitudes of riverbank erosion, long term meander cut-off locations, and the anticipated directions of future channel movements. Further, our work incorporates vertical erosion and deposition, providing a spatial dimension hitherto unaccounted for. Vertical erosion, including floodplain scour poses threats to transmission towers, potentially exposing protective cofferdams to corrosion (Price, 2014), while the verticality of eroding riverbanks affects the cone of slump failure and the amount of floodplain removed (Nardi et al., 2012).

Using our modelling results, we can enhance the qualitative model of system function of JBA (2009) by quantifying which towers are most at risk. Assuming a critical threshold of ≥ 0.5 m of erosion or deposition puts a location under sufficient risk that mitigation is necessary, we can classify risks to transmission towers on their proximity to a location that experiences change equivalent to this erosion/deposition threshold. Here, towers located in the same 15 m grid cell as ≥ 0.5 m of erosion or deposition by 2050 are classed as being at 'Severe' risk; for towers located up to 30 m (or 2 grid cells) away, towers are classed as being at 'Moderate' risk; for towers located up to 75 m (or 5 grid cells) away, towers are classed as being at 'Slight' risk; the remaining towers > 75 m away are classed as 'Unaffected'. The resulting transmission tower risk maps of the Low and High model simulations are presented in Figs. 10 and 11, respectively. We selected these risk thresholds in consultation with National Grid. Other stakeholders may have a different interpretation of erosion and deposition risk thresholds.

Across all the Low model simulations, lateral erosion primarily threatens towers, ZZN024 and ZO005A, placing these at severe risk (Fig. 9). Channel cut-offs and erosion at the top of the reach, near ZZN018, are captured poorly by our model. Despite this, significant overbank deposition and floodplain scour is predicted to occur at this tower location. Hence, ZZN018 is classed as a tower at severe risk.

The High model results produce similar spatial distributions of tower risks to the Low model results (Fig. 10). Here, towers ZZN018 and ZO005A are threatened under all of the flow scenarios. Again, ZZN018 is threatened by significant overbank deposition (albeit, with less discernible floodplain scour). ZO005A is threatened by bank erosion but about 10 years earlier (by ~ 2025) than the Low model results suggest (Fig. 8), which underscores the uncertainty in predicted timings. ZQ005 is placed under severe risk from the two

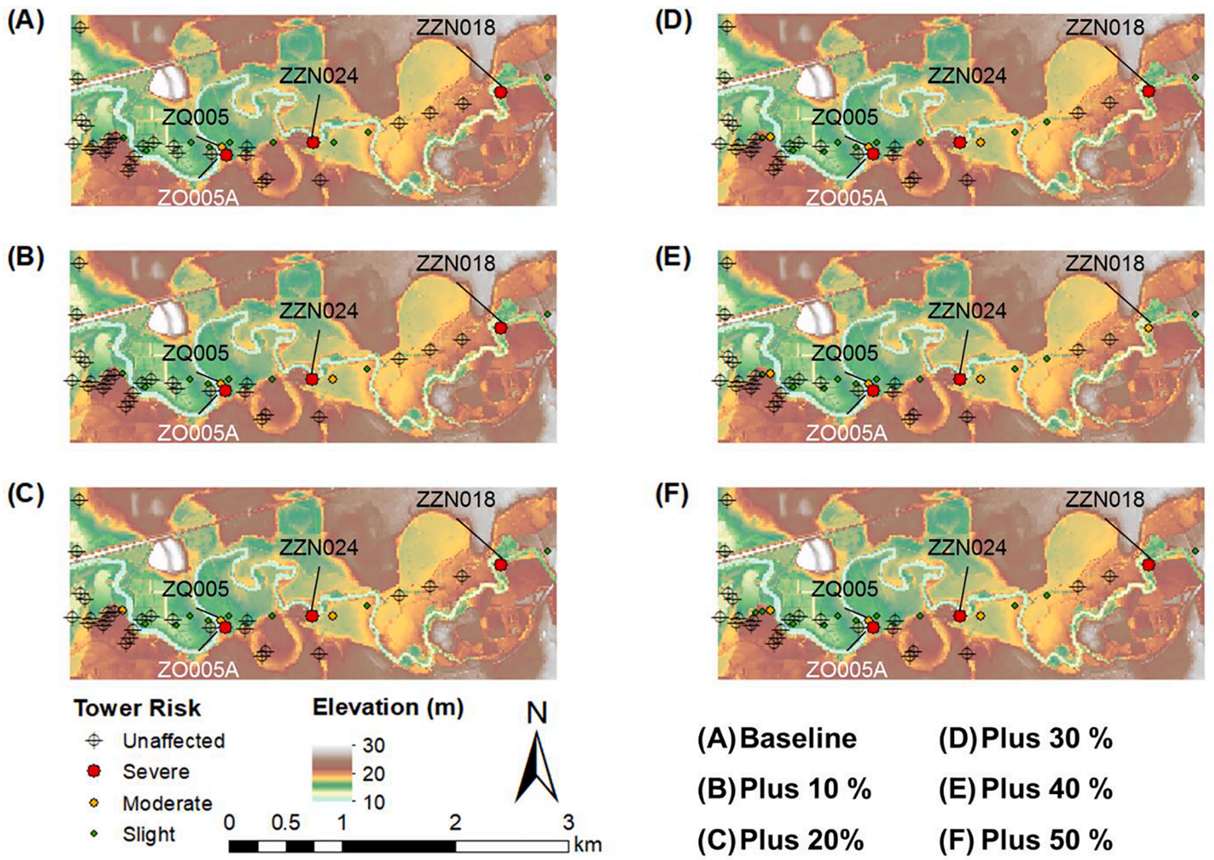

Fig. 9. Transmission tower risk maps illustrating the risk of erosion and deposition hazards according to the Low model. The severity of risk is based on the proximity of each grid cell in which the towers are situated to ≥ 0.5 m of erosion or deposition (Severe: occurring at the tower location; Moderate: within a 30 m radius of the tower location; Slight: within a 75 m radius of the tower location; Unaffected: the tower is located>75 m away from ≥ 0.5 m of erosion/deposition). Four towers: ZZN018, ZZN024, ZQ005 and ZO005A referenced in the discussion of the results are labelled. Transmission tower points © National Grid UK.

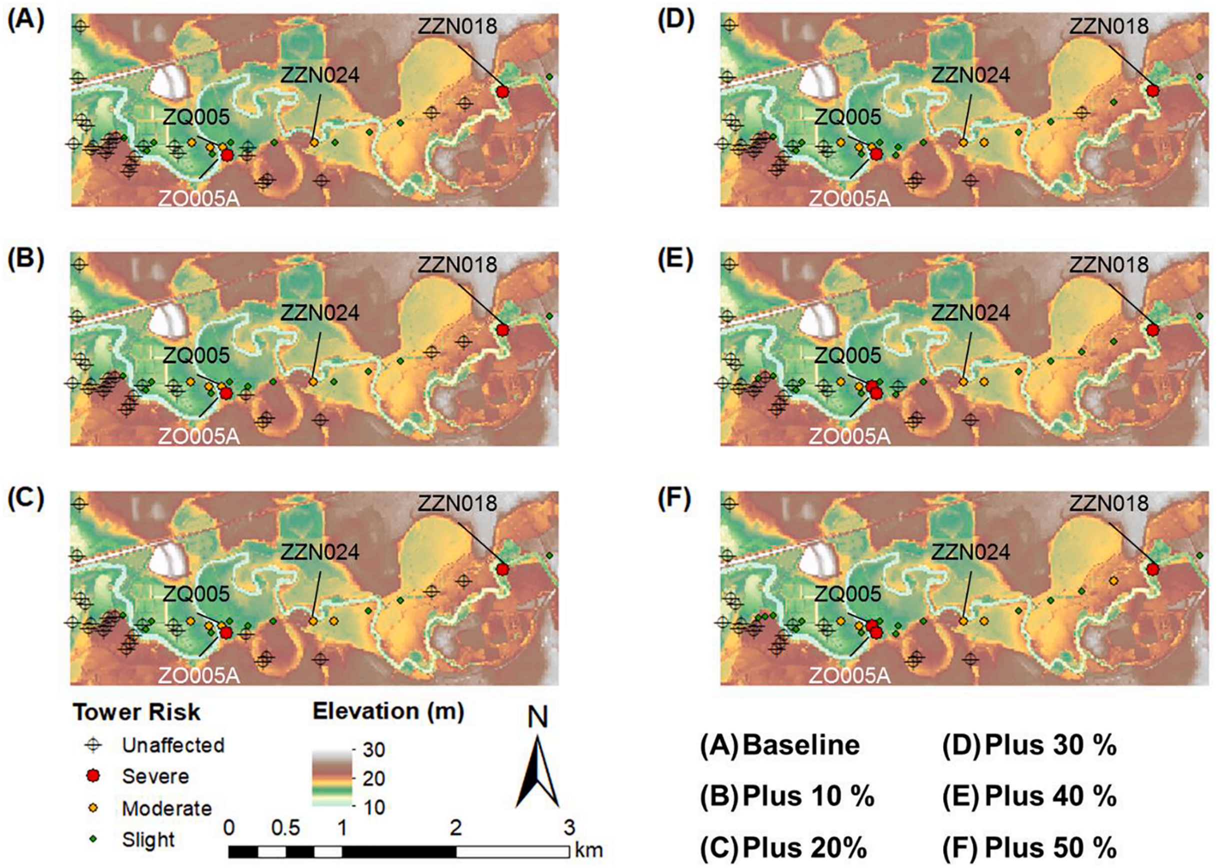

Fig. 10. Transmission tower risk maps illustrating the risk of erosion and deposition hazards according to the High model. The severity of risk is based on the proximity of each grid cell in which the towers are situated to $\geq$ 0.5 m of erosion or deposition (Severe: occurring at the tower location; Moderate: within a 30 m radius of the tower location; Slight: within a 75 m radius of the tower location; Unaffected: the tower is located>75 m away from $\geq$ 0.5 m of erosion/deposition). Four towers: ZZN018, ZZN024, ZQ005 and ZO005A referenced in the discussion of the results are labelled. Transmission tower points © National Grid UK.

strongest flow scenarios as a result of significant overbank deposition. The High model results suggest that ZZN024 is put at moderate risk by 2050. The reason for this risk appears to be that, as a result of the over-estimation of lateral erosion predicted by the High model during calibration, the tower location starts erroneously in the channel. By 2050, lateral channel migration means the tower is located on the opposite riverbank. This limitation means we cannot rely on the High model to predict threats to ZZN024. However, despite this over-exaggerated erosion extent, the pattern of bend translation in a south-western direction that is evident in the map record continues in this area, meaning ZZN023 to the east of the bend is unlikely to be placed at risk by 2050.

5.3. Potential interventions and recommended future work

Understanding the potential rate of erosion, and the impact of climate change, is key to the development of an appropriately resourced mitigation strategy. Changes in river flow patterns have the potential to alter drastically the characteristics of how erosion occurs in the future. The conditions a tower and its foundations were designed for originally may be radically different under future climate conditions. To demonstrate how the model results can be used to assist in the design of a response strategy for the protection of assets, we have summarised for the four most vulnerable towers, potential protective interventions, and recommendations to evaluate intervention suitability (Table 1). Reducing bank erosion rates locally can be achieved through bank revetment installation or removing existing structures that deflect flows into eroding banks. Palaeochannel reactivation and installing flow modification structures, such as upstream flood storage zones may reduce the erosivity of flows over time. Reducing bank erodibility and erosive flow magnitudes have been applied successfully in previous river restoration projects in UK rivers (see River Restoration Centre, 2013 for several examples). As well as process modelling, targeted monitoring using low-cost arrays of action cameras to construct detailed 3D representations of riverbanks over time could guide the selection of bank erosion mitigation strategies. Such monitoring has already been demonstrated in coastal settings (Godfrey et al., 2020).

Following an earlier survey in 2009, JBA recommended that failed structures deflecting flows towards vulnerable riverbanks should be removed immediately and where possible, cantilever failure along tall, steep banks should occur to armour their highly

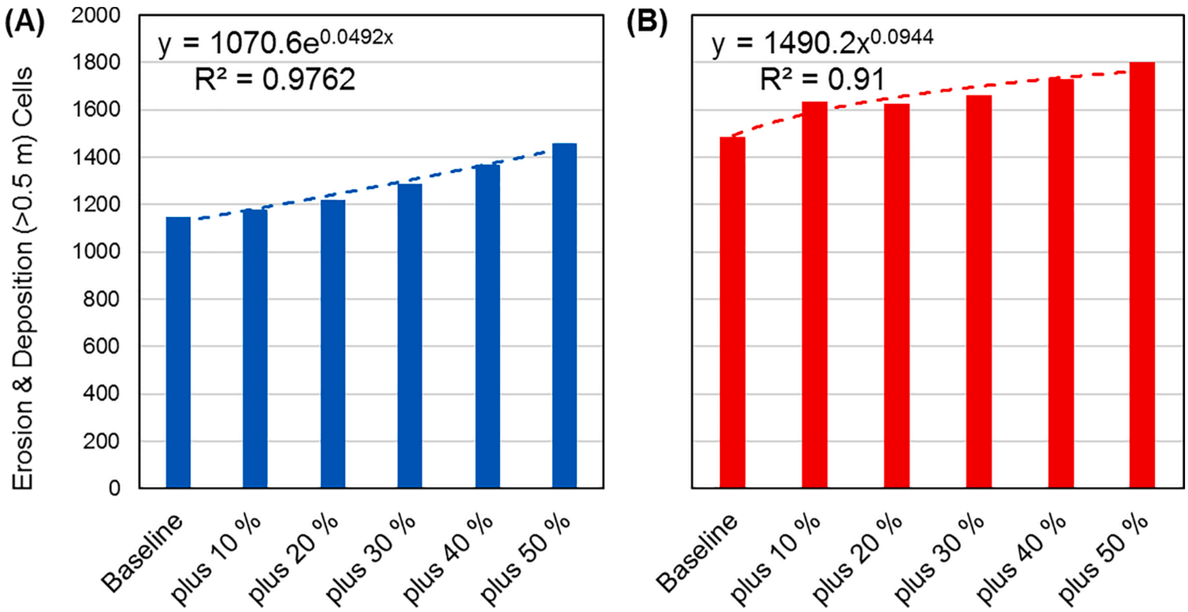

Fig. 11. Variations in the total grid cells that experienced ≥ 0.5 m of erosion and deposition (based on the 2018–2050 DOD) between each scenario for (A) the Low; and (B) the High models. Best-fit linear regressions illustrate how non-linear changes in erosion and deposition manifest from linear changes in average flow magnitudes.

Table 1
Potential interventions to protect the four towers that face 'Severe' risk across the twelve simulations. Towers are listed in order from upstream to downstream.

Tower	Potential intervention to reduce threat	Modelling to test the efficacy of interventions
ZZN018	Likely opportunities for palaeo-channel activation due to the recent history of cut-offs. High-energy flows may preclude revetments.	Further simulations to quantify the effects of palaeo-channel activation on dissipating flood flows. This site is likely to benefit the most from flow modification up-stream (assess with catchment-scale modelling).
ZZN024	Inner bank floodplain re-profiling, chute channel and palaeo-channel activation locally / upstream to help dissipate flood flows. Potentially, this approach could work alongside soft revetment.	Further simulations comparing different configurations of floodplain re-profiling, chute & palaeo-channel activation under different flood scenarios at reach-scale. Sub-reach-scale modelling of flow depths, velocities & vectors along channel boundaries.
ZQ005	Direct revetment along the outer bank where the tower is located, possibly with realignment of the main channel to reduce forces at the base of the outer bank.	Sub-reach-scale modelling of flow depths, velocities & vectors along channel boundaries and effects of in-channel features e.g. pool-riffle sequences. This modelling could guide the type of revetment (soft vs hard options) and the viability of channel realignment as a strategy.
ZO005A	Direct revetment along the outer bank where the tower is located, possibly with realignment of the main channel to reduce forces at the base of the outer bank.	Sub-reach-scale modelling of flow depths, velocities & vectors along channel boundaries and effects of in-channel features e.g. pool-riffle sequences. This modelling could guide the type of revetment (soft vs hard options) and the viability of channel realignment as a strategy.

erodible gravel bases with a fresh barrier of cohesive substrate. Our work suggests that concrete and masonry revetment might also be effective at erosion reduction, though they are expensive to install and ecologically deleterious, removing natural bankside morphology and vegetation. Hard engineering solutions are also prone to failure if installed incorrectly or inadequately account for the risk of mass wasting processes (Florsheim et al., 2008). The handling of invasive species (e.g. Himalayan Balsam) in accordance with UK law poses further challenges. Alternatively, to reduce the erosiveness of stream flows, channel (re)activation and/or increased flood storage upstream could be undertaken.

From aerial imagery, ZZN018 is visibly threatened by active bank erosion along a sharp right-angle bend. While our modelling did not capture active bank erosion at this location very well, it did predict significant levels of deposition associated with regular overbank flooding. The results of the 'Low' model suggest that these overbank deposits would be subject to regular flood scour (see ZZN018 graph in Fig. 7). At this location, we therefore recommend a range of measures to try to reduce flow velocities to complement recently implemented reinforcement of eroding banks. A legacy of recent meander bend cut-offs presents an opportunity to reactivate nearby palaeochannels to dissipate higher energy flows. Flow depths and velocities could be lowered via increased flood storage upstream of Ashton Weir and by 'slowing the flow' in the upper catchment areas. For example, installation of runoff attenuation features have been shown to increase physical water storage capacity in the Belford Burn catchment, Northumberland, UK (Nicholson et al., 2012). Other modelling studies provide encouraging results, showing high flow events can be attenuated through these approaches (e.g. Dixon et al., 2016; Pathak et al., 2020). However, water retention measures may yield unintended effects, such as foregone farm income from targeted flooding of fields (Collentine & Futter, 2018).

Tower ZZN024 is arguably the most challenging to manage for several reasons. First, the Low and High model results differ, with results from the former suggesting erosion by the early 2020s and the latter, due to errors in this calibrated model, suggesting the tower location begins within the channel itself. Given that recent historical channel changes suggest a pattern of translation of meander bends that will intersect with ZZN024 if this process continues, we assume the Low model to be more accurate than the High model in this instance. Second, there is uncertainty over the long-term impact bank protection recently installed just upstream of ZZN024 may produce on flow and erosion (as this could not be incorporated into our model). One long-term effect could be the deflecting of stream flows in such a way as to exacerbate erosion along the bank where ZZN024 is located. Third, a spoil heap is situated on the same bank as tower ZZN024 (see location in Fig. 29 in da Luz et al., 2015). Were a third-party to install protection measures along this section of riverbank, they would likely become liable for any unintended release of potentially harmful materials from that spoil heap into the river. Fourth, any intervention to protect local riverbanks at this location would need to avoid exacerbating erosion towards tower ZZN023. ZZN023 is a tension tower, sitting at the junction between multiple routes of towers, thus, any relocation would require major re-routing and restructuring of several towers on routes up and down the transmission routes, costing several million pounds. Any relocations would also be subject to planning regulations, which may introduce even more issues that limit options. Thus, the best approach might be to remove failed bank protection measures and reduce the depths and velocities of high flows. Local bank protection will also be necessary if bend translation continues towards ZZN024, but given the complex land ownership and management context, this may prove difficult and necessitate the need for coordinated solutions involving all stakeholders.

Towers ZQ005 and ZO005A sit adjacent to each other along the east bank of the river near Carrington. Here, localised bank protection is recommended because this section of the valley is in the ponded reach and the eroding bank at this location is relatively far from other eroding banks. We would recommend that more detailed hydraulic modelling of flow vectors, depths and velocities, under various flow scenarios, be undertaken to determine precisely what type of revetment should be installed and how spatially extensive this protection ought to be.

5.4. Limitations, uncertainties and wider applicability

The novelty of the modelling undertaken lies in the following aspects: 1) the long-term prediction of risks to electricity transmission towers, accounting for different flow magnitude scenarios; 2) the quantification of which towers are at risk; and 3) a hybrid approach, combining several streamflow scenarios and two calibrated models to assess changes that occur within an envelope of potential future conditions. Despite these novelties, a number of limitations and uncertainties exist in the modelling approach.

The flow scenarios tested were synthetic and we assumed that (a) flow magnitudes will increase in the near future (in line with UKCP18 projections), and (b) only flow magnitudes, and consequently to some extent the frequency of geomorphologically effective flows, will change, keeping model uncertainty bounds to a minimum. Although the timings and/or durations of high flow events may change and flow magnitudes may decrease in the future, overall forecasts show the most likely scenario is for annual flow magnitude to increase (Sayers et al., 2015). To account for more than just changing streamflow magnitudes, it would be useful to predict river channel changes under flows forecast by future rainfall patterns. Future flows climate data (Prudhomme et al., 2012) could be used to generate streamflow predictions at Ashton Weir using catchment-scale modelling. However, this catchment-scale modelling would also need to predict sediment fluxes and landscape evolution upstream as these factors contribute to river channel change within our study reach. This combined catchment and reach-scale modelling would be achievable in principle, but would expand the scope of the project far beyond its funding period (February 2019 – March 2021).

Some small-scale channel features cannot be captured by CAESAR-Lisflood, including riffle-pool sequences, existing bank protection structures, and in-channel vegetation that could disrupt flow and sediment flux. Even if the model could represent these theoretically, the 15 m grid resolution precludes this practically. Most simulations produced very little detectable lateral erosion during model calibration, with near indistinguishable results between many trialled runs. These under-estimated erosion extents are not uncommon. Feeney et al. (2020) showed that for most UK reaches investigated, the most accurate model under-estimated erosion extents, whereas along other reaches, erosion extents were over-estimated to similar extents to our Low model results. We believe that the reduced accuracy in the projections of lateral erosion extent was caused primarily by our choice of grid resolution. Such DEM scaling issues have been noted for rill/gully erosion modelling in CAESAR-Lisflood (e.g. Hoober et al., 2017; Schneider, 2013). Future improvements to computational power would allow finer spatial resolution DEMs – and finer temporal resolution flow series (e.g. hourly) – to be modelled, thus minimising the scaling effects characteristic of coarse resolution data.

This paper has focussed on showcasing the feasibility of the model to assess erosion hazards in one study area. Despite our calibrated models performing well overall in simulating a complex fluvial system, the Low and High erosion versions of the model over-predicted erosion extent and the modelled channel position and morphology did not match up perfectly with the map record. Thus, the onset of erosion hazards to towers may occur later than our modelling anticipates. Future work needs to investigate further the consequences of climate change on erosion hazards in different river catchments to gain greater understanding of the potential impacts on the climate-resilience of critical infrastructure. CAESAR-Lisflood has been applied in several countries mainly within Europe, North America, Asia and Australia. For instance, Howard et al. (2016) used the model to predict erosion threats in the Derwent Valley, UK to heritage assets under future climate change. This was later followed up with simulations of weir removal on river channel change dynamics in the same region (Howard et al., 2017). The multiple flow direction algorithm in CAESAR-Lisflood is suitable for simulating different river systems, including braided rivers on alluvial fans, river deltas, and across depositional plains (Coulthard et al., 2002). However, for lowland catchments, this highly topography-dependent algorithm may lead to flow stagnation, and erosional processes in other environments will differ due to their distinctive biomes, particularly semi-arid (e.g. Hooke et al., 2005; Hughes, 2008; Shannon et al., 2002) and tropical environments (e.g. Grenfell et al., 2014; Latrubesse et al., 2005). Therefore, when applying this model further afield, modifications to the hydro-sedimentary model component may be necessary to faithfully replicate real-world topographic change.

River channel change is a 'chaotic' process. Chaos is characterised by non-linearity in which outputs (erosion and deposition rates) are not proportional to inputs (flow magnitudes) across the entire breadth of inputs (Phillips, 2003). For instance, linear increases in daily-averaged flow magnitudes between the scenarios tested here results in exponential and power law increases in the number of cells with $\geq$ 0.5 m of erosion or deposition for the Low and High models, respectively (Fig. 11). The formation of meander bend cut-offs can drastically reduce the predictability of future channel dynamics. Following a cut-off, the newly formed channel section may: (1) re-migrate to the same position before the cut-off occurred; (2) migrate in a totally different direction; or (3) remain laterally stable while other sections of channel begin to laterally migrate faster, owing to the steeper local slope caused by a newly shortened flow path. Such changes were observed along the River Bollin (Hooke, 2004), where, following extreme flooding, a short reach experienced several cut-offs, resetting the trajectory of future channel dynamics. While it is difficult to comprehend when chaos might render channel changes along the Mersey unpredictable, keeping our simulations time-bound to the start of 2050 was judged short enough to avoid too many trajectory re-setting cut-offs occurring, but long enough to quantify erosion hazards to transmission towers over useful management timeframes.

6. Conclusions

A reach-scale coupled hydrodynamic and landscape evolution model has been applied, for the first time (to the authors' knowledge), to quantify the threats posed by river channel change to electricity transmission towers located in an urban river valley. Using a 4.5 km reach of the River Mersey, UK as a case study, we have demonstrated as a first pass of modelling that riverbank erosion, under current or future higher discharge and sediment flux scenarios, will pose significant threats to multiple transmission towers located along the river, requiring intervention to avoid becoming destabilised by the moving channel. The total area of floodplain erosion and deposition $\geq$ 0.5 m deep was positively related to increasing projected flow magnitudes. By running a 'Low' and 'High' erosion version of the model, the simulations revealed these threats were most sensitive to the calibration of the erosion component of the model, demonstrating the uncertainty in forecasting long-term river morphological change. We have demonstrated that long-term simulations can assist in the protection of electricity transmission towers, showing that future interventions along this section of the Mersey should focus on attenuating high energy flow magnitudes in the upper 'active' sub-reach, and protecting riverbanks with revetments where towers are threatened by erosion in the lower 'ponded' sub-reach. Further modelling that better accounts for the frequency and specific timings of large (e.g. 1 in 100 year) flood events will help to refine the timing of erosion hazards to electricity transmission towers.

The vulnerability of other electricity infrastructure such as production and distribution assets needs to be assessed. Future work could also focus on the economic costs caused by tower damage and resulting disruption in power supply to further aid distribution network operators in making decisions about erosion control (e.g. Prime et al., 2018). Such an approach may also be used to help decide when to deploy interventions and where, for example, which sections of riverbanks require erosion control, or where additional monitoring may be needed. In addition, the impact of climate change on the sequencing of extreme flow events on erosion hazards needs to be considered. A previous storm may make towers more vulnerable to future floods, dependent upon factors such as flood duration and intensity, sediment availability and topography.

The modelling approach applied here provides mechanisms for visualising how future riverine erosion risk compares with the present, and where and when erosion control may need to be implemented according to the location of the tower and the scale of the problem. Thus, the modelling output provides energy transmission sector stakeholders with an erosion hazard assessment that can ultimately feed into a strategy to achieve climate change resilience.

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.

Acknowledgements

This work was supported by the UK Natural Environment Research Council research grant: 'Erosion Hazards in River Catchments: Making Critical Infrastructure More Climate Resilient' (NE/S01697X/1). Since beginning this work in December 2019, the lead author moved from the University of Liverpool to UKCEH. The authors would therefore like to acknowledge financial support from the Soils and Land Use science area, Catchment to Coast group and the SOC-D project of the UK-SCAPE programme delivering National Capability (NERC award no. NE/R016429/1) which allowed the lead author time to write up this manuscript. The authors would like to thank Dr. David Cooper (UK Centre for Ecology & Hydrology) whose comments on an earlier draft improved this manuscript prior to journal submission. We acknowledge the BGS, UKSO, EA, OS, National Grid UK, Google Earth and NRFA for datasets, JBA Consulting for their 2009 report on a qualitative assessment of erosion hazards to towers in our study reach, and the creators of CAESAR-Lisflood and associated RasterEdit and Grainfile Maker tools used here.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2022.100439.

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