Can geomorphologic channel design deliver better outcomes for river restoration than reconnecting historic meanders?
A study of the River Adur

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EXECUTIVE SUMMARY

This study aimed to assess whether channel design based on geomorphological methods can deliver better outcomes for river restoration than reconstructing historic meanders at a straightened lowland river. It evaluated whether flood risk and physical habitats (instream and on the floodplain) are altered by channel design methods at the River Adur, West Sussex.

Human modification of rivers and their catchments has led to the widespread degradation of fluvial ecosystems. River restoration therefore aims to rehabilitate ecosystems by altering fluvial forms and processes and is recommended by key legislation for both environmental protection (EU Water Framework Directive) and flood defence (e.g. EU Flood Directive and the UK Government's *Pitt Review*). A popular restoration technique for artificially straightened channels is to engineer a meandering course to increase hydromorphic diversity and, in principle, physical habitat heterogeneity. The 'carbon copy' approach of reconstructing historic meandering planforms has been criticised since turning back the clock to restore landforms does not restore the hydrologic and sedimentary processes that sustain them (Downs et al., 2002). Therefore, geomorphologists have developed methods to predict the three-dimensional geometry of channels (width, depth and slope) using equations based on empirical relationships between flow and channel dimensions or by solving the governing equations of continuity, flow resistance and bedload transport (Soar and Thorne, 2001).

This study is novel in that it revisits a completed restoration scheme based on carbon copy meanders to examine whether outcomes could have been improved by predicting channel dimensions with geomorphological methods. A linked one-dimensional (1D), two-dimensional (2D) hydraulic model was used to simulate the impact of channel design on flooding and physical habitats using Flood Modeller software. Simulations were run for three channel designs (A: pre-restoration, B: post-restoration/carbon copy, C: geomorphic design) for hydrographs of varying magnitudes. The alternative channel (C) used empirical regime equations to compute cross-sectional topography (Simons and Albertson, 1960) and planform (Soar and Thorne, 2001). In the upstream reach where planform modifications occurred, sinuosity rose to 1.54, compared to the carbon copy (1.25) and pre-restoration (1.13).

The hydraulic model indicated that, overall, the geomorphologic design did not outperform the carbon copy channel. Geomorphologic design would not substantially increase flood risk compared to reconstructing the historic planform, despite an increased magnitude of flooding. Whilst overall flood risk was minimal due to the lack of floodplain development, the increased water depths could present a hazard at sites where housing, industry or infrastructure exist. The findings suggest the absence of a 'planform effect' on instream habitat diversity, indicated by the variability of water depth and velocity, in the upstream reach. Conversely, physical habitat diversity was greater for the carbon copy channel downstream where planform was not altered. This suggests that cross-sectional topography has a greater impact than planform on instream hydraulic habitats, supporting earlier research which indicate that planform adjustments may be less important than 'softer' measures like woody debris, planting bank vegetation (Rhoads et al., 2003), or the cessation of weed-cutting (Friberg et al., 2014). On the floodplain, geomorphologic channel design can deliver slightly enhanced habitats through a flood pulse of longer duration.

This study demonstrates ecological enhancement and flood risk management should not be treated as mutually exclusive restoration goals for lowland rivers like the Adur, although their synergy cannot be guaranteed. Therefore, a range of restoration techniques, including geomorphologically appropriate channel design, must be carefully chosen to achieve these twin objectives. For instance, wetland scrapes delivered increased flood storage and temporary habitats, indicated by higher water depths, compared the pre-restoration river-floodplain. This emphasises the role of geomorphologic expertise in designing projects, as well as linked 1D-2D hydraulic models for evaluating the potential outcomes of different restoration techniques.

RATIONALE FOR STUDY

Introduction

The influence of human activity on aquatic ecosystems has never been more widespread. It is estimated that up to 96% of river catchments in lowland Britain have been anthropologically modified (Brookes and Long, 1990, cited by Brookes and Shields, 1996) and 77% of flows in large rivers in Europe, North America and the former Soviet Union are ‘moderately or strongly’ affected by regulation and fragmentation (Dynesius and Nilsson, 1994). But the human modification of river systems is no recent phenomenon. Deforestation and conversion to agriculture have influenced catchments since around 9,000 BC (Roni and Beechie, 2013), whilst the Greeks regulated flows to harness the power of streams for grinding cereals into flour 2,000 years ago (International Renewable Energy Agency, 2012). However, the scale and severity intensified following the Industrial Revolution through the straightening of channels for navigation, flood control and drainage (Roni and Beechie, 2013), flow regulation by dams, weirs and reservoirs (Brookes and Shields, 1996b), altering their chemistry by discharging sewage and industrial pollutants (Bell et al., 2013), as well as reclaiming floodplains for agriculture or urbanisation (Nienhuis and Leuven, 2001).

What is river restoration?

An increasing recognition of the degradation of fluvial habitats has driven a growing interest in their restoration among government agencies, utility companies, NGOs and scientists, which has accelerated since the late 1980s (Roni and Beechie, 2013). It has been estimated that around £15 million is spent annually to restore fluvial habitats in the UK, often involving the adjustment of longitudinal and cross-sectional river profiles (M. Diamon cited in Sear and Newson, 2004). Whilst no single definition of river restoration exists, the European RESTORE Partnership (2013) propose the following broad aim:

“...to improve the quality and function of rivers and to restore them to support healthy and thriving ecosystems.”

A debate exists in the literature over whether restoration, implying the full return to a historic or 'natural' state, is an achievable aim (Bradshaw, 1996). Many channels and catchments have been so heavily modified that 'rehabilitation' or 'enhancement' of ecosystems may be more realistic objectives (Environment Agency, 2010, Rutherford et al., 2000), illustrated by the conceptual continuum in Figure 1.

River restoration in practise

Regardless of the approach, Schiemer et al. (1999) argue that projects should be based on restoring processes (physical and biological) and functions (hydrological and geomorphological), in order to 'let the river do the work' of creating sustainable landforms and habitats. Following Beechie et al. (2013), this study uses 'restoration' to refer to any such activities, whether representing full or partial recovery. Table 1 summarises the wide range of techniques which can be used to restore or enhance river habitats, the use of which should be carefully tailored towards the goals, scale and context of a project.

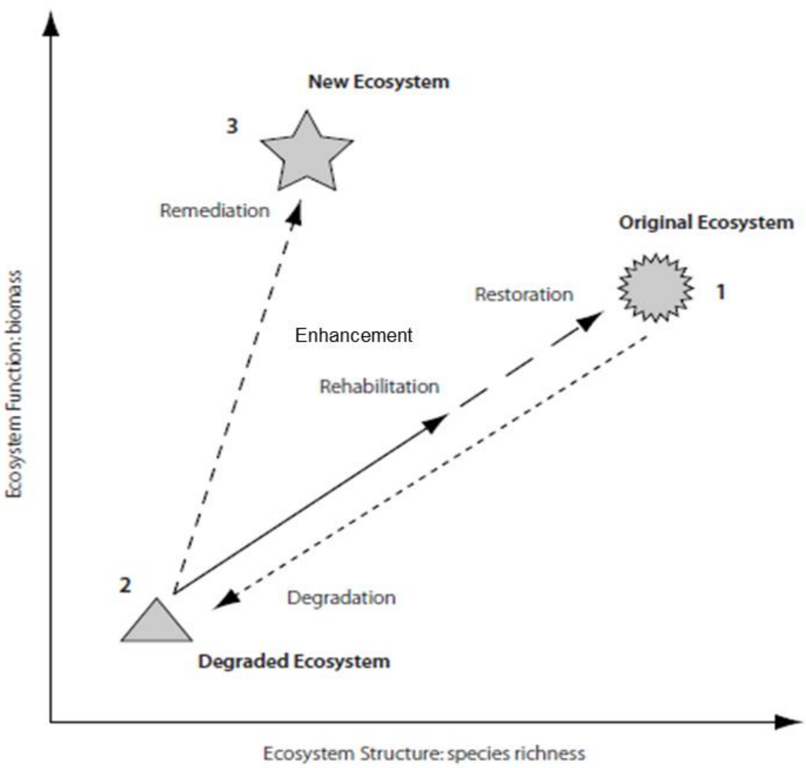

Figure 1. Conceptual approaches for improving river ecosystems. Source: Adapted from Bradshaw (1996) reproduced by Rutherford (2000).

Table 1. List of common river restoration techniques. Sources: Downs et al. (2002), Gilvear et al. (2013), Roni et al. (2013) and Schueler and Brown (2004).

Technique	Key objectives
Bank modifications	
Bank vegetation establishment	Bank stabilisation, erosion prevention
Coir fibre logs	Bank stabilisation, erosion prevention
Removal of bank protection	Lateral connectivity, restore hydrological and sediment transport processes
Instream techniques	
Planting instream vegetation	Improve aesthetics and instream habitats
Flow deflectors e.g. log jams, large woody debris	Increase diversity of flow and habitats
Berms	Increase diversity of flow and habitats
Substrate placement e.g. spawning gravel	Improve instream habitats e.g. fish populations
Riffle-pool features	Increase diversity of flow and habitats
Mycofiltration bags	Improve water quality and biota
Lunkers	Improve instream habitats e.g. fish populations
Floodplain techniques	
Backwater zones	Habitat creation
Wetland scrapes / washlands	Habitat creation, flood storage
Side channels	Habitat creation, flow attenuation
Managing riparian vegetation (e.g. reforestation, removal of invasive species)	Increase biodiversity, restore hydrological and sediment transport processes
Engineering techniques	
Channel engineering e.g. remeandering	Increase diversity of flow and habitats, create ‘natural’ aesthetics, floodplain connectivity
Weir removal or breaching	Longitudinal connectivity, improve fish migration
Daylighting / culvert removal	Longitudinal connectivity, improve fish migration
Fish and eel passes	Longitudinal connectivity, improve fish migration

Sinuosity and remeandering

Increasing sinuosity is a common technique for improving hydromorphic diversity and instream habitats which have been degraded by channel straightening (Roni et al., 2013). Table 2 summarises the main approaches for increasing sinuosity, ranging from passive restoration, which allow the river to create its own shape through hydrologic and geomorphic processes, to the excavation of new, highly engineered channels (Roni et al., 2013). Gilvear et al. (2013) found that remeandering is one of the most effective rehabilitation techniques for

Table 2. Typical methods for increasing channel sinuosity in river restoration. Source: Downs et al. (2002) and Roni et al. (2013)

Approach	**Techniques**	**Resource requirements**	**Response time**
Passive restoration	Removal of bank protection	Low	Slow
	Cessation of dredging and bank vegetation clearance		
Bioengineering / instream structures	Installation of berms made from gravel or wood	Low-medium	Fast-medium
	Flow deflectors e.g. large wood, boulders		
	Substrate reinstatement		
	Pool-riffle features		
	Planting instream vegetation to narrow channels		
Remeandering	Excavation of new channels or reconstruction of historic planform (typically in conjunction with other techniques)	High: complex design including modelling	Rapid

delivering long-term ecosystem services, producing ‘high’ or ‘good’ benefits for biodiversity, fisheries, physical habitat quality and amenity; additionally, it can provide ‘moderate’ benefits for sustainable flood management by attenuating velocities and increasing storage.

However, remeandering requires significant resources for design and construction. For instance, total project costs for the EU-LIFE demonstration projects at the Rivers Cole and Skerne in England exceeded £140,000 per km (Vivash et al., 1998). Alternatively, reconnecting remnant meanders can reduce design costs, for instance, a 900 m stretch of the Little Ouse at Thetford was restored to its original course for £15,000 (Janes et al., 2005).

Approaches to channel design

When designing stable rivers for restoration schemes, features like meanders cannot be installed at random, therefore various techniques have been developed to predict the three-dimensional shape of channels (Hey, 1997). The three main approaches for designing the morphology of restored channels, often used in combination (Soar and Thorne, 2001), are discussed below.

Carbon copy and analogue approaches

One of the most popular techniques in northern Europe is the carbon copy approach (Brookes and Sear, 1996, cited by Soar and Thorne, 2001), where rivers are returned to their pre-disturbance planform by reconnecting remnant meanders visible in the floodplain or using historic maps (Brookes and Shields, 1996a). Where information on the pre-disturbance morphology is unavailable, channel geometry can be extrapolated from undisturbed 'analogue' reference reaches (Shields, 1996). Both approaches assume that the catchment's geomorphic, hydrological and land use characteristics are similar between the pre-disturbance state or reference reach and the target site for restoration (Soar and Thorne, 2001).

Hydraulic geometry and the empirical approach

The theory of 'hydraulic geometry' was first proposed by Leopold and Maddock (1953) to explain how a river adjusts its width, depth and velocity in response to discharge and, therefore predict key channel dimensions. They identified the following relationships when plotting field observations on graphs which were similar even for different types of river system (ibid.):

$$w = aQ^b \quad (1)$$

$$d = cQ^f \quad (2)$$

$$v = kQ^m \quad (3)$$

where *w*, *d* and *v* = water surface width, mean depth and mean velocity, respectively; and *a*, *b*, *c*, *f*, *k* and *m* are numerical constants. These equations assume that a river is 'in regime', meaning that there are no net changes in channel morphology and discharge capacity over a period of years (Biedenharn et al., 2000). The coefficients (a, b, c) and power functions (b, f, m) vary according to the dataset, reflecting environment variables such as the mobility of bed material (e.g. gravel or sand), whilst some equations incorporate grain size and bedload transport (see Singh (2003) for a list of power functions published in the literature). For instance, Hey and Thorne (1986) developed a set of regime equations for gravel-bed rivers according to the coverage of bankside vegetation.

Analytical approach

Alternatively, the analytical or 'rational' approach to channel design is based on solving the governing equations of continuity, flow resistance and bedload transport to predict mean channel depth, slope and width (Soar and Thorne, 2001), rather than fitting relationships to empirical observations. Hey (1997) proposed that the morphology of stable channels can be determined by the bankfull flow rate, bedload transport rate, slope, as well as the calibre of bed and bank material which, in turn, lead to the adjustment of the nine independent variables listed in Table 3. However, whilst channels can adjust their dimensions according to these nine degrees of freedom, only three equations are available (computing depth, slope and width), thus leaving the majority of the variables unknown and the overall channel dimensions indeterminate (Shields, 1996, Soar and Thorne, 2001).

River restoration for habitat improvement

One of the key drivers for river restoration is the enhancement of instream and floodplain habitats. It is a widely regarded concept in ecology, including stream ecosystems, that the

Table 3. Variables controlling and defining stable channel morphology. Source: Hey (1997).

Controlling (independent) variables	**Dependent variables**
Bankfull discharge, Q_b	Bankfull mean width, W_b
Sediment load, Q_s	Bankfull mean depth, d_b
Sediment grain size, D	Bankfull maximum depth, d_{max}
Bank material	Bankfull slope, S_b
Bank vegetation	Velocity, v
Valley slope, S_v	Sinuosity, p
	Meander arc length, z
	Height (Δ) and wavelength (λ) of bedforms

heterogeneity of physical habitats can promote species diversity (Palmer et al., 2010, Nakano and Nakamura, 2008). For instance, evidence suggests that instream physical conditions influence the biodiversity of benthic macroinvertebrates (Kemp et al., 2000) and salmonoid fish (Ahmadi-Nedushan et al., 2006), with the most important factors being the hydraulic variables of water depth and velocity, alongside cover and substrate (Ahmadi-Nedushan et al., 2006, Jowett and Duncan, 2012). In particular, velocity and depth are used to construct habitat suitability curves (Figure 2) which can be used to define optimal values for instream target species at different life stages (Vismara et al., 2001), as well as computing indices like the weighted usable area (WUA) to evaluate habitat suitability at river sections (Bocchiola, 2011). High instream water depths and lower velocities are often considered to promote habitat suitability, for instance, by providing refugia for spawning salmon and trout (Bocchiola, 2011).

In addition to absolute and mean values, a range of flows is also considered to be ecologically beneficial (Jowett et al., 2008, Millidine et al., 2012) and the variability of water depth and velocity are often used as indicators of physical habitat diversity (Nakano and Nakamura, 2008). For instance, fish taxa may prefer the upper distribution of depths or lower distribution of velocities, thus, variance may have a stronger influence on physical and biological processes than the mean (Rosenfeld et al., 2011). Restoration can also enhance floodplain habitats through improving lateral connectivity, or creating permanent or temporary

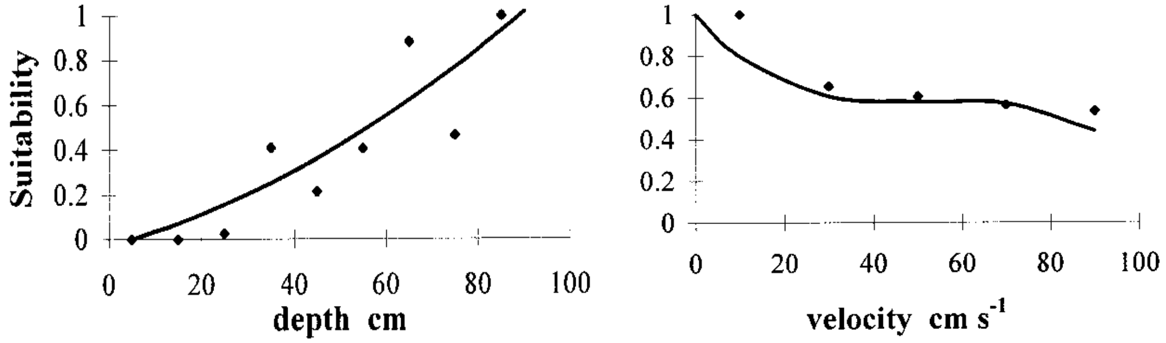

Figure 2. Adult brown trout habitat suitability curves for depth and velocity at the River Adda, Italy. Reproduced from Vismara et al. (2001).

wetlands by excavating backwaters and flood storage zones (English Nature et al., 2003, Defra, 2004).

EU Water Framework Directive

The European Union Water Framework Directive (WFD) (2000/60/EC) is a major driver for physical habitat restoration, representing the most significant piece of recent legislation concerning river management (European Commission, 2000). Described as ‘unprecedented’, it commits Member States to “protect, enhance and restore all bodies of surface water” (excluding artificial or heavily modified water bodies) with the aim of achieving ‘good ecological status’ as defined by a range of biological, hydromorphological and physico-chemical criteria (Wharton and Gilvear, 2007). In the UK, 50.1% of water bodies are expected to achieve good ecological status by 2015, with 41.5% reaching good chemical status (WRc plc, 2015). In a recent evaluation of progress on the WFD, the European Commission (2015a) stated that hydromorphology, changes to the flow and physical form of water bodies, is a major obstacle to achieving good status. The European Commission therefore recommended the restoration of physical habitats in conjunction with addressing hydrological issues (e.g. abstraction and flow regulation) to achieve WFD targets for protecting ecological flows, defined as the "amount of water required for the aquatic ecosystem to continue to thrive and provide the services we rely upon" (European Commission, 2015a, European Commission, 2015b). Given this legislative context, the number of river restoration projects is expected to continue to rise (RESTORE, 2013).

Flood risk management

In addition to providing habitats for flora and fauna, rivers deliver a range of benefits to human society, known as ‘ecosystem services’ which include water supply and purification, food, recreation, nutrient cycling, and flood control (Loomis et al., 2000, Millenium Ecosystem Assessment, 2005). Consequently, the degradation of fluvial ecosystems compromises their capacity to deliver these services, such as flood defence (Millenium

Ecosystem Assessment, 2005). Nienhuis and Leuven (2001) argue that river restoration can contribute to flood protection by attenuating flood peaks, reducing velocities, as well as increasing channel roughness and floodplain storage. However, the empirical evidence supporting river restoration as a flood protection strategy is currently limited (Wharton and Gilvear, 2007).

Legislative drivers

Between 1998-2009, floods across Europe displaced half a million people, causing 1,126 deaths and economic losses of €52 billion – greater than any other natural hazard (European Environment Agency, 2011). It is therefore unsurprising that new legislation has been passed to address flooding and the risks it poses; these include proposals for utilising natural processes for flood management, signalling a paradigm shift away from 'hard' engineering to working with nature. In the UK, the Department for Environment, Food and Rural Affairs proposed a new strategy, *Making Space for Water* (Defra, 2004), at the heart of which was an understanding that some flood risks can never be removed entirely and that policy should 'allow space for water' to better manage the adverse consequences of flooding. It recommended a 'less interventionist' approach with greater reliance on natural processes, such as the realignment of river corridors and use of constructed wetlands, including on agricultural land (ibid.) Following the catastrophic flooding of summer 2007, the government's *Pitt Review* (Pitt, 2008) also recommended working with natural processes for flood defence, acknowledging that using farmland and artificial wetlands to hold flood water has been an 'increasingly successful' technique.

At the European level, whilst the WFD aims to "contribute… to mitigating the effects of floods and droughts" (European Commission, 2000: Article 1 (e) L 327/5), it was complemented by the subsequent EU Floods Directive (2007/60/EC) which requires Member States to assess and map flood risks and manage them to reduce the adverse consequences and likelihood of flooding (European Commission, 2007). Additionally, the EU *Best Practise*

Guidelines on Flood Prevention, Protection and Mitigation recommends restoration techniques, in particular, reconnecting rivers with their floodplains to take advantage of their natural storage capacity, as well as reversing the straightening of watercourses, thus 'letting the rivers spread' (European Commission, 2004).

Flood defence and habitat enhancement – synergy or conflict?

Whilst extensive research exists to support the use of river restoration for habitat enhancement, the evidence base for flood protection is more limited (Wharton and Gilvear, 2007), prompting a debate over whether a synergy or conflict exists between these objectives (Nienhuis and Leuven, 2001). For instance, artificially straightened channels may have been oversized and shortened, thus increasing their flood conveyance compared to meandering courses (Janes et al., 2005). Therefore, in principle, restoration techniques can increase the risk of inundation by reducing conveyance and elevating water levels where roughness is increased, or where channels are narrowed or made more sinuous (Janes et al., 2005, HR Wallingford, 2004). Research has shown that managing flood risk may compromise ecological objectives, for instance, restoration (bank reprofiling, flood deflectors, reed beds and bankside trees) was proposed to increase the hydromorphological diversity and, thus habitat heterogeneity at the River Idle, a heavily modified lowland river in Nottinghamshire. However, hydraulic modelling indicated that whilst flood defence was not compromised, restoration would 'underachieve' in terms of habitat and species diversity (Downs and Thorne, 2000). Scale is also important when considering flood risk, since local effects may be different to those at the network-scale. The choice of restoration technique is also key, for instance, whilst *Making Space for Water* recommends the creation of floodplain wetlands to hold flood waters, it notes that the flood protection benefits of remeandering and variable bed morphology are 'less clear' (Defra, 2004).

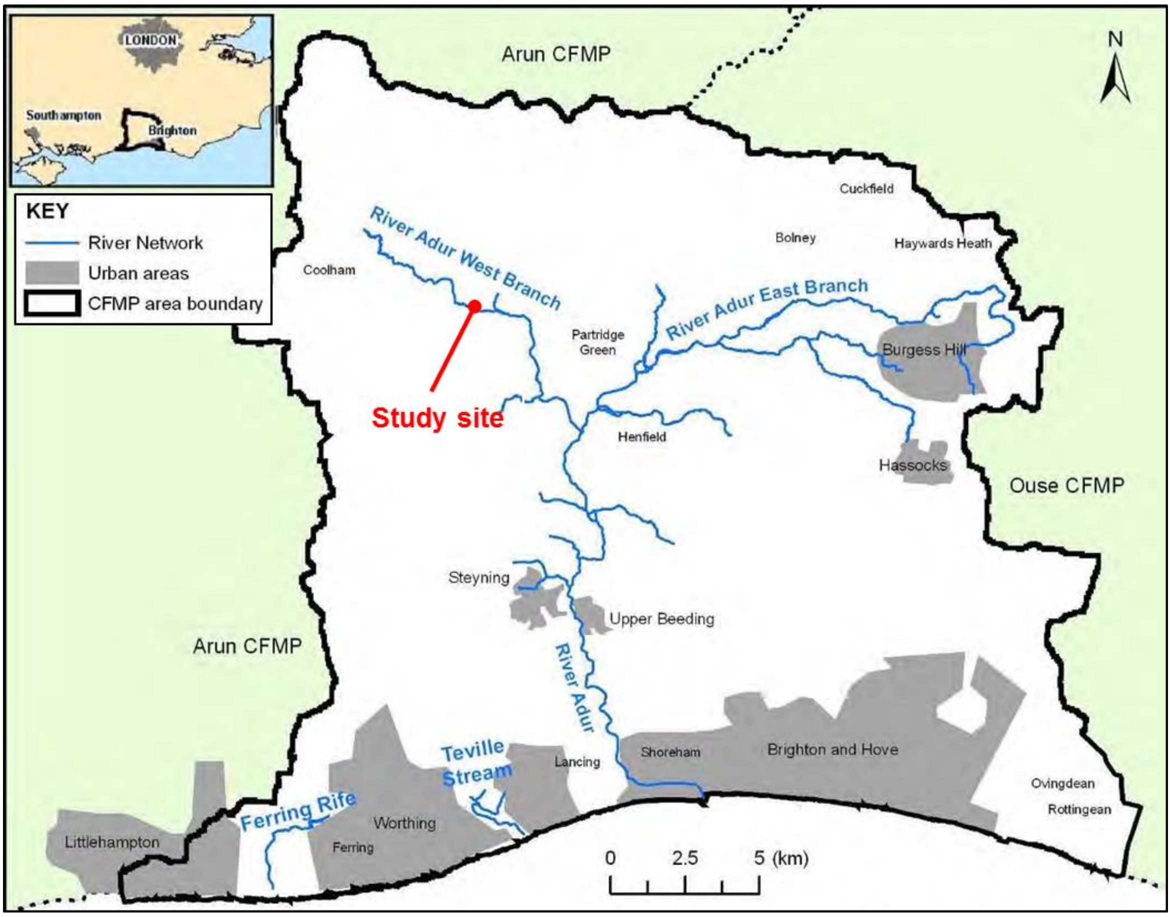

Figure 3. The River Adur catchment. Reproduced from the River Adur Catchment Flood Management Plan (Environment Agency, 2008). Contains Ordnance Survey data © Crown copyright.

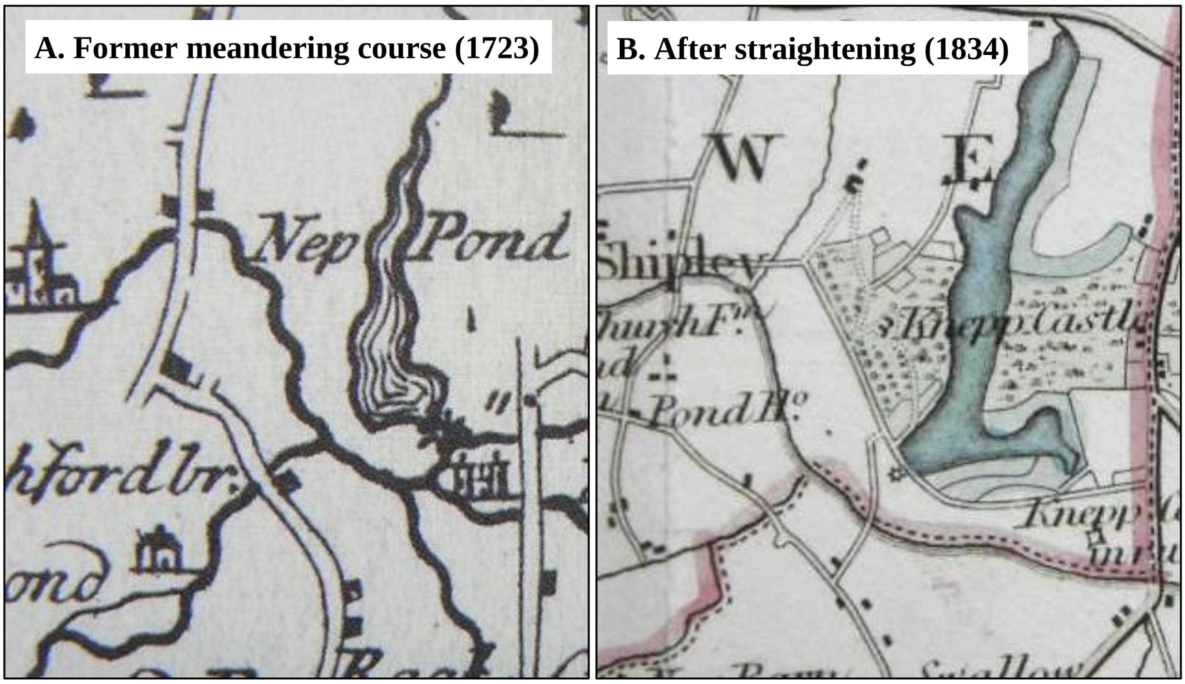

Figure 4. Historic maps of the River Adur at the Knepp Castle Estate showing A) its former meandering course in 1723 and B) in 1834 after straightening. Sources: Richard Budgen (1723), the first large-scale map of Sussex, and Benjamin Rees Davies in Horsfield's History of Sussex (1834), both reproduced from Symonds (2012).

STUDY SITE

The River Adur, West Sussex

The River Adur is a low gradient clay-bed stream in West Sussex, southern England. Its western branch, where the study reach is located, rises at Slinfold (70 m AOD) before converging with the eastern branch west of Henfield and eventually flowing into the English Channel at Shoreham-by-Sea (Figure 3). Human modification of the Adur dates back to the early 1800s when the river downstream of the Knepp Castle Estate was widened and straightened following the 1807 River Adur Navigation Act to facilitate navigation and land drainage (Symonds, 2012). Historic maps and documents indicate that the channelisation of the Adur at the Knepp Castle Estate took place between 1820-1847 (Figure 4); whilst there is no direct documentary evidence explaining these modifications, historian Richard Symonds (2012) argues that the river was straightened to drain the swamped floodplain for agriculture.

River and floodplain restoration

The River Adur at the Knepp Castle Estate was chosen for this study partly due to the scale of restoration, which claims to be the 'biggest proposed stretch of river to be naturalised in Britain' (Dennis, n.d.) Major restoration works were carried out on a 2.4 km straightened reach between 2011-2013. The project was led by the Estate in partnership with the Environment Agency, Sussex Wildlife Trust, West Sussex County Council, Natural England and Royal HaskoningDHV consultants, with the aim:

"To enhance the channel and floodplain habitat diversity by physical manipulation of channel planform, bed levels and flow patterns with a particular emphasis on reconnecting the floodplain to the river channel." (Janes et al., 2006)

Restoration methods focused on returning the planform upstream of the Lancing Brook tributary to its original meandering course, still visible across the floodplain, in conjunction with 'softer' techniques including large woody debris to deflect flows, installation of pool-riffle features, planting instream vegetation, raising bed levels, filling floodplain ditches and drains, alongside the creation of permanent backwaters and temporary floodplain wetlands (scrapes) (Figure 6). Downstream, planform modification was limited to a single meander loop excavated to bypass a weir, whilst increased sinuosity was achieved by including installing gravel berms and instream measures described above, in contrast to the channel engineering upstream. Throughout the site, the channel was narrowed and reduced in depth, although it was wider and deeper at the downstream reach (Figure 9). The planform is illustrated in **Figure 5** and typical cross-section plans are presented in Appendix I.

The Adur restoration runs in parallel with the Knepp Wildland Project which, launched in 2001, aims to convert most of the 3,000 acre estate from intensive arable farming to a 'near-natural grazing' system with low stocking densities of rare breed cattle, ponies, pigs and deer (Greenaway, 2007) to create a 'minimal-intervention' landscape (Dennis, n.d.) Low-intensity grazing can support species-rich grassland ecosystems (Madgwick and Jones, 2002), hence, the Estate envisages that restoring historic land use will improve biodiversity. Like the adjacent land, the river has been modified; thus, the project aims to 'rewild' the river, floodplain and parts of the catchment, returning them to similar forms and processes that existed before human intervention (Greenaway, 2006).

Project costs totalled approximately £400,000, over three-quarters of which were for construction, with the rest covering design, modelling and permitting (Ian Dennis, Royal HaskoningDHV, personal communication, 24 July 2015), representing a major transformation of the landscape and investment by project partners. As a finalist of the River Restoration Centre's 2015 UK River Prize, it may be regarded in the future as a 'flagship' project for British lowland rivers, so it is therefore prudent to appraise the scheme. In particular, since this large site has the potential for many different designs, it is worthwhile evaluate whether alternative designs to the historical planform could reduce flood whilst satisfying ecological objectives.

Figure 5. Pre- and post-restoration planforms and key floodplain modifications at the River Adur at the Knepp Castle Estate. Reproduced courtesy of Royal HaskoningDHV and annotated by the author.

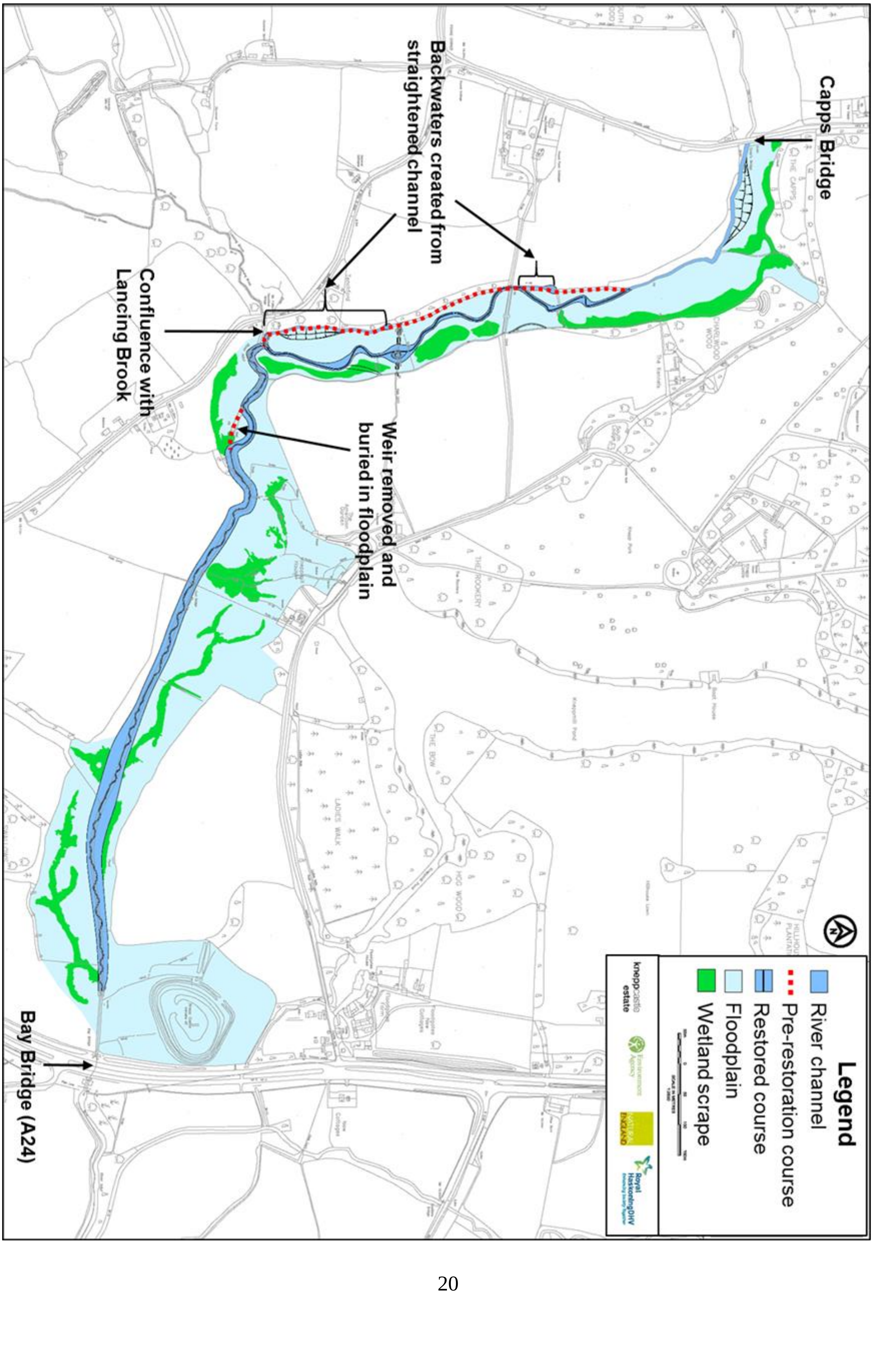

Figure 6. The River Adur at Knepp Castle Estate before, during and after restoration. Pre-restoration and restoration works are courtesy of the River Restoration Centre, post-restoration images were taken by the author.

Table 4. Catchment characteristics of the River Adur gauging station at Hatterell Bridge, 2 km downstream from the Knepp Castle Estate (based on data from 1961-2005). Source: *UK Hydrometric Register* (Marsh and Hannaford, 2008).

Grid reference	Catchment area, km^2	Elevation, m AOD	Maximum catchment elevation, m AOD	Mean daily flow, m^3s^{-1} (1961-05)	Median annual flood, m^3s^{-1} *	Mean annual rainfall, mm	Mean annual runoff, mm	Base flow index
TQ178197	109.1	3.6	106.7	1.18	11.3	803	355	0.31

* Flood flows were truncated at around 11 m^3s^{-1}.

Catchment characteristics and flood risk

The catchment land use is predominantly rural (40% grassland, 36% arable and horticulture), with some woodland (17%) and limited urban development (1%); geology is dominated by impervious Weald Clay (Marsh and Hannaford, 2008). Table 4 summarises hydrological data recorded at an Environment Agency gauging station at Hatterell Bridge, 2 km downstream of the restoration site; mean daily flows were 1.18 m^3s^{-1} and the flow regime has been described as 'sensibly natural' and 'very responsive' (ibid.)

Figure 7 illustrates that areas adjacent to the restoration site are at high risk of flooding. Whilst most of the area is rural, flooding still poses a threat to property and infrastructure, including local farms, cottages and their access roads. The River Restoration Centre identified the A24 (Bay Bridge) and Capps Bridge as major constraints for restoration, as well as Tenchford Bridge at Lancing Brook where water levels could potentially backup, recommending that existing flood levels should not be increased (Janes et al., 2006).

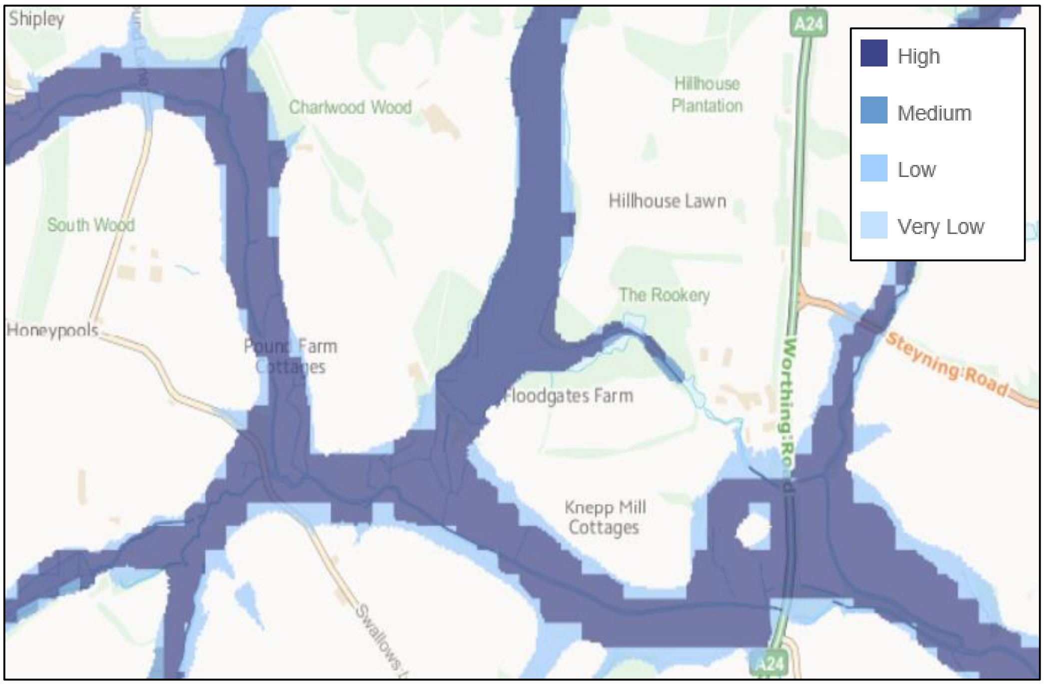

Figure 7. Areas at risk of flooding from river water at the River Adur in and around the Knepp Castle Estate, West Sussex. Scale: 1:10,000. High risk = 1 in 30 annual probability of flooding, medium risk = 1 in 100 to 1 in 30 probability, low risk = 1 in 1,000 to 1 in 100 probability. Source: maps.environment-agency.gov.uk © Environment Agency copyright and database rights 2015 © Ordnance Survey Crown copyright.

AIMS AND OBJECTIVES

The overall aim is to test the hypothesis that geomorphologic channel design can deliver better outcomes for river restoration (flood risk management and habitat suitability) than reconnecting historic meanders at the River Adur, West Sussex. Specific research objectives are to:

1. **Evaluate whether flood risk is altered under a meandering channel based on geomorphologic principles, compared to reconstructing the historic planform**
2. **Assess the extent to which this alternative design enhances the diversity of instream physical habitats by analysing water depth and velocity as indicators of physical habitat**
3. **Assess the extent to which geomorphologic channel design promotes floodplain habitats**
4. **Evaluate whether ecological enhancement and flood risk management are mutually exclusive goals for river restoration at the site.**

METHODS

To assess the impact of channel design (planform and cross-sectional geometry) on flooding and habitat suitability, computer models were built to simulate three designs for the River Adur: A = pre-restoration, B = post-restoration, C = an alternative design based on hydraulic geometry equations. Data on the extent of floodplain inundation, as well as water depth and velocity in the channel and on the floodplain were generated to assess flood risk and physical habitats. The upper and lower reaches are defined as the River Adur upstream and downstream of the confluence with Lancing Brook, respectively. The methods used are described below.

Hydraulic modelling

Simulations of floodplain inundation were run using Flood Modeller Free software (version 4.0.5595), an industry-standard package used by the Environment Agency and the private sector. Numerical modelling is a popular tool for assessing the impact of channel engineering, including habitat restoration, where the intervention is likely to have a substantial effect on the flow regime, conveyance or sediment budgets. For instance, the River Restoration Centre recommend that modelling should be an ‘integral’ part of the design for complex projects, such as reconnecting remnant meanders where rerouting flows and reducing channel slope will have implications for stage and inundation (Janes et al., 2005).

Flood Modeller was used to link a one-dimensional (1D) hydraulic model of flows within the channel with a two-dimensional (2D) model of water flowing across the floodplain. On their own, 1D models are limited since they assume unidirectional flows and do not accurately represent floodplain storage (Néelz and Pender, 2009). 2D models have the advantage of more accurately simulating variations in water levels and velocity, thus reducing uncertainty in predicting flood hazards (Syme, 2006). Linking 1D and 2D models can therefore utilise the benefits of both approaches.

1D model components

The characteristics of the three 1D river networks are summarised in Table 5 with planforms illustrated in Figure 8 (Flood Modeller .dat files can be viewed in the Supplementary Data disc). The model components are described in detail below.

Channel A. Pre-restoration

The pre-restoration planform was based on a 1 m resolution LIDAR (Light Detection and Ranging) Digital Terrain Model (DTM) obtained from the Environment Agency and design plans produced by Royal HaskoningDHV (Figure 5). LIDAR data featured the planform for both the original straightened channel and the post-restoration design upstream of the confluence with Lancing Brook since it was captured during the restoration works (10-11 December 2011). A river centre line was drawn in Flood Modeller following the channel planform, then nodes for the 1D network were assigned automatically to each vertex using the Cross Section Generator tool. Since no data was available for the cross-sectional topography, this was derived from the DTM. Cross-sections were originally 24 m wide, comprised of 16 units representing the channel, banks and the start of the floodplain; sections were subsequently extended to 56 m using the Extend All River Sections tool following warnings from initial 1D simulations to improve model performance. The 1D network included 50 cross-sections (including 11 interpolated nodes added following warnings during initial 1D simulations). An overall sinuosity of 1.09 was computed by diving channel length by valley length, indicative of a relatively straight channel. Bed slopes of 0.0015 (upper reach) and 0.0004 (lower reach) were computed from long section plans obtained from Royal HaskoningDHV consultants by dividing the change in elevation, ∂z, (upper reach=1.63 m, lower reach=0.51 m) by channel length.

Channel B. Post-restoration

The restored channel was modelled using the same approach for Channel A, with the planform also based on LIDAR images and Royal HaskoningDHV design plans. The network included more nodes than Channel A to represent the increased sinuosity of 1.14, including 79 cross-sections. In the upper reach, the meandering channel was 84 m longer than Channel A, representing an increase in sinuosity from 1.13 to 1.22; downstream, the channel was 23 m longer, delivering a slight rise of 1.06 to 1.08. The first six cross sections were replicated from Channel A since the cross-sections and planform were not modified in practise. For the remaining nodes, the topography across the sections was based on Royal HaskoningDHV's plans for a two-stage channel, with a shallower more narrow profile (bankfull width, W_b=6.0 m, bankfull depth, D_b=1.0 m) in the upper reach and a deeper, wider downstream channel

Table 5. Key planform and cross-sectional characteristics of the three channel designs. * Bankfull depths for Channels B and C do not include the 0.5 m deep low flow channel. ** Slope for Channel A was computed by dividing the change in bed elevation in pre-restoration long sections from Royal HaskoningDHV by channel length; for Channels B and C, slope was based on the change in bed elevation in Royal HaskoningDHV's plans.

	A. Pre-restoration	**B. Post-restoration**	**C. Alternative design**
Upper reach			
Nodes in 1D network	27	35	46
Channel length (m)	980	1,064	1,339
Valley length (m)	870	870	870
Sinuosity	1.13	1.25	1.54
Bankfull width (m)	Variable	6.00	8.60
Bankfull depth (m)	Variable	1.00 *	0.75 *
Bed slope (m/m) **	0.0015	0.0012	0.00092
Channel roughness (Manning's n)	0.045	0.045	0.045
Lower reach			
Nodes in 1D network	23	44	44
Channel length (m)	1,155	1,178	1,178
Valley length (m)	1,090	1,090	1,090
Sinuosity	1.06	1.08	1.08
Bankfull width (m)	Variable	12.40	8.60
Bankfull depth (m)	Variable	2.30 *	0.75 *
Bed slope (m/m) **	0.0004	0.0004	0.0004
Channel roughness (Manning's n)	0.045	0.045	0.045
Total reach			
Nodes in 1D network	50	79	90
Channel length (m)	2,135	2,262	2,517
Valley length (m)	1,960	1,960	1,960
Sinuosity	1.09	1.15	1.28
Area of wetland scrape (m^2)	-	36,965	34,337

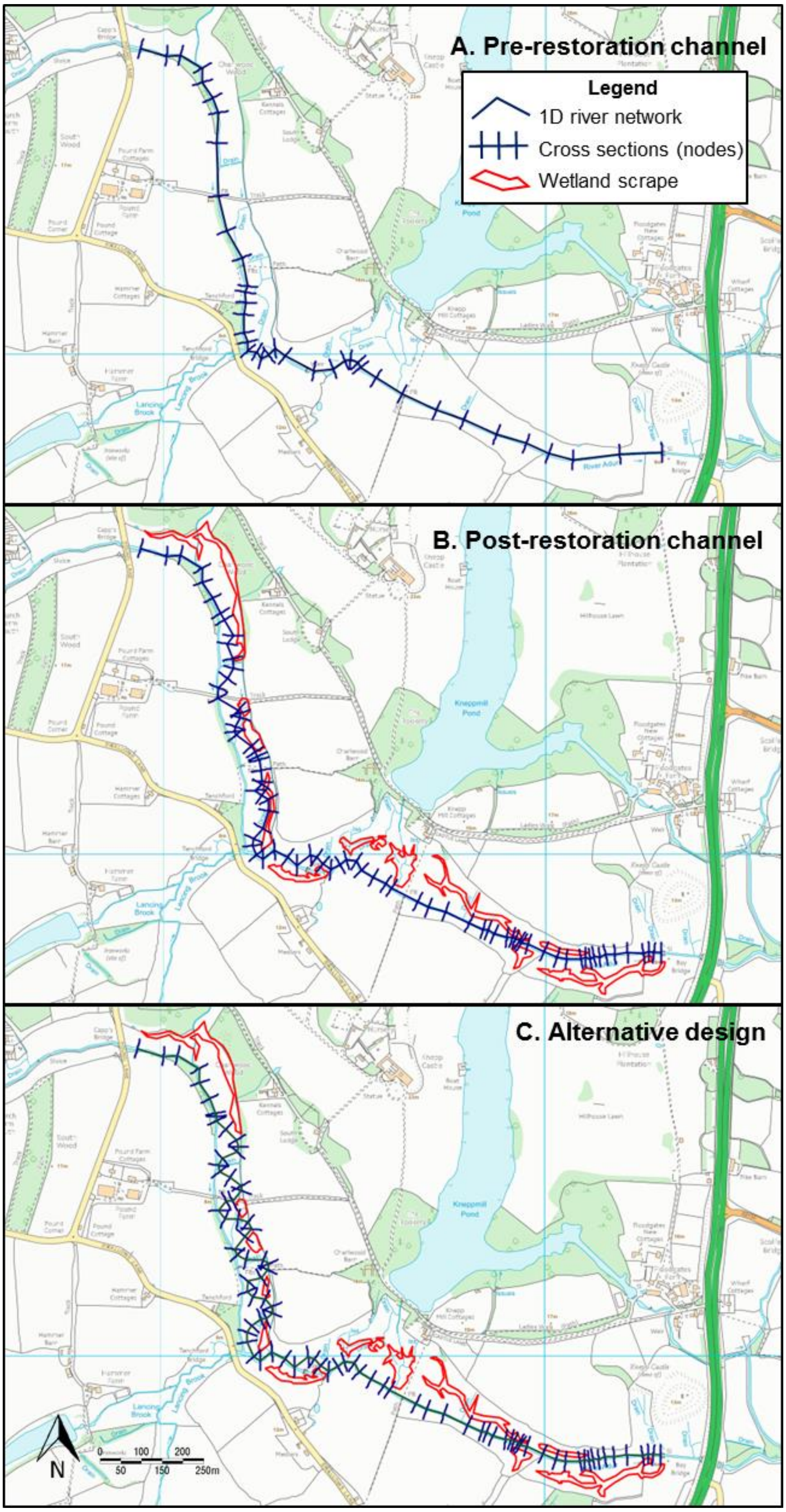

Figure 8. 1D river networks for the three channel designs. Elevation in the digital terrain model was reduced by 0.5 m at the wetland scrapes which are based on the restoration design by Royal HaskoningDHV. Scale: 1:10,000. Source: © Crown Copyright and Database Right 2015. Ordnance Survey (Digimap Licence).

(W_b=12.4 m, D_b=2.3 m) (see Figure 9). (It is not known what methods were used by Haskoning to calculate cross-sectional dimensions.) The topography was manually entered for each 16 m wide section, based on a floodplain elevation derived from the highest DTM value at each section; each section was subsequently extended to 56 m based on the DTM. Like Channel A, slope was based on Royal HaskoningDHV's plans, which was lower in the upper reach (0.0012) due to raised bed elevation (∂z=1.23 m), whilst bed levels and thus slope (0.0004) were unchanged downstream where limited planform modification occurred.

Channel C. Alterative design

Using the same methods as the previous two channels, an alternative restoration design was modelled with a new meandering planform in the upper reach, whilst a shallower cross-sectional profile relative to Channel B was applied to the entire network (see Figure 9). Channel dimensions were predicted using equations from in the literature to compare its impact on flood risk and habitat suitability with the actual carbon copy restoration design. Since the Adur is a clay-bed river with relatively cohesive bed and banks, the most appropriate method for predicting hydraulic geometry are empirical equations based on data sets for sand bed rivers, since they adjust much more slowly than gravel bed channels. An 'alignment-first' approach was taken, as outlined by Shields (1996), where planform (meander wavelength and amplitude) is computed based on channel width. This was preferred to a 'slope-first' approach, where bed slope is calculated using hydraulic geometry formulae from which meander arc length is subsequent predicted, since the coefficients in regime slope are considered to be less accurate than for width or depth (ibid.)

Cross-sections

Firstly, bankfull depth and mean width (W_m) were computed using regime equations published by Simons and Albertson (1960) based on canal studies in India and the United States (n=22) and subsequently modified by Henderson (1966), as summarised in Soar and Thorne's (2001) *Channel Restoration Design for Meandering Rivers*. These are presented in

Table 6 alongside equations from other datasets for comparison. Equations [4] and [5] were selected since the study reach was classified as having 'cohesive bed and banks' given the high clay content observed in the channel during a site visit.

$$D_b = 3.59\ Q_b^{0.36} \qquad [4]$$

$$W_m = 0.49\ Q_b^{0.50} \qquad [5]$$

Based on a bankfull flow (Q_b) of 3.25 m^3s^{-1} estimated by Royal HaskoningDHV (2010) in their modelling report for the Environment Agency, D_b and W_m were computed as 0.75 m and 6.47 m respectively; consistent with Channel B, a low flow channel was added with an additional depth of 0.5 m. Bankfull width (W_b) was estimated by multiplying W_m by the ratio

Table 6. Selected regime equations for predicting channel width and depth at a range of river types

Source / channel type	Bankfull depth, D_b	Mean width, W_m	Bankfull width, W_b
Simons and Albertson (1960) after Henderson (1966)[1]			
Sand bed and banks	5.71 $Q_b^{0.36}$	0.69 $Q_b^{0.50}$	-
Sand bed and cohesive banks	4.24 $Q_b^{0.36}$	0.58 $Q_b^{0.50}$	-
Cohesive bed and banks	3.59 $Q_b^{0.36}$	0.49 $Q_b^{0.50}$	-
Coarse non-cohesive material	2.85 $Q_b^{0.36}$	0.31 $Q_b^{0.50}$	-
Soar and Thorne (2001) [2]			
Sand-bed rivers with <50% tree cover on banks (discharge exponent of 0.51)	-	-	4.88 $Q_b^{0.51}$
Sand-bed rivers with <50% tree cover on banks (discharge exponent fixed at 0.50)	-	-	5.19 $Q_b^{0.50}$
Hey and Thorne (1986)[3]			
Gravel-bed rivers with 0% trees and shrubs on banks	-	-	*4.33* $Q_b^{0.5}$

Notes: [1] Simons and Albertson's (1960) equations based on 22 canal studies in India and the United States are presented in Soar and Thorne (2001: 66), [2] the equations developed by Soar and Thorne (2001: 248) are based on a dataset of 58 sand bed sites in the United States, [3] Hey and Thorne's (1986) equations were presented by Hey (1997).

Table 7. Ratios used to compute bankfull width (W_b) and width of the low flow channel (W_{lf}) for Channel C, based on channel geometry in the Royal HaskoningDHV design plans used for Channel B. W_m is the mean channel width and W_{ch} is the width of the channel bed.

	Upper reach	Lower reach	Mean
W_m:W_b	0.783	0.722	0.753
W_{ch}:W_b	0.567	0.444	0.505
W_{lf}:W_b	0.167	0.121	0.144

calculating the mean of W_b and the width of the channel bed (W_{ch}). Similarly, the width of the low flow channel (W_{lf}) was calculated by multiplying the W_b for Channel C by the W_{lf}:W_b ratio in the Royal HaskoningDHV design. Based on the ratios presented in Table 7, the following dimensions were calculated for Channel C: W_b=8.60 m, W_{ch}=4.34 m , W_{lf}=1.24 m (see Figure 9). W_b is comparable to the lower range of bankfull widths computed with Soar and Thorne's (2001) equations for channels with <50% bankside tree cover (8.90-9.36 m); however, the latter were not used since the authors do not present equations for D_b, thus, Simons and Albertson's (1960) methods were preferred to enable a consistent methodology for computing bankfull depth and width. These new 24 m wide cross sections were applied to the 90 nodes comprising the 1D network and widened to 56 m based on the DTM, with the exception of the first six nodes which, for consistency, were replicated from Channel A.

Planform

A new meandering planform was computed using hydraulic geometry relationships for meander wavelength (L_w) and radius of curvature (R_c) (Figure 10). Studies have shown that L_w can be expressed as a power function of channel width, however, this relationship can differ according to region and river type (Soar and Thorne, 2001) and a selection of these are presented in Table 8. This study used equations developed by Soar and Thorne (2001) since their coefficients are based on relationships derived from a linear regression of a composite dataset of 438 sites from 9 studies, primarily in North America, but also including UK

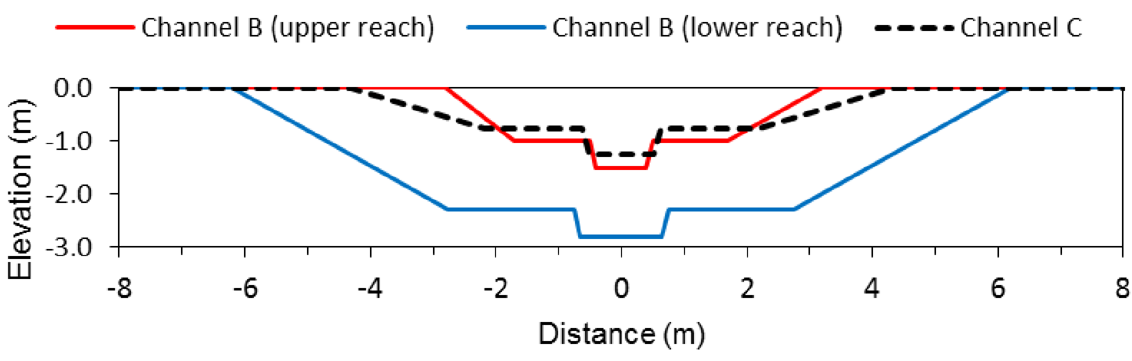

Figure 9. River cross-sections used for nodes in the 1D networks for the two restoration designs (floodplain elevation=0.0 m). Dimensions for Channel B are based on typical river sections according to Royal HaskoningDHV's design plans.

European and Asian rivers. In addition to encompassing a range of river types and environments, this approach has the advantage that the relationship was derived from logarithmic transformed data to normalise the error variance; thus, meander wavelength can be expressed as:

$$L_w = F\ a\ W_b \qquad [6]$$

where a is the coefficient and F is a correction factor to account for bias resulting from logarithmic transformation. The bias-corrected relationship between meander wavelength and bankfull width by Soar and Thorne (2001) is expressed in equation [7]; the 95% confidence limits in equation [8] were used to compute L_w in the range of 96.8-107.2 m. Thus, the meander wavelength of Channel C was derived from the mean (102.0 m).

$$L_w = 1.158 * 10.23 * W_b \qquad [7]$$

$$L_w = (11.26 \text{ to } 12.47)\ W_b \qquad [8]$$

Table 8 indicates that these values fell within a similar range to those computed from equations derived from other studies, such as Carlston (1965) (108.4 m) and Leopold and Wolman’s (1960) seminal work (96.7 m).

The radius of curvature was also based on relationships defined by Soar and Thorne (2001) (see Table 8). The mean of the 95% confidence intervals (20.4 m) was used to design the meanders. This new meandering planform was only applied to the River Adur upstream of Lancing Brook, since only this reach experienced significant planform modification in the actual restoration scheme; thus, the planform and number of nodes in the lower reach were identical to Channel B. In the upper reach, the new channel was 275 m longer than Channel B, representing the highest sinuosity of the three channels (upper reach=1.54, overall=1.28) (Table 6). The slope of 0.00092 (upper reach) was calculated based on the same change in elevation as Channel B divided by the new channel length; slope was identical to Channel B in the lower reach since planform remained constant.

Flood hydrographs

For each 1D network, an upstream Flow-Time Boundary was used to model a hydrograph. Downstream, a Normal Depth Boundary generated flow-head relationships (CH2M HILL, 2015) where slope was inputted according to the values in Table 5. Each network was replicated with four different 37 hour hydrographs, representing a 1 in 2 year flood (peak flow

Table 8. Equations used for predicting planform for Channel C.

Source	Equation	Result (m)
Meander wavelength, L_w		
Soar and Thorne (2001): upper confidence limit (95%)	$12.47\ W_b$	107.2
Soar and Thorne (2001): lower confidence limit (95%)	$11.26\ W_b$	96.8
		Mean = 102.0
Carlston (1965)	$12.6\ W_b$	108.4
Leopold and Wolman (1960)	$11.0\ W_b^{1.01}$	96.7
		Mean = 102.5
Radius of curvature, R_c		
Soar and Thorne (2001): upper confidence limit (95%)	$2.49\ W_b$	19.4
Soar and Thorne (2001): lower confidence limit (95%)	$2.25\ W_b$	21.4
		Mean = 20.4

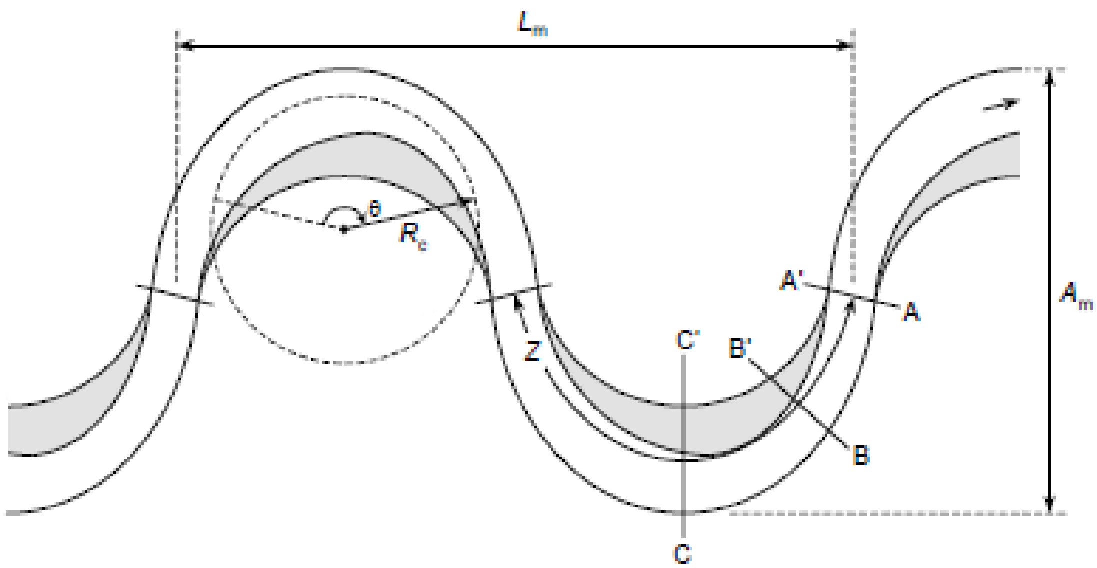

Figure 10. Meander planform dimensions used in restoration design. L_m = meander wavelength, R_c = radius of curvature, Z = meander arc length, A_m = meander belt width, θ = meander arc angle. Reproduced from Soar and Thorne (2001).

flow=13.5 m^3s^{-1}), 1 in 5 year flood (peak flow=20.1 m^3s^{-1}), 1 in 10 year flood (peak flow=25.3 m^3s^{-1}) and 1 in 100 year flood (peak flow=45.2 m^3s^{-1}) at the upstream end of the site. The hydrographs were obtained from the River Restoration Centre who generated them with the Flood Estimation Handbook (FEH) method for a pre-restoration feasibility report (Janes et al., 2006); the flow time series for each hydrograph are presented in Appendix II.

Channel roughness

A global channel roughness of n=0.045 (Manning's coefficient) was applied to sections in each of the 1D networks, representing a winding stream with some weeds and stones (Chow, 1959). Based on a field survey conducted on 2 August 2015, channel roughness in the restored sections of the river was estimated at 0.045, with a value of 0.07 for the unrestored sections, since it matched Chow's (ibid.) description of 'sluggish' reaches with deep, weedy pools. However, a global channel roughness of 0.045 was applied to each 1D network since initial linked 1D-2D simulations with variable channel roughness generated flood extents and volumes which were greater for Channel A than Channel B. This was inconsistent with both the expected result and the findings of hydraulic modelling conducted by Royal Haskoning (2010) for the Environment Agency; it is therefore hypothesised that the unexpectedly high flooding under Channel A was due to higher roughness and, therefore, flow resistance.

2D model components

The following components were inputted into the 2D model: active area, floodplain roughness grid (both constant, see Figure 11), and a Digital Terrain Model (DTM) which varied according to channel design (see Appendix III). The roughness grid simulated variable land use and was produced in ArcMap 10.2.2, based on land use from OS Vectormap and Aerial Photography. A DTM was generated for each design by modifying LIDAR data to create new channels or fill in the existing ones, as well as creating a backwater zone in the upper reach (Channels B and C only); this was done using the Rasteredit[1] application to interpolate new elevation values based on surrounding cells (e.g. the adjacent channel or floodplain). Once the channel planform had been created, wetland scrapes constituting ~10% of the floodplain were simulated by reducing the DTM elevation by 0.5 m for Channels B and C following plans obtained from Royal HaskoningDHV (Figure 8). This was achieved by converting polygons of the scrapes to a grid in ArcMap, then using map algebra to subtract 0.5 m from the DTM elevation; some scrapes were modified for Channel C due to overlap with the river, covering a slightly smaller area (34,337 m^2) than Channel B (36,965 m^2).

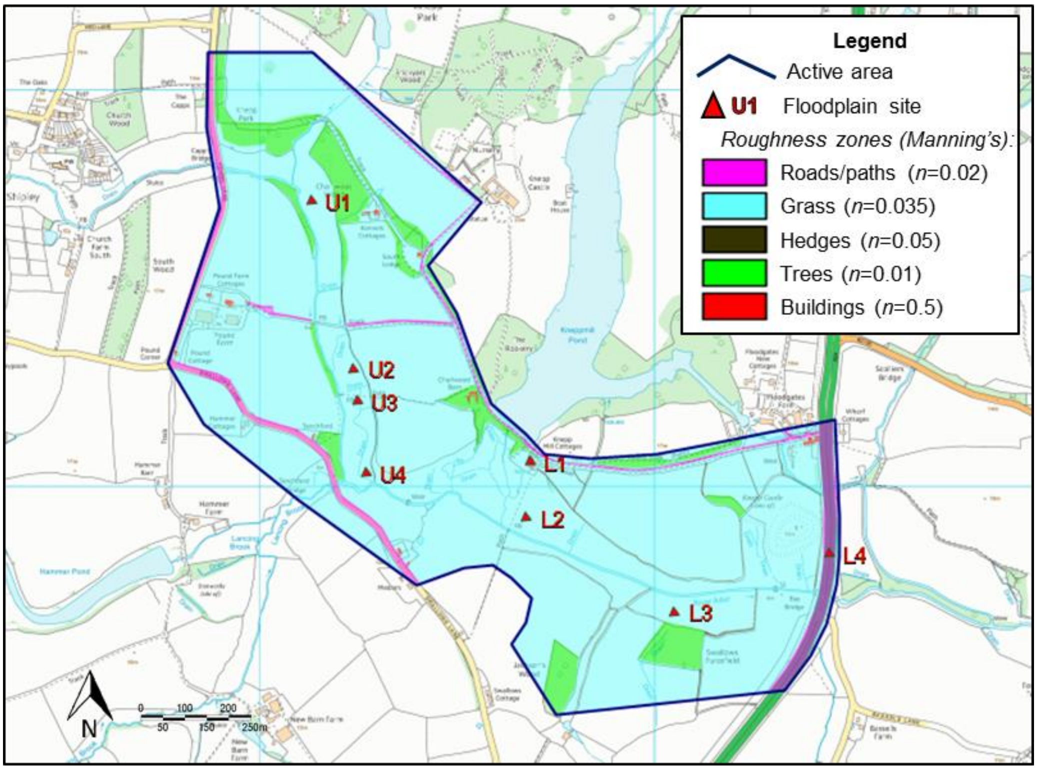

Figure 11. Map of the River Adur restoration site showing variable floodplain roughness and the active area used in 2D models. Scale: 1:10,000. © Crown Copyright and Database Right (2015) Ordnance Survey (Digimap Licence).

[1] Rasteredit software can be downloaded for free at: www.coulthard.org.uk/downloads/downloads.htm [Accessed 12.07.2015]

Running the simulations

The following procedure was then used to model floodplain inundation: (A) run a steady (direct) 1D simulation based on the 1D river network, (B) run an unsteady (fixed timestep) 1D simulation using the initial conditions file generated by the steady run (containing flow, stage, velocity and Froude number for each node), (C) run a linked 1D-2D simulation. This was repeated for each channel under each of the four hydrographs.

The steady 1D simulations used the direct method since, unlike the alternative pseudo-timestepping method, they do not require initial conditions for flow and stage; as well as being faster and more accurate, it adds extra interpolated nodes automatically and advises where additional nodes should be added to the network (CH2M HILL, 2015). Flood Modeller automatically based steady flows on the initial discharge of each hydrograph (0.85 m^3s^{-1}). The 1D and 2D models were coupled using the event file from the 1D unsteady run, as well as 'Level' Link Lines. The latter enable water levels from the unsteady 1D simulation to be passed to the 2D model where they become a boundary condition, thus, dynamically linking the two models so that overbank flows in the 1D network are transferred to the 2D floodplain as boundary conditions (CH2M HILL, 2015, Néelz and Pender, 2009). A timestep of 2 seconds was used in the 1D and linked 1D-2D simulations to improve model stability since simulations with larger timesteps either failed or produced highly unstable models with very large depths (e.g. >100 m). All other settings remained at default.

Data analysis

The results of each simulation were exported from Flood Modeller as a time series of the area and volume inundated; raster flood maps of maximum depth and velocity were also used to compute the area and volume of inundation in the upper and lower reaches in ArcMap using the Zonal Statistics tool. Time series of the depth and velocity at each node (instream) and at eight floodplain sites were also exported and analysed in SPSS. The sites shown in Figure 11 were chosen to evaluate the spatial variability of flooding and habitat suitability at a range of locations, including the unmodified floodplain (U1, U3, L2), wetland scrapes (U2, U4, L3), property (L1, Knepp Mill Cottages) and infrastructure (L3, the A24 at Bay Bridge).

The depth and velocity time series were found to violate the assumptions of normality since Kolmogorov-Smirnov tests were significant ($p<0.01$) for all hydrographs and channel designs (Pallant, 2005). For instance, inspection of histograms indicated that the instream velocity data were positively skewed (mean skewness=0.164), which may be partly due to the presence of outliers with high values; instream depth exhibited limited skewness (mean skewness=-0.091), however, they had strong negative kurtosis (mean kurtosis=-0.880) indicated by a relatively broad distribution. Therefore, significant ($p<0.05$) differences between the channel designs were determined by Kruskall-Wallis Tests and post-hoc Mann-Whitney Tests. Since the variability of water depth and velocity are often used as indicators of physical habitat diversity (Nakano and Nakamura, 2008), the interquartile range (IQR) was used to indicate variability as the data were not normally distributed. The IQR is preferable as it is not influenced by outliers, unlike other measures of variability such as standard deviation or range (Whitley and Ball, 2002), which are not effective indicators of spread in skewed data (Bonett, 2006).

RESULTS

Flood area and volume

The time series of the area inundated and volume of flood water simulated by the hydraulic model are illustrated in **Figure 12** and Figure 13 respectively. According to the model runs, a ~4% larger area was inundated in the restored channels (B and C) compared to the straightened pre-restoration channel (A) under the 1 in 2 year flood simulation, however, these differences diminished as the flood discharge increased (e.g. 1 in 10 year: 0.8-1.0% larger flood extent, 1 in 100 year: 2.0-2.3% higher) (see Table 9). The similarity in the area inundated is also visualised in the flood maps for the largest (Figure 14) and smallest (Figure 15) flood discharges. Whilst the time series were broadly similar for both restoration designs, a 5.4-7.2% larger area remained inundated under the geomorphic channel design (C) after the

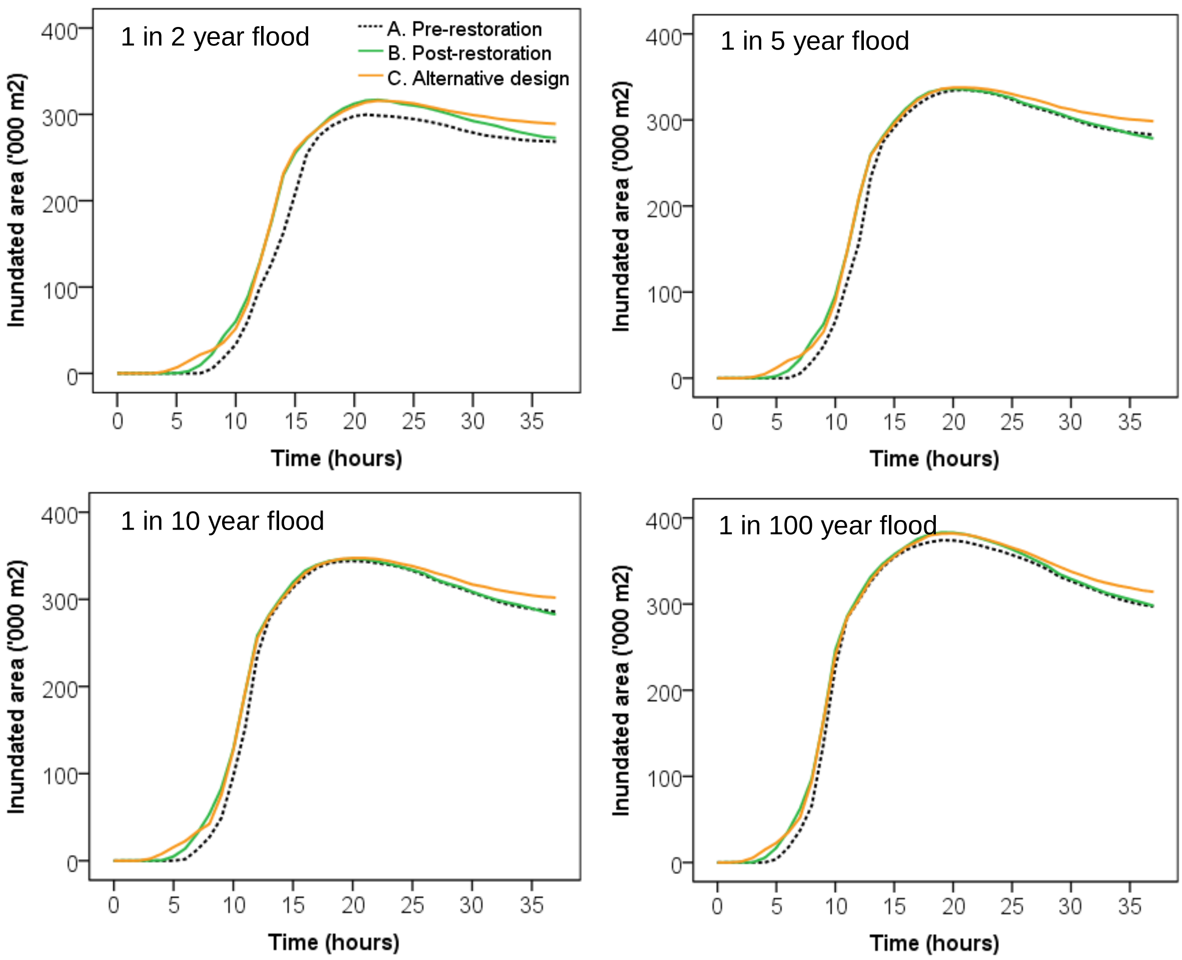

Figure 12. Time series of the total area inundated during linked 1D-2D flood simulations comparing different channel designs.

flood peak compared to the actual restoration design (B), which fell to levels close to Channel A; this trend was not observed for volume. In contrast, much larger differences in the volume of water were observed, with higher maximum volumes observed in the two restoration designs across all flood discharges (Figure 13). In common with the area inundated, the difference in water volume between the channels diminished as discharge increased: 1 in 2 year (20.4-24.9% higher in channels B and C), 1 in 100 year (8.8-10.6% higher in Channels B and C) (see Table 9).

For each design, the majority of the total flood volume (78-87%) was simulated in the lower reach, whilst mean depths were also higher downstream (Table 9). As discharge increased, the proportion of the total volume in the upper reach also increased under each design. Spatial variation in the maximum water volume was also observed between channels:

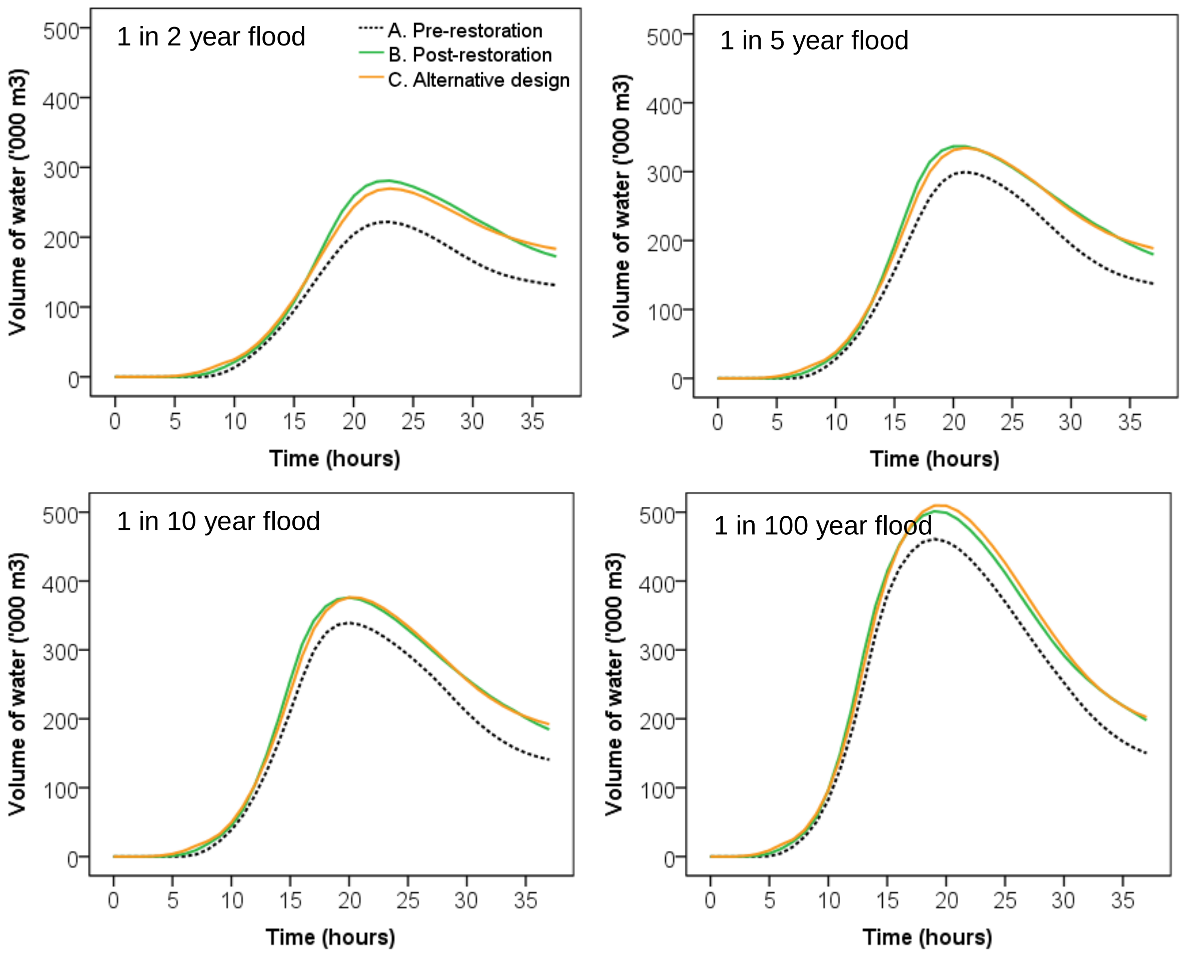

Figure 13. Time series of the total volume of water inundated during linked 1D-2D flood simulations comparing different channel designs.

upper reach (C>B>A), lower reach (B>C>A). These patterns were consistent across all return periods, although the differences between the channels diminished with increasing discharge.

Mean depths were higher in both restoration designs by 6.4-8.2% (1 in 2 year flood) to 13.9-17.7% (1 in 100 year flood) compared to the straightened channel. Table 9 shows that mean depths in the upper reach (including the channel and floodplain) were higher in Channel C than Channel B, whilst the opposite was true downstream; it was not possible to determine whether the variation in mean depths was statistically significant since values were generated by ArcMap (Zonal Statistics tool), thus the depth for each cell was not available.

Table 9. Area inundated and volume of flood water at maximum flood extents at the River Adur simulated in Flood Modeller. Depths are presented as mean ± standard deviation.

	A. Pre-restoration channel			**B. Post-restoration channel**			**C. Alternative design**		
	Upper reach	**Lower reach**	**Total**	**Upper reach**	**Lower reach**	**Total**	**Upper reach**	**Lower reach**	**Total**
				1 in 2 year flood					
Area (m^2)	-	-	306,750	-	-	319,800	-	-	319,425
Volume (m^3)	28,871	199,346	228,217	44,360	240,598	284,958	48,736	226,071	274,807
Mean depth (m)	0.36±0.41	1.01±0.55	0.83±0.59	0.50±0.42	1.17±0.59	0.97±0.63	0.54±0.53	1.12±0.58	0.94±0.63
				1 in 5 year flood					
Area (m^2)	-	-	336,150	-	-	337,100	-	-	339,350
Volume (m^3)	48,071	255,771	303,842	58,593	282,338	340,931	64,307	274,104	338,411
Mean depth (m)	0.47±0.42	1.23±0.59	0.98±0.65	0.58±0.45	1.33±0.63	1.09±0.67	0.62±0.54	1.30±0.62	1.08±0.68
				1 in 10 year flood					
Area (m^2)	-	-	344,350	-	-	347,050	-	-	347,950
Volume (m^3)	58,660	283,595	342,256	69,143	309,837	378,981	75,352	304,272	379,624
Mean depth (m)	0.55±0.43	1.33±0.62	1.07±0.67	0.65±0.46	1.43±0.65	1.17±0.70	0.69±0.56	1.41±0.65	1.17±0.71
				1 in 100 year flood					
Area (m^2)	-	-	374,750	-	-	383,450	-	-	382,100
Volume (m^3)	92,192	371,597	463,789	105,321	399,382	504,703	112,980	399,796	512,776
Mean depth (m)	0.78±0.48	1.61±0.72	1.33±0.76	0.87±0.53	1.68±0.76	1.41±0.79	0.94±0.61	1.69±0.76	1.44±0.80

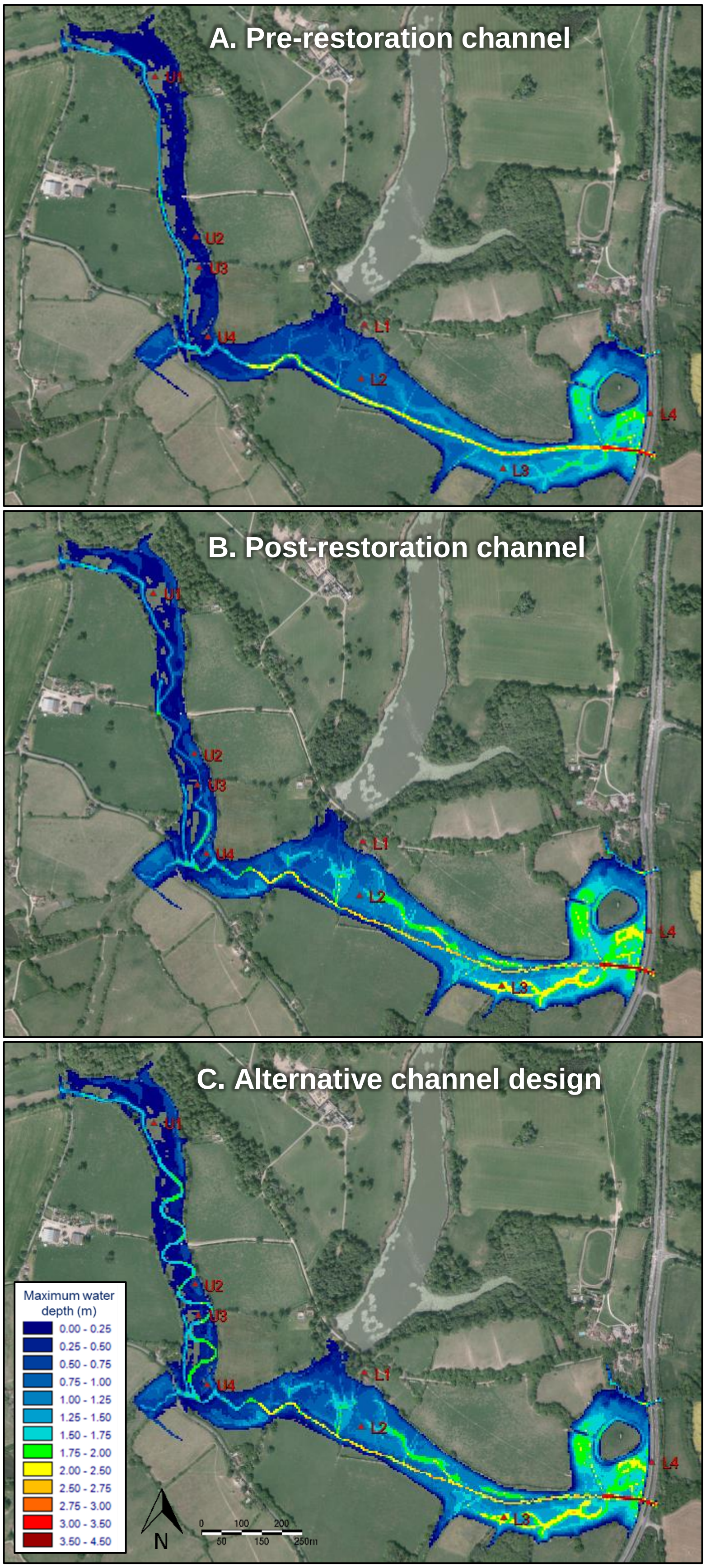

Figure 14. Comparison of maximum water depths simulated for different channel designs during a 1 in 2 year flood event at the River Adur. Scale: 1:10,000. © Crown Copyright and Database Right (2015) Ordnance Survey.

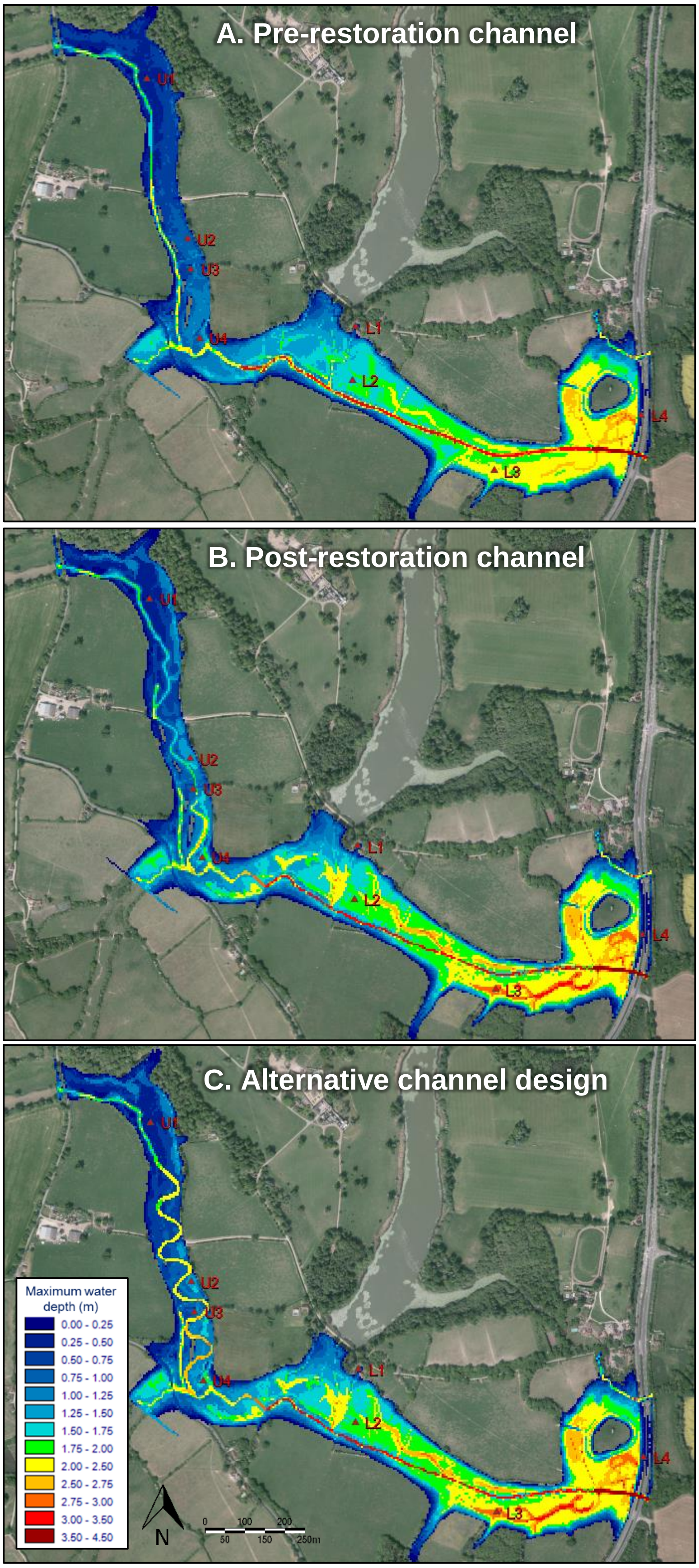

Figure 15. Comparison of maximum water depths simulated for different channel designs during a 1 in 100 year flood event at the River Adur. Scale: 1:10,000. © Crown Copyright and Database Right (2015) Ordnance Survey.

Instream depth and velocity

Instream depth

Figure 16 illustrates that the carbon copy planform (B) had significantly ($p<0.001$) higher median instream depths than the original (A) and geomorphic design (C) across all flood events, according to the hydraulic model. For the lowest discharge (1 in 2 year), the alternative design also had significantly ($p<0.001$) higher depths than the straightened channel. These trends were observed in both reaches, but the differences in depth between the designs were amplified in the upper reach.

Table 10 shows that, upstream of Lancing Brook, depth was most variable for Channel A across the 4 flood events (interquartile range (IQR)=0.54-0.92 m), with similar results for Channel C (IQR=0.52-0.77 m) and Channel B (IQR=0.51-0.75 m). In the lower reach, IQR was 26.8-30.5% higher in Channel B (0.52-0.98 m) compared to C (0.47-0.78 m) for all but the smallest flood event (6.5% lower).

Instream velocity

In the upper reach, median instream velocities were significantly ($p<0.001$) higher in the straightened channel compared to the two restoration designs, as follows: A>B>C; (1 in 2 year flood: A>C>B) (Figure 17). Downstream, significant differences were observed (A,B>C, $p<0.001$) for all flood events, except for the 1 in 2 year flood where: B>A>C ($p<0.05$). In common with instream depth, the differences in velocity between the three channel designs were of a smaller magnitude in the lower reach than upstream. In the lower reach, median velocities were not significantly different, apart from the 1 in 2 year flood. Trends for the variability of instream velocity were clearer than for depth, as follows: A>B>C (except for the lower reach, 1 in 100 flood: A>C>B). IQR was 4.1-27.9% higher upstream in Channel B (0.21-0.23 m) than Channel C (0.17-0.21), and 23.7-39.8% higher downstream (Channel B=0.17-0.19 m, Channel C=0.12-0.16 m, excluding the 1 in 100 year flood).

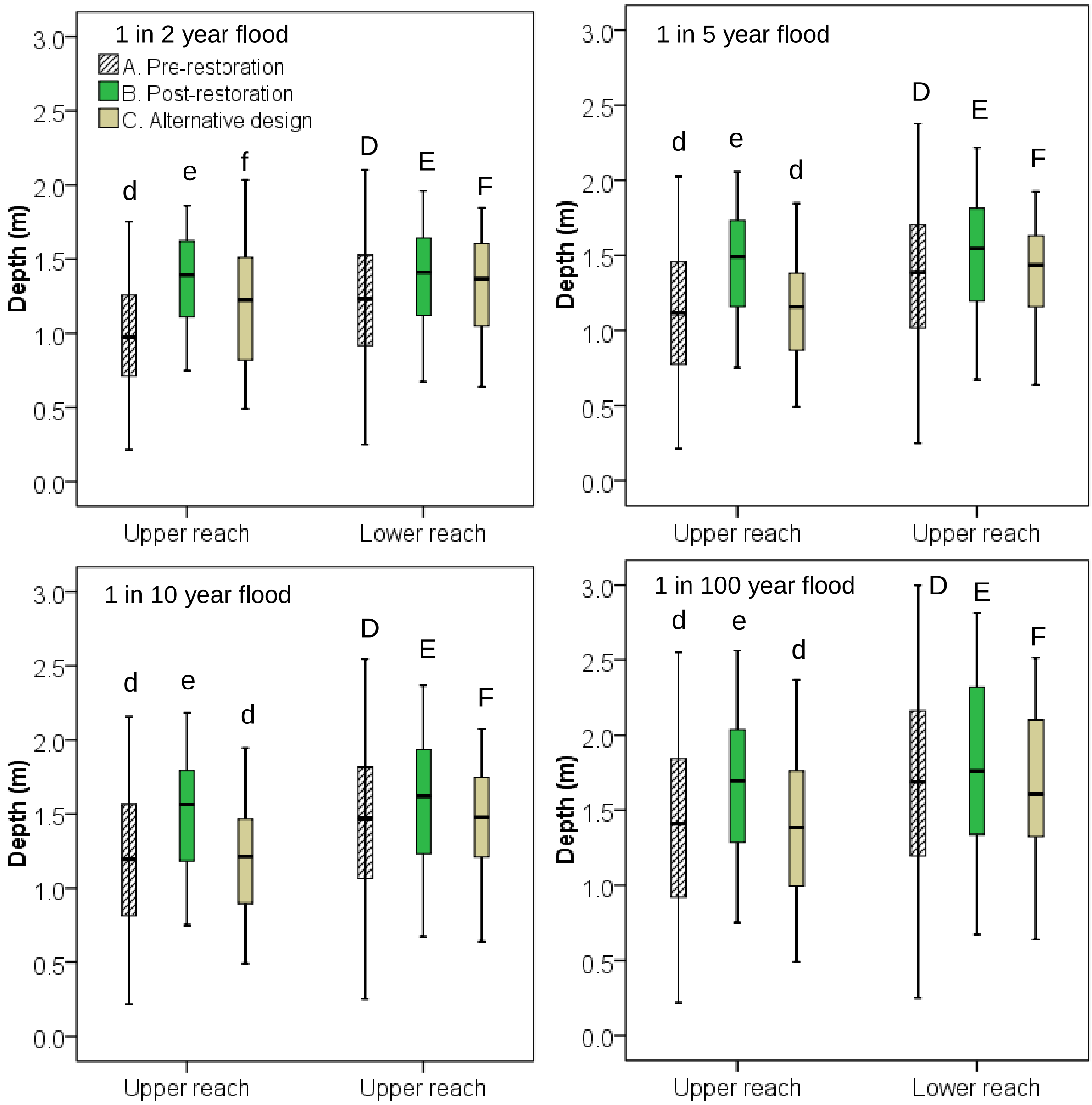

Figure 16. Comparison of instream depth for different channel designs at the River Adur. Values are based on the time series of water depth at all nodes in 1D river networks during 2D flood simulations. Boxes represent the 25th and 75th percentiles with the median identified by a line; error bars show the minimum and maximum. Significant differences (Mann-Whitney Test, $p<0.001$) between the channel designs are indicated by different letters with the upper (upper case) and lower reaches (lower case) considered separately.

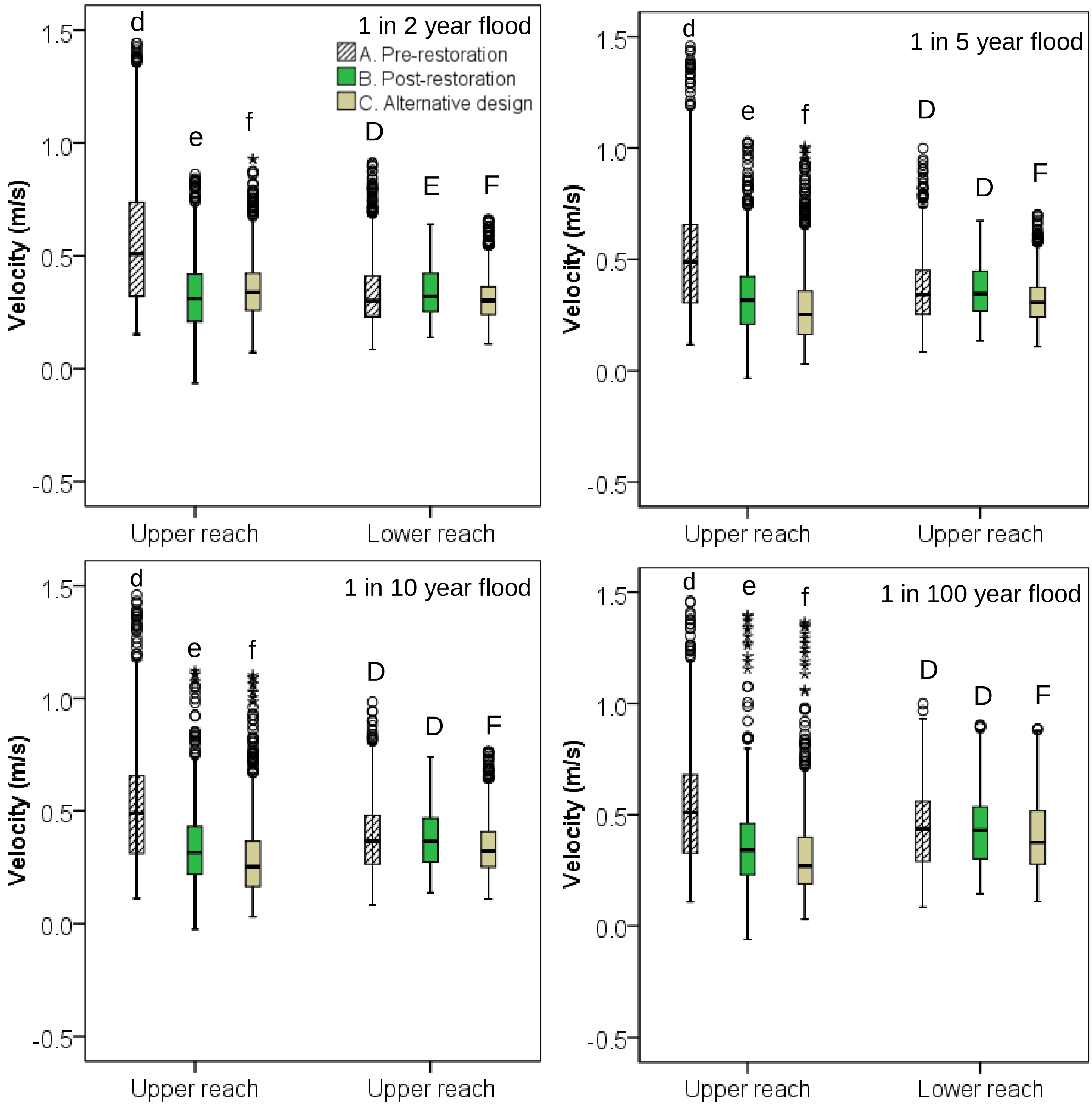

Figure 17. Comparison of instream velocity for different channel designs at the River Adur. Values are based on the time series of water velocity at all nodes in 1D river networks during 2D flood simulations. Boxes represent the 25th and 75th percentiles with the median identified by a line; error bars show the minimum and maximum. Significant differences (Mann-Whitney Test, $p<0.05$) between the channel designs are indicated by different letters with the upper (upper case) and lower reaches (lower case) considered separately. Values over 1.5 box lengths from the edge of the box are labelled as outliers (o) and extreme values more than three box lengths from the edge of the box are indicated by an asterisk (*).

Table 10. Median, interquartile range (IQR) and range of instream water depths (m). Values are based on the time series of water velocity at all nodes in 1D river networks during 2D flood simulations.

		1 in 2 year flood			1 in 5 year flood			1 in 10 year flood			1 in 100 year flood		
	n	**Median**	**IQR**	**Range**	**Median**	**IQR**	**Range**	**Median**	**IQR**	**Range**	**Median**	**IQR**	**Range**
	4,104						**Upper reach**						
A. Pre-restoration	1,026	0.97	0.54	1.54	1.12	0.68	1.81	1.20	0.75	1.94	1.41	0.92	2.34
B. Post-restoration	1,330	1.39	0.51	1.11	1.49	0.58	1.31	1.56	0.61	1.43	1.70	0.75	1.82
C. Alternative design	1,748	1.22	0.70	1.54	1.16	0.52	1.36	1.21	0.57	1.46	1.39	0.77	1.88
	4,218						**Lower reach**						
A. Pre-restoration	874	1.23	0.61	1.85	1.39	0.69	2.13	1.47	0.75	2.30	1.69	0.97	2.75
B. Post-restoration	1,672	1.41	0.52	1.29	1.55	0.61	1.55	1.62	0.70	1.70	1.76	0.98	2.14
C. Alternative design	1,672	1.37	0.56	1.21	1.44	0.47	1.29	1.48	0.54	1.43	1.61	0.78	1.88

Table 11. Median, interquartile range (IQR) and range of instream water velocities (ms^{-1}). Values are based on the time series of water velocity at all nodes in 1D river networks during 2D flood simulations.

		1 in 2 year flood			1 in 5 year flood			1 in 10 year flood			1 in 100 year flood		
	n	**Median**	**IQR**	**Range**	**Median**	**IQR**	**Range**	**Median**	**IQR**	**Range**	**Median**	**IQR**	**Range**
	4,104						**Upper reach**						
A. Pre-restoration	1,026	0.51	0.42	1.29	0.49	0.35	1.34	0.49	0.35	1.35	0.51	0.35	1.35
B. Post-restoration	1,330	0.31	0.21	0.92	0.32	0.21	1.06	0.32	0.21	1.15	0.34	0.23	1.46
C. Alternative design	1,748	0.34	0.17	0.86	0.25	0.20	0.98	0.25	0.20	1.07	0.27	0.21	1.34
	4,218						**Lower reach**						
A. Pre-restoration	874	0.30	0.18	0.83	0.34	0.20	0.92	0.37	0.22	0.90	0.44	0.27	0.91
B. Post-restoration	1,672	0.32	0.17	0.50	0.35	0.18	0.54	0.37	0.19	0.60	0.43	0.23	0.76
C. Alternative design	1,672	0.30	0.12	0.55	0.31	0.13	0.59	0.32	0.16	0.65	0.38	0.24	0.78

Floodplain depth and velocity

Figure 18 and Figure 19 illustrate that simulated floodplain water depths were highest in the downstream sites (L1-L4), whilst the greatest velocities were seen in the upper floodplain (U1-U4) (Figure 20 and Figure 21). The depth and velocity of water traversing the floodplain were an order of magnitude lower than those simulated within the channel.

Floodplain depth

Figure 18 and Figure 19 indicate that, overall, the depths of water inundating the floodplain at selected locations were higher than the straightened channel. However, these differences were only statistically significant ($p<0.05$) in the wetland scrapes (U2, U4, L3) where floodplain elevation was 0.5 m lower than the pre-restoration DTM (this trend was observed under all hydrographs, with the exception of the 1 in 100 year event at U4). No clear patterns could be observed at the unmodified floodplain sites (U1, U3, L2); significant differences in depth were limited to site U1 (1 in 5 year flood only) where A>B,C ($p<0.05$), as well as U3 (1 in 2 year flood only) where B,C>A ($p<0.001$). Median depth did not vary significantly between the two restoration designs, apart from at Knepp Mill Cottages (L1, 1 in 100 year flood only).

The hydraulic model indicates that property and infrastructure will be inundated during the higher flood hydrographs only. Knepp Mill Cottages (L1) were inundated under the 1 in 100 year event; median depths were very low under all channels, with A and C (median=0.11 m, IQR=0.26-0.36 m) significantly ($p<0.005$) higher than Channel B, where water depth was negligible (median=0.00 m, IQR=0.21 m). For all channels, median depths were lowest (<0.00 m) at the A24 at Bay Bridge (L4), which was only inundated under the 1 in 10 and 1 in 100 year floods. For Channel A, the site was not inundated under the 1 in 10 year flood, thus, depth was significantly ($p<0.05$) higher for the two restored channels despite the low values (maximum depth=0.05-0.07 m). During the 1 in 100 year simulations, median depths were not significantly different between the channels, although maximum depths were higher for the restored designs (Channel B=0.46 m, Channel C=0.47 m) than the straightened channel (0.37 m).

The variability in depth followed a broadly similar pattern to median depth (Figure 18 and Figure 19). At six of the eight sites, the variability in water depth was higher for the two restoration designs than the straightened channel. The differences were most pronounced at the scrapes (U2, U4, L3), with smaller differences at two of the unmodified floodplain sites (U3, L2) and Bay Bridge (L4). Variability was similar (IQR=0.27-0.28 m, 1 in 100 year flood) for all channels at U1, located upstream of the planform modifications. IQR was broadly similar for the two restoration designs, with some minor differences observed, albeit lacking a consistent pattern; at U2 variability was higher for channel C (IQR=0.69-0.79 m) than channel B (IQR=0.43-0.71 m) under all hydrographs.

Floodplain velocity

At the upper floodplain sites, velocities followed a similar pattern to depths. Median water velocity was significantly ($p<0.05$) higher for Channel A at Knepp Mill Cottages (U1) (1 in 5 year flood only), whilst median velocity for the two restoration designs were significantly ($p<0.05$) higher than the straightened channel at site U2 (1 in 2 year flood), U3 (1 in 2 year flood) and U4 (1 in 2, 5 and 10 year floods). Downstream, median velocities were much lower than in the upper reach, but no significant differences were found in velocities between the three channel designs, unlike for water depth.

It is difficult to determine clear trends in the variability of velocity according to channel design at most of the sites (U1, U2, U4, L1 and L4). At one unmodified floodplain site in the upper reach (U3), Channel B delivered the highest IQR, followed by Channels C and A. However, at the unmodified floodplain downstream (L2), IQR was highest for the straightened channel. At the two downstream sites on the middle of the floodplain, IQR was just 0.010-0.022 ms^{-1} for the 1 in 100 year flood, with lots of outliers and extreme values (Figure 21). On the edge of the floodplain (L1, Knepp Mill Cottages and L4, Bay Bridge), limited inundation and therefore negligible velocities were observed (median=0.00 m, IQR=0.00 ms^{-1}).

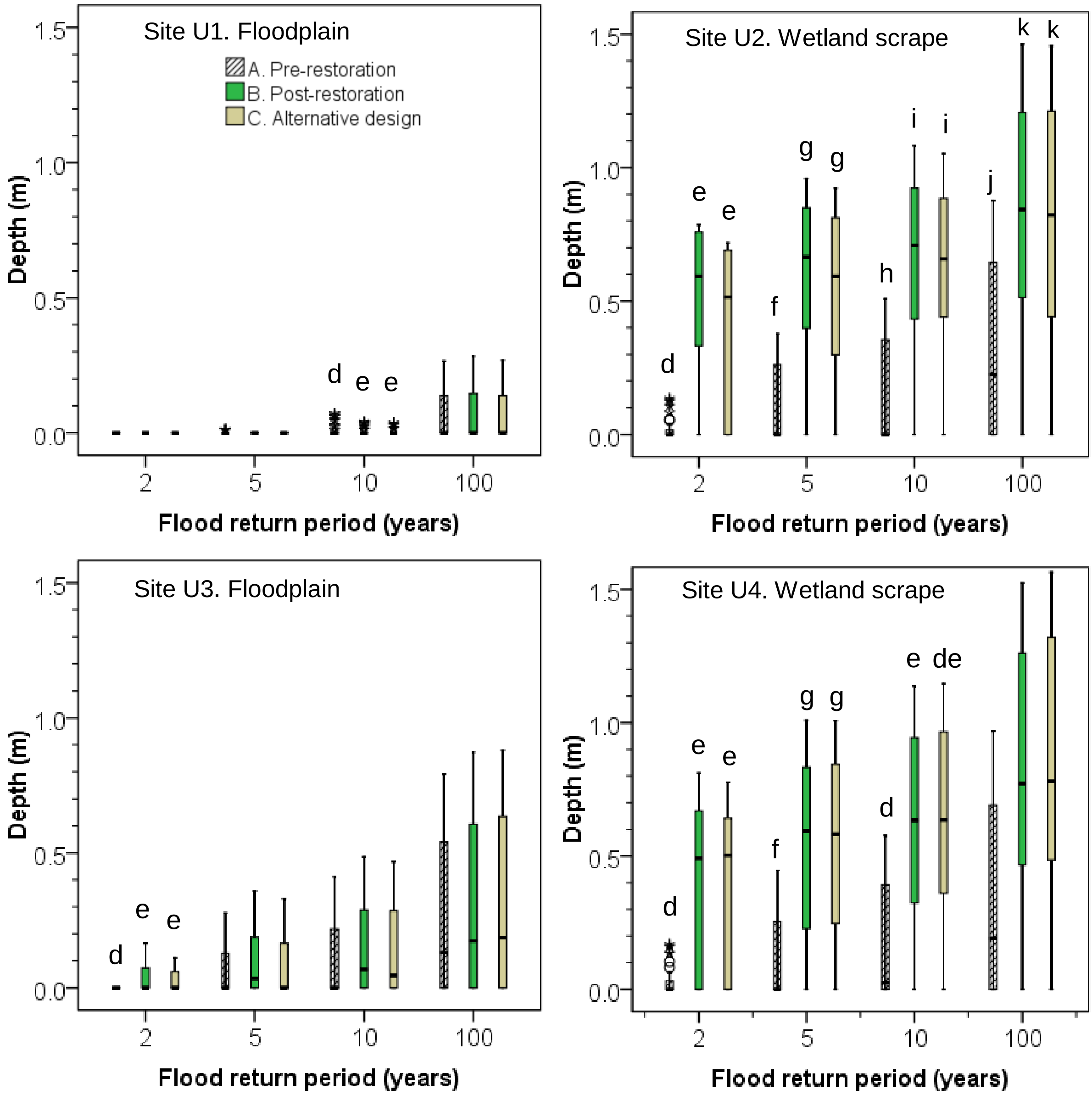

Figure 18. Comparison of water depth at sites on the floodplain (upper reach) for different channel designs at the River Adur. Values are based on the time series of water depth at single cells during 2D flood simulations. Boxes represent the 25th and 75th percentiles with the median identified by a line; error bars show the minimum and maximum. Significant differences (Mann-Whitney Test, $p<0.05$) between the channel designs are indicated by different letters with each flood return period considered separately. Values over 1.5 box lengths from the edge of the box are labelled as outliers (o) and extreme values more than three box lengths from the edge of the box are indicated by an asterisk (*).

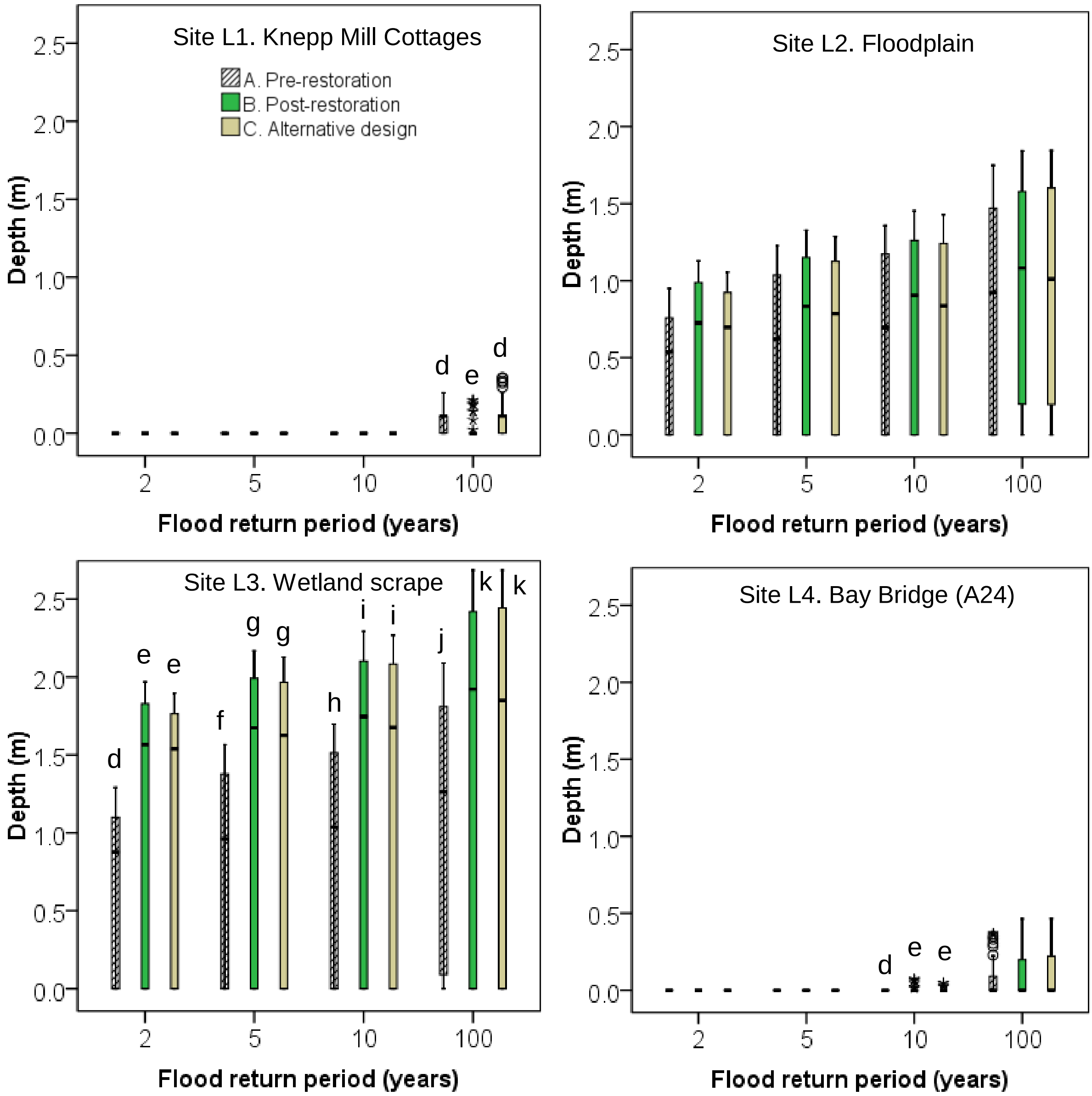

Figure 19. Comparison of water depth at sites on the floodplain (lower reach) for different channel designs at the River Adur. Values are based on the time series of water depth at single cells during 2D flood simulations. Boxes represent the 25th and 75th percentiles with the median identified by a line; error bars show the minimum and maximum. Significant differences (Mann-Whitney Test, $p<0.05$) between the channel designs are indicated by different letters with each flood return period considered separately. Values over 1.5 box lengths from the edge of the box are labelled as outliers (o) and extreme values more than three box lengths from the edge of the box are indicated by an asterisk (*).

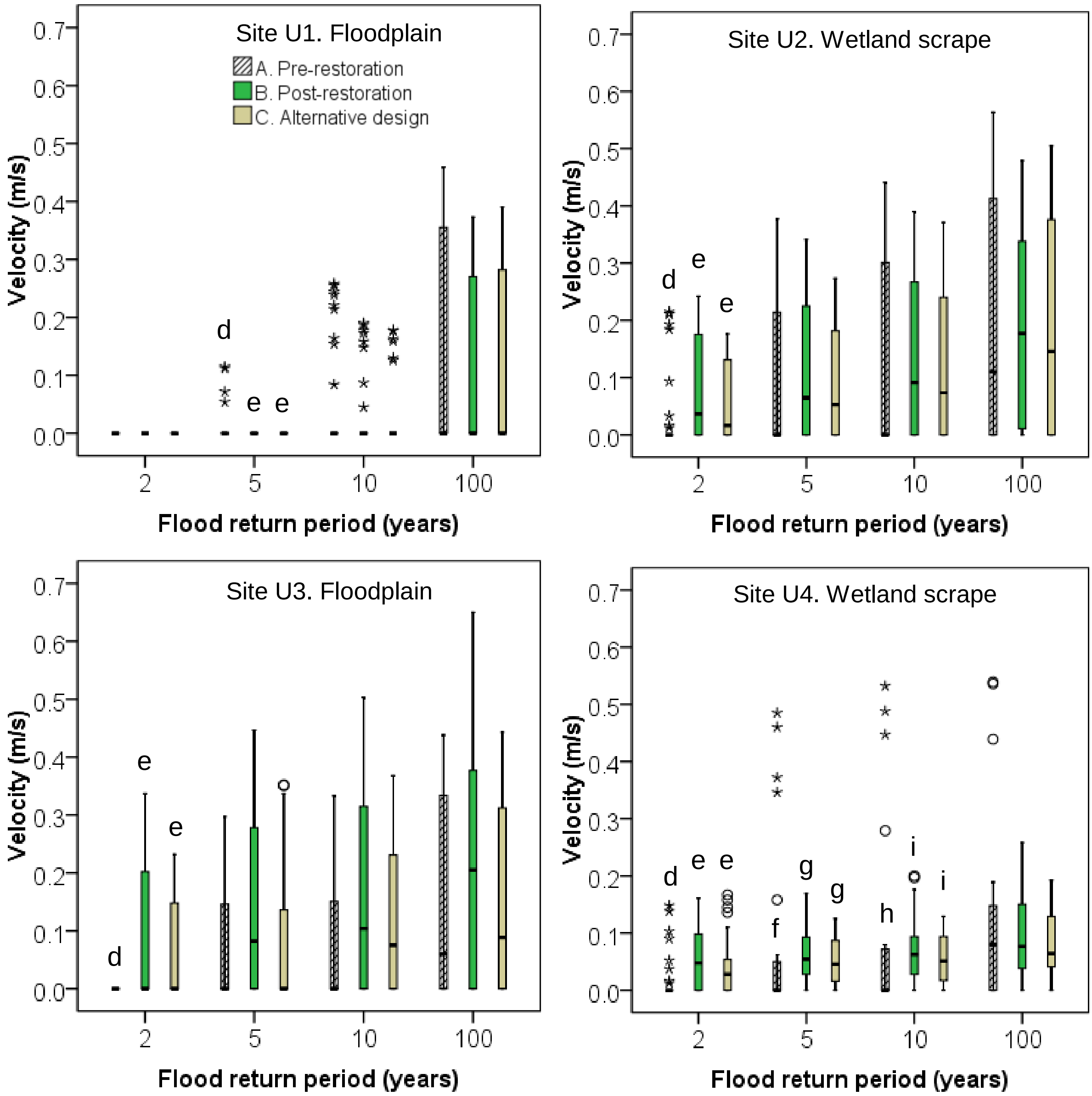

Figure 20. Comparison of water velocity at sites on the floodplain (upper reach) for different channel designs at the River Adur. Values are based on the time series of water depth at single cells during 2D flood simulations. Boxes represent the 25th and 75th percentiles with the median identified by a line; error bars show the minimum and maximum. Significant differences (Mann-Whitney Test, $p<0.05$) between the channel designs are indicated by different letters with each flood return period considered separately. Values over 1.5 box lengths from the edge of the box are labelled as outliers (o) and extreme values more than three box lengths from the edge of the box are indicated by an asterisk (*).

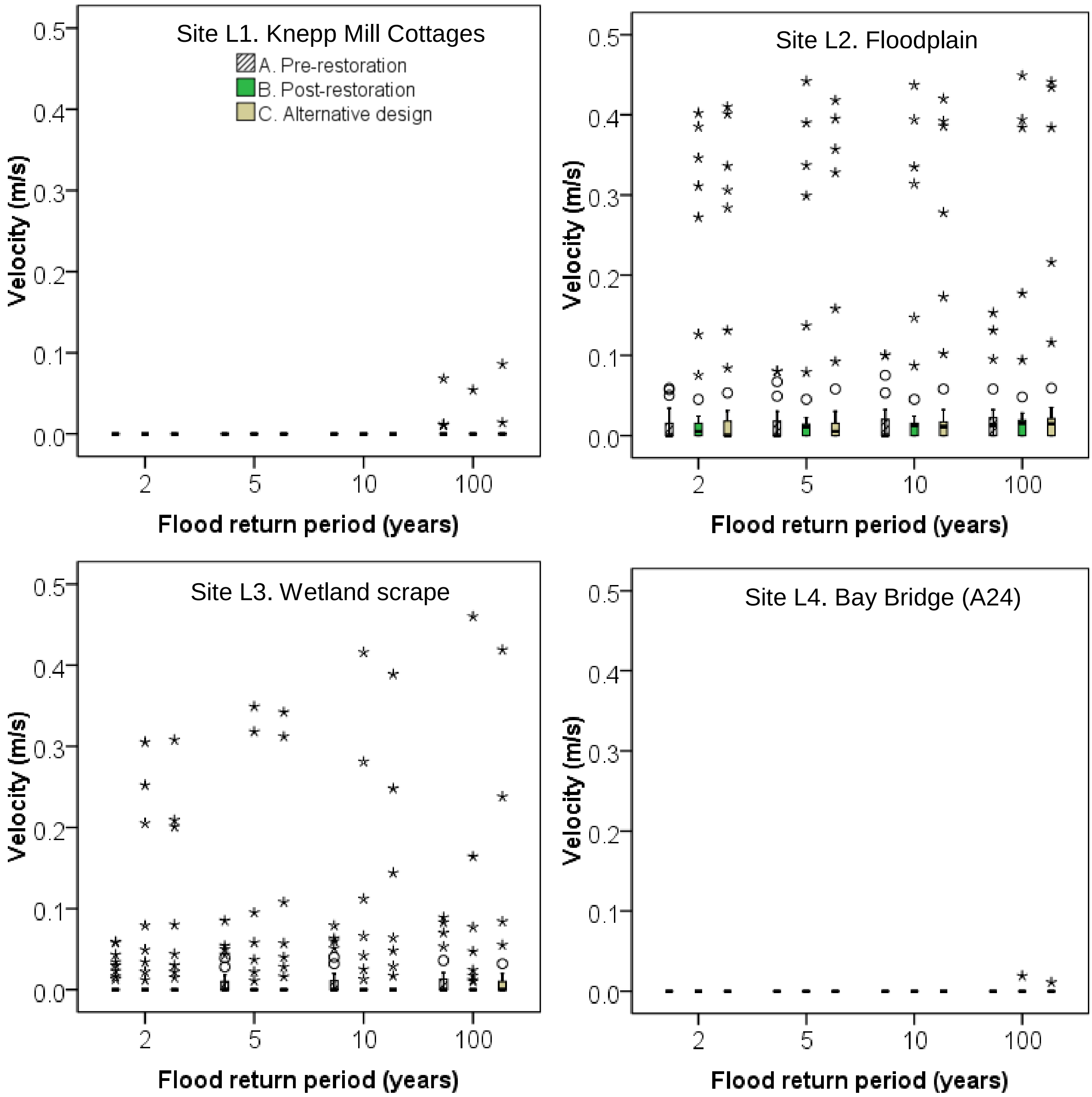

Figure 21. Comparison of water velocity at sites on the floodplain (lower reach) for different channel designs at the River Adur. Values are based on the time series of water depth at single cells during 2D flood simulations. Boxes represent the 25th and 75th percentiles with the median identified by a line; error bars show the minimum and maximum. Values over 1.5 box lengths from the edge of the box are labelled as outliers (o) and extreme values more than three box lengths from the edge of the box are indicated by an asterisk (*).

DISCUSSION

This section discusses the study's key findings and their implications for restoration design methods at the River Adur and modified lowland rivers. Its limitations are considered, with recommendations for improvements and further research.

Summary

Overall, remeandering the River Adur at the Knepp Castle Estate using geomorphologic design methods (Channel C) would not substantially increase flood risk compared to reconstructing the historic planform (Channel B), despite increased magnitude of flooding. Planform modifications upstream of Lancing Brook did not alter the diversity of instream habitats between the restored channels. Downstream, where the planform was not modified, a greater habitat diversity was indicated for Channel B than Channel C, suggesting the influence of cross-sectional topography on hydraulic variables (depth and velocity). On the floodplain, geomorphologic channel design can deliver slightly enhanced habitats through a flood pulse of longer duration. This research therefore suggests that synergy between flood risk management and ecological restoration can be achieved by river restoration.

Remeandering increases the magnitude and likelihood of flooding

These results suggest that a meandering channel based on geomorphic design methods (empirical regime equations) (Channel C) increased the magnitude and, to a lesser extent, likelihood, of flooding in the upper reach of the River Adur compared to the carbon copy planform (Channel B): the maximum flood volume was 7.3-9.9% greater for Channel C than Channel B, whilst the reverse was true downstream (volumes were 1.8-6.4% higher for Channel B than C). However, these differences were limited for the total reach for both total inundated area (0.1-0.4% differences) and maximum flood volume (0.2-3.7%). This may indicate the effect of Channel C's increased sinuosity in the upper reach (1.54, compared to 1.25-1.13), leading to increased flow resistance and overbank flows; Channel B appears to have higher conveyance, maybe partly due to its greater depth, thus transporting more flood water downstream leading to greater flood volumes.

Both restored channels increase the likelihood and magnitude of flooding relative to the pre-restoration Channel A. This impact was most pronounced for maximum flood volume, which was 8.8-24.9% higher for both restoration designs compared to Channel A across the four hydrographs; mean depths were higher in both restoration designs by 6.4-8.2% (1 in 2 year flood) to 13.9-17.7% (1 in 100 year flood). Whilst the flood extent was greater for both restoration designs, the differences were much smaller (0.8-2.3%). The similarity in flood extents for the three channels, especially as return period increased, is probably related to floodplain topography since relatively steep slopes constrain the flat valley floor (Royal Haskoning, 2010).

These findings concur with hydraulic modelling commissioned by the Environment Agency (ibid.) which predicted that reconnecting remnant meanders would not increase the flood extent substantially, although there would be some increases in water depth (the study linked a 1D model in ISIS, Flood Modeller's predecessor, with a 2D TuFlow model). However, it found that substantial areas of the floodplain were not inundated for the pre-restoration channel during the smallest flood (1 in 1 year, peak flow=12.8 m^3s^{-1}) (see Figure 22), whilst this study predicted inundation across most of the floodplain (1 in 2 year flood, peak flow=13.5 m^3s^{-1}); this could reflect differences in the cross-sections or channel roughness in the EA study.

Restoration causes limited additional flood risk

Whilst the *likelihood* of flooding was amplified under the restored channels, this does not necessarily equate to an increased flood *risk* at this site. Since flood risk is typically defined as the probability of flooding × consequences (Kallen et al., 2009), additional flood risk due to either restoration design is limited since the floodplain is predominantly pasture, including areas converted from intensive arable production under the Knepp Rewilding Project.

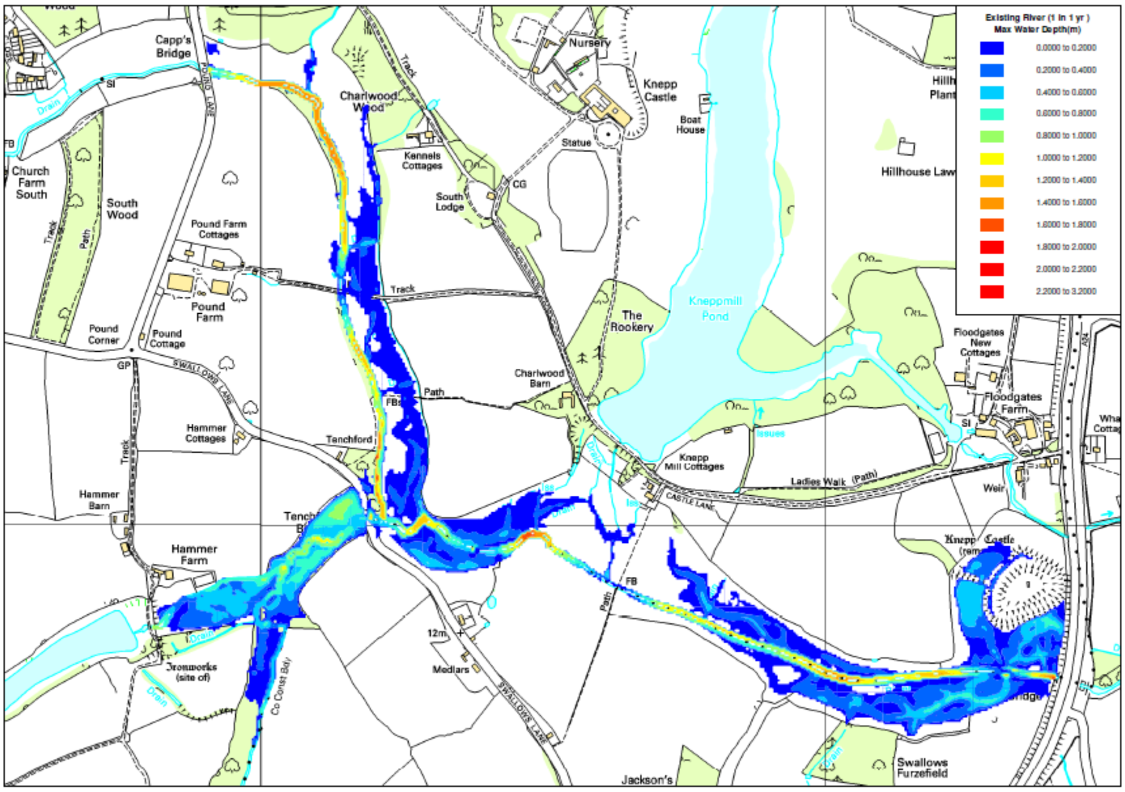

Figure 22. Maximum water depths during a 1 in 1 year flood for the pre-restoration River Adur showing large areas not inundated by water. Reproduced from a 1D-2D hydraulic modelling study for the Environment Agency (Royal Haskoning, 2010).

Consequently, flooding represents a limited hazard to property, infrastructure or safety. Addressing research objective 1, this study's findings therefore suggest that, overall, the channel based on geomorphologic principles (Channel C) would not substantially alter flood risk at the River Adur floodplain, compared to reconnecting historic meanders (Channel B). Additionally, the model indicates that neither restoration design would substantially increase flood risk relative to the straightened channel.

However, some important local variations were observed at infrastructure, notably, the A24 at Bay Bridge. Here, flood risk was higher under the two restoration designs compared to the straightened river, although risk did not vary between the two meandering channels. It is the most sensitive of the 8 floodplain sites given the hazard standing water poses to road safety; the AA advises motorists not to drive in floodwater over 0.1 m deep (Automobile Association, 2015). According to the model, there was no pre-restoration flood risk to the structure during return periods below 1 in 100 years. However, flood risk was significantly ($p<0.05$) higher for both restoration designs since the bridge was inundated during the 1 in 10 year flood; whilst maximum depths were relatively small (0.05-0.07 m), they still present a potential risk to road safety. Logically, flood risk was most acute during the highest discharge (1 in 100 year), where maximum depths were highest for the two restored channels (0.46-0.47 m) compared to the straightened river (0.37 m), although all three could potentially lead to closure of the dual carriageway. The modelling report for the EA did not identify any flood risk to Bay Bridge during floods of any return period (Royal Haskoning, 2010). At Knepp Mill Cottages, flood risk was lowest for Channel B, indicated by significantly ($p<0.005$) smaller median depths (1 in 100 year event only). Whilst median depths were relatively low for Channels C and A (0.11 m, IQR=0.11 m), this could still damage property and restrict access to the cottages. Whilst restoration does not substantially increase flood risk at the study site, the increased water depths could present a greater hazard at lowland rivers where the floodplain has been developed for housing, industry or infrastructure. Additionally, restoration could enlarge the flood extent at sites where the floodplain is less not as tightly constrained by topography.

Meander design does not alter instream habitat diversity

These findings suggest that, upstream of Lancing Brook, the diversity of instream physical habitats for the restored channels at the River Adur was not altered by the design method (research objective 2). According to the hydraulic models, similar variability (IQR) in depth (Channel B=0.51-0.75 m, Channel C=0.52-0.77 m) and velocity (Channel B=0.21-0.23 ms^{-1}, Channel C=0.17-0.21 ms^{-1}) were observed in the upper reach where sinuosity was increased considerably, from 1.13 pre-restoration to 1.25-1.54 post-restoration.

Downstream, where sinuosity was increased by just 0.02 compared to the pre-restoration channel, habitats were more heterogeneous in Channel B than Channel C, indicated by the 26.8-30.5% higher variability in depth and 23.7-39.8% higher spread of velocity (excluding the 1 in 100 year flood). These differences may reflect the geometry of the 1D model cross-sections, since the greater depth of Channel B will lead to higher water depths than Channel C's shallower profile (Figure 9). This may suggest the absence of a 'planform effect' on upstream habitat diversity whilst, conversely, cross-sectional topography has a greater impact on hydraulic habitats since planform was not altered downstream.

It is widely acknowledged that channelisation can degrade instream habitat heterogeneity by simplifying cross-sectional topography and constraining velocities (Allan and Flecker, 1993, Brookes, 1988). For instance, Nakano and Nakamura (2008) found that cross-sectional habitat diversity, indicated by the range of water depth and velocities, was significantly lower at straightened reach in a Japanese lowland river compared to a restored meander; total macro invertebrate taxon richness was higher at the restored reach, suggesting that this was promoted by remeandering. However, in this study, the range of instream depth and velocity for the straightened River Adur was higher than both meandering designs, suggesting that the pre-restoration channel delivers greater instream habitat diversity. Some research also indicates that planform alterations do not necessarily lead to expected changes in velocity distribution, for instance, Rhoads et al. (2003) observed that dramatic increases in sinuosity, including between reaches just 500 m apart, resulted in similar cumulative frequency distributions of downstream velocity at four low-energy streams in Illinois, USA; the authors proposed that bank vegetation or woody debris may be more important than planform in altering velocity distributions. Since instream structures and variable bank material/roughness were not modelled in this study, this unexpected variability in habitat diversity may therefore be related to modelling parameters. For instance, the use of uniform channel cross-sections in the 1D networks for the two restoration designs, compared to river sections based on the more heterogeneous LIDAR topography in Channel A. Nevertheless, Rhoads et al.'s (2003) findings underline the importance of considering a range of restoration techniques to promote instream habitats. Although they were not modelled in this study for simplicity, instream measures such as large woody debris, berms, and planting vegetation were used at the River Adur in conjunction with planform engineering.

Meandering enhances floodplain ecology through the flood pulse

On the floodplain, geomorphologic channel design can deliver slightly enhanced habitats compared to the carbon copy meanders through a flood pulse of longer duration (research objective 3), indicated by the 5.4-7.2% larger inundated area at the end of each 37 hour hydrograph. Following Junk et al.'s (1989) concept that the pulsing of river discharge is the major force influencing the biota of river-floodplains systems, it is understood that overbank flows do not just transport water – they exchange sediments, chemicals and biota between the channel and floodplain, or 'aquatic/terrestrial transition zone' (ATTZ) (Heiler et al., 1995). Consequently, biological production and carbon dynamics tend to be enhanced as the temporal and spatial extent of floods increase (Schiemer, 1994). Additionally, the flood pulse for both meandered channels enhanced the ATTZ compared to the straightened channel, indicated by a ~4% larger flood extent during the 1 in 2 year event. That this was simulated for the most regular flood event is noteworthy since regular pulses enable biota to adapt to and make use of the floodplain's resources, rather than relying on permanently submerged or dry habitats (Junk et al., 1989).

Wetland scrapes improve habitats and flood storage

Restoration techniques on the floodplain itself also enhanced habitat value compared to the straightened channel, indicated by significantly ($p<0.05$) deeper water in the three wetland scrapes analysed, although this did not vary according to the restoration design method (research objective 3). As the scrapes, modelled as 0.5 m deep depressions, constitute ~10% of the floodplain area, they represent a substantial additional habitat covering 34,337-36,965 m^2 (assuming that overall increases in water depth are similar to those identified by this study). The scrapes can be considered 'washlands', manmade areas allowed to flood by nearby rivers for flood management, including zones surround by banks (Morris et al., 2004), as distinct from ‘wetlands’ which occur, often naturally, where the water table is high (Wharton and Gilvear, 2007); in practise, however, overlap exists between the two (English Nature et al., 2003). The RSPB recommend that constructing washlands and improving river-floodplain connectivity can assist flood risk management by increasing floodplain storage and slowing conveyance (Johnstonova, 2009). Where the floodplain was unmodified, the findings suggest that the meandering designs created some additional habitats, indicated by increased variability (IQR) in depth, albeit to a lesser extent than the scrapes since median depths were not significantly ($p>0.05$) different between the three channels. Furthermore, two backwaters were created from the straightened channel providing additional habitats in the upper reach, although their depths and velocities were not analysed. In addition to enhancing habitats, the wetland scrapes provide extra storage capacity of 17,168-18,482 m^3, representing ~6% of the maximum flood volume during a 1 in 2 year event which could, in principle, attenuate flood peaks (English Nature et al., 2003), illustrated by Figure 23.

Geomorphological design vs turning back the clock

The carbon copy approach for reconstructing meanders, such as that practised at the Adur, has been widely criticised since form-based restoration is often seen as less desirable than process-led techniques (Downs et al., 2002, Downs and Gregory, 2004). Turning back the clock to restore historic planforms will be unsustainable unless accompanied hydrologic

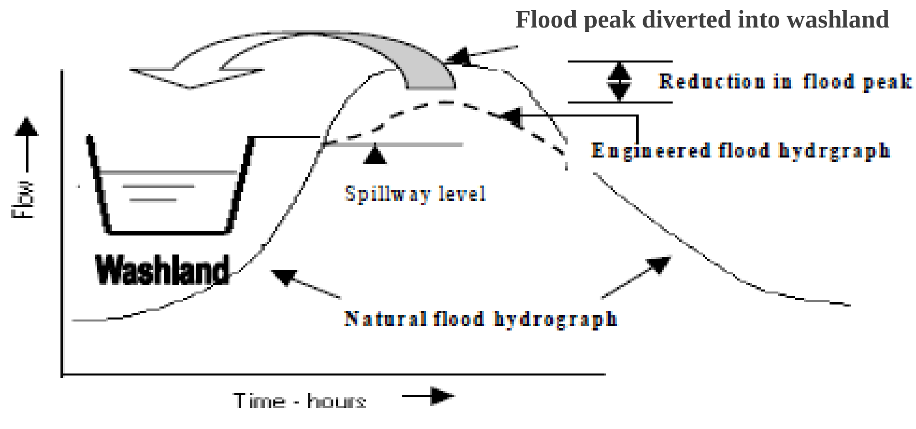

Figure 23. Impact of washland/wetland storage on the peak flow during a flood hydrograph. Reproduced from English Nature et al. (2003).

and sedimentary processes that maintain the landforms (Downs et al., 2002), leading to unstable rivers or failure due to sedimentation, erosion and washout (Sear et al., 1998, Soar and Thorne, 2001, Shields, 1996). However, morphological reconstruction may be the only appropriate strategy for low energy streams where natural recovery is too slow or modification severe (Downs and Gregory, 2004, Sear and Newson, 2004). Sear et al. (2007) argue that design accuracy is critical in such systems since any mistakes would leave a lasting legacy, underlining the role for geomorphological expertise. At the Knepp Castle Estate, land use has remained predominantly rural according to maps from the 1830s (Figure 4). Whilst this suggests limited catchment modification compared to more urbanised areas, one cannot assume that the hydrological regime and sediment budgets will be analogous to those prior to channelisation. For instance, the intensification of agricultural methods, such as ploughing, soil compaction by machinery and increased livestock numbers in the UK, have been correlated with increased runoff and erosion (Pattison and Lane, 2012), whilst abstraction to supply a growing population and industry can affect flow regimes. It is therefore significant that the River Adur restoration was conceived in conjunction with the 'rewilding' of the floodplain; converting ploughed fields applied with nitrogen fertilisers to extensive pasture with low densities of livestock may potentially mitigate some of the historical changes to local hydrology and sediment budgets by improving soil structure and reducing runoff.

Implications for restoration design

This study suggests that habitat enhancement and flood risk management are not mutually exclusive goals for the restoration of channelised lowland rivers, such as the River Adur (research objective 4). Targets set by the WFD, EU Floods Directive and UK legislation mean that future restoration schemes will have to deliver multi-functional river-floodplain systems. However, the lack of guidance and often contradictory scientific evidence for restoration outcomes pose a challenge for river managers tasked with choosing restoration techniques (Friberg et al., 2014, Millidine et al., 2012). Moreover, these findings underline the importance of holistic restoration strategies that target the channel, floodplain and process restoration. The limited overall variation in flood risk and habitat suitability between the two restoration designs suggests that modifying planform and cross-sectional topography are not the only techniques to consider when planning a multi-objective restoration scheme. In addition to satisfying ecological objectives, large 'visible' restoration projects like the River Adur also have the advantage of enhancing recreational and amenity value, as well as community engagement. However, restoration stakeholders should also consider whether their objectives could be achieved without expensive and disruptive 'active' restoration. Gilvear et al. (2013) argue that short-term disturbances caused by remeandering can potentially harm biota and cause siltation downstream. Hydraulic modelling of the River Adur suggests that cross-sectional topography may have a greater impact on physical habitat diversity, indicated by the differences in variability of instream depth and velocity in the downstream reach. For instance, little difference in macroinvertebrate diversity was found 19 years after remeandering a 1.8 km reach of the River Gelsa in Denmark, compared to a straightened control reach; researchers partly attributed this to the cessation of weed cutting at the control reach which improved habitat heterogeneity, including increased sinuosity and gravel substrate cover, in spite of its linear planform (Friberg et al., 2014). Bank vegetation and woody debris may be more important for controlling the diversity of hydraulic habitats than planform, according to Rhoads et al. (2003). This study therefore also confirms the importance of hydraulic modelling for evaluating the impact of different channel designs on hydraulic variables (Millidine et al., 2012) since it is a relatively fast and inexpensive tool, particularly at the initial planning stages.

Limitations and improvements

1D networks

Due to time restrictions, the symmetrical river sections shown in Figure 9 were used across the entire 1D network for both restoration designs (Channels B and C). In a sinuous channel, however, river sections are typically be asymmetrical at meander bends, incorporating pools and point bars caused by erosion and deposition (Nakano and Nakamura, 2008). The fact that uniform sections were used at both straight reaches and bends may affect 1D model results, notably as velocity and stage, with consequences for the water levels which become the 2D model boundary condition. However, the aim of this study was to make general comparisons of channel design, rather than to create a ‘true to life’ representation of the natural environment.

An additional limitation was the use of LIDAR data to generate cross-sections for the pre-restoration channel. Since conventional LIDAR does not penetrate water bodies, the accuracy of a DTM for submerged terrain may be inferior to that for dry areas (Smart et al., 2009). LIDAR was used in this study since data on the pre-disturbance cross-sections were unavailable, however, it is recognised that the 1D model for Channel A could have been improved by adjusting the channel sections generated from the DTM to account for the water surface. The deviation between the DTM and the actual topography could be estimated by conducting bathymetric ground surveys of unrestored river sections (e.g. directly downstream of Capp’s Bridge) using a total station or GPS since depths are relatively shallow or, alternatively, an acoustic Doppler current profiler (ADCP) (Hilldale and Raff, 2008); the deviation between the DTM and survey could then be used to model 1D river sections.

Channel design

This study examined a single channel design based on two sets of empirical equations (cross-sections: Simons and Albertson (1960), planform: Soar and Thorne (2001)). To more robustly test the hypothesis that geomorphologic channel design can deliver better outcomes for river restoration, further research should model 1D river networks with dimensions computed from alternative regime equations. For instance, an analytical approach could be used, such as Chang (1980) who developed a numerical model of flow and sediment transport based on the concept of minimum stream power, which hypothesises that, for given a discharge and sediment load, alluvial channels adjust their width, depth and slope so that the stream power is a minimum, subject to given constraints (Chang, 1979a and b, cited by Singh, 2003). In common with empirical equations, Chang's formulae assume a channel with mobile bed material at bankfull flow (Thorne et al., 1988), although the analytical approach does not reflect the nature of survey data (Hey and Heritage, 1988).

Additional analyses

This study used the interquartile range (IQR) as a measure of variability of water depth and velocity to indicate the diversity of instream physical habitats. Whilst it is suited to non-normal distributions, a standardised measure of dispersion would have the advantage of allowing comparison of datasets with different characteristics e.g. magnitudes of depth and velocity. For instance, Nakano and Nakamura (2008) used the coefficient of variation (standard deviation divided by the mean) to compare instream depth and velocity. Bonett (2006) notes that the coefficient of quartile variation (CQV) (equation 9) is preferable to the coefficient of variation where data is not normally distributed, such as this study.

$$\text{CQV} = \frac{Q_3 - Q_1}{Q_3 + Q_1} \qquad [9]$$

where Q_1=25th percentile and Q_3=25th percentile. However, CQV was not suited to this study since the 25th percentile values of depth and velocity were <0.000 for many of the downstream floodplain sites; this computed CQV values of unity for data with different spreads which were therefore useless for comparing variability.

Rather than relying solely on statistical measures of variability, the physical habitat diversity could also be quantified by analysing the occurrence of hydraulic variables which may promote habitats for particular species, such as low depth-high velocity (e.g. spawning fish) and high depth-low velocity (e.g. certain macrophytes) (Millidine et al., 2012). Additionally, Rhoads et al. (2003) demonstrated that plotting cumulative frequency distributions of reach-standardised velocity can be used to visually compare the range of velocity between reaches or models. Kemp (2000) hypothesised that habitat occurrence can be described by the Froude number, which he linked to physical habitat units defined by surface flow, known as ‘flow biotopes’. Further research could therefore investigate instream hydraulic habitats using Flood Modeller since it calculates the Froude number at each section.

Scale of flood risk

This study modelled flood risk at the reach-scale, simulating inundation of the floodplain directly adjacent to the restoration site. To improve our understanding of the link between river restoration and flood risk management, it may be useful to test the hypothesis that localised flooding at the Knepp Castle Estate can reduce downstream flood risk through by reducing flows. This could be achieved by further linked 1D-2D models using the flows simulated during unsteady model runs in this study to estimate boundary conditions for a downstream site.

CONCLUSION

Despite its popularity, the ‘carbon copy’ approach of reconstructing historic meanders planforms has been widely criticised since turning back the clock to restore landforms does not restore the hydrologic and sedimentary processes needed to sustain them (Downs et al., 2002). However, this hydraulic modelling study found that, overall, geomorphologic design methods did not outperform the carbon copy channel at a British lowland river.

Remeandering the River Adur at the Knepp Castle Estate using geomorphologic design did not substantially increase flood risk compared to reconstructing the historic planform, despite an increased magnitude of flooding. Important infrastructure, notably the A24 at Bay Bridge, would only experience dangerous water levels during extreme events e.g. 1 in 100 year floods. Whilst overall flood risk was minimal due to the lack of development on the floodplain, the increased water depths could present a hazard at sites where there is housing, industry or infrastructure.

The findings also suggest the absence of a 'planform effect' on habitat diversity in the upstream reach where sinuosity was increased to 1.82 from 1.43 in the carbon copy planform. Conversely, physical habitat diversity downstream was greater for the carbon copy channel, indicated by the variability in water depth and velocity. This suggests that cross-sectional topography has a greater impact than planform on instream hydraulic habitats, supporting previous research indicating that planform adjustments may be less important than 'softer' measures like woody debris, planting bank vegetation (Rhoads et al., 2003), or the cessation of weed-cutting (Friberg et al., 2014). On the floodplain, geomorphologic channel design can deliver slightly enhanced habitats through a flood pulse of longer duration.

This study therefore demonstrates that ecological enhancement and flood risk management should not be treated as mutually exclusive restoration goals for lowland rivers like the Adur, although their synergy cannot be guaranteed. Therefore, a range of restoration techniques, including geomorphologically appropriate channel design, must be carefully chosen to achieve these twin objectives. This emphasises the role of geomorphologic expertise in designing projects, as well as linked 1D-2D hydraulic models for evaluating the potential outcomes of different restoration techniques.

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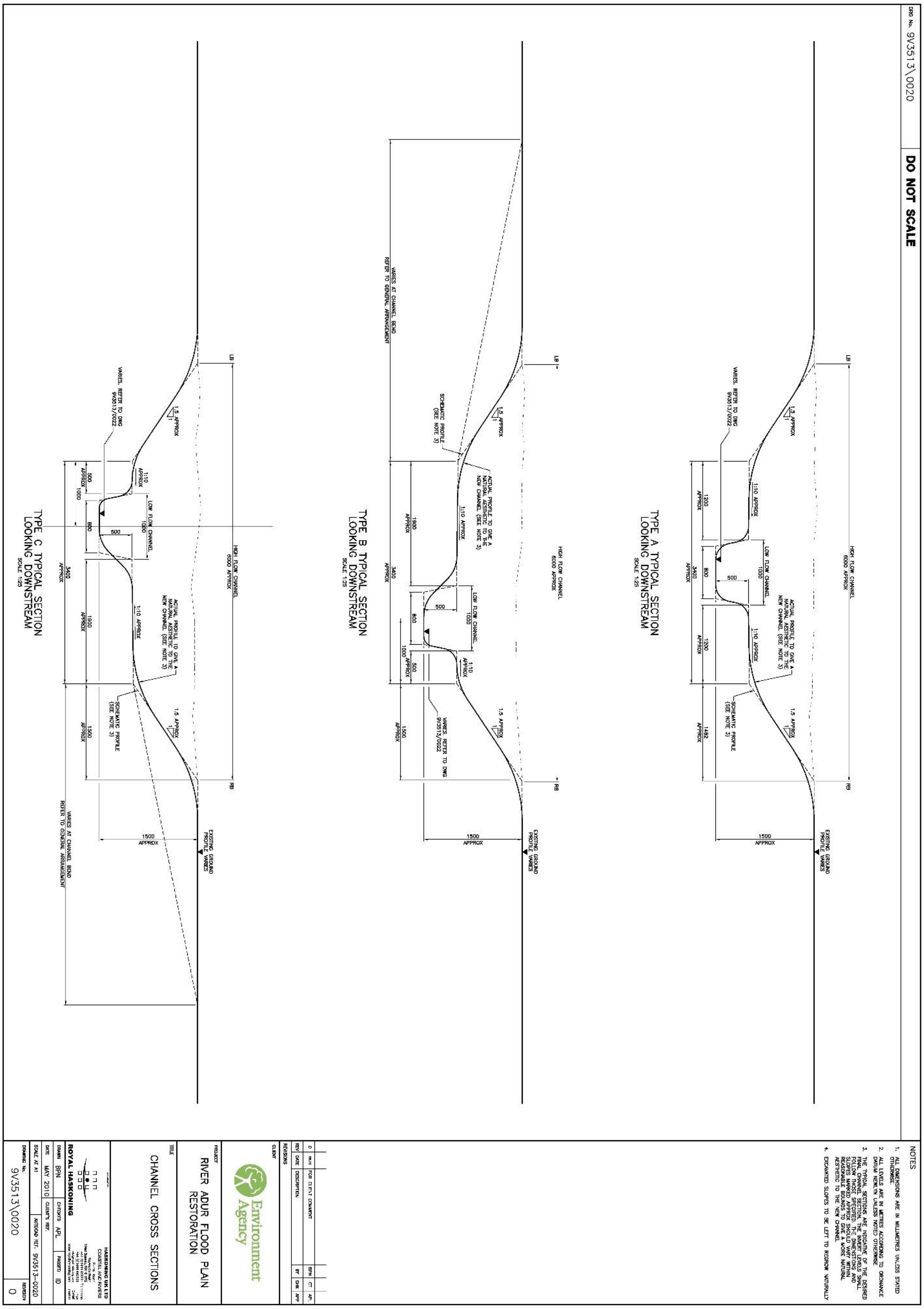
Greatest thanks are due to my parents for their support without which I would not have been able to pursue this Master's Degree. I am also grateful to my supervisor, Alex Henshaw, for his advice and guidance during my research, as well as invaluable assistance from Ian Dennis (Royal HaskoningDHV), Penny Green (Knepp Castle Estate) and Jenny Mant (River Restoration Centre). I would also like to express my gratitude to the Worshipful Company of Water Conservators for their generous bursary towards my studies.

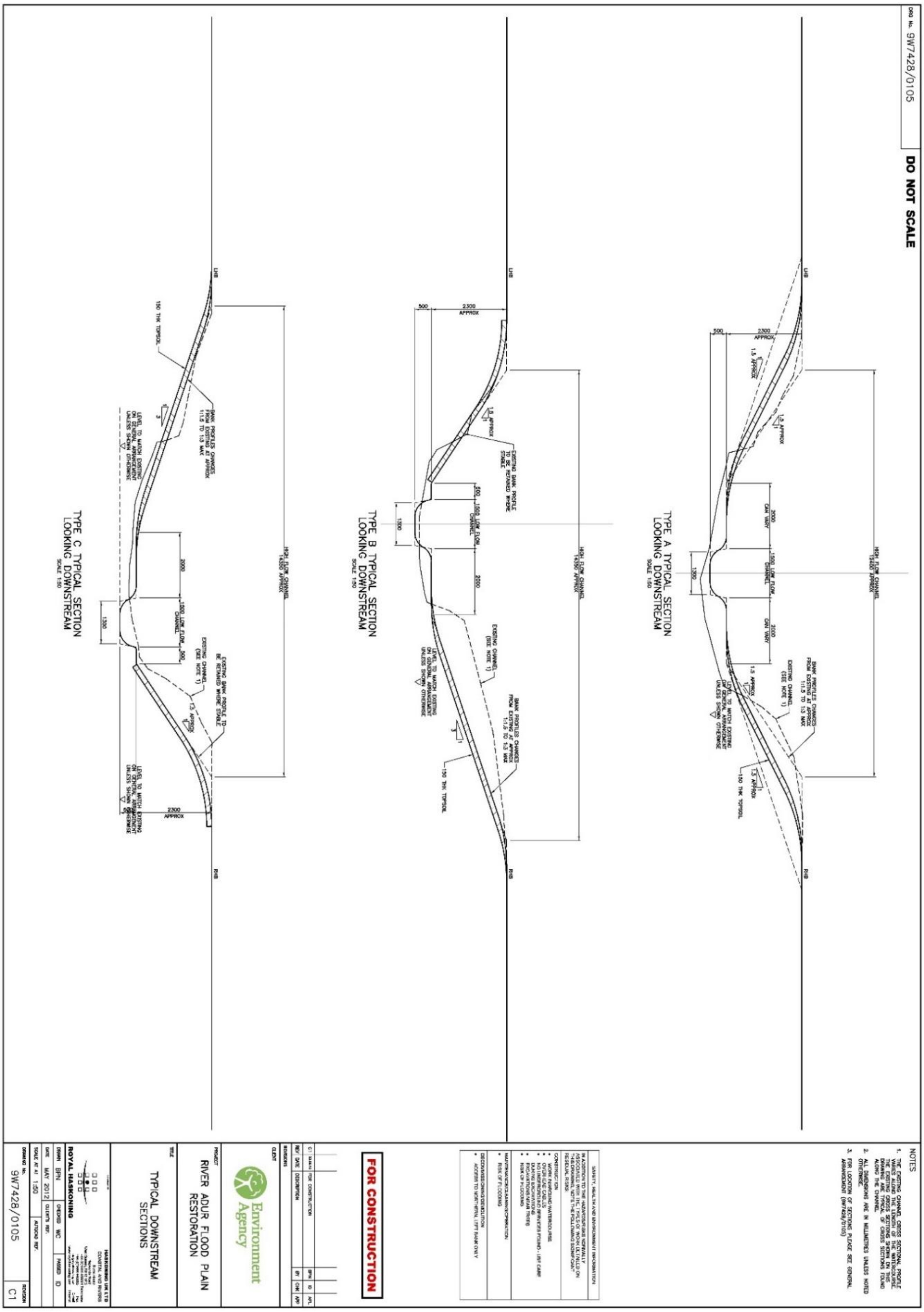
Appendix I. Restoration design plans

The design plans below for typical cross-sections for the River Adur restoration scheme are reproduced courtesy of Royal HaskoningDHV.

A. Cross-sections, upper reach

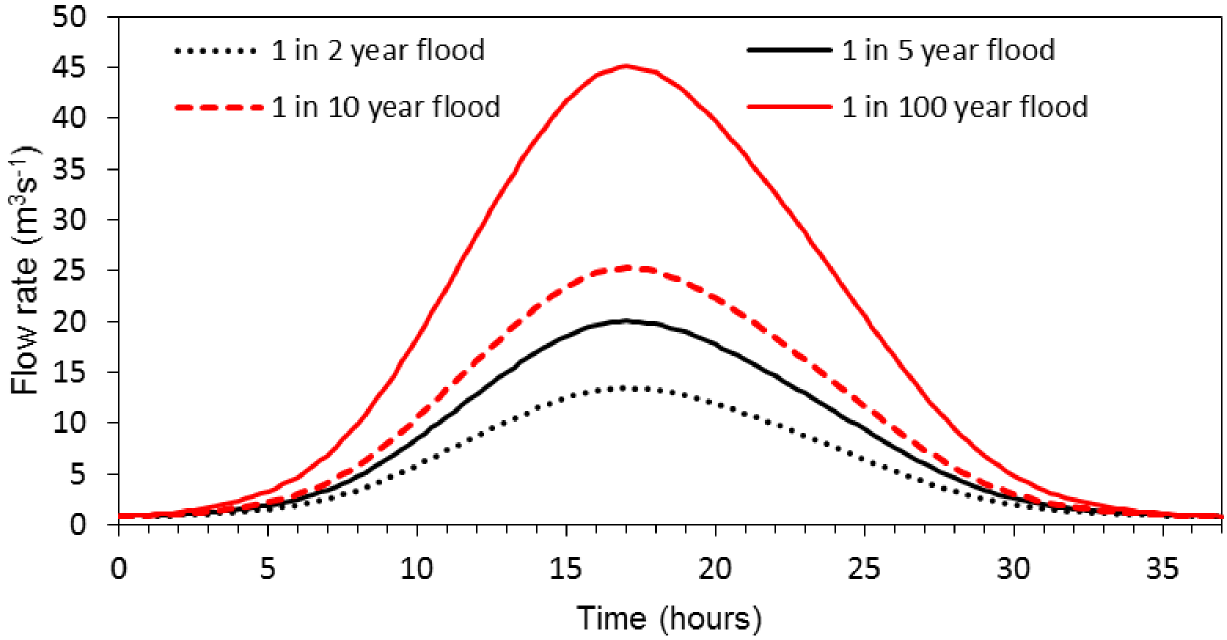


B. Cross-sections, lower reach



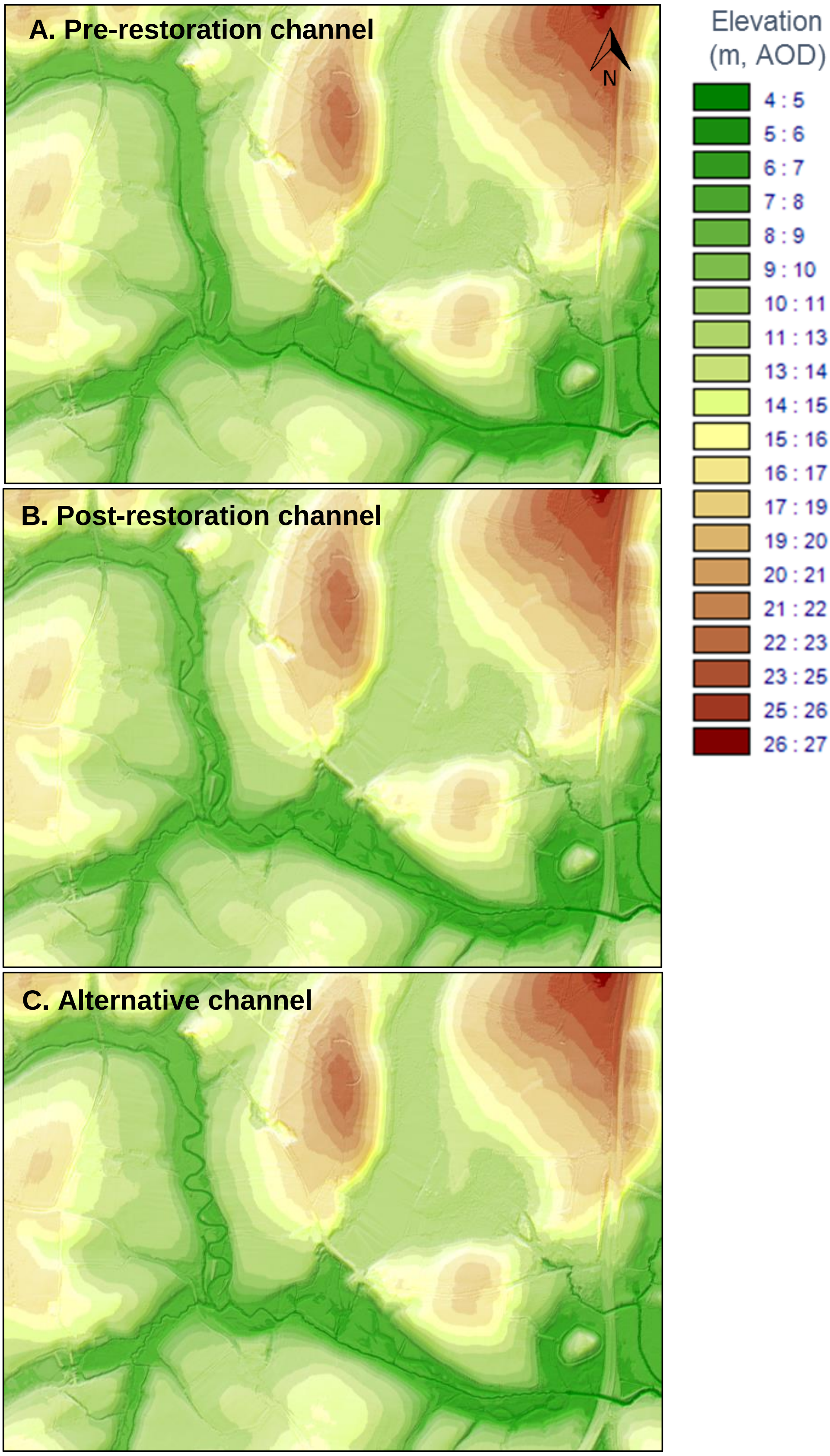
APPENDIX II. HYDROGRAPHS USED IN FLOOD MODELLER SIMULATIONS

The four hydrographs below were used to simulate flood events in each of the 1D networks modelled with Flood Modeller Software. They were provided by courtesy of the River Restoration Centre who generated them with the Flood Estimation Handbook (FEH) method for their pre-feasibility report of the River Adur restoration scheme (Janes et al., 2006).



APPENDIX III. DIGITAL TERRAIN MODELS

Presented below are the Digital Terrain Models for each of the channel designs based on 1 m resolution LIDAR data obtained from the Environment Agency. Scale 1:10,900.



APPENDIX V. PROJECT POSTER

Can geomorphologic channel design deliver better outcomes for river restoration than reconnecting historic meanders?

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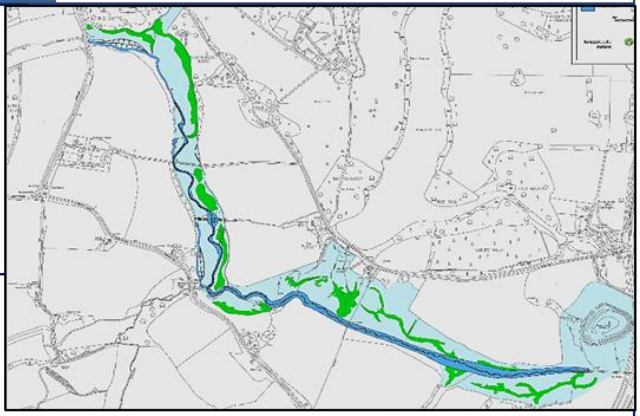
MSc Environmental Science: Integrated Management of Freshwater Environments

Introduction

- Channelisation of rivers has led to the widespread degradation of fluvial habitat
- Restoration methods, including remeandering, are used promote habitats by increasing hydromorphological diversity, however, a potential conflict exists with flood risk management.



Aim: to assess whether geomorphologic channel design can deliver better outcomes for river restoration than reconnecting historic meanders.
Research objectives are to:

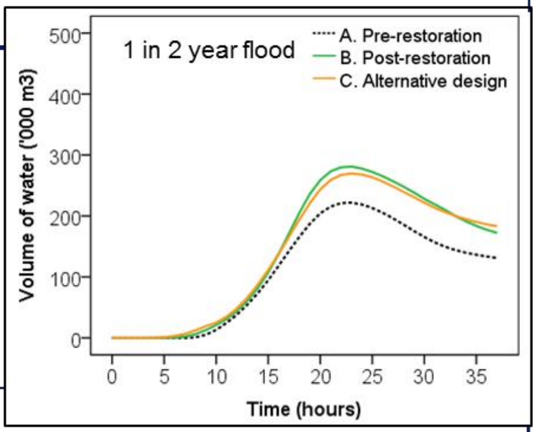
- **Evaluate whether flood risk is altered by geomorphic design**
- **Assess whether design enhances instream and floodplain habitats**
- **Evaluate whether ecological enhancement and flood risk management are mutually exclusive.**

Methods

- Linked 1D-2D hydraulic models were run with Flood Modeller to simulate inundation for three channel designs at the River Adur: A) pre-restoration, B) restored channel, C) geomorphologic design
- Channel C was designed using empirical hydraulic geometry equations to predict cross-sections (Simons and Albertson, 1960) and planform (Soar and Thorne, 2001).

Results

- The restored channels experience a ~4% larger area was inundated and larger flood volume
- Upstream, variability in depth and velocity were similar between Channels B and C
- Downstream, variability of depth was ≤30.5% higher and velocity ≤39.8% higher in Channel B than C
- Floodplain scrapes had significantly ($p<.0.05$) deeper water in Channels B and C than A



Conclusions

- Geomorphic design did not outperform the historic planform in terms of flood risk and habitat diversity
- The absence of a 'planform effect' on instream habitats chimes with research suggesting that other factors may be more important e.g. bank vegetation, woody debris (Rhoads et al., 2003)
- A range of restoration techniques, including geomorphologically appropriate channel design, must be carefully evaluated to achieve the twin objectives of ecological enhancement and flood risk management.

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Simons and Albertson (1960) Uniform water conveyance channels in alluvial material. *Journal of the Hydraulics Division,* 86, 33-71
Soar and Thorne (2001) *Channel Restoration Design for Meandering Rivers.*

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