Unveiling Stage Zero conditions in the New Forest National Park: A drone-based Structure-from-Motion Photogrammetry and LiDAR approach for reconstructing an anastomosing wet woodland at the Avon Water.

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##### Abstract

In recent years there have been significant technological advances in Unmanned Aerial Vehicles and in particular the use of drones. This, combined with the development of structure-from-motion (SfM) technology have provided river restoration practitioners with a new tool that can be used to give an affordable, repeatable and objective assessment of river restoration projects. In this study, SfM photogrammetry is utilised on a section of the Avon Water, a small watercourse in the New Forest National Park. It was subjected to extensive Victorian-aged straightening and channelisation which have left the SSSI in an unfavourable ecological and morphological condition. Much of this is now being reversed by river restoration projects led by the New Forest Higher Level Stewardship Scheme. Whilst historic maps reveal the rivers former alignment, the straightening pre-dates these maps in places. Furthermore, even where the former route is shown, it is likely that anthropogenic modification began much earlier, and these maps may not represent the natural course of the river. High-resolution orthophotos and 3D photogrammetric models of the site are created that reveal a palaeolandscape consisting of a mosaic of anabranching channels. These are interpreted to represent a former anastomosing wet woodland and ‘Stage Zero’ of the river system. It is inferred that early human habitation and associated land clearance within the catchment altered hydrological and hydrogeological conditions, reducing floodplain connectivity and promoting single-threaded planform configurations. This was then followed by the most recent Victorian-aged straightening. The palaeolandscape revealed by the study provides a template for future Stage Zero river restoration in the New Forest and elsewhere, demonstrating the capabilities of low-cost, UAV‑derived photogrammetry in river restoration research.

# Introduction

Humans have caused fundamental changes to our landscape, particularly to the rivers that drain the land. Nowhere are these change more obvious than the lowland rivers of the United Kingdom, which have undergone centuries of modification which has included straightening, impoundment by weirs and dredging (Brown et al., 2018). Reference reaches are often used in these systems as templates for natural conditions (Newson and Large, 2006); however, the extent of modification is such that finding a suitably unmodified reference reach that reflects the river in its natural state is rarely possible.

Historical maps are commonly used to determine historic planform configurations that may be assumed to represent the pre-modified course (River Restoration Centre, 2021). However, old maps are often limited in their historical extent. Whilst Ordnance Survey mapping from the 1880s gives fairly reliable indications, maps predating these are often limited and rarely of sufficient accuracy to make reliable interpretations on planform configuration.

There has also been increasing recognition that anthropogenic influence on rivers often dates back thousands of years. The early to mid-Holocene floodplains that developed following deglaciation were likely to be thickly-wooded with birch, willow, poplar and later alder and oak (Brown et al., 2018; Ejarque et al., 2015; Lechner, 2009). Biogeomorphological interactions (see review in Viles, 2011), and in particular the occurrence of large woody debris, has been recognised as a key factor in controlling river styles since the establishment of extensive woodland habitats in the Carboniferous Period (Davies and Gibling, 2011). The importance of changes to biogeomorphological interactions has become increasingly recognised as a major driver to Holocene planform changes (Brown et al., 2018; Marshall and Wohl, 2023; Wohl et al., 2021).

Studies into floodplain chronostratigraphy (Brown et al., 2013, 2018; Zolitschka et al., 2003) reveal major changes to river planforms often coincided with large-scale deforestation and the cultivation of the land. This altered the hydrology and enhanced surface runoff which led to the delivery of large amounts of fine sediment to river systems, much of which became stored on the floodplain (Collins and Walling, 2007; Jones et al., 2012; Macklin et al., 2014). This led to channel incision and/or raising of the adjacent floodplain, leading groundwater levels to fall relative to the floodplain surface. This reduction in floodplain connectivity as well as increases in stream power and reduced biogeomorphological interactions promoted the development of larger, mostly single-threaded passive meandering planforms. For most of the 20th century this formed the idealised planform configurations that more intensely modified rivers may be compared to.

The realisation that the single-threaded planforms that characterise many of the worlds lowland rivers for centuries if not millennia do not represent the evolved state of the river, but are rather a product of anthropogenic modification, has caused a ‘paradigm shift’ in approaches to river restoration (Castro and Thorne, 2019; Cluer and Thorne, 2014; Wohl et al., 2021). This has led to the establishment of the concept of Stage Zero restoration where efforts focus on attempts to restore rivers to an anastomosing wet woodland or wet grassland that would have naturally been present prior to anthropogenic modification of the catchment (Cluer and Thorne, 2014). These states are generally thought to deliver the most benefits in terms of habitat creation, natural flood management, geomorphological resilience and carbon sequestration.

Not all rivers are suitable for Stage Zero restoration, and in many places catchment alterations are so extreme that whilst measures can be put in place to increase floodplain connectivity, the establishment of true Stage Zero conditions as per the definition of Cluer and Thorne (2014) are unlikely to be achievable. Furthermore, anastomosing planforms naturally develop only in certain situations, the fundamental drivers of which are not completely understood.

Good indicators of suitability for Stage Zero restoration can come from evidence of historical anastomosing planform configurations. However, whilst palaeochannels that often depict former planform configurations may be readily observed on the floodplain (Jones et al., 2007), these features often only reveal single meandering thread configurations. This likely because floodplain deposition, associated with increased sediment delivery following catchment deforestation, has often buried former bifurcating channels (Brown et al., 2018). Even where this has not occurred, most catchments have undergone centuries of intense cultivation which have smoothed the floodplain surface, largely removing evidence of former historic planform configurations.

Remote sensing, and in particular the widespread availability of LiDAR (light detection and ranging), have enabled small-scale floodplain features to be detected, that are otherwise indiscernible on the ground (Kondolf and Piégay, 2003). Whilst becoming increasingly affordable, the collection of LiDAR data involves specialist equipment. Whilst some is freely available (e.g. The UK Environment Agency National Lidar Programme), the resolution is limited and these data are often of insufficient resolution to pick out small-scale floodplain details.

Recent technological advances associated with UAVs (drones) have provided new tools that can be used to give an affordable, repeatable and objective assessment of fluvial environments (Westoby et al., 2012). In particular, structure-from-motion (SfM) photogrammetry enables the production of high resolution orthophotos and 3D point clouds that can be used to create digital elevation models (DEMs). These have provided new means to investigate and map floodplain features that may enable landscape reconstructions of Stage Zero configurations.

To investigate the potential of this technique, this study examines a catchment in the New Forest National Park. Whilst still heavily modified compared to its natural state, the New Forest has largely escaped the widespread land use changes to intensively cultivated land that make up the majority of lowland catchments in the UK. Furthermore, some studies have shown that some areas have remained wooded throughout the Holocene (Grant et al., 2014). Distinct wet woodland environments occur in many of the valley bottoms and the role of large wood in maintaining these features are well-documented (Brown et al., 2018; Jeffries et al., 2003; Sear et al., 2010a).

Whilst historic management focussed around land drainage, to help improve the condition of the New Forest rivers, there has been a recent trend towards river restoration. As part of this, the Wootton Wetland Restoration Project was completed in 2019. This returned a 4 km reach of the artificially straightened Avon Water to its ‘natural’ meandering planform (Mott MacDonald, 2024). The project, led by the New Forest Higher Level Stewardship (HLS) scheme, involved the reconnection of palaeomeanders, infilling of the old straightened channel, and localised bed raising/bank lowering to improve floodplain connectivity. Historical maps were utilised to design the restoration work, revealing the locations of former meanders which were used as a framework for palaeomeander reconnection.

The restoration did not include the upper reaches of the Avon Water where historic maps do not show the former planform configuration (Figure 4). To investigate this area, this study utilises UAV-acquired SfM photogrammetry to produce high-resolution orthophotographs and DEMs of these upper reaches of the Avon Water. This data is combined with analysis of LiDAR data and more traditional field-based techniques (sedimentology) to investigate the landscape history of the area and the development of the modern floodplain configuration.

The aims of this study are to reconstruct the landscape evolution of the Avon Water and thereby provide a framework for the natural wet woodland planform configuration. It is hoped that this can be used to aid future river restoration activities both in the New Forest and elsewhere. In doing so, a secondary aim is to evaluate the ability of the technique to provide information on geomorphological evolution of an area where limited pre-modified information is available on prior planform configuration.

# Geomorphological background

## Site characteristics

The Avon Water is located in the New Forest National Park (Figure 1). The study area forms part of the New Forest SSSI (Unit 527), classified as broadleaved, mixed and yew woodland lowland stream habitat. It was classed as being in an unfavourable recovering condition in 2008. The river originates in upland areas at Whitten Bottom (47 mAOD), where it flows along a southeasterly course, reaching the Solent at Keyhaven.

The catchment area is 47 km2, draining an undulating topography. It sits within the Hampshire Basin, comprising mostly clays, silts and sands of the Barton Group, deposited between 41.2 and 37.8 Ma in the Eocene period (King et al., 2016). Superficial deposits mostly comprise a plateau of Pleistocene gravels that form a terrace at elevations between 50 and 60 mAOD and alluvium in the valley bottoms. Peat is recorded in upland areas (Tubbs, 2011).

The study reach (Figure 4) comprises a largely straight single channel, sitting within an alluvial floodplain roughly 100 m wide. At the study reach the floodplain has been deforested, comprising open lawn areas. However, the floodplain is bounded by inclosures including Brownhill and Holmsley Inclosure to the south and Wilverley Inclosure to the north. Bogs, whilst less extensive than they were historically, are still a common feature within the catchment, most notably the Wilverley Bog SSSI (unit 525). The water within the channel is notably dystrophic as a result, likely containing high amounts of humic substances and organic acids.

## Landscape evolution

The oldest Quaternary deposits comprise the Pleistocene sands and gravels which are well-developed within the upland areas of the catchment (British Geological Survey, 1997). At the time when these were deposited, a land connection existed between the Hampshire Basin and the Purbeck Monocline. The latter formed a continuous topographic ridge, preventing flow to the south (Allen and Gibbard, 1993). A major river, commonly referred to as the Solent River (Everard, 1954), is thought to have drained the area occupying the present-day Solent area, roughly following the basin axis, flowing towards the east. Sediment supply was likely abundant in the immature glacial landscape, and large volumes of meltwater from retreating ice to the north deposited significant quantities of sand and gravel within a major braided channel network, leaving behind a sequence of Pleistocene gravel terraces (Allen and Gibbard, 1993).

The terraces within the study area comprise the Homlsey Ridge (Allen and Gibbard, 1993; Bates et al., 2010), thought to have been deposited during the Cromerian interglacial (MIS 13 ~524 - 474,000 Ka) (Bates et al., 2010). Episodes of deposition occurred during subsequent interglacial periods, forming additional terraces towards the south. However, the long-term trend was one of erosion. As such, the Solent River progressively incised into the underlying Eocene deposits. The resulting terraces, representing periods of episodic deposition of the braided river system, were deposited at progressively lower elevations, forming an outcrop pattern younging towards the southeast (Allen and Gibbard, 1993; Bates et al., 2010).

Following deposition of the Homsley Ridge terrace deposits, the Avon Water catchment likely formed as a tributary to the subsequent iterations of the Solent River. Landscape evolution was probably relatively static during glacial periods, where the climate was probably cold and dry. Aeolian deposition occurred depositing loess, sometimes observed on top of the Pleistocene terraces (Reynolds et al., 1996). Erosion likely dominated the interglacial periods controlled at least in part by sea level.

Overall the system was predominantly erosive. The river progressively carved out the valley during repeated glacial/interglacial cycles, incising through the river terrace deposits and into the underlying Barton Group by up to 30 m. However, episodes of deposition probably occurred as forests became established and the drainage network became evolved during interglacial periods.

The most recent deposits are Holocene in age (11.7Ka to present) and comprise valley alluvium, that typically fills the valley bottom (British Geological Survey, 1997). These deposits presumably represent a temporary return to depositional trends as fluvial systems became evolved following maturation of the drainage network and increases in channel resistant associated with the expansion of woodland across the floodplain.

## Anthropogenic history

The first evidence of human habitation in the New Forest was in the Neolithic and Mesolithic (Putman, 1986). Whilst the early inhabitants probably lived largely as hunter gatherers and did not cultivate the land, they did contribute to large-scale forest clearance. This pattern of deforestation continued into the Bronze Age when the land first started to be cultivated (Tubbs, 2011). However cultivation was short-lived as fertility rapidly declined on the acidic soils and large areas were abandoned becoming heathlands. Thus by the start of the Iron age, large areas of open heathland were developed on the deforested ground, suitable only for livestock grazing.

The New Forest was designated as a Royal Forest in 1069. This largely prevented further significant changes in land use such as reclamation of the land for agriculture as technology improved. Direct changes to the watercourses were probably limited up until now. The earliest evidence of land drainage comes from the occurrence of post-medieval water meadows and associated drainage systems (Cook, 2018). This began the trend towards land drainage which continued up until recent times.

The value of the land for timber production became increasingly realised from the seventeenth century onwards. Areas of the land were inclosed for commercial tree production, and pollarding was banned to encourage the production of straight growth. Much of this was initially oak, but was eventually replaced with the faster growing conifer in the 20th century.

Commercial tree production, particularly conifer, requires well-draining soils and therefore large areas were likely subjected to land drainage activities, probably culminating in the Victorian period (1837-1901). As part of this, the majority of the New Forest rivers were extensively straightened and deepened (Tubbs, 2011; Tuckfield, 1980), which continued into the 1960s. This resulted in extensive damage to the fluvial and wetland environments including habitat fragmentation, reduced ecological and geomorphological diversity and lowering bed levels (Sear et al., 2010a).

The effects of this are clearly seen within the Avon Water catchment and at the study reach. Prior to the most recent restoration activities, the course of the Avon Water was straight. As depicted on historic maps (Figure 4), the previously meandering planform, was cut by a straight canalised channel. Activities relating to drainage have also affected other parts of the catchment. In particular, a network of drainage ditches were incorporated into the inclosures, which have probably reduced attenuation, channelling water directly to the river. Peat is observed within the catchment (Tubbs, 2011) suggesting bogs and other wetland areas were once much more extensive, prior to being being destroyed by the drainage activities.

In recent years, there have been somewhat of a reversal in the drainage trends, and modern management approaches are changing (Cook, 2018). Recent works focussed around river restoration include the Wootton Wetland Restoration Project (Mott MacDonald, 2024) led by the New Forest Higher Level Stewardship (HLS) scheme.

# Methods

The site visits and drone surveys were undertaken in ‎2023. Vertical aerial photographs were captured on a DJI Mavic Air 2S quadrocopter, equipped with a GPS and a gimbal. The flight was undertaken at an altitude of 90 m and images captured in RAW with a frontal overlap of 75% and a side overlap of 70% using Dronelink (version 4.9.0). In total 177 photos were obtained at 20 megapixel resolution.

Sedimentary logging was undertaken through a 1 m recently eroded bank section through the floodplain. Logging was undertaken using standard sedimentary techniques, following the facies classification approach (Miall, 1977).

Following the collection of site data, high-resolution orthophotos and DEMs were created using SfM photogrammetry. The orthophotomosaic, 3D point cloud and DEMs, were generated in WebODM (OpenDroneMap), largely following default settings. Six ground control points (GCPs) of known positions were used to calibrate the model and check its accuracy. The resulting model recorded mean longitudinal errors (x and y) of 5 cm and vertical error (z) of 13 cm and had an average ground sampling distance of 3.4 cm. A summary of the model statistics is shown in Table 1.

The resulting georeferenced, high-resolution orthophotos, DEMs, and 3D point clouds were analysed in QGIS. DEM data was visualised in three dimensions, utilising the Qgis2threejs plugin (Version 2.7.3).

To aid analysis, the LIDAR Composite Digital Terrain Model (DTM) (updated 2024) of the Avon Water catchment was analysed, providing independent topographical information to that of the drone-acquired DEM. Once features were characterised using the high-resolution drone DEM and orthophotos, the study area was expanded using the LiDAR DEM to other parts of the Avon Water catchment. Whilst being of lower resolution (typically 1 m), the LiDAR data was sufficient to map out additional areas of former wet woodland once the framework was established at the study reach.

The Ordnance Survey 25-inch series Hampshire Sheet LXXIX.7 (surveyed nm 1870, revised 1895) was analysed to provide information on historical planform configurations. BGS (British Geological Survey) data was obtained from OpenGeoscience to provide information on the local bedrock and superficial geology. Boreholes records were also analysed to provide information on the thickness and composition of the superficial deposits.

Floodplain features were mapped in QGIS, categorised by their interpreted genesis and chronology. S0 represents the relicts of natural unmodified features that developed prior to significant anthropogenic changes within the catchment (inferred to be >2000 Ka). S1 features represent landforms that developed following initial land-use changes (e.g. deforestation) inferred to be 2ka BP – 200 BP). S2 features represent the modern artificial landforms associated with land drainage (inferred to be <200 BP). The inferred chronology of events were based on interpretations of the likely post-Holocene drainage history, the morphology of the features and relationship to other features (e.g. cross-cutting relationships), the floodplain sedimentology and analysis of the historical maps.

# Results

The high-resolution orthophoto and DEM data from the SfM photogrammetry are shown in Figure 5. The current alignment of the Avon Water is shown by the tree-lined channel running roughly east-west. The SfM photogrammetry reveal a mosaic of floodplain features, many of which are detectable within the DEM, forming subtle linear depressions on the ground surface. To enable interpretation of these features, the results from the field-based assessment are described below, this is followed by mapping and categorisation of the floodplain features. Finally the exercise is applied to wider parts of the catchment using LiDAR data, to determine the relationship to other areas.

## Geomorphology and sedimentology

At the study reach, the main channel of the river is mostly 3-4 m wide. The bed is undulating and pool-riffle sequences are well-developed. There is a shallow depth over the riffles, with pools up to 0.5 m deep. Banks are mostly between 0.3 and 0.5 m high and comprise alluvium. Whilst artificial, these are in relatively ‘natural’ condition (e.g. Figure 2a), with mature and diverse bank side and riparian vegetation.

Sections of the river display minor embankments. These are probably historic and the result of dredging or spoil from the initial channel excavation during straightening, but serve to reduce overall floodplain connectivity. The river has a poorly sorted gravel bed, comprising sub-angular flints likely sourced from Pleistocene terrace deposits. The channel displays relatively good flow diversity with glides, pools, runs and riffles. Gravels point bars are well developed, promoting some sinuosity in flow within the otherwise straight reach. Several artificial drainage ditches meet the main channel, likely serving to drain the floodplain on either side of the channel.

The banks are eroding along numerous sections, which appear to be beginning to return a degree of sinuosity to the channel. The source of the erosion is mostly fluvial although some bank poaching is noted.

The erosion has in places exposed clean cross sections through the floodplain stratigraphy. A sedimentary log of the observed sequence is shown in Figure 3 (See Figure 5 for location). The current channel is incised into the underlying Barton Group, comprising light-grey clay with a weathered top surface. This is unconformably overlain by 0.5 m of floodplain deposits of presumably Holocene age. The sequence can be divided into two units:

Unit A consists of mottled, dark-grey silt. Gravel (flints) are found at the base, otherwise larger clasts are rare. Organic material is abundant, comprising rootlets and woody fragments. The dark colouration suggests a high organic content.

Unit B consists of reddish-brown sandy silts. A number of gravel stringers are observed, comprising subangular pebbles of flints and cherts. Roots are also abundant (as expected given the proximity to the ground surface), but woody material is noticeably less abundant than the underlying units. The more reddish colouration suggests less abundant organic material and/or oxidation in relation to soil forming processes.

Much of the floodplain has been historically cleared and a number of linear features, forming darker zones, can be clearly seen. These features roughly follow the current alignment of the Avon Water. Most have a much more sinuous planform, but some are linear. Some display an anastomosing pattern, particularly in the eastern areas (Figure 5b). The DEM data reveals that these features typically represent shallow depressions on the floodplain (Figure 5aii and bii), mostly 2-5 m wide and 50-150 mm deep.

Whilst relatively well defined in the aerial imagery, the features are more subtle on the ground. Some are demarked only by slight variations in topography darker patches in the overlying grasses (e.g. Figure 6a and e), Other features are more prominent, and form more pronounced depressions, often ephemeral in nature (e.g. Figure 6d).

## Feature mapping

A geomorphological mapping exercise was undertaken to mark the locations of floodplain features (Figure 7). The features were classified into three groups based on their inferred genesis and chronology.

S2 features are categorised as those related to recent anthropogenic modification. This includes the current straightened channel (Figure 6e). Also included are modern drainage ditches that drain the wooded ‘inclosures’ south of the study area. Other straight unnatural features were also included in this category, such as a straightened palaeochannel at Ossemley Ford (Figure 6f), marked as a channel on the historic maps (Figure 4).

The prominent single-threaded meandering palaoechannels are categorised as S1 features. These features are more noticeable on the ground, some displaying ephemeral connection to the main channel. Whilst not recorded on the maps within the study reach, downstream these features are often recorded as a channel on historical maps and are inferred to represent the pre-straightened planform configuration prior to the extensive drainage activities.

The anabranching palaeochannel network is characterised separately as S0

features. These palaeochannels are not recorded on historic maps. Furthermore these features are sometimes cross-cut by S1 features suggesting they existed prior to the development of the main S1 channel. It is therefore interpreted that their formation largely predates the development of the main S1 channel.

## Analysis of the wider catchment

LiDAR data was analysed of the wider Avon Water river corridor. As well as Ossemley Ford (the study reach), two additional downstream localities were identified where S0 features were also developed. These areas were mapped based on the same feature categories (Figure 8).

The downstream areas have been affected by similar anthropogenic modification; however, these section has been enhanced by recent river restoration activities as part of the Wootton Wetland Restoration Project (Mott MacDonald, 2024) led by the New Forest Higher Level Stewardship (HLS) scheme. River restoration techniques included the reconnection of palaeomeanders, infilling of the old straightened channel, and localised bed raising/bank lowering to improve floodplain connectivity.

The Wilverley bog site is located 1 km downstream of Ossemley Ford (Figure 8b). The river corridor is currently wooded, but the former S2 is can clearly be depicted from the LiDAR data. As with the Ossemley Ford site, an anastomosing network of depressions is visible on the floodplain, interpreted as palaeochannels. A prominent S1 single-threaded channel can be seen forming a deeper depression, recorded on the historical map (Figure 4). In addition a network of anabranching channels can be seen representing S0 features.

A similar arrangement can be seen at the Sheepwash Lawn site (Figure 8c). Here, apart from a small clearing, most of the river corridor is wooded. However, the LiDAR data reveals the straightened S2 palaeochannel and S1 single-threaded meandering channel (now reconnected following river restoration). A mosaic of additional palaeochannels can be seen on the floodplain representing the S0 features.

# Discussion

## Chronology and geomorphological evolution

Interpretations of the chronology and landscape evolution of these features are shown in Figure 9. Following deglaciation and climate stabilisation, it is envisaged that an evolved river corridor developed (Figure 9a), akin to the river-wetland corridors of Wohl et al. (2021) and the anastomosing wet woodlands of Cluer and Thorne (2014). The relatively low gradients mean stream energy and erosive power was probably low, which led to the development of relatively stable channel configurations. The forested, undrained catchment limits surface runoff promoting groundwater recharge into the underlying Pleistocene gravels and Eocene sandstone aquifers. This ensures a significant groundwater supply and reduces the magnitude of flood peaks.

The area is considered to have been extensively forested prior to the Bronze age (Tubbs, 2011). This would have led to the development of diverse tree habitats along the river corridor. The importance of large wood has been previously recognised as a key factor in controlling channel floodplain interactions within small fluvial systems of the New Forest (Jeffries et al., 2003; Sear et al., 2010a). Logjams trap debris as it moves downstream and can significantly reduce channel capacity, increasing the frequency and duration of out of bank flows. Those out of bank flows, scour out new drainage pathways, eventually leading to the creation of new channels. Reduced flow, and lower velocities may lead to deposition in the former channel leading to channel avulsion or multiple channels may remain connected either permanently or during high flows resulting in the development of an anastomosing channel morphology (Harwood and Brown, 1993; Montgomery and Piégay, 2003; O’Connor et al., 2003).

At the Avon Water, biogeomorphological interactions, and in particular the occurrence of large wood, combined with the high groundwater levels and low valley gradients led to the establishment of an anastomosing wet woodland and ‘Stage Zero’ of the river system. These carved out a network of anastomosing channels, which are represented by the S0 floodplain features, depicted in this study.

The frequent out of bank flooding, and high degree of floodplain connectivity supports the development of wetland environments within the river corridor. A wet woodland likely developed featuring a diverse succession of aquatic, emergence, riparian and floodplain plants. Floodplain soils are organic rich, and the high water table ensures organic material is retained and carbon sequestrated, depositing the dark-grey, presumably organic-rich sediments of Unit A.

Whilst Victorian-age straightening had probably the most pronounced effect on planform configuration, anthropogenic-induced changes are envisaged to have begun much earlier (Figure 9b). Given the key role of biogeomorphological interactions, the importance of forest clearance and land-use changes both within the catchment and the river corridor itself is becoming increasingly recognised (Cluer and Thorne, 2014; Sear et al., 2010b). Whilst the New Forest today still contains a high proportion of forested areas. Most of these areas are not natural and are related to commercial tree production. Most of the original woodland was removed during Bronze-age land clearance (Putman, 1986).

Numerous studies have recognised the effects of historical deforestation on river systems which is generally thought to have increased surface runoff and delivered large quantities of sediment to fluvial systems in the mid-Holocene (e.g. Brown et al., 2018; Collins and Walling, 2007). This accelerated floodplain sedimentation and promoted a lowering of the groundwater level.

Thick deposition of floodplain silts associated with these events are not recognised at the study reach. Instead, a thin interval of reddish-brown silts (Unit B) is recorded (Figure 3), which may be associated with these changes. Alternatively, these could be the result of soil forming processes and oxidation associated with the lowered of groundwater levels. However, this may struggle to explain the genesis alone due to the compositional differences between Unit A and Unit B.

Rivers with former anastomosing planforms without the associated thick floodplain alluvium do occur (Brown et al., 2018), mostly in catchments that have not been intensively cultivated. The absence of a thick unit at the Avon Water is likely reflective of the relatively small catchment area and possibly more prolonged episodes of clearance, without the extensive land cultivation of neighbouring areas.

The increased surface runoff associated with deforestation would have reduced groundwater recharge, and probably resulted in a lowering of groundwater levels. This may have reduced the baseflow component to the river and exacerbated flood peaks. These changes would have led to conditions that favoured the development of single-threaded planform configurations. This resulted in the establishment of the S1 floodplain features. These features signify reduced floodplain complexity and preference towards single-threaded planform configurations. The S0 channels are retained, but become perched on the floodplain. Connectivity decreases becoming intermittent and ephemeral at best.

The final stage of floodplain evolution was likely associated with Victorian-aged straightening and drainage (Figure 9c). Coppicing has been occurring in the New Forest since the early human settlers (Cook, 2018). However, by the 1660s, demand for timber increased significantly. Oak was initially planted, switching almost entirely to conifer as the need for straight timber increased. As the economic importance of the timber production became realised nationally, large areas were inclosed for timber production alone. Artificial drainage was installed to make the land more suitable for conifer which prefers drier conditions. The former meanders were cut by a straight channel running roughly east west across the landscape. These created the S2 floodplain features (Figure 9c).

This shortened reach lengths, increased the channel gradient and ultimately increased stream energy. The effects were compounded by the widespread land drainage activities associated with timber production. This perturbation likely increased flood peaks, leading channel incision to accommodate the altered hydrologic and hydraulic conditions. Channel adjustment is occurring as observed by areas of bank erosion and bar deposition, which should eventually increase sinuosity. However, rates of change are probably slow leading a long-term state of degradation. Some of which is now being reversed by the recent river restoration works recently undertaken within the catchment.

## Controls on wet woodland development

The catchment conditions within the Avon Water likely make it preferential for natural wet woodland development. The valley is sufficiently wide such that the river is unconfined and free to adjust its position across the floodplain. The groundwater is naturally high providing a significant proportion to flow and keeping the river corridor persistently wet. Energy is low limiting the erosive power of the river itself, limiting channel change through erosional processes. The extensive, mostly wooded nature of the natural river corridor would have allowed biogeomorphogical interactions to develop, with large wood causing the development of logjams which trap wood and sediment, leading to an increase in the frequency and duration of out of bank flows, allowing the wet woodland mosaic to develop.

These conditions are not unique to the Avon Water catchment. Wet woodland environments, are observed elsewhere in the New Forest, recognised at Highland Water and Blackwater. Where they persist today, they typically comprise anastomosing planform configurations, representing a network of paleochannels over the floodplain surface (Brown et al., 2018). However, these channels typically only have ephemeral connection to a main channel (Jeffries et al., 2003; Sear et al., 2010a), becoming active during high flows. This ephemerality is suited to the current altered hydrological conditions at these areas. Following the results of this study, it could be interpreted that the ephemerality of these environments represents the early stages of degradation from their natural evolved states (towards Stage 1 inFigure 9). Under these interpretations, these systems would have historically been better connected, possibly with simultaneously active channels.

The lack of intensive land cultivation and limited land-use changes has helped preserve the former channel network that reveal former anastomosing planform configurations in the New Forest. However, the underlying catchment conditions are not necessarily unique and the conditions that meet the criteria for wet woodland development occur commonly.

Recognition of Stage Zero states can be difficult, particularly elsewhere in more modified catchments. In the larger lowland rivers of the UK, the relicts of these former anastomosing planforms can sometimes be seen in the historical patterns of development around these rivers (Booth et al., 2007). In some cases, these former planform configurations have been buried beneath subsequent floodplain deposits (Brown et al., 2018). Where they remain, the scars have largely been removed by intensive agricultural practices. However, it is highly likely that anastomosing planforms, and particular wet woodlands along the river corridor were once much more common than they are today.

## Use of drones in river restoration

This study provides one example of how ‘off-the-shelf’ consumer-grade drones can be utilised for SfM photogrammetry to provide meaningful insight into floodplain development. This is particularly useful for areas like the study reach, where information on prior planform configurations is lacking and the S1 planforms, recorded on old maps (e.g. Figure 4) and have historically been used to inform palaeomeander reconnection as part of river restoration activities. The results of this study suggest that whilst these states are less modified, they are unlikely to represent true ‘natural’ states of the river and demonstrate the importance of having a robust geomorphological understanding of the catchment prior to undertaking river restoration activities.

Through the techniques applied in this study, it is possible to reconstruct the longer-term history of river systems. The outputs of this can be used as a template for future restoration efforts within the Avon Water, ensuring that river restoration that best suits the natural state of the river can be implemented.

The methodologies developed in this study can also be applied to other areas and has significant potential to be able to aid river restoration research. Low-cost, drone-acquired SfM photogrammetry gives river restoration practitioners the ability to rapidly collected photographic and topographic data. Whilst there should be acknowledgement of the limitations in accuracy over professional-grade surveys, the technique provides practitioners and researchers with a powerful new tool, that complements traditional field techniques and other remote sensing data. By adopting such techniques, combined with an understanding of landscape evolution, river restoration can be focussed on interventions that help accelerate return to their natural evolved states, thereby maximising the additional benefits that come with these conditions.

# Conclusions

This studly has utilised the novel application of SfM photogrammetry, to reconstruct a former anastomosing wet woodland in the New Forest, and its subsequent evolution to its modern planform configuration. The main conclusions can be summarised as follows:

* Whilst escaping extensive land-use changes and intensive agriculture, the Avon Water catchment has been affected by significant anthropogenic catchment modification.
* An anastomosing wet woodland likely developed by the mid Holocene, in response to biogeomorphological interactions occurring within an unconstrained valley and high groundwater levels. This represents an evolved Stage Zero state.
* Early anthropogenic modification, particularly Bronze-aged land clearance and drainage, are inferred to have altered hydrological and hydrogeological conditions leading to the preferential development of single-threaded planform configurations. The resulting planform probably had ephemeral connectivity to floodplain paleochannels that reflect the former anastomosing planform configurations.
* Extensive Victorian straightening canalised this meandering planform, leaving both the former planform configurations as scars forming subtle depressions on the land surface.

The study demonstrates that drones are an effective way to assess river restoration. When combined with existing datasets such as LIDAR they can be used as a low-cost and powerful tool for river restoration appraisal, which can be utilised in other areas to improve catchment understanding and provide a template for future restoration activities.

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##### Tables

**Table 1 –** Summary of the WEBODM outputs after processing

|  |  |
| --- | --- |
| Reconstructed Images | 177 over 177 shots (100.0%) |
| Reconstructed Points (Sparse) | 87729 over 87834 points (99.9%) |
| Reconstructed Points (Dense) | 19 |
| Average Ground Sampling Distance (GSD) | 3.4 cm |
| Detected Features | 1 |
| Reconstructed Features | 1 |
| Geographic Reference | GCP |
| X Y error | 5 cm |
| Z error | 13 cm |

##### Figure legends

**Figure 1** **–** (a) Map showing the location of the New Forest. (b) LIDAR Composite Digital Terrain Model (DTM) (updated 2024) of the Avon Water catchment, showing the locations of the analysed reaches. Longitudinal profile of the River Avon. A = Ossemley Ford (study site). B = Wilverly Bog. C = Sheepwash Lawn.

**Figure 2** **–** Photographs of the study area. (a) Typical channel characteristics showing artificial straightened channel. (b) Drone photograph showing linear features on the floodplain at Ossemley Ford. (c) Historic ford with minor bank erosion and poaching. (d) J-shaped trees now growing along straightened channel. (e) Palaeomeander reconnection at Sheepwash Lawn showing newly created channels with Large Wood. (f) Wet woodland restoration at Sheepwash Lawn.

**Figure 3** **–** Sedimentary log through the floodplain stratigraphic sequence exposure on the banks of eroding parts of the Avon Water at Ossemley Ford.

**Figure 4** **–** Historic map of the River Avon within the study area showing historic straightening. Only the straightened channel is shown at Ossemley Ford, whilst the former meandering channel is mapped for downstream sections.

**Figure 5** **–** High resolution drone orthophotos (i) and DEMs (ii) of the Avon Water at Ossemley Ford (scale in meters). (a) Sinuous features representing subtle depressions on the floodplain close to the historic ford. (b) Larger sinuous depression meandering within an anastomosing network of dark linear features.

**Figure 6** **–** Photographs of floodplain features viewed from the ground. (a) Anabranching linear depression looking west. (b) Anabranching linear depression looking east. (c) Subtle meandering depression looking west. (d) More prominent depression partially filled with water showing ephemerality. (e) Artificial, straightened main channel with small embankment. (f) Artificial channel, recorded in old maps, but now disconnected from the main channel.

**Figure 7** **–** Interpretation of high resolution drone orthophotos and LiDAR DEM, showing the chronological classification of floodplain features.

**Figure 8** **–** Geomorphological map of the study area, showing the locations of additional areas along the River Avon where former wet woodland mosaics can be mapped. Also shown is three dimensional projection of DEMs, revealing the channel features.

**Figure 9** **–** Schematic box models showing the evolution of the river corridor within a wet woodland mosaic of the Avon Water. (a) 2Ka BP, showing the natural wet woodland that developed as the drainage system matured following deglaciation. (b) 200 years BP, showing the initial anthropogenic modifications to the catchment (tree clearance) and envisaged subsequent effects on drainage configuration. (c) Present-day channelised system that developed as a result of Victorian-age straightening and land drainage.