Late Quaternary evolution of a lowland anastomosing river system: geological-topographic inheritance, non-uniformity and implications for biodiversity and management

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Abstract

Lowland multiple-channel rivers are characterised by floodplain-corridor heterogeneity, high ecological and heritage value, and can be in quasi-stable states. This holistic study of a surviving temperate zone example (Culm, UK) using geomorphological mapping, ^{14}C, direct sediment dating (OSL, fallout radionuclides), and palaeoecology, reveals the evolution of a channel-floodplain system from an initial braided state in the Late Pleistocene to its late Holocene anastomosing state. After the Pleistocene-Holocene transition the reduced channel system incised into its braid-plain, only able to rework gravels locally due to reduced competence in relation to inherited bounding sediment calibre. This resulted in the creation of terrace islands, palaeochannels, and a stable anastomosing pattern dominated by channel junctions, bifurcations and palaeochannel intersections. Survey, coring and excavation reveal a persistence of mid-channel bars and riffles at channel junctions, and where channels crossed palaeochannel fills. In common with most other European lowland rivers this system evolves in the later Holocene due to both climate and catchment changes with a major hydrological critical transition in the mid-Holocene (c. 5300 BP). However, in the case of the Culm, the increase in fine sediment supply often seen in lowland catchments in the Middle-Late Holocene, occurred later, and was insufficient to convert the system to a single medium-low sinuosity channel-floodplain. This allowed the persistence of high heterogeneity and biodiversity (including the persistence of riffle beetles) as part of multiple-scales of non-uniformity. Indeed the pool-riffle persistence is an example of this system's non-uniformity, being due, at least in part, to the effects of previous channel history. This paper reveals why this river survived in a multichannel state, and by implication, why others did not. These results are being used in the bespoke eco-heritage management of the Culm, but could also inform the restoration of other former multi-channel lowland temperate river systems worldwide.

Keywords: landform non-uniformity, river corridors, catchment change, floodplain ecology, Coleoptera, rewilding

1. Introduction

To Quaternary geologists rivers are geological agents directionally forced by climate and tectonics (Rittenour et al., 2007; Macklin et al., 2015; Prins and Andresen, 2019); whereas fluvial geomorphologists have been particularly interested the degree to which rivers can be regarded as equilibrium forms balancing discharge, sediment and slope (Leopold et al., 1964; Nanson and Huang, 2018; Chartrand et al., 2019), although most rivers are not in a state of equilibrium, but are self-adjusting and are subject to a range of inherited conditions (Tooth and Nanson, 2000; Brookes and Brierley, 2000; Lewin, 2011; Fryirs et al., 2016; Gallagher et al., 2018). Non-equilibrium conditions have generally been seen as arising due to forcing factors or anomalies, associated with bedrock outcrops, or large organic debris and related turbulence fluctuations (Thompson and Wohl, 2009). The conceptual gap between process and evolutionary approaches is largely explained by a differing temporal and spatial perspective, and questions of generality (Schumm and Lichty, 1965; Schumm, 1977; Lane and Richard, 1997; Gregory and Lewin, 2015). However, identifying the effect of inherited boundary conditions remains fundamental to understanding channel stability and resilience, and has fundamental management implications. The role of the resisting factors as well as the driving factors is highly relevant to ecological conditions allowing a variety of disturbance regimes to dominate the system (Gurnell et al., 2005; Brown et al., 2018). This paper takes a holistic approach to one lowland multiple-channel floodplain system, the Culm in SW England, over the current interglacial and assesses how its evolution has influenced its current geomorphological state, equilibrium vs non-equilibrium conditions, and ecological resilience in the face of climate and land use change.

1.1. The demise of the multi-channel river

The low-energy multiple-channel river state can be meta-stable, and there is abundant evidence that it was a common, if not the most common, state of lowland rivers in the early-middle Holocene at least in NW Europe (Petts et al., 1989; Lewin, 2010; Brown et al., 2018). Multiple-channel river floodplains are also of high ecological value given their high biodiversity due to high-patch heterogeneity, and spatially variable disturbance regimes (Harper et al., 1997; Brown, 1997; Gurnell and Petts, 2002; Davis et al., 2007; Brown et al., 2018). These floodplain-channel systems therefore represent a desirable state to which rivers can be restored or ‘rewilded’ (Oakley, 2010; Lezpez et al., 2016; Cluer and Thorne, 2013; Powers et al., 2018; Marcinkowski et al., 2018). However, ecological aspirations and present management are constrained by our limited understanding of what promoted the stability of multiple-channel systems and how resilient these systems are in response to a variety of stressors (Power et al., 2018), although physical modelling has undoubtedly made major contributions here (Kleinhans and Berg, 2010; Nicholas et al., 2013). This paper uses Quaternary data from one of the few surviving multiple channel systems in the UK to reconstruct the system’s evolutionary history, emergent and persistent fluvial properties, temporal and spatial changes in habitats, and system response to catchment change. The ultimate aim is to assess system resilience given anticipated climate and catchment change and management options.

Historical evidence gathered over the last half century shows how 18th-20th century CE river channelization forced many rivers, including major rivers, such as the Mississippi, Volga, Po, Danube, Seine, Rhone and Rhine, into embanked channels, and in most cases into a single large channel (Alexander et al., 2012; Middelkoop, et al., 2005; Braga and Gervasoni, 1989; Pišút, 2002; Petts et al., 1989; Mordant and Mordant, 1992; Bravard et al., 2008; Berendsen and Stouthamer, 2001; Candel et al., 2020). Research, largely archaeological, also indicates that most larger UK rivers were anastomosing in the early-middle Holocene (Lewin, 2010) including the lower Thames (Siddell, 2000; Allen and Mitchell, 2001), Middle Trent (Buteux and Chapman, 2009), the midde-lower Nene (Brown 2004) and smaller rivers such as the Lea, in London (Lewin, 2010). Several of these rivers have retained anastomosing reaches, usually with two or three channels, including the Lower Severn, Nene, Axe and Hampshire Avon. Many small UK and mainland European rivers were also channelized (Brookes, 1988: Tockner et al., 2009), with early maps recording the original multiple-channel patterns prior to channelisation and arterial drainage (Brookes, 1983; Brown et al., 2018). With the exception of high-energy braided multi-channel systems, lowland multiple-channel systems have received less attention from Quaternary scientists, or geomorphologists, largely due to their comparative rarity in the temperate zone today, although there are notable exceptions (Lewin, 2010). Low energy multiple-channel rivers are taken here to include both anastomosing rivers and anabranching rivers. If defined as a multiple-channel system characterised by vegetated, or otherwise stable, alluvial islands that divide flow at discharges up to nearly bankfull (Nanson and Knighton, 1996), then anastomosing systems (*sensu* Knighton and Nanson, 1993) are low-energy variants, of a broader category of anabranching systems (*sensu* Smith and Smith, 1980; Schumann, 1989; Nanson and Knighton, 1996; Carling et al., 2014). However, there is some terminological confusion in the literature as Mollard (1973) used the term anastomosing for what others have described as wandering gravel bed rivers (Church, 1983) and in many cases this term has been used interchangeably with stable multiple-channel rivers. The problems are not just semantic as the distinction between high-energy gravel-dominated, laterally active anabranching rivers (Nanson and Knighton's Type 5), or gravel-dominated, stable anabranching rivers (Nanson and Knighton's Type 6), and wandering gravel-bed or braided rivers appears to be largely evidence of channel change and/or vegetated floodplain inundated at or above bankfull discharges. Modelling has suggested that the critical differentiating factors of braiding vs anabranching are bank resistance, a mixture of grain sizes and stabilisation by vegetation (Nicholas, 2013; van Dijk et al., 2013). These three factors are closely related and can be examined through time using sedimentology, palaeoecology and an alluvial chronology.

Multiple-channel systems can change 'abruptly' through avulsion (Stevaux and Souza, 2004), although in practice this usually occurs over several floods (Smith et al., 1989). Studies have also suggested that they can be in a stable-state representing a least-cost state in energy terms (Nanson and Huang, 1999). While this may explain their persistence, it is still not clear whether this state had always been the case, or if it has evolved from a meandering state, or from another channel pattern such as braiding. Here we are concerned with channels in regions which previously experienced glaciation, periglaciation, paraglaciation and major hydrological change associated with the last glacial-interglacial cycle. The transition to anastomosis and the question of system non-uniformity is important as it will condition system resilience to both catchment and climate change (White et al., 2010).

There is historical and contemporary ecological evidence of high biodiversity associated with the lowland multi-channel state from the relatively few systems that have persisted and which are now biodiversity hotspots (Brown, 1997; Brown et al., 2018). These include The Gearagh in SW Ireland (Brown, 1998; Cudmore, 2012), Narew in Poland (Marcinkowski et al., 2018) and Litovelski Pomoravi in Moravia (Simon et al., 2014). These systems have high species diversity in a number of organism groups including; vascular plants (particularly aquatics), pteridophytes (ferns), cryptogrammes (mosses, quillworts and liverworts), fungi, birds, and insects and this often includes rarities. Causes of this high diversity are the juxtaposition of channels of different sizes and hydrogeomorphological characteristics (flow velocity, turbidity, temperature etc.), abundant dead-wood and the disturbance state (Ward and Tockner, 2001; Davis et al., 2007; Tickner et al., 2020). A connection between these factors is a system-scale property relating to non-uniformity and the persistence of non-equilibrium states. The reasons given for the survival of the few extant multiple-channel systems in Europe include cultural-historical factors; such as being incorporated into protected environments in the Medieval period in the cases of the New Forest, UK, and Litovelsé Pomoravi (Harper et al., 1997; Sear et al., 2010), being remote (Wheaton et al., 2013) or being less impacted by catchment change, particularly increased fine sediment supply (Brown et al., 2018). All these explanations suggest that the anastomosing systems lacked resilience, and that they had a low ability to withstand changes in flow and sediment regime. This is examined in this paper in relation to a system that was not protected, not particularly remote and has had a regionally-typical NW European land use history.

1.2. The Culm floodplain

It is significant that the derivation of the name ‘Culm’ is believed to be ‘a tie or knot’ (Ekwall, 1960; Hesketh, 2008) which is thought to refer to the rivers pattern of twists, loops and intersections, and it implies that this was a notable feature of the river pattern at least 1000 years ago (Ekwall, 1960: Pears et al., 2020a). This is reinforced by other placenames, most notably the existence of two farmstead called ‘Five Fords’, in two of the reaches utilised here. The floodplain is 55 km long in a small-medium sized catchment (276 km^2) of moderate relief (Fig. 1) which drains into the River Exe and the English Channel. The catchment drains the western edges of a plateau of moderate relief (Blackdown Hills) and has a mean discharge is 3-5 m^3 s^{-1} and a maximum gauged flow of ~ 100 m^3 s^{-1} (Woodmill, Drissoll et al., 2017, Supplementary Table S1). Importantly approximately 30% of mean discharge is baseflow (baseflow index 0.54 *sensu* Gustard et al., 1992) from the variably-permeable Permo-Triassic and Upper Greensand strata of East Devon and a set of springlines around the Blackdown Hills (Sherrell, 1970; Institute of Geological Sciences, 1982; Brown et al., 2014).

The floodplain gradient is typical of UK piedmont rivers (i.e. transitional lowland to upland) at 0.001-0.005 m m^{-1} and given a bankfull discharge of ~10 m^3 s^{-1} this places the system in the upper meandering zone to the transitional zone between meandering and wandering channel patterns *sensu* Miall (1977), or braiding (Buffington and Montgomery, 2013). The catchment is underlain by approximately horizontally bedded Mesozoic sedimentary rocks including sandstones, mudstones, conglomerates and breccias. The thickness and relatively un-cemented nature of these Breccias (Triassic Budleigh Salterton Pebble Bed formation) has led to the reworking of clasts into well-developed Pleistocene terraces that are dated for the first time here. Floodplain and channel sediments are well exposed in natural bank sections, and vary from grey and red sandy silts, though well-sorted sands to gravels composed of pebbles and cobbles. In the upstream floodplain reaches, small flat-topped terrace remnants are preserved at heights of 0.5-2 m above the active floodplain, with a more significant terrace preserved on the valley sides 2-4 m higher (Brown et al., 2010). In the upper reaches of the Culm, the river is anastomosing, while closer to its confluence with the Exe, it becomes a single sinuous-planform channel (Fig. 1). The Culm has a classic longitudinal profile with no clear bedrock steps but the effect of weirs is just discernible (Fig. 2).

Process geomorphology has been studied in the Culm for over 40 years, including studies of bank erosion (Hooke, 1979), overbank sedimentation (Simm, 1995; Walling et al., 2004), overbank flow sedimentation and modelling (Gregory 1997; Nicholas and McLelland, 1999; Hardy et al., 2000; Marks and Bates, 2000), development and application of sediment fingerprinting (Walling and Woodward, 1995) and use of short-lived fallout radionuclides for the measurement of erosion and floodplain sedimentation (Lambert, 1986; Walling and Bradley, 1989; Simm, 1995; Sweet et al., 2003). This provides an unusually good present-day reference-base and process understanding for this study (Supplementary Table S2).

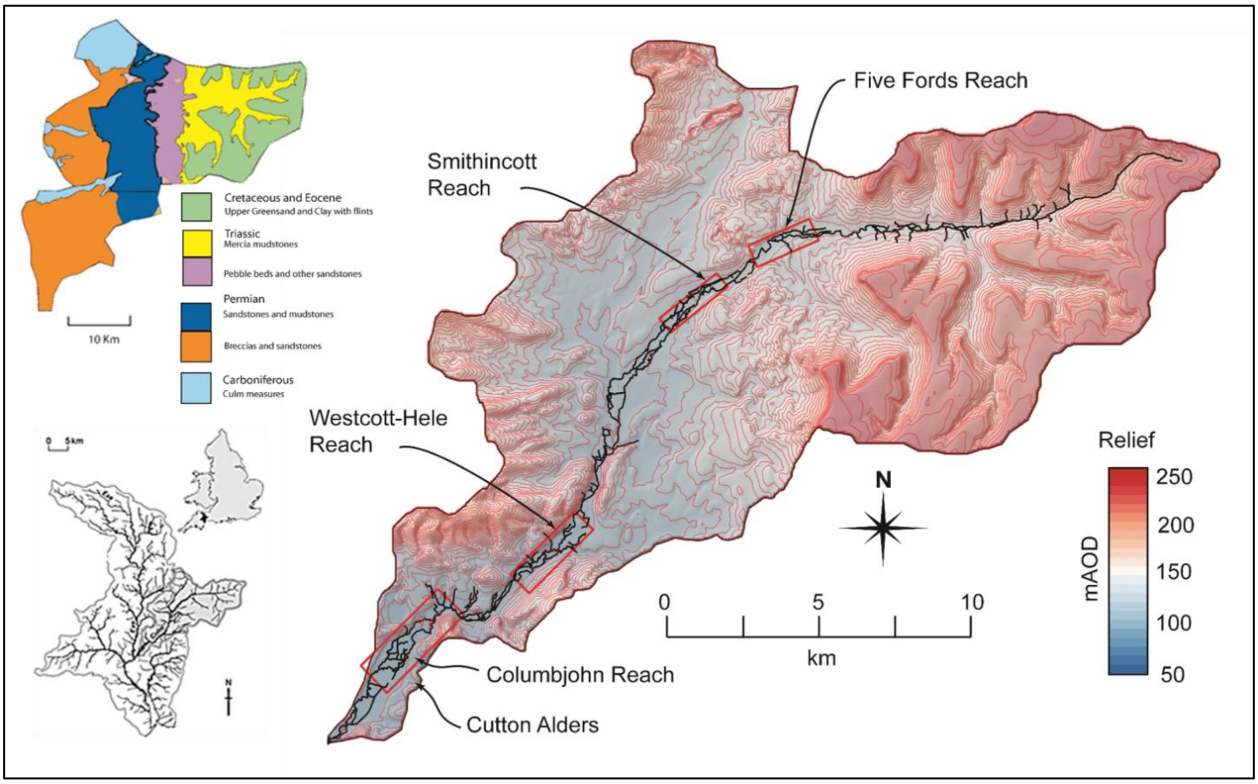

Fig. 1. location of the Culm catchment in East Devon, UK (Inset bottom left), geology adapted from British Geological Survey online data, and catchment relief from 50 m resolution Lidar DTM basemap (Environment Agency 2017). The location of the Cutton Alders site is also shown. The centre-point of the basin at the head of the Smithincott Reach is Lat. 50.904614°N, Long. -3.324311°E

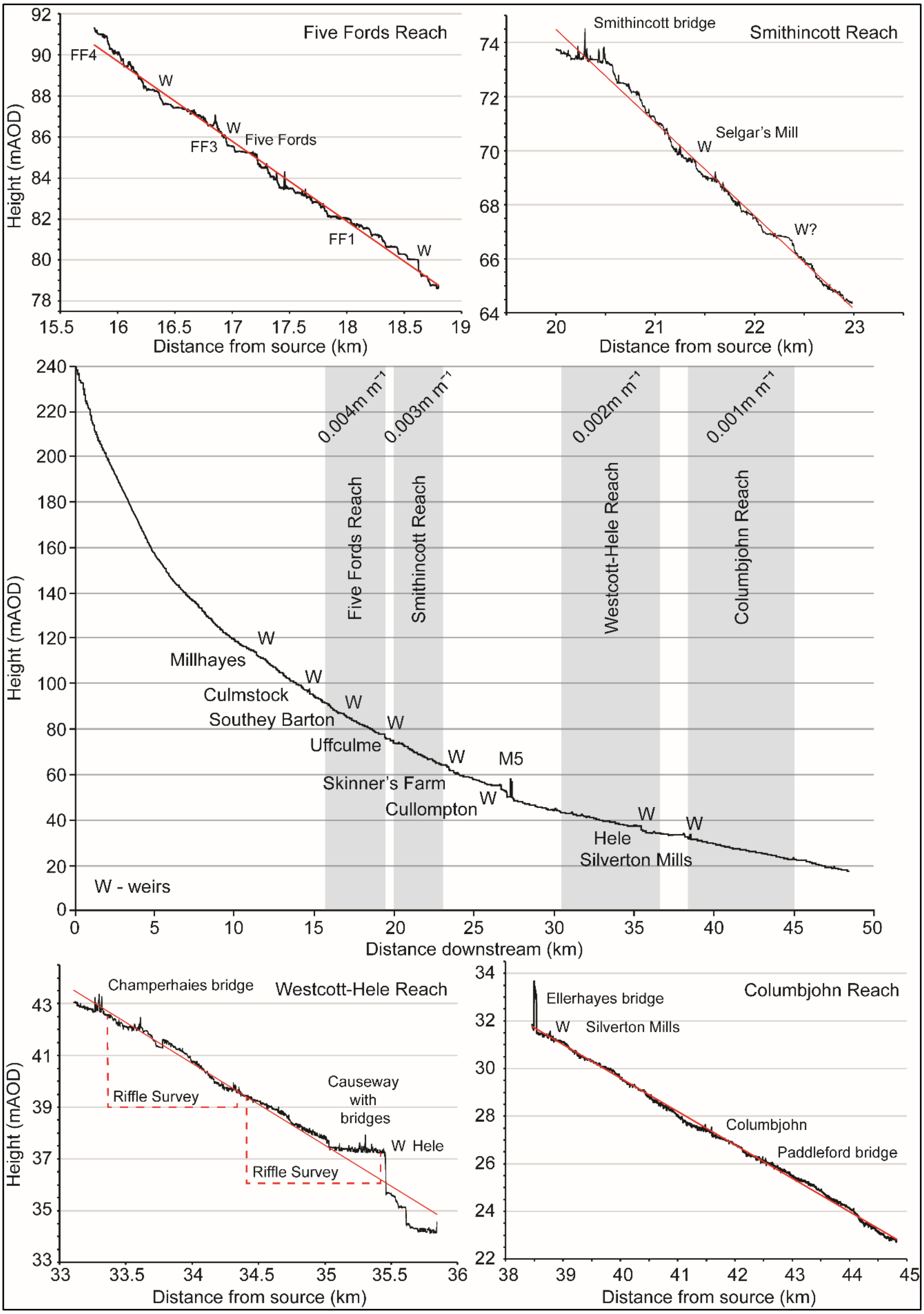

Fig. 2. Culm floodplain gradient and channel gradients extracted from 1 and 2 m Lidar DTM (Environment Agency 2019) at 0.1 m intervals with 1 m smoothing. Gradient models show locations of four research reaches; Five Fords (FF), Smithincott (SM), Westcott-Hele (WH), Columbjohn (CJ) with key settlements and locations of major weirs, mills and bridges.

2. Methods

2.1. Mapping, survey and lithology

Four reaches were chosen which together comprise 40% of the floodplain length (Fig. 1c, Fig. 2). In these reaches channel pattern was mapped from aerial photographs and field survey at a scale of 1:2,500 undertaken field by field. This turned out to be important as, aerial mapping only revealed a maximum of 37% of the length of palaeochannel mapped in the field. A long-profile survey of selected sub-reaches involved standard topographic surveying (using a total station) down the channel thalveg during low-flow. Floodplain lithology and sub-surface stratigraphy was determined by, hand-augering, coring and test pits augmented by ground penetration radar (GPR) using a Pulse Echo 1000 at 225 MHz. Historical channel change was determined from topographical maps including the 1st Edn., OS map (1840 CE). Sediments from cores, exposures and test pits were described using standard sediment field-methods and organic sediments described using the modified Troels-Smith system. The maps presented here in Supplementary Figs. F1-F4, are the original channel survey maps overlaid onto the relevant sections of the GIS-based mapping of the historic watercourse and feature polygons and land use produced by Fjordr Ltd. For Historic England, reproduced here by permission and full sources are given in the captions.

2.2 Dating: ^{14}C, OSL and radionuclides.

Radiocarbon samples were selected from organic-rich sediments and where possible, identified, plant macro-remains. Thirty samples of identified plant remains were submitted for AMS radiocarbon dating and where possible, selected samples were used to provide a basal date for each palaeochannel sequence and a date from the centre of each coleopteran sample. Radiocarbon dates (Supplementary Table S3) were calibrated to 2σ (95% confidence) using CALIB7·1/IntCal13 (Stuiver et al., 2020). To minimise preservation bias associated with ^{14}C, we collected 26 samples for optically stimulated luminescence (OSL) dating from 15 different locations within the target reaches (Supplementary Table S4). OSL samples were collected using opaque PVC tubes pushed into cleaned vertical sections. In-situ NaI gamma spectrometry was undertaken at each sample position to measure the natural environmental dose rate. Only sediment from the central portion of each sample tube was used for dating, to ensure that it was not exposed to daylight; sediment from the end of the sample tubes was used for neutron activation analysis (NAA) of K, Th and U content, in order to estimate beta dose rates. Quartz preparation followed standard procedures (Rhodes, 1988) under controlled laboratory lighting, involving dilute HCl treatment to disaggregate grains and dissolve carbonate, concentrated (40%) HF treatment of wet-sieved 125-180 µm sand grains to dissolve feldspar and remove the outer, alpha irradiated zone of each quartz grain, followed by removal of heavy minerals using a sodium polytungstate liquid of density 2.68 $g.cm^{-3}$. Samples were agitated continuously during the HF treatment, which was performed for 100 minutes at room temperature. After drying, each sample was re-sieved using a 125 µm mesh to remove partly digested grains, and mounted on 1cm diameter aluminium discs using a viscous silicone oil.

All OSL measurements were made using the single aliquot regenerative-dose (SAR) protocol of Murray and Wintle (2000) (Supplementary Table S5). OSL was determined at 125ºC using an array of blue LEDs and measured through 7.5mm U340 with an EMI 9235QA photomultipler tube (PMT). Natural and regenerative-dose OSL measurements were preceded by a 10s preheat at 220ºC, while test dose OSL measurements were preceded by a 10s preheat at 200ºC. This preheating combination has been found to provide excellent agreement between OSL and radiocarbon age control for Holocene sediment samples from a wide range of different geomorphic and archaeological contexts (Rhodes, 2011). IRSL measurements were used to identify potential feldspar contamination, and the OSL performance of these samples was assessed using recycling ratios and thermal transfer magnitude following a zero dose. For each sample, 12 aliquots were measured; variation in equivalent dose (D_e) between the aliquots was in many cases clear cut, indicating incomplete zeroing at the time of deposition for several samples or the introduction of younger intrusive grains from higher up the profile (for example by root activity). To assess the degree to which grains may have their OSL signals reduced by daylight exposure under natural conditions, the OSL from two modern samples was also measured. Both ^{14}C AMS and OSL dates are quoted in the text as median ages BP where P is 1950 CE, but full data including errors is given in Supplementary Table S3 and S5. Dates are not rounded in the text only in order to facilitate comparison with the full date tables.

Two field sampling schemes for fallout radionuclides were employed. One was cluster sampling, where stratified geomorphic units were targeted and cores taken within that unit and from nearby contrasting units. The other was transect-based, with cores taken across the floodplain width. Coring was to a depth of 0.60-0.80 m, or less if gravels were encountered, and was carried out using a motorised percussion corer to drive a sampling tube into the sediment. A single bulked sample was extracted from the tube. A steel tube with an area of 38 cm^2 was used to obtain these cores, which were used in determining their total caesium-137 (^{137}Cs) and excess lead-210 (^{210}Pb$_{ex}$) inventories. For some sampling points, information on the depth distribution of ^{137}Cs and ^{210}Pb$_{ex}$, as well as the total inventory, was obtained. In this case, a larger PVC soil pipe with a cross section of 82 cm^2 was used with the percussion corer to collect the core. Undisturbed cores were extracted by slitting and removing the PVC tube in the laboratory and extracted cores were then sectioned into 1 cm depth increments. All samples were air dried, prior to oven drying at 100°C, disaggregation and homogenisation and sieving to recover the < 2mm fraction for subsequent radiometric analysis. The small samples provided by depth incremental slicing of cores were processed manually. In the case of the larger bulked samples, a mechanical rotary sieve was used for this purpose. For radiometric analysis, samples were packed into Marinelli containers (for bulked samples) or plastic pots (for sectioned samples) and sealed with PVC-tape for >21 days before being counted using a low-background HPGe gamma detector for at least 24 hours. Activities and inventories of ^{137}Cs and ^{210}Pb$_{ex}$ were measured and calculated with reference to established calibration relationships derived using standards with known activities. Excess lead-210 activities were determined from measurements of total ^{210}Pb and ^{226}Ra (via ^{214}Pb). Cores were also collected from reference sites situated above the floodplain which were unaffected by erosion or deposition. Sedimentation rates were quantified using either the bulk inventories or the down-core profile distributions of the two radionuclides. Details of the methodologies used are provided in the Supplement (Supplementary Text and Supplementary Table S6). For particle size analysis, samples were pre-treated with hydrogen peroxide to remove organic matter, chemically dispersed using sodium hexametaphosphate, and then passed through a 63 µ sieve to separate the sand fraction. A Malvern Mastersizer was used to determine the particle size distribution of the <63 µ fraction. Surface scrape samples from points adjacent to the bulk cores were also collected and analysed for particle size distribution to estimate the correction factor required for the estimation of sedimentation rates.

2.3 Palaeoecology: macro-remains, pollen, insects

Samples were taken from cores or where possible large monolith tins from excavations and bank sections. Macrofossil sub-sampling was combined with the insect sampling (see below). Where macrofossil samples were taken directly from the bulk samples, a 500 ml wet sample was removed and placed in a bucket of warm water and disaggregated by hand or overnight. Samples were then passed through a series of >1 mm; 500 µm and 250 µm sieves. The remaining sample was then sorted and macrofossils were removed for identification using a low power microscope. Macrofossil keys used were Beijerinck (1947) and Katz, Katz et al. (1965) in addition to the Exeter University macrofossil reference collection. Where wood fragments were suitable for identification radial, X-sectional and tangential thin sections were cut from each piece for identification, under 400x magnification and diagnostic features were recorded using Schweingruber (1982; 1990). Pollen used standard processing with HF and acetolysis, and mounted using silicone oil. Identification used standard flora (Stace, 2010) and the University of Exeter and later University of Southampton reference collections.

For insects, bulk samples of 7–10 l sediment were collected and where possible, multiple sediment samples for beetle analysis were collected in 10–15 cm spits. Sample preparation followed a standard paraffin flotation technique (Kenward et al., 1980). The resulting ‘flot’ was decanted and washed with warm water and detergent to remove the excess paraffin. The flots were then sorted for insect remains under a low power stereomicroscope and the resulting remains stored in denatured ethanol. Coleoptera were identified with reference to the collections housed in the Royal Albert Memorial Museum, Exeter with the aid of standard entomological keys. Taxonomy follows that of Lucht (1987) with revisions by Böhme (2005). Coleopteran data were analysed using Detrended Correspondence Analysis (DCA) in the form of both raw count and binary (presence–absence) data using the CANOCO 4·5 computer package (ter Braak and Smilauer, 2002). Detrending was performed by segments, rare taxa down-weighted and raw count data were square root transformed. Ordination employed environmental categories based upon the ecological groupings devised by Robinson (1981, 1993), which were treated as supplemental variables. These were supplied as a percentage of individuals belonging to each ecological category. Coleopteran taxa were assigned to ecological categories using detailed modern ecological information derived from the BUGS Coleopteran Ecology package (Buckland and Buckland, 2006).

3. Results and data specific interpretations

3.1 Channel pattern, stratigraphy and lithology

The floodplain increases in width downstream, and all four reaches are characterised by a dense palaeochannel network (Fig. 3, Supplementary Figs. S1-4), with varying amounts of surface expression (0-3.0 m). The palaeochannel length in each reach in all cases exceeds the active channel length by between 40% and 120% (Table 1). The planforms of the active main channels display low sinuosity (1.1-1.5) but taking the entire active channel system this almost doubles (1.6-2.6). This is still lower than the palaeochannel sinuosity although it is unlikely that the whole system was ever active simultaneously, except in floods (Table 1). In several areas, particularly at the edges of the floodplain, but also in mid-floodplain, low terraces could be mapped at c. 0.5-2.0 m above the general floodplain surface. These terraces are also dissected by channels and bounded by intersecting channels, effectively forming islands in the floodplain. Of particular note are intersections of palaeochannels. The most common junction number is 3 but many junctions have 4 and one case of 5 was noted.

Table 1. Channel and palaeochannel statistics for each reach with reach abbreviations. Figures in parentheses are the sinuosity based upon the total reach length. C junctions are ‘conformable’ junctions, U junctions are ‘unconformable’ junctions (for explanation see text).

Reach (abbreviations)	Reach length (m)	Floodplain rel. relief (m)	Main channel length (m)	Total channel length (m)	Total palaeo-channel length (m)	Total AP palaeo-channel length (m)	No of C junctions	No of U junctions	Mean Depth to gravels (m) and (2σ)	Reach slope (m m^1)
Five Fords (FF)	2040	2.90	2825 (1.38)	4865 (2.38)	6925 (3.40)	5637	31	8	0.62 (0.2)	0.005
Smithincott (SM)	2000	2.26	2390 (1.19)	3315 (1.65)	7285 (3.64)	3929	16	19	0.66 (0.4)	0.004
Westcott-Hele (WH)	3120	2.85	3904 (1.25)	7544 (2.42)	16320 (5.23)	8223	45	10	0.8 (0.2)	0.003
Columbjohn (CJ)	3538	1.95	5407 (1.52)	9214 (2.60)	14707 (4.15)	10245	32	10	2+	0.001
Total	10,698	-	14,526	24,938	45,237	28,034	124	47	-	-

Surveying and coring revealed that in most palaeochannel junctions the channel joined at the same elevation but also that many dry junctions contained small islands (buried bars) composed of gravel (Fig. 4, Fig. 5 and Supplementary F1-F4), which are here termed *conformable junctions* (C junctions). In other cases either topography and/or coring revealed the channel beds to be at different altitudes (by up to 0.5 m) with the junction often at a high angle; these are referred to as *unconformable or intersection junctions* (U junctions). Statistical evaluation of the length of palaeochannels, channel-palaeochannel ratio, and the number of palaeochannel bifurcations and intersections reveals differences between the reaches with the Smithincott reach having a proportionately lower total active channel length, lowest main channel sinuosity and reversed ratio of bifurcations to intersections with more unconformable junctions than conformable (Table 1). This suggests that the channel history of this reach has differed from that of the other three, being characterised more by a dominant main-channel and meandering state.

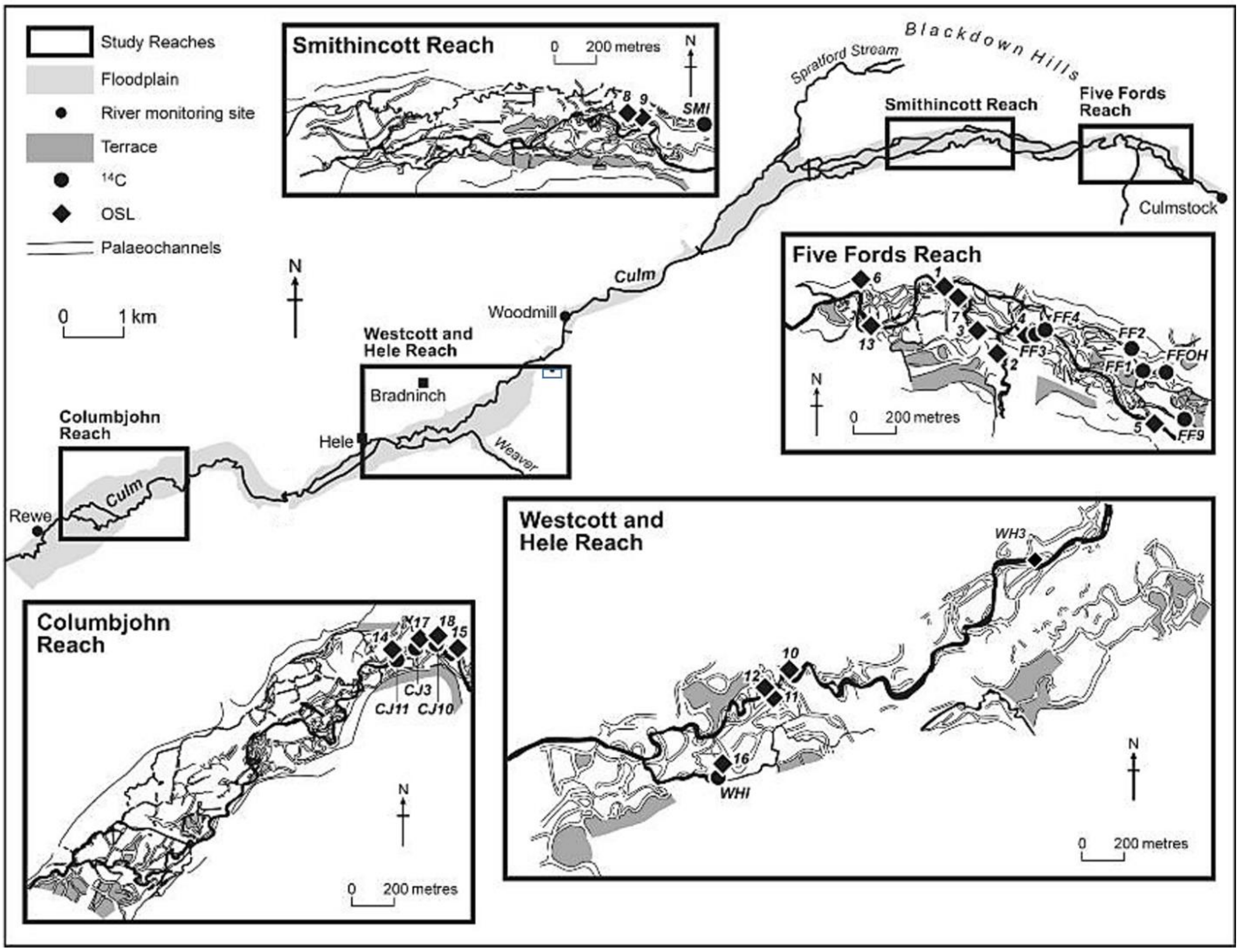

Fig. 3. Summary maps of the reach active channel, palaeochannels and terraces with sampling locations for Five Fords (FF1, FF2, FF3, FF4, FFOH), Smithincott (SM1), Westcott-Hele (WH1, WH3) and Columbjohn (CJ3, CJ10, CJ11). The numbered triangles refer to the OSL sampling locations. For more detailed maps of each reach see Supplementary Figs. S1-S4.

Other distinctive fluvial features include goose-neck planforms and closed loops, presumably formed by meander expansion, and neck cutoffs. Another rather distinctive feature is a channel spur, which is normally located where a palaeochannel re-joins an active channel, and their persistence is probably due to confined flow off the floodplain as the river stage falls on the declining limb of the hydrograph and as modelled by Nicholas and McLelland (1999). Features indicative of lateral channel migration, such as unilateral benches and scroll bars, exist but are uncommon (Supplementary Figs. S1-4). Transects surveyed across the entire floodplain (Fig. 4) reveal considerable relative relief. The relative relief is greatest upstream at the Five Fords reach (Table 2; 2.9 m mean total and up to 2m above bankfull) and declines downstream to under 2 m in mean total at Columbjohn (with under 1 m above bankfull). For the Five Fords and Smithincott reaches the floodplain relative relief is similar to the range of channel depths, whereas at Westcott-Hele and Columbjohn channel depths exceed floodplain relief. Coring, and GPR survey, along these transects revealed that the depth to gravels reflected the topography except across some palaeochannels where buried bars were present. Coring revealed that the palaeochannels could be divided into four groups:

a) topographic expression but no significant fine (sand-clay) sediment fill;
b) topographic expression and a significant fine sediment fill over a gravel bed;

b) no topographic representation but with a fine sediment fill over a gravel bed;
c) no topographic representation with fine sediment fill buried by gravels (buried palaeochannel).

The mean depth to gravel between the gravel islands increases downstream from <1m to >2m and becomes more uniform (Fig. 4, Table 1).

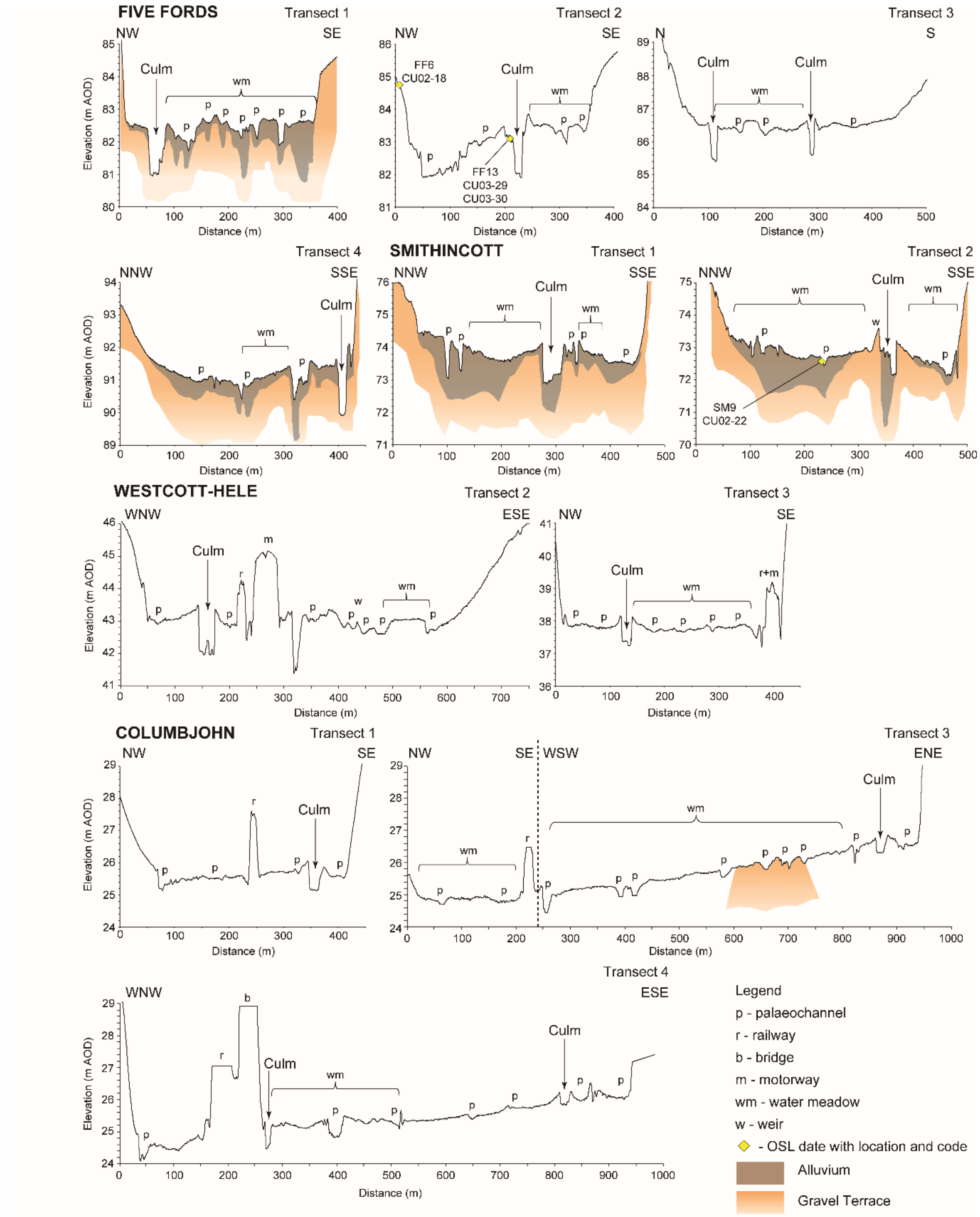

Fig. 4. Surveyed topographic floodplain cross-sections with depth to gravels for some sections.

3.2. River channel long-profile survey

While the survey was being undertaken an apparent relationship was noticed between the location of thalweg highs/riffles, mid-channel bars and sites with organic channel fills. Riffles were just identified as topographic highs in the thalweg and so included mid channel bars, and diagonal bars as well as classical riffles downstream of pools, so both forced and free-form *sensu* Montgomery et al. (1995). Riffles and in some cases islets (vegetated bars), appeared to occur at the point of intersection or just at the edge of palaeochannels particularly on the upstream. In these cases, the riffle appeared to be a continuation of the point bar of the intersecting palaeochannel. In order to investigate this further riffles were located onto the reach maps and a topographic survey of the main channel in the Westcott-Hele reach was conducted at low flow which allowed creation of a long-profile of the and the plotting of all riffles on the floodplain map (Fig. 5a,b).

The number of riffles appears relatively constant in the different reaches and equates with a mean channel width of 10-20 m and hence conforms approximately to the classical spacing of 5-7 times the channel width (Table 2, Leopold et al., 1964). However, locally, the spacing is extremely variable and also clustered in apparent association with palaeochannel intersections (Fig. 5b).

Table 2. Long-profile survey, riffle numbers, statistics and dates for the excavated riffles.

Reach with reach code used subsequently	**Sub-reach length (m)**	**Riffles Total**	**Mean spacing λ (m)**	**Riffles associated with palaeochannels (expected based on intersections)**	**Tot. of intersections (% channel length estimate)**	**Dates below riffles years cal-BP (sites)**
Five Fords (FF) main channel	2185	22	99	17 (7)	43 (29%)	3002 (FF1.1) 3030 (FF2.2) 1291 (FF3.1)
Smithncott (SM) *N channel*	*1990*	*20*	*99*	*13 (4)*	27 (20%)	-
Smithncott S channel	*1895*	*20*	*94*	*12 (5)*	34 (26%)	-
Westcott-Hele (WH)	2480	22	112	17 (5)	30 (24%)	-
Columbjohn (CJ) upstream	620	7	88	3 (1)	7 (17%)	-
Columbjohn downstream (N channel)	*2055*	*24*	*85*	*10 (4)*	19 (18%)	-
Columbjohn downstream (S channel)	*2450*	*27*	*94*	*11 (5)*	24 (19%)	
Mean	*1953*	*20.2*	*95.8*	*11.8 (4.4)*	26.2(21.8%)	

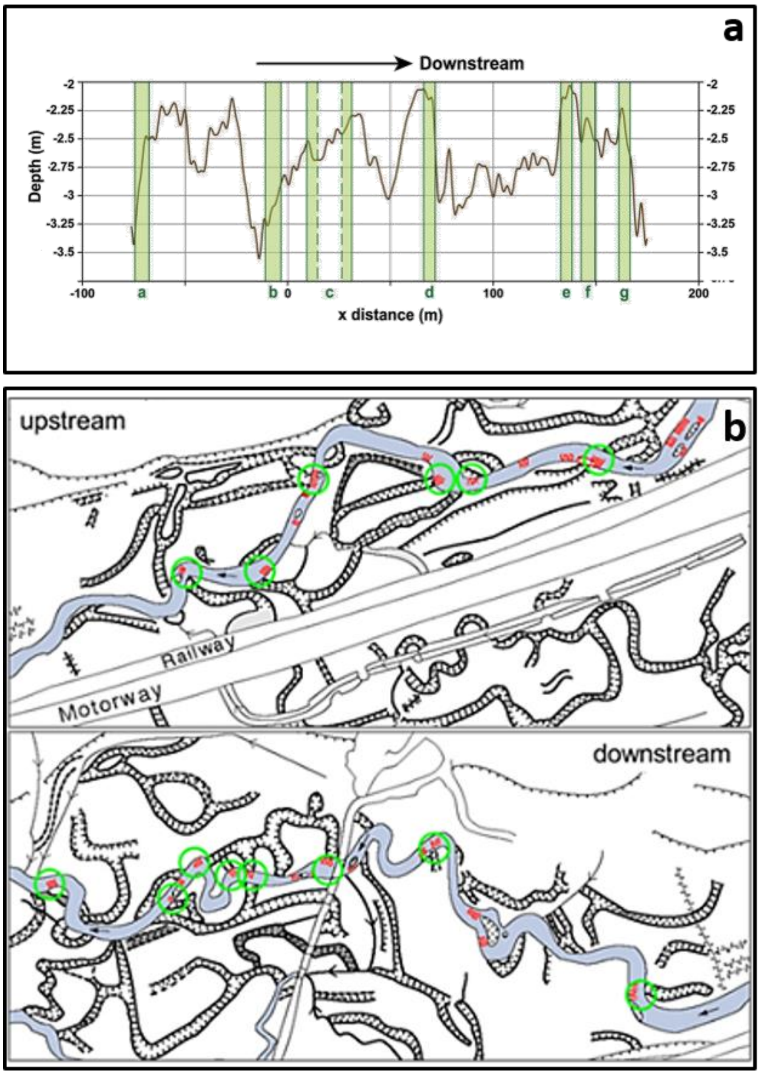

Fig. 5. (a) the thalweg long profile for the downstream Westcott-Hele reach, the location of palaeochannel intersections is given by the vertical green shading, (b) riffles plotted onto the floodplain maps of the Westcott-Hele sub-reach. Green circles highlight the riffles associated with palaeochannel intersections.

It is also clear that, particularly in upstream reaches, over half the riffles occur on or adjacent to active channel intersections (e.g. 77% or 17 riffles out of 22 in the Five Fords reach), and even in the downstream Columbjohn reach this is still approximately half. The total channel length of intersection was not measured due to difficulty in defining buried palaeochannel edges, but taking double the mean channel width (to allow for the obliquity of intersections) this would equate to only a maximum of 26% of the channel length and in most reaches far less. This association is therefore 2-3 times higher than would be expected by a random allocation along the channel.

In order to investigate this association further at three sites in the Five Fords reach the riffles were excavated, or cored, to sample organics at the underlying intersection with the riffle gravels (Fig. 6). In one case the underlying channel dates to 3002 years cal- BP (FF1.1) in another to 3030 years cal- BP (FF2.2) and in the third the channel dates to pre 1291 years cal-BP (FF3.1). The sedimentology of the riffle at FF3 was poorly sorted crudely horizontally bedded gravels (0.3-0.5 m) over the clay palaeochannel fill. Since the palaeochannel sediments are in-situ the riffle cannot be older than these dates, but the active channel has had to cross the topographic high of the clay-rich channel fill which has caused local gravel accumulation in the form of a riffle or mid-channel bar. In the case of FF2 there were two organic bed layers under the riffle separated by c. 260 years (Supplementary Table S3). It was also noticed in all three cases the gravel of the riffle contained brick and post-medieval pottery and so had been deposited or reworked in the recent past. The process implications of this association are discussed further in section 4.

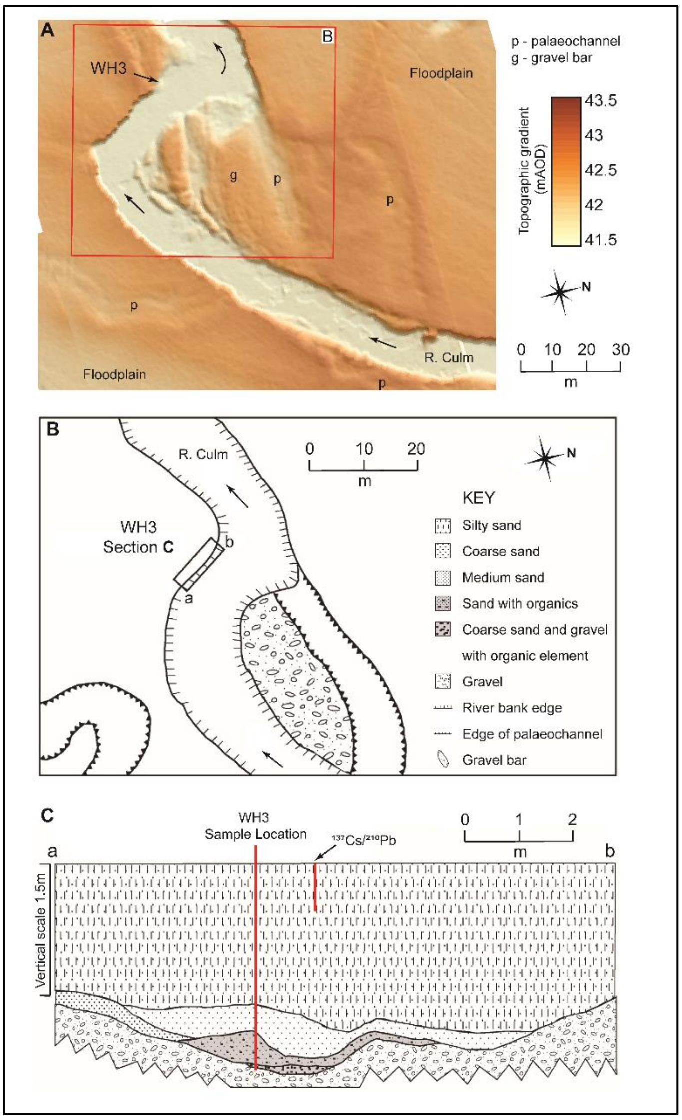

Fig.6. Lidar topography (A), site field plan (B), and stratigraphic sections through the palaeochannel (C) that runs under the riffle-island complex from Five Fords reach FF3 with basal ^{14}C palaeochannel date range. The symbols in D use the standard Troels-Smith system (L = clay). Hillshade model and topographic gradient of section of River Culm floodplain and palaeochannels at Five Fords derived from 1m resolution Lidar DTM data grid square ST0813 (Environment Agency, 2019).

3.3. Dating, chronology and accumulation rates

Using the 30 AMS ^{14}C dates and 26 OSL dates reach chronologies can be established. As can be seen from Supplementary Tables S3 and S4 there were few reversals and only one radiocarbon date is thought to be too old (CJ10 1.60-1.70 m), and one OSL date appears anomalous (WH4, Supplementary Table S4). From the ^{14}C dates it is clear that in all cases the organic deposition and infilling of palaochannels was rapid, at least until capped by inorganic sediments, producing dates overlapping at the 2σ level. OSL samples were taken from palaeochannel fills and superficial and adjacent overbank silts.

At Five Fords 6 palaeochannels were radiocarbon dated. They were abandoned at; 3287 years cal BP (FF2), 3125 years cal BP (FFOH), 3002 years cal BP (FF1), 2501 years cal BP (FF9). 1291 years cal BP (FF3) and 717 years cal BP (FF4). From Westcott-Hele palaeochannel infill WH1 produced a radiocarbon date of c. 1004 years cal BP and OSL dates of 990 BP for the basal sands and 290 BP for the start of sandy silt clay deposition. A typical clastic palaeochannel sequence at WH3 produced a basal radiocarbon date of 5415 years cal BP but OSL dates of 1380 years BP for the clay fill and 130 years BP for the overlying sandy silt unit. A buried palaeochannel at Westcott-Hele (WH4) gave an anomalously old OSL date of 28,400 years BP for the sandy infill, but OSL dates of 340 years cal BP from adjacent overbank silts and 90 years BP for overbank sediments overlying the channel fill. This anomalous date was probably caused by a lack of bleaching of the sands that were derived from the surrounding gravel terrace. At Smithincott only one palaeochannel was AMS dated and its basal radiocarbon date was 854 years cal BP (SM1). At Columbjohn 3 palaeochannels were dated one with a basal radiocarbon age of 5409 years cal- BP (CJ10), another with 918 years cal BP (CJ3), and lastly one with a basal date of c. 708 years cal BP (CJ11). In total 13 palaeochannels were dated and all post-date 5415 years cal BP (WH3). In addition, several channels can be dated using historic map evidence at the Five Fords reach from a set of 5 historic maps (Fig. 7). Since 1802 CE there has been relatively little channel change, however, several sections of channel cutoff meanders straightened between 1802 CE and 1891 CE, and there was one neck and one chute cut-off (Fig. 7, near FF10).

The oldest palaeochannel sequences, at Cutton Alders (CA, for location see Fig. 1, Supplementary Fig. S10), which has a basal date of 7872 years cal BP, is 2.8 km from the Culm floodplain, being located on a saddle between the Culm valley and the Clyst catchment. It is almost certainly of periglacial origin associated with an earlier Pleistocene drainage of the Blackdown Hills, but does provide the only continuous Holocene vegetation sequence for the lowland part of the catchment.

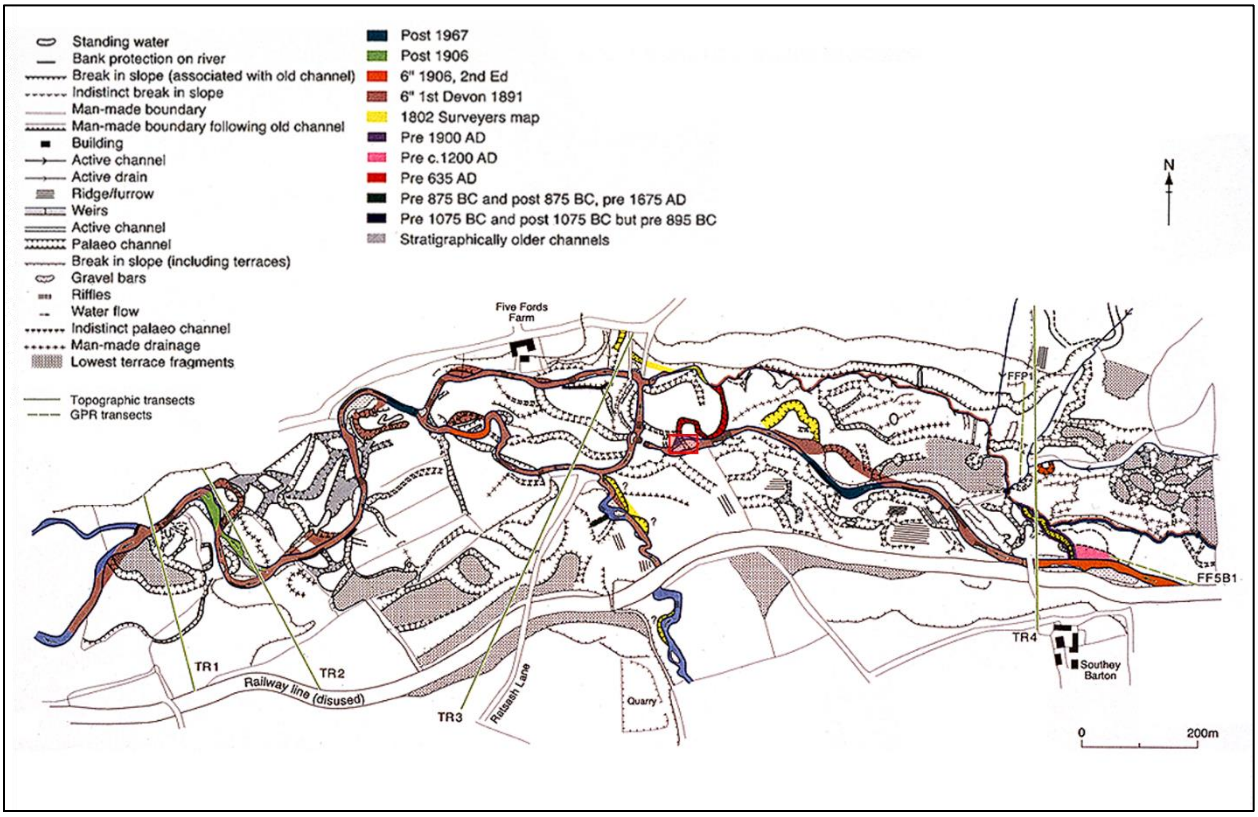

Fig. 7. Historic channel changes in the Five Fords reach derived from historical maps and the palaeochannel network. Red shaded box is site FF3 as shown in Fig. 6. Adapted from Brown et al. (2018).

The OSL dates also provide estimates for both the gravels and the clastic units within or overlying organic sediments. At Five Fords the terrace bounding the floodplain is dated to 39,400 years BP confirming that it is of Late Pleistocene age and probably pre LGM (MIS3). This date is correlative but slightly later than those obtained for the Exe Valley terrace 3 (Brown et al., 2010) and supports a pre-LGM date for this major aggradation throughout the basin.

The oldest date from a buried sand bar comes from above a stone-layer adjacent to the FFOH Hall palaeochannel and is dated to 6500 years BP. A sample from the nearby fill of FF2 (540 years cal BP) is consistent with the basal radiocarbon age (3287 years cal BP). Two samples from a sand lens in the fill of palaeochannel FF3 (960 and 880 years cal BP) also post-dated the basal fill by 350-450 years. All the sandy-clay OSL dates from the Five Fords sites post-date 1300 years cal BP. Two OSL samples from Smithincott reach both gave dates for the transitional sand unit below the sandy-clay of 2500 years BP and 2070 years cal BP. At Westcott-Hele four sites were OSL dated (WH1-WH4). At WH2 a date of 780 years cal BP came from a clayey silt under a thin gravel band showing that channel floods were capable of moving gravels locally onto the floodplain in the late Holocene. This phenomena was also noted in the floods of 1999 CE (see discussion). At Columbjohn four clastic sites were dated using OSL (CJ3, CJ9, CJ10, CJ11). They were all bankside exposures of typical overbank sequences (Supplementary Fig. S5). The oldest sand overlying the gravels at CJ9 dated to 870 years cal BP (CU03-37) but the other three all dated to between 220 and 300 years cal BP.

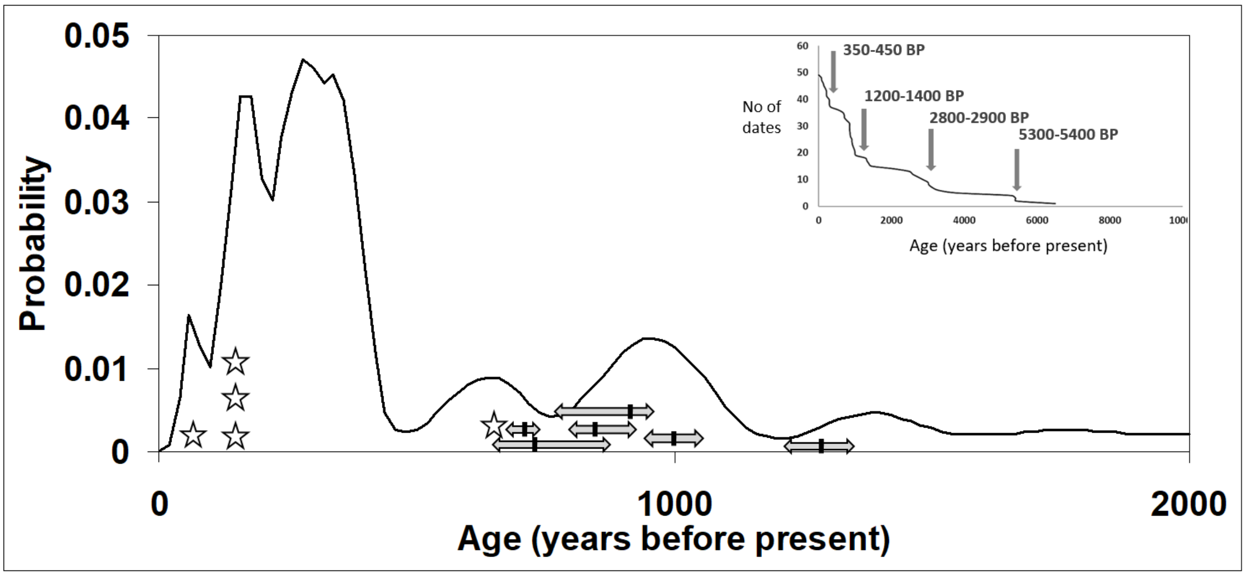

Fig. 8. Diagram of the OSL dates frequency distribution for the last 2000 years with the radiocarbon basal channel dates (arrows with 2 sigma and median date) and the documented channel abandonments (open stars). The inset shows the cumulative number of all (palaeochannel and overbank) AMS and OSL dates excluding pre-Holocene dates and Cutton Alders (CA), using the median age estimates.

By combining these OSL dates, from the different sites, it is appears that there is an increased frequency/magnitude of flood occurrence over the last 400 years and possibly a record of flood peaks with an average periodicity over the last 2000 years of c. 380 years (Fig. 8). This is similar to that identified for wetter periods from bog surface wetness records throughout the UK (Barber et al., 2000). Measured ^{137}Cs and ^{210}Pb profiles of sampling sites within the study reaches over the same period also suggest an increase in sedimentation rates over the last 400 years from rates below 0.5 mm yr^{-1} to rates of 2 mm yr^{-1} and above (Fig. 8). ^{137}Cs and ^{210}Pb sampling sites within the study reaches provide dates and accumulation rate estimates for this period (Supplementary Table S7).

The ^{137}Cs and ^{210}Pb$_{ex}$ measurements reveal two contrasting groups of sites; first, aggrading sites located within active river channels and below bankfull level and second, aggrading sites on floodplain surfaces above bankfull level. The lower sites are characterised by coarser material with relatively low activity and a relatively uniform down-core distribution (Fig. 9a,b). The floodplain surface sites have insignificant >2 mm fractions and are characterized by higher activities, well-defined ^{137}Cs peaks (presumed representing the 1963 fallout peak) and well-defined maximum ^{210}Pb$_{ex}$ activities at the surface (Fig. 9c, d). These differences likely reflect contrasting flow regimes, with near or within channel sites being subject to higher flow velocities and sediment suspension and remixing under convective flow, whereas those on the floodplain surface are subject to only overbank diffusive flows with limited transport capacity and with the driver being topography (Nicholas and McLelland, 1999; Marks and Bates, 2000). These ‘hybrid’ sites are located in major palaeochannels and reflect their abandonment and subsequent reduced frequency of inundation. For overbank sedimentation sites where information on the depth distribution of ^{137}Cs and ^{210}Pb$_{ex}$ is available, comparison of the depth distributions of the two radionuclides for the same core can assist in the detection of temporal trends in sedimentation rates over the last 100 years. While the majority of profiles indicate continuous sedimentation throughout the last century, there was a temporal discontinuity at one site at Columbjohn (Fig. 9g,h) where the ^{210}Pb$_{ex}$ profile indicates little aggradation before 1963 CE but increased sedimentation thereafter.

Sedimentation rates can be quantified from the ^{137}Cs and ^{210}Pb$_{ex}$ profiles and the inventory data for the bulk cores using the methodology outlined in the supplementary information (Supplementary Text). The sampled areas are located >20 km apart and are representative of the majority of the floodplain where sedimentation is active. Collection of cores from all geomorphic units provides the basis for estimating the reach-specific sedimentation rates. Frequency distributions of ^{137}Cs-derived sedimentation rates are shown in Fig. 10. All are negatively skewed with sedimentation rates < 0.2 g cm^{-2}yr^{-1} at > 60% of the sites on three reaches (Five Fords, Smithincott, Columbjohn) with the corresponding figure for Westcott-Hele being 40%. However, sedimentation rates > 1 g cm^{-2}yr^{-1} were also found at several sites in all reaches except Five Fords. They were mostly associated with recently abandoned channels and near-channel enclosed depressions. At the reach scale, Five Fords registered the lowest sedimentation rates, Westcott-Hele the highest and the other two in-between (Fig. 10).

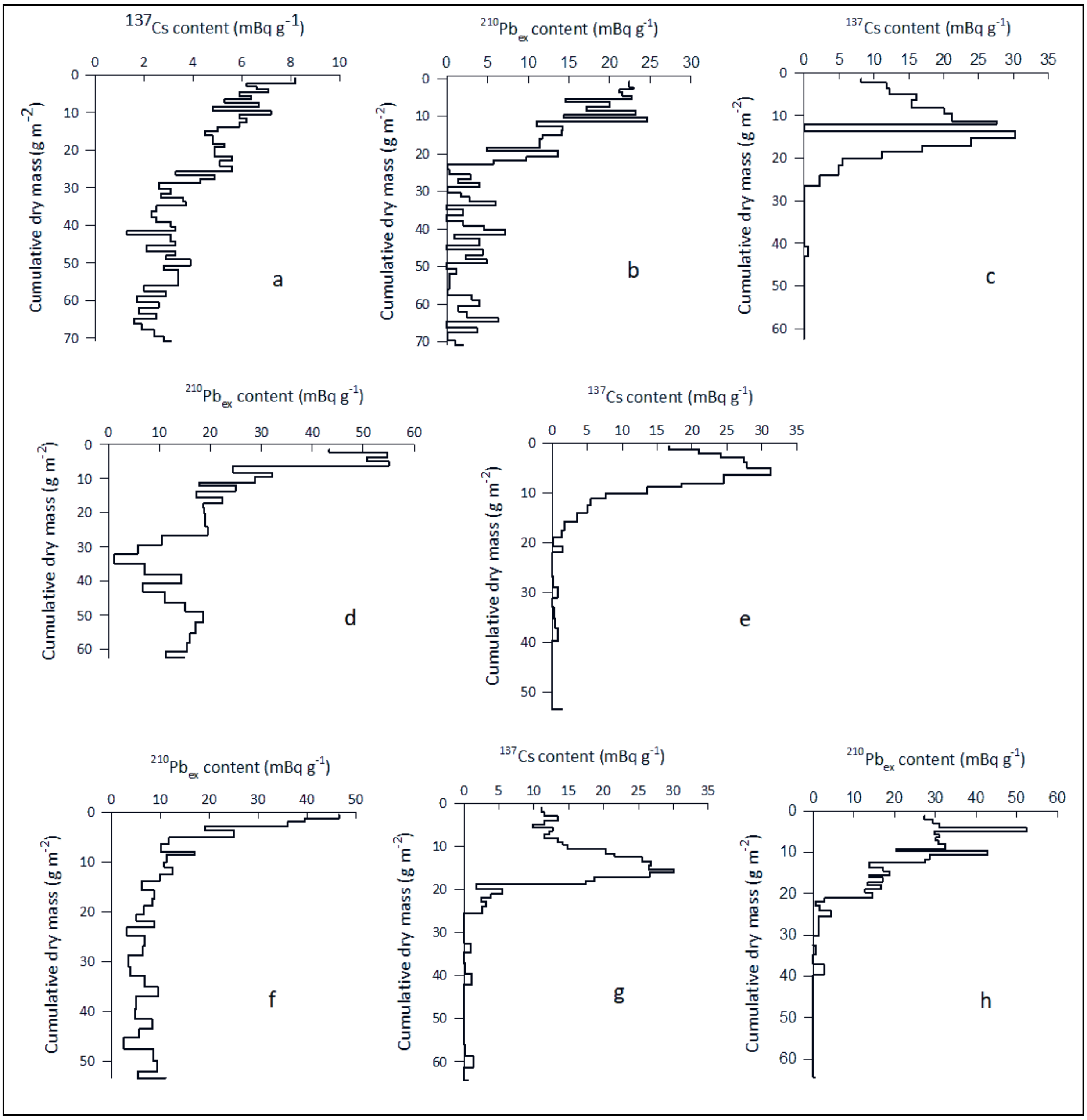

Fig. 9. Fig. 9. Radionuclide fallout profiles; a) near WH channel bench 137Cs profile; b) near WH channel 210Pbex profile; c) WH overbank floodplain surface 137Cs profile; d) WH overbank floodplain surface 210Pbex profile; e) and f) 137Cs and 210Pbex profiles from the Smithincott reach with combined characteristics; g) and h) 137Cs and 210Pbex profiles from Columbjohn showing a change in sedimentation regime at 20 cm depth. For core locations see Supplmentary Figs. S3-S4.

However, some profiles appear to be a combination of both categories, since they have a near uniform distribution of $^{210}Pb_{ex}$ near the bottom of the profile and a clear ^{137}Cs peak in the upper part of the profile (Fig. 9e,f). This may be caused by an abrupt change in sedimentation patterns at some point during the last 150-100 years. It is notable that these ‘combined’ sites are also in the major palaeochannels, indicating abandonment and an increased return interval of flooding.

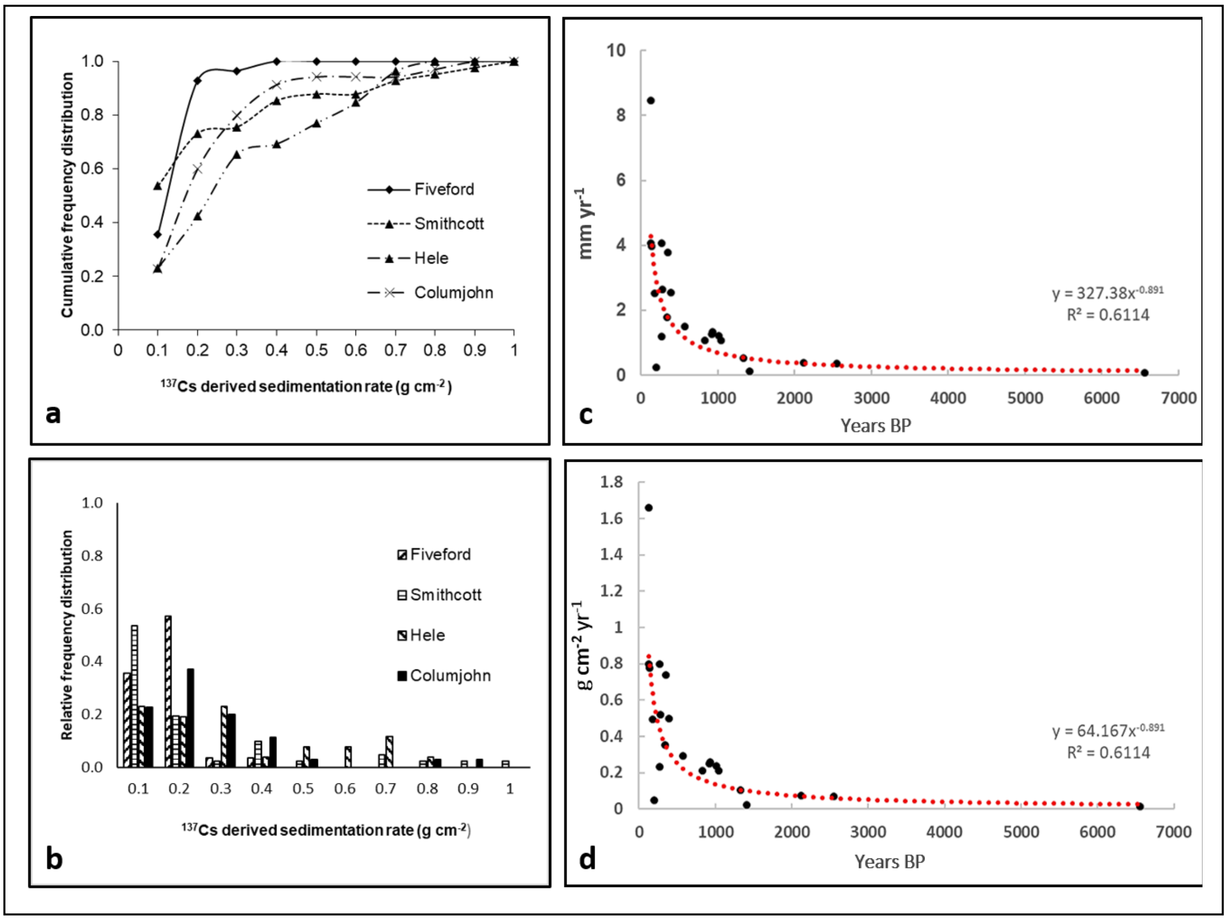

Fig. 10. **a**, **b** Frequency distributions of ^{137}Cs-derived annual sedimentation rates by reach and sedimentation rates derived from all floodplain OSL dates expressed in mm (**c**) and g cm^{-2} yr^{-1} (**d**). OSL rates converted to mass using a linear adjustment of 1.3-1.9 gm cm-3 from 0-1 m depth. Note that OSL derived rates are similar in magnitude to the range of ^{137}Cs rates.

Difference in the temporal distribution of ^{137}Cs and ^{210}Pb$_{ex}$ fallout provides a means of estimating sedimentation rates over the last 40 (^{137}Cs i.e. since 1963) and 100 years (^{210}Pb$_{ex}$). Some major mapped palaeochannels have much higher ^{210}Pb$_{ex}$-derived sedimentation rates than those derived from the ^{137}Cs measurements, indicating a reduction in sedimentation rate within the last century. It is likely that these channels were abandoned more than a century ago; this was followed by rapid infilling, and these sites now only occasionally receive overbank flow from a distant channel. Several sites at Five Fords, however, have higher ^{137}Cs-derived rates than ^{210}Pb$_{ex}$-derived rates suggesting that sedimentation rates have increased in the last 40-50 years. This is in agreement with the best fit function for the OSL derived accumulation rates (Fig. 9d).

Both the fallout radionuclides (equivalent mean 2.71 yr^{-1} st. dev. 2.93 yr^{-1}) and OSL-derived rates (mean 2.09 mm yr^{-1}, st. dev. 1.92 yr^{-1}) are comparable with the measured rates of overbank deposition and particularly the rates measured inside bends and depressions (<1-3 mm yr^{-1}) and levees of 3-6 mm yr^{-1} (Walling et al., 1991; Supplementary Table 2). Using an average sediment bulk densities of 1.9 g cm^{-3} for the radionuclide-based rates equate to just under 1 to 5 mm yr^{-1} and 0.2-1 g cm^{-2} yr^{-1} whist the OSL rates (adjusted for a bulk density of 1.3-1.9 g cm^{-3}) from the floodplain vary from 0.1 - 4 mm yr^{-1} (0.1-0.8 g cm^{-2} yr^{-1}) with the highest rates being the most recent.

3.4. Pollen, spores and macro-plant remains

These new data will only be summarised here given the large number of sites (8), but the pollen diagrams are presented in Supplementary Figs. S6 to S10, along with details on the site and source area in each case. Summarising this here the pollen and macrofossil sites are as close as possible to the OSL sites and are all from small palaeochannel organic infills. In theory, because the sites are all very small (under 20 m diameter), the sources areas for plant remains, pollen and spores is very small (Greenwood, 1991). In the case of pollen this site size would suggest that approximately 80% would have been from local sources (Jacobsen and Bradshaw, 1981; Brown, 1999) although the relationship between pollen assemblage derived and floristic richness is Birks, 2016), however, they clearly all had river-flow and especially flood inputs. However, work on the fluvial transport of pollen and spores nearby in the Exe catchment has shown that the aquatic flood transport actually reflects the catchment better than the airborne input so we can reasonably assume that the sites represent predominantly the surrounding riparian vegetation with a small input from upstream habitats and the catchment as a whole (Brown et al., 2007). Pollen from all sites is dominated by floodplain taxa, particularly alder (*Alnus*), hazel (*Corylus*), grasses (Poaceae), daisy family (*Aster* type), dandelions (Lactuceae) and a range of herbs typical of rough and wet grazed land (Table 3). Macrofossils support this interpretation, showing that *Alnus glutinosa* was growing on or near all sites, together with *Sambucus nigra* in all but two. Fruits and seeds from both wet grassland and a variety of mesotrophic fen or riparian environments with shallow standing and moving water, were also present. At Five Fords (FF1, Supplementary Fig. S6) there is evidence of a local deforestation at c. 1450 years cal BP but almost complete regrowth of the wet woodland, suggesting a temporary clearing on the terrace adjacent to the palaeochannel. The appearance of barley (*Hordeum* type) and grazing indicators suggests this was agricultural. Macrofossils also show disturbance indicators including stinging nettle (*Urtica dioica*) and *Chenopodium* sp. A second site in the Five Fords reach (FF9) has a uniform assemblage dominated by alder and hazel reflecting wet woodland around 2500 years cal BP covering the floodplain. In the Smithincott reach the palaeochannel (SM1, Supplementary Fig. S7) was surrounded a by a cleared floodplain c. 940 years cal BP as is also the case at the youngest of the sites at Westcott-Hele (WH1, Supplementary Fig. 8) which is similar in age (Table 3), whereas the much older site c. 5400 years cal BP (WH3, Supllementary Fig. S9) reflects an uncleared floodplain dominated by alder and hazel, as shown by the pollen percentages and high numbers of *Alnus glutinosa* seeds and less frequent *Corylus avellana* nut fragments. Seed remains show that other trees in this woodland included *Sambucus nigra* and *Betula pendula*. The Columbjohn reach site (CJ10, Supplementary Fig. 9) reveals wet woodland present c. 4600 years cal BP but the other two sites (CJ3, CJ11) reveal that it had largely been cleared by 936 years years cal BP and almost completely replaced by grazed pasture by 800 years cal BP. The sites are surprisingly consistent with the deforestation of the wet alder-hazel woodland starting, probably on the terraces, around 3000 years cal BP and its replacement largely by wet grazed pasture by about 1400-800 years ago.

Table 3. Summary of pollen results from palaeochannel infills in approximate age order, old to young. Main taxa are in order of their relative % TTP (Total Terrestrial Pollen).* based on the total range of

dates but probably an almost instantaneously deposited fill, ** the basal date appears too old so the sequence probably spans a much shorter period of time. Shading approximates to degree of tree cover indicated. Further details on each site environment is given in Table 4.

Site	Date range (median years cal yrs BP)	No of samples/ levels	Main taxa	% Trees of TTP	Environment	Events
CJ11	708	3	Poacaea, *Alnus*, Lactucea, *Corylus*	15-20	Open pasture with wet woodland	No change
SM1	953-933	14	Poacaea, *Alnus*, Lactucea,	15-45	Wet pasture	No change
CJ3	990-936*	10	Poacaea, Lactuceae, *Alnus, Corylus*	10-30	Open grazed floodplain with some wet woodland	No change
WH1	1004	6	Poaceae, *Quercus, Alnus*	35-40	Open grazed floodplain	No change
FF9	2501	6	*Alnus, Corylus*, Pteropsida, *Polypodium*, *Pteridium*, Poaceae	80-85	Wet woodland	No change
FF1	3125-0	22	*Alnus, Corylus*, Poacaea, *Aster*, Lactuceae, *Polpodium, Pteridium*	10-90	Wet woodland, with pasture, some arable	Local deforestation event at 1450 years cal BP
CJ10	4641-713**	4	Poacaea, Pteropside, Lactuceae, *Rumex, Plantago*	40-45	Open pasture with some wet woodland	No change
WH3	5415-5303	8	*Alnus, Corylus, Quercus, Tilia, Polypodium*, Pteropsida,	85-95	Wet woodland with dry woodland close by	No change
CA	7872-0	19	*Alnus*, Cyperaceae, Poacaea, *Quercus*, Pteropsida*, Polypodium, Tilia*	15-65	Wet woodland, fen (alder carr), dry woodland, pasture	Deforestation c. 3800 and within the last 1000 years (undated)

The closest continuous reference site for the catchment is Cutton Alders which has accumulated peat since c. 7900 years cal BP. The pollen diagram (Supplementary Fig. S10) reveals that although the site has remained an alder carr over this entire period, by removing alder from the total terrestrial pollen (TTP) sum, some reflection of the surrounding vegetation can be discerned including hazel, and oak (which are both also on-site) with some lime (*Tilia*), a little elm (*Ulmus*) and some, probably long-distance pine (*Pinus*). An elm decline is presented dated to 5394 years cal BP and there are also two lime declines: one at 4285 years cal- BP and one at 2067 years cal BP. This later decline also coincides with a the fall in all trees, rise in grasses and the appearance of cultivars (zone CA05). All these are typical dates for these events in southern England and suggest that the lowland around the Culm floodplain developed a full mixed deciduous woodland in the early-mid Holocene and underwent some deforestation in the Neolithic-Bronze Ages and a major final clearance episode in the late Iron Age.

This vegetation history differs significantly from the uplands of the catchment (Blackdown Hills) which have evidence from 4 sites of incomplete forest clearance in later-Prehistory (Bronze−Iron Age) with deforestation largely restricted to the Blackdown plateau (Brown et al., 2014). Woodland persistence on steep, but poorly drained, slopes, was probably due to the unsuitability of these areas for mixed farming. Instead, they may have been under woodland management (e.g. coppicing) associated with the iron-working industry. Later Iron Age and Romano-British impact was geographically restricted and documented Medieval land management maintained a patchwork of small fields, woods and heathlands with some evidence of landscape change in the 6th–9th centuries AD (Rippon, 2012; Brown et al., 2014).

So, in combination, the data suggests that the watershed slopes of the catchment (the plateau does not drain into the Culm) remained largely wooded until present times, but the lowlands of the catchment (below c. 170 m asl and on Permo-Triassic rocks) were deforested in Prehistory (Neolithic-Iron Age). The floodplain was partially deforested in the early Medieval period and has been managed as pasture and wood-pasture since. Indeed there is historical evidence of both alder and willow being grown on the floodplain into the 19th century CE (Firth and Firth, 2020).

Plant macrofossil data are available for 7 sites, and are only summarised here (data can be found in Supplementary Table S8 and Supplementary Fig. S11). All the sites have mixed assemblages with aquatics, damp and marshy ground, grassland, shrubs and woodland (Fig. S11). The raw ratios vary from tree macros being in the majority (WH3) to hardly being present (FF10). The total macrofossil-derived plant richness is 60 taxa, which is comparable with estimates from rich ditch communities (Armitage et al., 2003). This also varies with site and sample from 9 taxa (SM1 95-110 cm) to 28 taxa (CJ10 160-170 cm) with a mean of 21 taxa (standard deviation 4). As there is low correlation between the number of samples and number of taxa at a site (Pearson correlation coefficient 0.26), the variation is probably due to taphonomic factors and particularly the unknown ratio of flood debris to local *in-situ* accumulation. By far the most common elements are riparian trees (*Alnus*, *Corylus*), hedge tree/shrubs (*Sambucus nigra*, *Rubus* sp.), wetland herbs (e.g. *Cirsium palustris*) and grazing indicators (e.g. *Rumex acetosa*). Aquatics, especially marginal, plants are well represented as well as species indicating nutrient enrichment and anthropogenic environments (e.g. *Urtica doica*) and one grain of barley (*Hordeum*, CJ10 150-160 cm) which must be a flood input. The vascular plant list can be increased by adding the plants indicated by host-specific Coleoptera (Table 4). This increases the total taxa to 75 and largely supports the macrophyte data. Most of the taxa it adds (for a list see Supplementary Table S9) are additional trees (*Quercus*, *Salix*, *Fraxinus*, *Populus*), hedge or scrub species (*Vibernum*), and grazed pasture (*Viccia cracca*, *Plantago lanceolate*, *Cirsium arvensis*).

Table 4. Summary statistics for the macrofossil data at site and taxon level, with total number of taxa after the addition of Coleopteran data in parentheses. The site details given here also apply to the sites in Tables 3, 5 and 6 which came from the same samples and small pal. is small palaeochannel (all under 10m across) and W is in woodland and P is surrounded by pasture land.

Site	**Samples**	**Site desc.**	**No of Taxa**	**Trees and shrubs**	**Herbs, forbs, grasses**	**Adn. Taxa from Coleopt.**	**Aquatics**
FF1	4	small pal., W	19-24(27)	1 (*Alnus*)	12-17	3	4-6
SM1	5	small pal., P	9-28(33)	2-3 (*Alnus, Betula, Corylus, Sambucus nigra*)	2-28	5	3-5
WH1	1	small pal., P	20(24)	4 (*Alnus, Betula, Corylus, Sambucus nigra, Rubus* sp.)	14	4	2
WH3	3	small pal., P	15-19(24)	4 (*Alnus, Betula, Corylus, Sambucus nigra)*	11-13	5	0-2
CJ3	3	small pal., P	20-25(32)	3-4 (*Alnus, Betula, Corylus, Sambucus nigra*)	15-18	7	1-4
CJ10	2	small pal., P	16-28(32)	3-4 (*Alnus, Betula, Corylus, Sambucus nigra)*	11, 20	5	2,4
CJ11	1	small pal., P	26(35)	3 (*Alnus, Corylus, Rubus fruiticosus*)	16	9	7
Total	18		60(75)	7 (*Alnus, Betula, Corylus, Sambucus nigra, Rubus fruiticosus, R idaeus*	43	15	11

Although there is little evidence of a temporal trend the highest inputs of alder fruit and cones come from the lower levels of the oldest sites (WH3 and CJ10). However, in terms of both species or plant types/life forms there is little change in the vegetation with the similar richness being present at all sites. All show a mixed assemblage of channel edges (marginal aquatics), wet woodland, hedge/scrub and grazed pasture and meadow, although the proportions vary and there is as much variation between sites, than there is at sites over time.

3.5 Coleoptera

The primary environmental indicator used here is Coleoptera due to their wide range of habitats, tight ecological niches and high indicator value in riverine environments. Previous work using some of the data used here assessed the assemblages in relation to habitat types and disturbance regime, at the total system level (Davis et al., 2007). Here we reanalyse the data and relate it to the geomorphological evolution of the system and the pollen data. Coleoptera were well preserved in all the sites with organic sediments, particularly palaeochannel infills. Again only summary data are presented here (Table 5), but the taxa list is given in Supplementary Table 8.

Table 5. Summary of coleoptera results from palaeochannel infills. Modified ecological groups after Robinson (1993). * based on the total range of dates but probably an almost instantaneously deposited fill, ** the basal date appears too old, so the sequence probably spans a much shorter period of time. Elmidae (riffle) beetle taxa are in bold.

Site & Date range (yrs years cal BP)	**No of Samples/ ind.**	**Most common/notable taxa**	**No. of taxa**	**Environment & ecological group**	**Host plants/animals**
FF/Old Hall 3125-1450	4/240	*Coelostoma orbiculare, Chaetarthria seminulum, Plateumaris braccata, P. discolor, P. sericea, Othius punctulatus, Xantholinus longiventris, Stenus* spp., *Scolytus rugulosus, Hydrobius fuscipes, Helophorus* spp., *Pterostichus anthracinus, Pt. gracilis, Limnebius truncatellus, Apion subulatum, Anthonomous rubi, Aphodius* spp., *Geotrupes* sp., *Stenichnus bicolor*	141	Slow-stagnant water, but with a single riffle beetle (*Elmis aenea*), pasture some woodland	*Phragmites, Carex,* Brassicaceae, *Rumex, Trifolium,* Rosaceae, some dung, decaying wood, plant litter
FF9 2,501	1/139	*Bembidion guttula, Hydreana gracilis, Ochthebius bicolon, Limnebius truncatellus, Helophorus grandis, H. flavipes, Stenus* sp., Aleocharinae indet., ***Elmis aenea***, *Asphodius contaminates*	84	Fast-flowing water taxa with slow-water element, woodland and meadow/pasture	Brassicacea, Fabiaceae, Lamiaceae, *Caltha palustris, Persicaria amphibium, Quercus, Fraxinus*, Rosaceae, dead wood
SM1 953-933	5/1266	*Helophorus brevalpis, H. flavipes, H. grandis, Lesteva heeri, Anotylus rugosus, Xantholinus longiventris, Aleocharinae* sp. Indet, ***Esolus parallelopipedus***, *Phyllotreta nigripes, Chaetocnema concinna, Apion assimile, Notaris acridulus, Ceutoryhnchus contractus*	226	Slow-flowing water, some fast-water species (Elmids), marshy, pasture, woodland	*Sparganium, Rumex, Brassicaceae, Trifolium, Urtica dioica, Glyceria,* Ranunculaceae, *Lotus, Persicaria amphibium, Vibernum*, organic debris, dung,
WH3 5415-5303	3/188	***Oulimnus tuberculatus***, *Apion apricans, Sitona hispidulus, Phyllotreta nigripes, Galerucella tenella, Hydronomous alismatis, Dorytomus longimanus, D. tortrix, Polydrusus cervinus, Pterostichus anthracinus, Bembidion unicolor*	81	Fast-flowing oxygenated water (50% Elmids), muddy banks, gravel bed, pasture with managed woodland	*Glyceria, Caltha palustris, Alnus, Trifolium*, Brassicaceae, *Filipendula ulmaria, Alisma Plantago-aquatica, Populus*, rotting organic matter
WH1 1004	1/417	*Hydraena testacea, H. gracilis, H. flavipes, Limnebius truncatellus, Helophorus flavipes, Stenus sp., Lathrobium* sp., *Aleocharinae indet* **., *Elmis aenea, Esolus parallelepipedus,***	108	Fast-flowing water with slow water element,	Woodland*, Quercus, Fraxinus, Betula,* Apiaceae, Fabiaceae, *Urtica dioica, Sparganium,*

		Oulimnius tuberculatus, Limnius volckmari, Macronychus quadrituberculatus, *Corticaria* spp., *Phyllotela nigripes, Notaris acridulus*		submerged logs, woodland	*Alisma, Carex acutiflora, Veronica beccabungae*
CJ3 990-936*	5/793	*Hydraena gracilis, Sitona hispidulus, S. lepidus, Donacia marginata, D. simplex, Phyllotreta nigripes, P. consobrina, Apion hydrolopathi, A. curtirostre, A. gyllenhali, Ceutorynchus melanostichus, Aphodius* spp., *Anotylus rugosus, Geotrupes* spp. *Polydrusus pteryogmalis, Aspidophorus orbiculatus, Rhizophagus perforatus, Phyllobius glaucus, Rhinoncus pericarpius, Notaris acridulus*	182	Fast-flowing, some stagnant water sp., pasture (animal dung) with some woodland	*Trifolium*, Brassicaceae, *Rumex, Glyceria, Lotus corniculatus*, Lamiaceae, (*Mentha*), Apiaceae, *Vicia cracca, Cirsium arvensis, Urtica dioica, Alnus*, dung
CJ11 708	1/388	*Hydraena riparia, H. flavipes, Stenus* sp., *Aleocharinae* indet., ***Elmis aenea, Esolus parallelepipedus, Oulimnius tuberculatus, Limnius volckmari***, *Longitarsus* sp., *Sitona lineatus, Bagous* sp.	132	Fast-flowing water, with a slow-flowing water component, rich meadow with some woodland, grazing	*Alisma*, Apiaceae, *Cardamine pratensis, Sparganium*, Asteraceae, Fabiaceae, *Lotus corniculatus*, Brassicaceae, *Cirsium, Glyceria, Typha, Plantago lanceolata, Urtica diocia*, Polygonaceae, *Senecia, Salix, Alnus*, dung
CJ10 4641-713**	2/261	*Anotylus rugosus, A. nitidulus, A. acridulus, Stenus* sp., *Tchyporus hynorum, Aleocharinae* indet., ***Elmis aenea, Esolus paralletepipedus, Oulimnius tuberculatus, Limnius volckmari***	84	Fast-flowing water, with a small slow-flowing water component, open pasture no woodland	Brassicacea, *Glyceria, Sparganium, Plantago lanceolata*, Polygonaceae, *Rumex*, Ranunculaceae, *Malva*, dung/refuse

The Coleopteran assemblages relate closely to the pollen and macro-plant analyses adding more species-level vascular plant data (see section 3.5.) with a variation in sites from woodland dominated with some pasture (FF9, WH3) to almost exclusively grazed pasture (CJ10). The physical environments indicated by the assemblages vary from almost exclusively slow-flowing pool and palaeochannel habitats to fast flowing 'riffle' habitats and there is no obvious relationship to age. A similar range of species may be found within the floodplain samples, from the earliest palaeochannel sample (FF1, FF9, WH3) dated to c. 5400-2500 years cal BP to the latest sample at c. 700 years cal BP and today. The total number of species found is 239 and there does not appear any relationship between diversity and age. Of these 216 taxa (90%) are shared between the palaeo-samples and the modern samples.

Overall the frequency of Elmidae beetles (riffle-beetles) in the palaeo material is very high compared with the modern samples here or any modern sample dataset including exposed river sediment (ERS) data from SW England (Sadler and Bell, 2002) whereas the proportion of slow-water taxa is much the same (Supplementary Fig. S11). However, the silty samples have some elmids and are quite similar in this regard to some peaty samples. The peaty samples vary but they include a high number of aquatic species, relatively few wood-related species and a slightly higher proportion of dung and refuse species. The modern samples have an inflated number of mould and synanthropic species. This seems to be irrespective of which environmental category the samples belong to. Slightly surprisingly the grassland/meadow taxa also seem to be slightly less prevalent in the modern samples.

Of particular interest here are the Elmids or 'riffle-beetles' which are today only found in upland streams (Smith, 2001). They have plastron respiration and cannot tolerate high levels of suspended sediment, low dissolved oxygen and pollution (Elliott, 2008). There are 12 native species in the UK and 5 of them (*Elmis aenea, Esolus parallelepipedus, Limnius volckmari, Macronychus quadrituberculatus* and *Oulimnius tuberculatus*) occur in nearly all the palaeo-samples from all reaches other than those dominated by slow-water conditions. All except

Macronychus quadrituberculatus also appear in the modern overbank samples, but at lower frequencies (Table 5, Supplementary Fig. S12 and Table S9). This rare species (RDB3) was found in exposed river sediments (ERS) on the upper-piedmont section of the River Severn but not on the Exe (Sadler and Bell, 2002) and it is now largely restricted to the Severn Valley and Wales (NBN Atlas). It has been argued that these riffle beetles started to disappear from lowland river valleys in the Iron Age (c. 3000 BP) due to increasing levels of suspended sediment associated with cultivation (Osborne, 1988; Smith, 2001). An exception is their persistence into the Medieval period on the middle Trent, UK (Smith, 2001); however, this is an unusually high-energy reach which also experience continuous channel change (Brown et al., 2001). The persistence of five Elmid species throughout the late Holocene here suggests that conditions remained ‘upland’ in character in contrast to other lowland river systems, although the modern dataset presented here suggests that they may have already been impacted by changing water quality.

From ordination analyses (Fig. 11) we see that inclusion of percentage aquatic and terrestrial supplemental variables in the ordination establishes wetland-dryland as the primary gradient evident on Axis 1. Axis 2 of both raw data and presence–absence ordinations are of similar configuration, the most influential negative factor being the proportion of slow water individuals. Using supplementary variables derived from percentage taxa per ecological grouping within the ordination, woodland taxa are more influential on Axis 2, demonstrating that while present at high diversity these are not numerically well represented. The positioning of the ‘silty’ samples close to the origin on Axis 1, in addition to their plotting positively on Axis 2 is consistent with these being semi-terrestrial in nature. This is borne out by the presence of semi-terrestrial chironomid taxa within these samples (Z. Ruiz pers. comm.). Samples plotting most negatively on Axis 2 are consistent with having been deposited in a treeless environment. This is suggested not only by these samples plotting in the opposite direction to the woodland vector, but also as they are dominated by slow water taxa. It is likely that the majority of coleopteran remains recovered from these sites result from autochthonous rather than allochthonous deposition. The lack of separation between ‘silty’ and ‘sandy’ clusters in the presence–absence ordination is expected, as these samples although semi-terrestrial possess the highest proportion of aquatic taxa of all samples analysed (mean = 74%). This is because these samples include not only slow water taxa but those from the fast water group. Such samples, which include mixed fast and slow water assemblages, may have been deposited either in flood events or downstream of a pool-riffle sequence. When converted to presence–absence data these mixed assemblage samples appear statistically more like their predominantly aquatic counterparts, hence cluster with aquatic rather than terrestrial samples. Comparison of the age-related pattern of clustering with pollen data shows that samples in the > 3500 years cal BP age category pre-date local clearance of wet woodland while those of the youngest category are from sites where local woodland was largely absent.

These data were used to test the Intermediate Disturbance Hypothesis (IDH cf. Grime 1973; Wilkinson 1999). IDH has been widely discussed with relation to floodplain environments by a number of authors (e.g. Ward 1998; Ward and Tockner 2001; Ward et al., 2002; Amoros and Bornette, 2002; Biswas and Mallik, 2010; Rivaes et al., 2013). Here Axis 1 of all ordinations is strongly related to water velocity and in turn therefore to connectivity and flood-pulse frequency and magnitude. Fast-water-dominated sites, subject to a greater degree of flood disturbance plot most negatively, terrestrial dominated sites subject to low-level flood disturbance plot most positively and slow-water-dominated sites subject to moderate frequency/magnitude flooding plot centrally. In order for the data to fit the IDH, it would be expected that those sites with intermediate Axis 1 scores would possess the highest diversity, in a ‘hump-backed’ form of distribution (Fig. 11(d)). Taking x = 1·044 as the cut-off point includes all but one such sample and, with two samples (CA 50–60 cm and WH3 170–185 cm, both with the lowest overall species richness) removed as outliers, significant positive and negative correlations with Shannon’s H’ are observed.

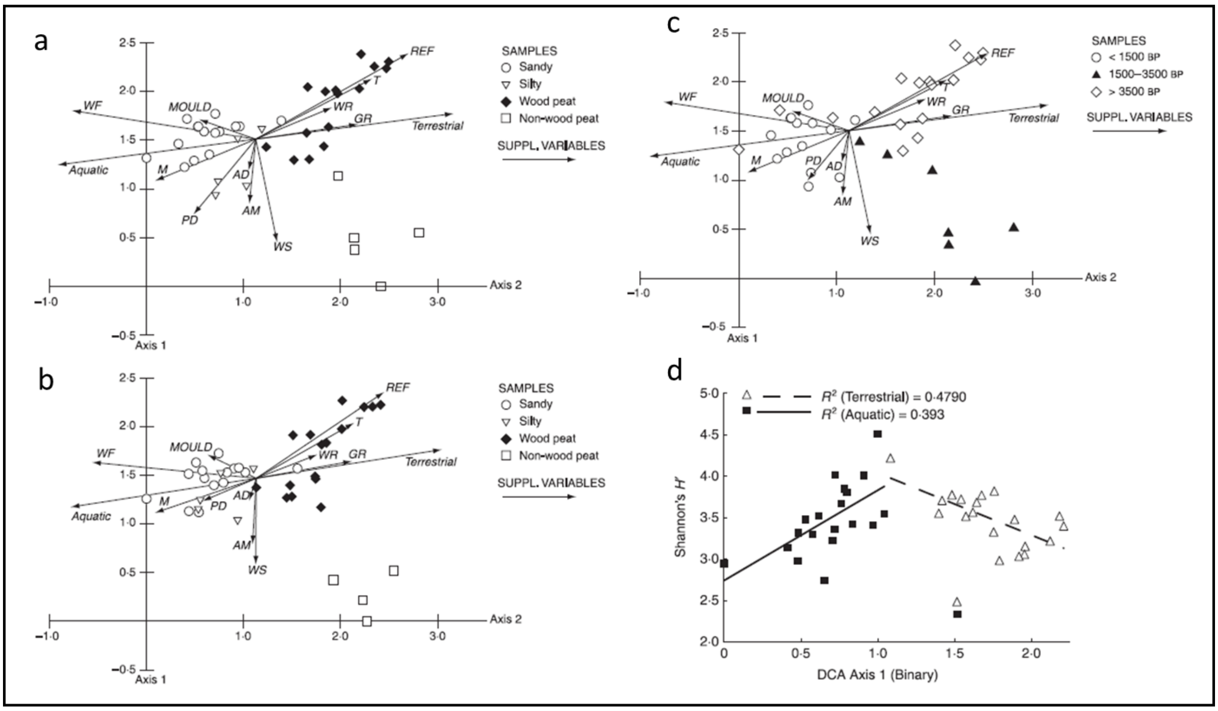

Fig. 11. DCA square-root transformed raw data transformations of coleoptera data a) with percentage individuals per ecological category as supplementary variables, b) as a) but using presence/absence data, c) by radiocarbon age incorporating percentage individuals per ecological category as supplementary variables, d) DCA axis 1 scores (presence/absence data) vs. Shannon’s H’, divided into aquatic and terrestrial categories (two outliers removed). Positive correlation evident in aquatic samples ($R^2=0.398$, $P<0.005$) and negative correlation between terrestrial samples and DCA Axis 1 ($R^2=-0.4790$, $P<0.005$). For the full dataset see Supplementary Table 8.

These results support the IDH and suggest a gradient in species richness, which is lowest in sites of high and low energy deposition, and highest in intermediate samples. Indeed the only identifying variable appears to be disturbance, and this is reflecting the inclusion of species from different nearby habitats due to flooding. The assemblages also reveal the continuous prevalence of plant debris, decaying wood and plant material, and submerged wood and emergent aquatic vegetation. So, despite moderate levels of disturbance, including the abandonment of each site, the floodplain ecosystem has maintained its ecological richness and habitat heterogeneity. Data on chironomids reinforce these conclusions with assemblages from 3 sites (FF1, SM1, CJ3) all being indicative of clean flowing water with both coarser (gravel) and sandy substrates but with more bankside plant macrophytes at CJ3, finer substrates and less oxygenated at SM1, and semi-terrestrial or peaty taxa at FF1 (Ruiz pers. Comm.).

The apparent naturalness of the assemblages is supported by reference to the collation of synanthropic species from the mid-late Holocene archaeological sites by Smith et al. (2020). Neither the Cutton Alders (CA) site nor any of the reach floodplain palaeo-samples contained any strongly synanthropic species (SS in Smith et al., 2020). The only strongly synanthropic species recorded were four taxa all from a modern cutoff and modern overbank sediments from the Columbjohn Reach. As can be seen from Table 6 the overall synanthropic value (SV, Smith et al., 2020) for all except two samples was below 10% which is equivalent to 'Mesolithic Urwaldrelikt (ancient) forest' and 'early Prehistoric farmland', neither of which of course are present. The Culm SV values are within the range of, but lower than 68% of, the examples Smith et al. (2020) present for farmed landscapes. The higher SV for the natural reference site (Cutton Alders) than the floodplain sites also strongly suggests that the mid-late Holocene floodplain had an essentially natural or non-archaeological fauna. The synanthropic species that were present were dominated by facultative synanthropes (SF) which are also characteristic of early stages of ecological successions and intermediate disturbance environments (Sousa, 1984; Smith et al., 2020). In contrast the modern samples which had a lower proportional richness than all the palaeo-samples, not only had the highest SV but also had the only strongly synanthropic taxa in the dataset (0.6%, 4 species). This is only one method of assessing the naturalness of an ecological community, and is imperfect, but since the floodplain has clearly been altered by human activity in the late Holocene, particularly deforestation and management, it noteworthy that it still displays a series of habitats where few human activities have led to synanthropes as illustrated by the low SV values.

Table 6. Data table of sample synanthropic taxa and riffle beetle data. R value is n/taxa so 1 = max possible richness. R is total richness (no. of species), SF is facultative synanthropes, ST is typically sysnthropic, SS is strongly synanthropic, SV is overall synanthropic value and MNI is minimum number of individuals. Synanthropic categorisation calculations based on Smith et al (2020) * all belong to *Atomara* spp. and *Latridius* spp.. * note effect of a low count on the SV value.

Site	**Date range (yrs years cal BP)**	**No of Samples/ individuals**	**No. of taxa**	**R**	**SF %**	**ST %**	**SS %**	**SV**	**No. of Elmidae taxa**	**Tot no. of Elmidae MNI**
Modern	-	27/3559	355	10.0	5.7	1.6	0.6	10.7	4	154
CJ11	708	1/388	132	2.9	3.0	0.2	0	3.5	5	151
SM1	953-933	5/1266	226	5.6	4.5	3.1	0	10.6	4	78
CJ3	990-936	5/793	182	4.3	1.8	1.5	0	4.8	5	398
WH1	1004	1/417	108	3.8	0.4	0.7	0	1.8	5	202
FF9	2500	1/139	84	1.6	4.3	0.7	0	5.7	4	9
FF/Old Hall	3125-1450	4/240	141	1.7	4.3	0.7	0	5.7	1	5
CJ10	4641-713	2/261	84	3.1	4.2	0.3	0	4.9	4	127
WH3	5415-5303	3/188	81	2.3	4.2	0	0	4.2	4	76
Chitterley	15,300-10,800	7/317	118	2.6	0.0	1.8*	0	3.6*	1	1
CA 50-60	2500-3020	1/12	12	1*	8.3	8.3	0	24.9**	0	0
CA 60-70	3020-3530	1/27	22	1.2*	0	3.7	0	7.4	0	0
CA 70-80	3530-4050	1/101	57	1.7	0.9	1.9	0	4.9	0	1
CA 90-100	4050-4600	1/74	42	1.7	2.7	1.3	0	5.4	2	2
CA 100-110	4600-5700	1/100	54	1.8	3.0	4.0	0	11.0	1	3

CA 110-120	5700-7540	1/73	51	1.4	1.3	0	0	1.3	2	2
CA 120-130	7540-8200	1/62	48	1.2	*4.8*	0	0	4.8	1	1
CA Total	2500-8200	7/449	152	2.9	2.4	2.0	0	6.4	-	

4. Discussion

4.1 Pleistocene – early Holocene

The OSL date from the terrace above the floodplain of c. 39 Ka BP firmly dates the down-cutting of 4-6 m to the late Glacial Maximum (LGM) or the post-LGM and most likely marine isotope stage (MIS) 2. There is unfortunately no evidence from this period from within the catchment, but only 5 km to the west in the Exe valley a palaeochannel at Chitterley has been dated from the Bølling/Allerød (Windermere Interstadial) to Younger Dryas (MIS 2, Fyfe et al., 2003). It lies 4-6 m above the floodplain suggesting continued down-cutting after the Younger Dryas into the early Holocene by c.10,800 years cal BP. The rapidity of this downcutting is suggested by the widespread fragments of terrace mapped in the Culm floodplain, especially in the upper reaches. Although poorly exposed, these deposits are coarse-medium horizontally and cross-bedded gravels, dominated by reworked Budleigh Salterton conglomerate pebbles with a matrix of coarse-medium sand derived from the Upper Greensand of the Blackdown Hills. The terrace fragments are the grouped remains of bars in the Lateglacial channel (Fig. 12).

The only palaeochannel abandoned in or before the early-middle Holocene, (Cutton Alders) which lies just outside the basin in a saddle on the interfluve between the Culm and Clyst system. It was probably an abandoned Middle-Late Pleistocene channel of the former drainage of the Blackdown Hills. Studies of the Axe system which drains the southern Blackdown Hills have shown that the Blackdown slopes were particularly susceptible to massive slope failures and erosion during deglaciations due principally to the hydrogeology of the layer-cake stratigraphy and high pore-water pressures (Brown et al., 2014a). After downcutting in the Late Pleistocene the Younger Dryas floodplain was confined into a likely pre-existing channel in the Permo-Trias breccias and sandstones forming a braided plain varying in width from 500 m at Five Fords (Fig. 12a) to 800 m at Columbjohn. The dramatic reduction in discharge at the end of the Younger Dryas would have caused channel shrinkage into the principal flow-paths of the braided system. The oldest date from the floodplain is 6400 years cal BP from a coarse sand just above a stone-capped bar-form of a terrace fragment at Five Fords, implying some overbank/levee alluviation probably close to the channel (FF1) prior to its abandonbment.

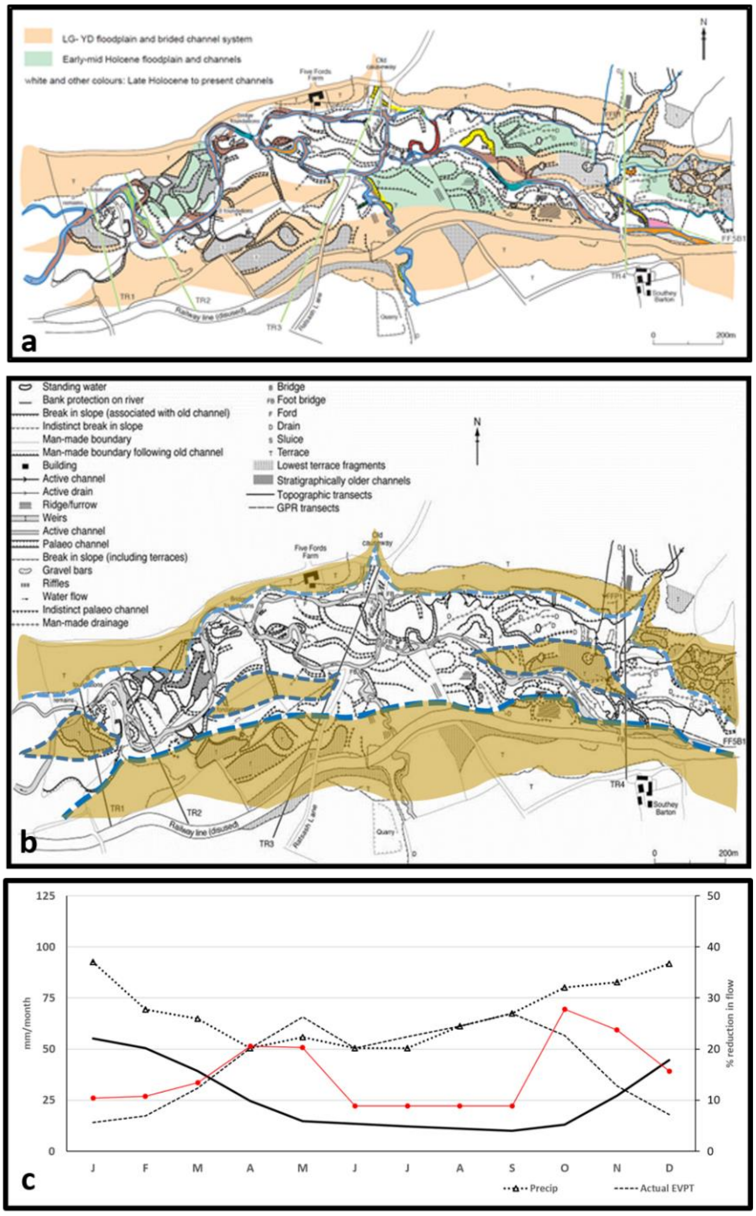

Fig. 12 a) the Lateglacial-Younger Dryas channel zone and floodplain, b) Holocene channel zone and late Holocene channel changes at Five Fords reach, adapted from Brown et al. (2018), c) A simple water balance estimate of runoff in the Culm catchment based on data for Cullompton (1982-2012) and the water balance for c. 6000-5000 BP based on the Thornthwaite equation. The red line is the estimated % reduction of mean monthly runoff compared to current conditions (solid black line). The broken lines are the precipitation (triangles) and actual evapotranspiration

During this research lithic scatters were discovered at Smithincott (Ford Farm, Huncote Wood), and from the Columbjohn reach (Lower Hayne, Bussell's Farm and Poundsland). The majority are very fresh (unabraded) flakes, blades and bladelets predominantly of local chert and flint (including the well-known Beer flint). The flint artefacts are often on pebbles with some very small flakes (microliths <20 mm in length). Finding these close to each other and in such fresh condition strongly suggests they are *in-situ*. The middle and final stages of knapping sequences are represented at these sites, but not the early stages. The lithics are mostly undiagnostic; some are early Mesolithic (10,000-7500 BP) but others are late Mesolithic and/or Neolithic (7500-4000 BP). These scatters are very similar to those that have been documented from the Exe Valley terraces just upstream of its junction with the Culm (Silvester et al., 1987). These finds confirm the lack of overbank deposition onto these terrace fragments (which with thin soils were probably open) and the existence of adjacent channels which were probably being utilised for both plant and animal resources.

4.2 Early-Mid Holocene stability

The lack of evidence for palaeochannel abandonment, or significant overbank deposition, cannot be explained by erosion due to the persistence of the terrace fragments and lack of any stratigraphic evidence of lateral erosion between the late Holocene channels. Hence both probably resulted from low discharge and high within-channel vegetation which caused the stability of the anastomosing system. In order to test this proposition, we undertook some simple palaeohydrological modelling and estimation. Starting from the seminal study by Lockwood (1979) we can make some hydrological estimates for the Culm basin in the early to middle Holocene. The simplest approach is due to use the Thornthwaite Equation (Supplementary Text Eqn. 4) to calculate the monthly potential evapotranspiration (PET) as a function of temperature based upon figures from the closest high-quality proxy estimates from northern England adjusted for distance south and west. Although Thornthwaite is not the most accurate method of estimation of PET (Shaw and Riha, 2011), and actual evapotranspiration would be less, the Thornthwaite equation does not require parameters such as radiation, wind speed or air pressure, which are difficulty to estimate historically. Mean monthly temperatures were estimated from chironomid data (Langdon et al., 2004) for 6000-5000 years cal BP. Indicative monthly catchment water budgets were derived for the Culm using: 1. current precipitation (and temperature); and 2. A 10% reduction in monthly precipitation (Swindles et al., 2013) and an increase in temperature of 10%. While the latter may under-estimate precipitation during the mid-Holocene climatic optimum due to the strong linkage between rainfall in SW England and North Atlantic Sea surface temperatures (McGregor and Phillips, 2003), this is likely to be balanced by greater interception and evapotranspiration that would have occurred under a fully forested catchment. The model incorporates a groundwater store to ensure a strong base flow component to river flow.

The result (Fig. 12c, Supplementary Table S11) suggests that in the early-middle Holocene runoff was at its lowest value with a reduction of discharge between 24% and 50% (particularly in October and November) and a runoff rainfall ratio of approximately 0.49 which close to the present value (0.54) and little river flow from June to September. However, groundwater recharge over winter would, as it does today, maintain a low baseflow discharge allowing aquatic vegetation to flourish in the channels. Given that forested conditions are also known to reduce flood-peak heights (Blöschl et al., 2015; Stratford et al., 2017) it is likely that this would have had an even greater effect on flood magnitudes with the mean annual flood falling below 10 m^3s^{-1} from the present 11.9 m^3s^{-1}. It is suggested here that this is the cause of an apparent lack of overbank sedimentation and stability with most floods contained within the inherited, over-capacity, anastomosing channel system. This also may explain the stability of the system which adjusts by reducing channel width as predicted by least-cost models (Nanson and Huang, 1999) and favoured by floodplain woodland providing high bank stability, localised debris dams and backwater effects (Brown et al., 1995). This, coupled with a stable climate and a lack of snowmelt is probably the cause of the relative lack of alluvial radiocarbon dates in the UK in the early-mid Holocene (Johnstone et al., 2006: Macklin et al., 2014). It is also probably characteristic of river systems more widely in Europe as the basal morpho-lithological units in many large European rivers suggest this was a common fluvial state and there is a relative lack of channel change in comparison to the later Holocene (Macklin et al., 2006; Lespez et al., 2015; Verstaeten et al., 2017; Brown et al., 2018).

4.3 Late Holocene – Anthropocene channel changes

The palaeochannel dates suggests that this situation changed c. 5400- 5300 years ago, and from then on channels were regularly abandoned and infilled reducing the active system to, on average, only 2-3 channels, probably due to a reduction in temperature-driven evapotranspiration and an increase in river runoff. This resulted in some neck and chute cutoffs, local incision and the reduction and expansion of channels, secondary channel abandonment and siltation. The lack of scroll bars and benches suggests that lateral instability was not a major factor although the main channel must have gained discharge and competence. The lack of significant bed aggradation, however, led to new channels being constrained to pass over palaeochannel fills and associated point bars, which became the foci for riffle development. The number of palaeochannels dated here (11) is not enough to allow a statistical comparison with palaeoclimatic data. However, it is likely that an increase in centennial-scale cool and wet conditions (Laskar et al., 2001; Magny et al., 2013) produced an increase in flood-dominated periods that is well illustrated in bigger UK rivers (Macklin et al., 2010; Charman, 2010; Pears et al., in press (b)) during the Later Holocene. This often coincided with a reduction in woodland cover both on catchment slopes and on floodplains (Macklin and Lewin, 1993; Smith et al., 2005; Brown et al., 2013; Goudie et al., 2016). However, this is not marked in this catchment (Fig. 13) and the dating of this change at c. 5400-5300 years cal- BP fits with the overall alluvial record in SW England and correlates broadly with Bond event 4 – a solar minimum driven iceberg advance in the N Atlantic and a likely reduction in N Atlantic SSTs (Bond et al., 2001; Steinhilber et al., 2009; Roland et al., 2015). The effect can be seen in the compilation of water-table-depths (WTDs) from Ireland which clearly shows a change in the water budget at this time (Swindles et. al., 2013). Indeed wetter conditions are seen across Europe (Magny et al., 2004, 2006) although the resolution of the record in the Culm system does not allow this association to be tested here. The data for floodplain sedimentation is more robust with a significant increase in all reaches during the last 400 years but with contrasting patterns in the last 100 years related to floodplain topography and distance downstream. If this increase in overbank sedimentation is driven by an increase in suspended sediment supply then, in the absence of major bank erosion, the cause is most likely increased arable cultivation in the catchment and particularly in the lowlands marginal to the floodplain. This is concordant with findings from both the Culm and other areas in the lowlands of the Exe valley that, irrespective of geology, cultivated land was a proportionately greater source of suspended sediment than pasture (Walling and Woodward 1995; Collins et al., 1998). This is in contrast to most other studies of small-medium lowland catchments that experienced large increases in fine overbank sedimentation from the 5th-4th millennium BP in the British Midlands (Brown and Barber, 1985; Smith et al. 2005; Brown et al, 2013), and eastern and southern England (Brown, 2004; Howard et al., 2016; Burrin, 1985). This pattern changes with more piedmont, western and northern rivers in the UK (Richard, 1981; Tipping, 1998; Hooke et al., 2020; Luchi et al., 2020; Macklin et al., 2010,2014) where terrace formation is more common and overbank alluviation later and more restricted.

4.4 Pseudo-cyclic channel morphology and planform

The data presented here, also suggests that in this system many of the riffles or within-channel bars and islands cannot be explained as purely equilibrium forms, but rather that the local increase in bed height caused flow divergence and gravel deposition on channel-bed steps and highs. This mechanism is not without precedence, as some pseudo-cyclic river bedforms on the river Suir in Ireland appear to have been inherited from the bounding geological-topography although this was not dominant (Gallagher et al., 2018). In fact ‘forcing elements’ for pool-riffle forms had already been recognised for semi-alluvial systems (alluvial fans and mixed-bed channels and bedrock outcrops), log jams, and tributary junctions (White et al., 2010). Understandably geomorphologists trying to uncover the dynamics of these bedforms have deliberately chosen reaches where they believed that there are no complicating factors. An example is near the river Culm, on the River Quarme in North Devon, where the classic pool-riffle sequence studied is atypical of the river zone in which bedrock acts as a key factor in both the channel and overbank flows (Clifford, 1993). Both avulsion and in more mobile systems, confined meandering, lead to channels having to cross old channels and their infills, and these locations can become nodes for bar growth and avulsion (Nicoll and Hickin, 2010; White et al., 2010) imparting an inherited pseudo-cyclicity related to past discharge (Gallagher et al., 2017). It is argued here that geological-topographic inheritance is for many rivers such as the Culm, the dominant bounding condition, and that this was the case for many more rivers in the temperate zone for much of the Holocene, depending upon the local rates of floodplain aggradation. Many of the features unusually well displayed in the Culm system, such as the channel spurs (remnant palaeochannel junctions), riffles and in this case anastomosis, are most easily explained by the non-uniformity of the floodplain that came into existence in the early Holocene. In glaciated regions rivers have all gone through a major metamorphosis with paraglaciation then a rapid reduction in both water and sediment supply, accompanied by uplift in some cases (Ballantyne 2002). What the Culm also shows is that the later Holocene channel patterns and fluvial morphology cannot be regarded as equilibrium forms but instead represent the adaptation of fluvial processes to forms, inherited from a previous or legacy state (Verstraeten et al., 2017) – and this is a continuous process which can confer both instability and stability, and non-linear responses even within the same reach.

A possible confounding factor in this analysis is the presence, or absence, of beavers (*Castor fiber*) which were present in Southern England from the Younger Dryas onwards and did not become extinct until c. 900 years ago (Coles, 2006; Lee, 2015). Whilst there is no evidence of beavers in the Culm valley (including place-name evidence), they were undoubtedly present in this region in the Early-Middle Holocene and, given their ecology, would have been in this river system. The re-introduction of beavers into nearby headwater catchments on Exmoor (Holnicote Estate), on the Tamar and accidentally into an adjacent catchment (The Otter) has shown how well they are adapted to this environment (Puttock et al., 2015). Ongoing monitoring of the Tamar reintroduction has shown an increase in fluvial landscape complexity with an increase in the area of standing water, creation of dams, a significant flow retention effect and increased biodiversity (Puttock et al., 2017; Brown et al., 2018). However, although they could have been responsible for some fluvial features, such as cross-cutting channels and right-angle river bends, beavers modify headwater river systems rather than creating anastomosing river systems downstream. The major effect they have in increasing biodiversity of vascular plants, bryophytes, insects and birds might have been a feature of the mid-late Holocene Culm system upstream of the reaches considered here.

4.5 Anthropocene biodiversity and management

The instability that has occurred in the later Holocene (after c. 5400 years cal BP) appears to have promoted and probably maintained high biodiversity due to channel heterogeneity, multiple-habitats and a complex spatial distribution of flooding, as predicted by the IDH model and as illustrated by the coleopteran data. The palaeoecological analysis here also shows that this is also partly anthropogenic, due to the use of the floodplain for traditional agricultural practices such as water-meadows, alder and willow growing, grazing by sheep and cattle, hay meadows and the maintenance of woodland, trees and hedges for a variety of purposes. This mix of land uses, rather than uniform grazing or arable land use, was also favoured by the high floodplain micro-topography, multiple channels and flooding and so to some extent can also be seen as a geological inheritance. So, although the model proposed here is primarily geomorphological, humans have had significant effects on the system, both in the floodplain and at the catchment scale. The floodplain is an example of a fluvio-cultural landscape (Brown et al., 2018) with features that are hybrid natural-anthropogenic. Examples here include numerous leats even including an aquaduct (Firth and Firth, 2020), watermeadows, short sections of straightened channel, some historical bank protection including riparian tree management, the long-term maintenance of numerous fords, causeways and the use of channels as ‘wet fences’ and even some re-alignment for a railway constructed in 1876 CE. The multiple channels also facilitated mills (grain, fulling and paper) at Five Fords (16th century), Woodmill, and at Southey Barton. Two of these activities require further research. The first is the extensive construction of water meadows on the Culm with evidence of both ‘bedworks’ on the floodplain and ‘catchworks’ on the valley sides. Although not dated here these were probably constructed in the 17th-18th centuries CE and were designed to increase and direct overbank deposition (Cook and Williamson, 2007; Firth and Firth, 2020). That overbank sedimentation was important is also suggested by a number of funnel-shaped meadows that are of probably medieval age (Firth and Firth, 2020). The second historical activity is the construction, or conversion of secondary channels into, mill leats which was happening as early as the 1290s CE in the vicinity of the Hele reach (Watts, 2016). It is speculation, but the complex network of channels may have been maintained rather than being ‘improved’ by encouraging or constructing a single channel because of the effectiveness of multiple channels in distributing water for agriculture and milling. Such a complex network could have resulted in too many interests in water to be readily reconciled or overruled, precluding a grand scheme, whilst the apparent absence of navigational interests might indicate a further reason why no single channel came to be dominant. So, although perhaps less than most, the Culm is still a genetically altered floodplain *sensu* Lewin (2013).

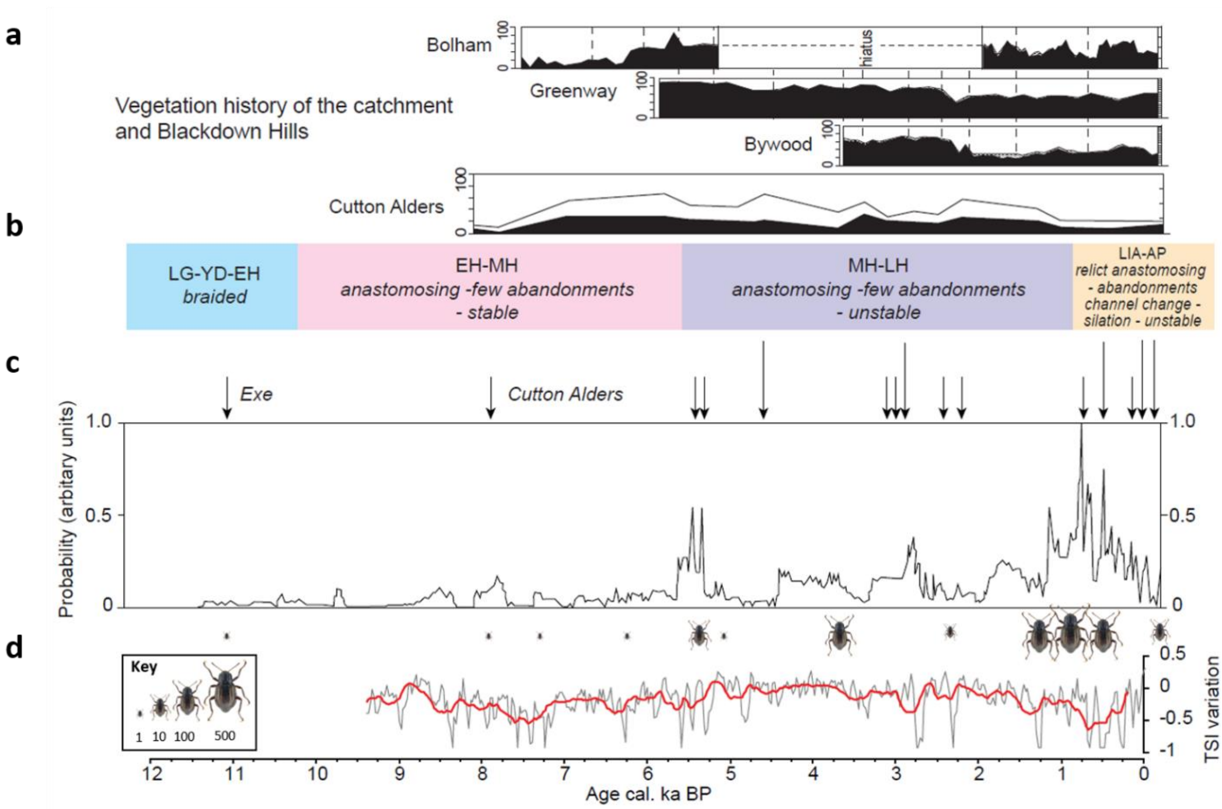

Fig. 13. A summary of the evolutionary history of the Culm floodplain, showing vegetation history (**a.** plotted as TTP with shrubs for Cutton Alders), **b.** palaeochannel history and abandonments (arrows), **c.** the SW regional alluvial ^{14}C derived summary from Macklin et al 2010, **d.** riffle beetle occurrence and the solar intensity record (TSI) from Steinhilber et al. 2012 (Grey - Total Solar Irradiance (TSI) (W/m^2) back to 9400 years cal BP. TSI given as difference to the value of the PMOD composite during the solar cycle minimum of the year 1986 AD (1365.57 W/m^2) as given in Frohlich 2009; Red - 1000yr running average.

Likewise the vegetation history of the headwaters in the Blackdown Hills is important, as, although floristically rich, the area was not deforested until later than most of southern England. Some of the steep valley slopes of the edges of the Blackdown Plateau may have never been deforested, but were instead managed as woodland pasture and for timber and fuel, for both domestic use and the iron working industry that developed from the late Iron Age into the Medieval period (Rippon, 2012; Brown et al., 2014). The catchment was characterised by ‘post-enclosure improvement’ in the late 18th to early 20th centuries CE with an emphasis on drainage of the poorly drained Blackdown soils to increase arable production, and with increasing mechanisation in the 20th century CE (Rippon, 2012).

As part of actions to increase river corridor biodiversity, ecological enhancement of the Culm floodplain began in 1989-99 CE when 5.8 ha of a hay meadow was planted with native mixed broadleaves particularly alder and willow to create a wet woodland habitat (Hunkin Wood, Woodland Trust, 2014). This occurred just prior to a large flood in the system which destroyed part of the wood and interacted with the newly planted saplings (Supplementary Fig. S13a,b). This flood also produced channel change but in only a few sensitive locations. An example of this was the palaeochannel excavated in the Five Fords reach (FF3), which expanded and migrated downstream (Supplementary Fig. S13b-c). So although the wood has generally established well, bank erosion, disease and outbreaks of insect damage have resulted in a more open mixture than was originally intended, and a more complex vegetation structure. The realisation that the Culm floodplain system has high potential for a nature-based approach to making the catchment more resilient to flooding and drought, and improving water quality and biodiversity, has stimulated the Connecting the Culm project, which is currently ongoing. Alongside Connecting the Culm, Historic England has funded the Historic Watercourses: River Culm project, which is developing a novel GIS-based methodology to flag human uses and interventions affecting the River Culm using evidence from historic maps, lidar data and a wide range of other archaeological and historical sources (Firth and Firth, 2020). This GIS layer, which is being shared with catchment managers, is also included in its draft form in Supplementary Figs. S1-S4 here. The inclusion of such data, together with the data contained in this paper, in the evidence-base for Connecting the Culm is a still-rare example of catchment management being based on an appreciation of the combined influence of cultural and natural processes over millennial timescales. An example of the practical use of this baseline data is the beetle diversity which using the palaeo-samples is 3.38 (Ln N+1) which is below a species-rich target floodplain of 3.8 but higher than improved grasslands (Woodcock and Mcdonald, 2010).

The high ecological (and landscape) value of the Culm valley is due to a combination of geological-topographical inheritance and its anthropogenic history which promoted high heterogeneity, intermediate disturbance and low abiotic uniformity. This channel-floodplain system was both quasi-stable and also resilient in that it adjusted to a threshold change in climate. However, the increase in overbank sedimentation in historical times illustrated here suggests that this may not be sustained and that the Culm is on a trajectory similar to the more heavily alluviated floodplains that are typical across most of lowland Europe, with negative ecological consequences, but which may also be avoidable.

5 Conclusions

1. A multiple-channel pattern classified as anastomosing occurs throughout the four study reaches of the river Culm, UK, and the floodplain exhibits morphological changes downstream –floodplain widening, and a reduction in floodplain slope and relative relief. The addition of the active secondary channels on average doubles channel sinuosity and proportionately increases channel bank length. Fragments of low Late Pleistocene- early Holocene terraces occur between channels and under the floodplain creating a complex pattern of inundation during floods. The topography of all four reaches is also dominated by palaeochannels, palaeochannel junctions, and palaeochannel intersections with the active channels. The length of palaeochannels (which also serve as flood channels) is between 1.4 and 2.1 x the active channel length.
2. From the dating (^{14}C and OSL) a model of floodplain development can be formulated commencing with down-cutting after LGM and the deposition of gravels in a braidplain a little wider than the present floodplain. There was only minor incision, leading to occasional palaeochannel formation and local reworking of terrace gravels in the early Holocene, due to the reduction in river competence. This initiated a multi-channel system which was stable in the early-middle Holocene. Simple water balance modelling using palaeoecological temperature estimates suggests that early-mid Holocene pattern stability was due to a lower discharge even more dominated by baseflow than that today.

3. Dating of the palaeochannels reveals that all date from the Middle-Late Holocene (post 5400 years cal- BP). This date for a critical transition from stability to instability suggests it was driven by the cooling event recorded in the North Atlantic and widely in European fluvial systems and not by deforestation. The combined dating also reveals several later peaks in avulsive activity with the largest peak in the last 400 years, probably forced by the Little Ice Age. The spacing of the peaks in the last 2000 years suggests a possible 380+ year cycle which could relate to solar forcing, although this is unproven.
4. In total 58% of the riffles in the surveyed sub-reaches were on or just adjacent to palaeochannel fills and associated buried point bars, whereas a random expectation would be 26%. In three cases excavation and coring also proved and dated the palaeochannel beneath the riffles. This is an example of geological-topographic inheritance, as is the high floodplain relief in the upper reaches. Although the system may have been stable in the past the Culm is an example of an anastomosing system that has persisted in a state of quasi-stability, maintaining an inherited form but still conveying both water and sediment. The Culm's quasi-stability was summed up more eloquently by one farmer "the funny thing about the Culm is that it is always changing but still remains the same" (Les Walsh, pers comm. 1999).
5. There has been constant oscillatory channel change and channel-switching over the last 400 years as well as channel management (including for watermeadows) and the rate of overbank sedimentation has increased significantly (average 4 mm yr^{-1}) particularly over the last 100 years. This is most likely due to the rather late conversion of pastoral land to arable cultivation and economic interest tied to a complex land-use mosaic and multiple-channels maintained for a variety of purposes. So the economic drivers that transformed other lowland rivers effectively preserved an anastomosing system in this case.
6. The high ecological value of the system, assessed here principally by Coleoptera, is driven by its non-uniformity and an associated pattern of land uses bounded by channels on the floodplain. This is best illustrated by the atypical persistence of riffle beetles in a lowland river system in the UK. Along with flooding and the multiple channels this has promoted an intermediate disturbance regime for both plants and animals. However, the largest threat to ecological value is probably changing catchment conditions, and particularly increased sediment load, driven by a combination of arable agriculture and climate change.

Data Availability

All the data used in this paper are contained in the text or in the Supplementary Information, except where otherwise stated.

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References

Alexander, J.S., Wilson, R.C., Reed Green, W. R., 2012. A Brief History and Summary of the Effects of River Engineering and Dams on the Mississippi River System and Delta. Circular 1375, U.S. Geological Survey, 43p.

Allen, T.G., Mitchell, N., 2001. Dorney, Eton Rowing Lake: fifth interim report. South Midlands Archaeology 31, 26-30.

Amoros, C., Bornette, G., 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. Freshwater. Biology 47, 761–776.

Armitage, P.D., Szoszkiewicz, K., Blackburn, J.H., Nesbitt, I. 2003. Ditch communities: a major contributor to floodplain biodiversity. Aquatic Conservation: marine and Freshwater Ecosystems 13, 165-185.

Bailey, R.M., Smith, B.W., Rhode,s E.J., 1997. Partial bleaching and the decay form characteristics of quartz OSL. Radiation Measurements 27, 123-136.

Ballantyne, C.K., 2002. A general model of paraglacial landscape response. The Holocene 12, 371-376.

Barber, K.E., Maddy, D., Rose, N., Stevenson, A.C., Stoneman, R., Thompson, R., 2000. Replicated proxy-climate signals over the last 2000 yr from two distant UK peat bogs: new evidence for regional palaeoclimate teleconnections. Quat. Sci. Rev. 19, 481–487.

Beijerinck, W., 1947. Zadenatlas Der Nederlansche Flora. Ten Behoeve Van De Botanie, Palaeontologie, Dodemcultuur En Warenkennis. H. Veenman & Zonen, Wageningen.

Bennett, K.D., 1989. A provisional map of forest types for the British Isles 5000 years ago. Journal of Quaternary Science 4, 141-144.

Berendsen, H. J. A., Stouthamer, E., 2001. Palaeogeographic development of the Rhine-Meuse delta, the Netherlands, Den Bosch, Assen., 225pp.

Birks, H.J.B., Felde, V.A., Bjune, A.E., Grytnes, J-A., Seppä, H., Giesecke, T. 2016. Does pollen-assemblage richness reflect floristic richness? A review of recent developments and future challenges. Review of Palaeobotany and Palynology 228, 1-25.

Biswas, S. R., Mallik. A. U., 2010. Disturbance effects on species diversity and functional diversity in riparian and upland plant communities. Ecology 91:28-35.

Böhme, J., 2005. Die Käfer Mitteleuropas. K. Katalog (Faunistiche Übersicht) (2nd ed.). Spektrum Academic, Munich.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent Solar Influence on North Atlantic Climate during the Holocene, Science 294, 2130-2136.

Blöschi, G., Gaál, L., Hall, J., Kiss, A., Komma, J., Nester, T., Parajka, J., Perdigão, R.A.P., Plavcová, L., Rogger, M., Sallinas, J. L., Viglioni, A., 2015. Increasing river floods: fiction or reality? Wiley Intersdciplinary Reviews (WIREs): Water 2015 doi:10.1002/wat2.1079

ter Braak, C.J.F., Smilauer, P., 2002. CANOCO reference manual and user's guide to Canoco for Windows: Software for Canonical Community Ordination Version 4·5. Microcomputer Power, Ithaca, NY.

Braga, G., Gervasoni, S., 1989. Evolution of the Po river: an example of the application of historic maps, in G. E. Petts (Ed.) Historical Change of Large Alluvial Rivers: Western Europe, Wiley, Chichester, 113-126.

Bravard, J-P., Provansal, M., Arnaud-Fassetta, G., Chabbert, S., Gaydou, P., Dufour, S., Richard, F., Valletaeu, S., Melun, G., Passy, P., 2008. Un atlas du paléo-environnement de la plaine alluviale du Rhône, de la frontière suisse à la mer. Collection EDYTEM. Cahiers de géographie 6, 101-116.

Brookes, A., 1988. Channelised Rivers: Perspectives for environmental management. Wiley, Chichester.

Brookes, A., Gregory, K.J., Dawson, F.H., 1983. An assessment of river channelization in England and Wales. Science of the Total Environment 27, 97-111.

Brookes, A. P., Brierley, G. J. 2000. The role of European disturbance in the metamorphosis of the lower Bega river. In Finlayson, B. L., and Brizga, S.A. (Eds.) *The Australian Experience.* Chichester, Wiley, UK.

Brown, A.G., 1997. Biogeomorphology and diversity in multiple-channel systems. Glob. Ecol. Biogeogr. Lett. 6, 179–185.

Brown, A.G., 1998. The maintenance of biodiversity in multiple-channel floodplains. In: Bailey, R.G., José, P.V., Sherwood, B.R. (Eds.), United Kingdom Floodplains. Westbury Press, Linnean Society, 83–92.

Brown, A. G., 1999. Biodiversity from pollen analysis: modern pollen studies and the recent history of a floodplain woodland in S. W. Ireland. Journal of Biogeography 26, 19-32.

Brown, A. G., 2004. The geoarchaeology of the Middle Nene valley. In: H. E. Langford and R. M. Briant (Eds.) Nene Valley Field Guide. Quaternary Research Association, Cambridge. 44-58.

Brown, A. G., Barber, K. E., 1985 Late Holocene palaeoecology and sedimentary history of a small lowland catchment in Central England. Quaternary Research, 24, 87 102.

Brown, A. G., Carpenter, R. G., Walling, D. E. 2007. Monitoring Fluvial Pollen Transport, its Relationship to Catchment Vegetation and Implications for Palaeoenvironmental Studies. Review of Palaeobotany and Palynology 147, 60-76.

Brown, A. G., Basell, L. S., Toms, P. T., 2014a. A stacked Late Quaternary fluvio-periglacial sequence from the Axe valley, Southern England with implications for landscape evolution and Palaeolithic archaeology. Quaternary Science Reviews 116, 1-16.

Brown, A. G., Stone, P., Harwood, K., 1995 The Biogeomorphology of a Wooded Anastomosing River: The Gearagh on the River Lee in County Cork, Ireland. Occasional Papers in Geography, No 32, University of Leicester, 76p.

Brown, A. G., Cooper, L., Salisbury, C. R., Smith, D. N., 2001 Late Holocene channel changes of the Middle Trent: Channel response to a thousand year flood record. Geomorphology 39, 69-82.

Brown, A. G., Basell, L.S, Toms, P.S., Bennett, J., Hosfield, R.T., Scrivener, R.C., 2010. Late Pleistocene Evolution of the Exe Valley. A Chronostratigraphic Model of Terrace Formation and its Implications for Palaeolithic Archaeology. Quaternary Science Reviews 29, 897-912.

Brown, A. G., Toms, P, Carey, C., Rhodes, E., 2013. Geomorphology of the Anthropocene: time-trangressive discontinuities of human-induced alluviation. The Anthropocene 1, 3-13.

Brown, A. G., Hawkins, C., Ryder, L., Hawken, S., Griffith, F. M., Hatton, J., 2014. Palaeoecological, archaeological and historical data and the making of Devon landscapes. I. The Blackdown Hills. Boreas 43 DOI 10.1111/bor.12074

Brown, A. G., Sear, D. A., Macaire, J-J., Brazier, R., Klimek, K. van Oost, K., Pears, B., 2018. Natural vs Anthropogenic Streams in Europe: History, Ecology and Implications for Restoration, River-Rewilding and Riverine Ecosystem Services. Earth Sci. Revs. 180, 185-205.

Buckland, P.I., Buckland, P.C., 2006. BugsCEP Coleopteran Ecology Package. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series # 2006-116. NOAA/NCDC Paleoclimatology Program, Boulder CO, USA. URL:http://www.ncdc.noaa.gov/paleo/insect.html or http://www.bugscep.com

Buffington, J.M., Montgomery, D.R., 2013. Geomorphic classification of rivers. In: Shroder, J. (Editor in Chief), Wohl, E. (Ed.), Treatise on Geomorphology. Academic Press, San Diego, CA, vol. 9, Fluvial Geomorphology, pp. 730–767.

Burrin, P.J., 1985. Holocene alluviation in southeastern England and some implications for palaeohydrological studies. Earth Surface Processes and Landforms 10, 257-271.

Buteux, S., Chapman, H., 2009. Where Rivers Meet: The Archaeology of Catholme and the Trent-Tame Confluence. Council for British Archaeology, London.

Candel, H.J.H., 2020. Ahead of the curve Channel pattern formation of low-energy rivers. PhD Thesis, University of Wageningen, Netherlands. DOI https://doi.org/10.18174/506616

Carling, P., Jansen, J., Meshkova, L., 2014. Multichannel rivers: their definition and classification. Earth Surf. Process. Landforms 39, 26–37.

Chartrand, S.M., Jellinek, A.M., Hassan, M.A., Ferrer-Boix, C. 2019. What controls the disequilibrium state of gravel-bed rivers? Earth Surface Processes and Landforms 44, 3020-3041.

Charman, D.J., 2010. Centennial climate variability in the British Isles during the mid-late Holocene. Quaternary Science Reviews 29, 1539-1554.

Church, M., 1983. Pattern of instability in a wandering gravel-bed channel, in J. D. Collinson and J. Lewin (Eds.) Modern and Ancient Alluvial Systems, International Association of Sedimentologists Special Publication 6, 169-180.

Clifford, N.J., 1993. Formation of riffle-pool sequences: field evidence for an autogenetic process. Sedimentary Geology 85,39-51.

Cluer, B., Thorne, C., 2013. A stream evolution model integrating habitat and ecosystem benefits. River Research and Applications 30, 135–154.

Coles, B. J., 2006. Beavers in Britain's Past. Oxbow Books, Oxford, 240p.

Collins, A.L., Walling, D.E., Leeks, G.J.L., 1998. Use of composite fingerprints to determine the provenance of the contemporary suspended sediment load transported by rivers. Earth Surface Processes and Landforms 23, 31-52.

Cook, H., Williamson, T., 2007. Water Meadows: History, Ecology and Conservation. Windgather Press, Oxford 160p.

Cudmore, A.V., 2012. The impacts of past land-use on the ecology of an ancient woodland in south-west Ireland. PhD Thesis, University College Cork. http://creativecommons.org/licenses/by-nc-nd/3.0/

Davis, S.R., Brown, A.G., Dinnin, M.H., 2007. Floodplain connectivity, disturbance and change: a palaeoentomological investigation of floodplain ecology from SW England. J. Anim. Ecol. 76, 276–288.

Drisoll, L., 2017. Cullompton Eastern Distributor Road. Design and Calibration Hydrology Report. ARCADIS Design and Consultance, Cardiff 0007-UA005763-NER-01.

Elliott, J.M., 2008. The ecology of riffle beetles (Coleoptera: Elmidae). Freshwater Reviews 1, 189-203.

Ekwall, E., 1960. The Concise Oxford Dictionary of English Place-names. 4th Edn., Oxford.

Firth, E., Firth, A., 2020, Historic Watercourses: Appendices. Draft document prepared for Historic England. HE ref: 7911.

Frohlich, C., 2009. Observational evidence of a long-term trend in total solar irradiance. Astronomy and Astrophysics, 501, L27-L30. https://doi.org/10.1051/0004-6361/200912318

Fryirs, K.A., Wheaton, J.M., Brierley, 2016. An approach for measuring confinement and ass4ssing the influence of valley setting on river form and processes. Earth Surface Processes and Landforms 41, 701-710.

Fyfe, R. M., Brown, A. G., Coles, B. J., 2003 Vegetational change and human activity in the Exe Valley, Devon, UK. Proceedings of the Prehistoric Society 69, 161-182. Doi: 10.1017/s0079497x00001298

Gallagher, C., Balme, M., Clifford, N., 2018. Discriminating between the roles of late Pleistocene palaeodischarge and geological-topographic inheritance in fluvial longitudinal profile and channel development. Earth Surface Processes and Landforms 43, 444-462.

Goudie, A, Viles, H., 2016. Geomorphology in the Anthropocene. Cambridge University Press.

Greenwood, D.R., 1991. The taphonomy of plant macrofossils. In S.K. Donovon (Ed.), The Processes of Fossilisation, Columbia University Press, Columbia, pp. 141-169.

Gregory, K. J., 1997. Fluvial Geomorphology of Great Britain. Joint Nature Conservation Committee/Springer Science+Business Media, Dordrecht DOI 10.1007/978-94-011-5816-9.

Gregory, K.J., Lewin, J., 2015. Making concepts more explicit for geomorphology. Progress in Physical Geography 39, 711-727.

Grime, J.P., 1973. Competitive exclusion in herbaceous vegetation. Nature, 242, 344–347.

Gurnell, A., Tockner, K., Edwards, P.J., Petts, G.E. 2005. Effects of deposited wood on biocomplexity of river corridors. Frontiers in Ecology and Environment 3, 377-382.

Gustard, A., Bullock, A., Dixon, J. M., 1992. Low flow estimation in the United Kingdom. Wallingford, Institute of Hydrology, 88pp. (IH Report No.108).

Hardy, R.J., Bates, P.D., Anderson, M.G., 2000. Modelling suspended sediment deposition on a fluvial floodplain using a two-dimensional dynamic finite element model. Journal of Hydrology 229, 202-218.

Harper, D., Mekotova, J., Hulme, S., White, J., 1997. Habitat heterogeneity and aquatic invertebrate diversity in floodplain forests. Glob. Ecol. Biogeogr. Lett. 6, 275–285.

Hesketh, R., 2008. Devon Placenames. Launceston: Bossiney Books. ISBN 978-1-899383-98-6.

Hooke, J.M., 1979. An Analysis of the Processes of River Bank Erosion. Journal of Hydrology 42, 39-62.

Hooke, J. M., Yorke, L., 2010. Rates, distributions and mechanisms of change in meander morphology over decadal timescales, River Dane, UK. Earth Surface Processes and Landforms, 35(13), 1601-1614. doi:10.1002/esp.2079 DOI: 10.1002/esp.2079

Howard, A., Chapman, H., Gearey, B., 2016. Down by the River: Archaeological, Palaeoenvironmental and Geoarchaeological Investigations of the Suffolk River Valleys. Oxbow Books, Oxford.

Institute of Geological Sciences, 1982. Hydrogeological Map of the Permo-Trias and other Minor Aquifers in South West England. NERC, Swindon.

Jacobsen, G.L., Bradshaw, R.H.W. 1981. The selection of sites for palaeovegetational studies. Quaternary Research 16, 80-96.

Johnstone, E., Macklin, M.G., Lewin, J., 2006. The development and application of a database of radiocarbon-dated Holocene fluvial deposits in Great Britain. Catena 66, 14-23.

Katz, N.J., Katz, S.V., M. G., Kipiani, M.G., 1965. Atlas and Keys of Fruits and Seeds Occuring in the Quaternary Deposits of the USSR. Academy of sciences of the USSR Forfattere N. J. 364p.

Kenward, H.K., Hall, A.R., Jones, A.K.G., 1980. A tested set of techniques for the extraction of plant and animal macrofossils from waterlogged archaeological deposits. Scientific Archaeology 22, 3–15.

Kleinhans, M.G., van den Berg, J. H., 2010. River channel and bar patterns explained and predicted by an empirical and a physics-based method. Earth Surface Processes and Landforms 36, 721-738.

Knighton, A. D., Nanson, G. C., 1993. Anastomosis and the continuum of channel pattern, Earth Surface Processes and Landforms, 18, 613-625.

Langdon, P.G., Barber, K.E., Lomas-Clarke, S.H., 2004. Reconstructing climate and environmental change in northern England through chironomid and pollen analyses: evidence from Talkin Tarn, Cumbria. Journal of Paleolimnology 32, 197–213.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. C. M., Levrard, B., 2001. A long-term 1107 numerical solution for the insolation quantities of the Earth. Astronomy & Astrophysics 1108 261–285.

Lambert, C.P., 1986. The suspended sediment delivery dynamics of river channels in the Exe basin. PhD Thesis, University of Exeter, UK.

Lane, S.N., Richard, K.S., 1997. Linking river channel form and process: Time, space and causality revisited. Earth Surface Processes and Landforms 22, 249-260.

Leopold, LB., Wolman, M.G., Miller, J.P., 1964. Fluvial Processes and Geomorphology. W.H. Freeman, San Francisco.

Lee, R., 2015. The early extinction date of the beaver (*Castor fiber*) in Britain. Historical Biology 27, 1029-1041.

Lespez, L., Germaine, M.-A., Barraud, R., 2016. L'évaluation par les services écosystémiques des rivières ordinaires est-elle durable? VertigO URL. http://vertigo. revues.org/17443.

Lespez, L., Viel, V., Rollet, A.-J., Delahaye, D., 2015. The anthropogenic nature of present day low energy rivers in western France and implications for current restoration projects. Geomorphology 251, 64–76.

Lewin, J. 2011. Medieval environmental impacts and feedbacks: The lowland floodplain of England and Wales. Geoarchaeology 25, 267-311.

Lewin, J., 2013. Enlightenment and the GM floodplain. Earth Surface Processes and Landforms 38, 17–29.

Lewin, J., Bradley, S.B., Macklin, M.G., 1983. Historical valley alluviation in Wales. Geological Journal 18, 331-350.

Lockwood, J. G., 1979. Water Balance of Britain, 50,000 yr B.P. to the Present Day. Quaternary Research 12, 297-310.

Luchi, R., Hooke, J. M., Zolezzi, G., Bertoldi, W., 2010. Width variations and mid-channel bar inception in meanders: River Bollin (UK). Geomorphology, 119(1-2), 1-8.

Lucht, W.H., 1987. Die Kãfer Mitteleuropas, Katalog. Goeke & Evers, Krefeld.

Macklin, M.G, Lewin, J., 1993. Holocene alluviation in Britain. Zeitschrift fűr Geomorphologie Supplement-Band 88, 109-122.

Macklin, M.G., Jones, A.F., Lewin, J., 2010, River response to rapid Holocene environmental change: Evidence and explanation in British catchments: Quaternary Science Reviews 308, 1555-1576.

Macklin, M.G., Lewin, J., Jones, A., 2014. Anthropogenic alluvium: an evidence-based meta-analysis for the UK Holocene. Anthropocene 6, 26-38.

Macklin, M.G., Benito, G., Gregory, K.J., Johnstone, E., Lewin, J., Michczńska, D.J., Soja, R., Starkel, L., Thorndycraft, V.R., 2006. Past hydrological events reflected in the Holocene fluvial record of Europe. Catena 66, 145-154.

Macklin, M.G., Toonen, W.H.J., Woodward, J.C., Williams, M.A.J., Flaux, C., Marriner, N., Nicoll, K.; Verstraeten, G., Spencer, N., Welsby, D., 2015. A new model of river dynamics, hydroclimatic change and human settlement in the Nile Valley derived from meta-analysis of the Holocene fluvial archive. Quat. Sci. Rev. 130, 109–123.

Magny, M., 2004. Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. Quaternary International 113, 65-79.

Magny, M., Leuzinger, U., Bortenschlager, S., Haas, J.N., 2006. Tripartite climate reversal in Central Europe 5600–5300 years ago. Quaternary Research 65, 3-19.

Magny, M., Leroux, A., Bichet, V., Gauthier, E., Richard, H., Walter-Simonnet, A.V., 2013. Climate, vegetation and land use as drivers of Holocene sedimentation: A case study from Lake Saint-Point (Jura Mountains, eastern France). The Holocene 23, 137-147.

Marcinkowski, P., Giełczewski, M., Okruszko, T., 2018. Where Might the Hands-off Protection Strategy of Anastomosing Rivers Lead? A Case Study of Narew National Park. Polish Journal of Environmental Studies 27(6), 2647-2658.

Marks, K., Bates, P., 2000. Integration of high-resolution topographic data with floodplain flow models. Hydrological Processes 14, 2109-2122.

McGregor, G., Phillips, I.D., 2003. Specification and prediction of monthly and seasonal rainfall over the south-west peninsula of England. Quat. J. Roy. Meteological Society 130, 193-210.

Miall, A.D., 1977. A review of the braided river depositional environment. Earth Science Review 13, 1–62.

Middelkoop, H., Schoor, M.M., Babich, D.B., Alabyan, A.M., Shoubin, M.A., van den Berg, J.H., de Kramer, J., Dijkstra, J., 2005. Bio-morphodynamics of the lower Volga river – a reference for river rehabilitation in the Netherlands. Large Rivers 15, 89-103.

Mollard, J. D., 1973. Airphoto interpretation of fluvial features, Proceedings of the 9th Canadian Hydrology Symposium, Edmonton, Alberta, National Research Council of Canada, 341-380.

Montgomery, D.R., Buffington, J.M., Smith, R.D., 1995. Pool spacing in forest channels. Water Resources Research 31, 1097-1105.

Mordant, D., Mordant, C., 1992. Noyen-sur-Seine: a Mesolithic waterside settlement. In: The Wetland Revolution in Prehistory. Wetland Archaeological Research Project Occasional Paper 6, Exeter. B. Colespp. 55–64.

Nanson, G. C., Knighton, A. D., 1996. Anabranching rivers: their cause, character and classification. Earth Surface Processes and Landforms 21, 217-239.

Nanson, G. C., Huang, H. Q., 1999. Anabranching rivers: divided efficiency leading to fluvial diversity. In A. Miller and A. Gupta (eds.) Varieties of Fluvial Form, Wiley, Chichester, 477-494.

Nicholas, A.P., 2013. Modelling the continuum of river channel patterns. Earth Surface Processes and Landforms 38, 1187-1196.

Nicholas, A.P., McLelland, S.J., 1999. Hydrodynamics of a floodplain recirculation zone investigated by field monitoring and numerical simulation. In S.B. Marriott and J. Alexander (Eds.) Floodplains: Interdisciplinary Approaches, Geological Society of London, Special Publications 163, 15-26.

Oakley, S., 2010. Turning back the clock. In: River Restoration News 35, 2-3.

Osborne, P., J., 1988. A late Bronze Age insect fauna from the river Avon, Warwickshire, England: its implications for the terrestrial and fluvial environment and climate. Journal of Archaeological Science 15, 715-727.

Pears, B., Brown, A.G., Carroll, J., Toms, P., Wood, J., Jones, R., 2020a. Early medieval place-names and riverine flood histories: a new approach and new chronostratigraphic records for three English rivers. European Journal of Archaeology 23, 3, 381-405.

Pears, B., Brown, A.G., Toms, P., Wood, J., Sanderson, D., Jones, R., 2020, A sub-centennial-scale OSL chronostratigraphy and Late-Holocene flood history from a temperate river confluence Geology, 48, 819-825.

Petts, G.E., Möller, H., Roux, A.L., 1989. Historical Changes of Large Alluvial Rivers: Western Europe. Wiley, Chichester, UK.

Pišůt, P., 2002. Channel evolution of the pre-channelised Danube near Bratislava, Slovakia (1712-1886). Earth Surf. Process. Landforms 27, 369–390.

Powers, P.D., Helstab, M., Niezgoda, S.L., 2018. A process-based approach to restoring depositional river valleys to Stage 0, an anastomosing channel network. River Res Applications 2018, 1–11.

Prins, T.K., Andresen, K.J., 2019. Buried late Quaternary channel systems in the Danish North Sea – Genesis and geological evolution. Quaternary Science Reviews 223, 105943

Puttock, A.K., Cunliffe, A., Anderson, K.A., Brazier, R.E., 2015. Aerial photography collected with a multirotor drone reveals impact of Eurasian beaver reintroduction on ecosystem structure. J. Unmanned Vehicle Systems 3, 123–130.

Puttock, A.K., Graham, H.A., Cunliffe, A.M., Elliott, M., Brazier, R.E., 2017. Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands. Sci. Total Environ. 576, 430–443.

Rhodes, E.J., 1988. Methodological considerations in the optical dating of quartz. Quaternary Science Reviews 7, 395-400.

Rhodes, E.J., 2011. Optically Stimulated Luminescence Dating of Sediments over the Past 200,000 Years. Annual Review of Earth and Planetary Sciences 39, 461–488.

Richard, K.S., 1981. Evidence of Flandrian valley alluviation in Staindale, North York Moors. Earth Surface Processes and Landforms 6, 183-186.

Rippon, S., 2012. Making Sense of an Historic Landscape. Oxford University Press, Oxford.

Rittenour, T.M. Blum, M.D. Goble, R.J., 2007. Fluvial evolution of the lower Mississippi River valley during the last 100 k.y. glacial cycle: Response to glaciation and sea-level change. Geol. Soc. Am. Bull. 119, 586–608.

Rivaes, R., Rodriguez,-Gonzales, P.M., Albuquerque, A., Pinheiro, A.N., Egger, G., Ferreira, M.T., 2012. Riparian vegetation responses to altered flow regimes driven by climate change in Mediterranean rivers. Ecohydrology 6, 413-424.

Robinson, M. 1981. Appendix I: the use of ecological groupings of Coleoptera for comparing sites. In: M. Jones and G. Dimbleby (eds.) The Environment of Man: the Iron Age to the Anglo-Saxon Period pp.279-281. B.A.R. Brit. Ser. 87

Robinson, M., 1993. The scientific evidence. In: T.G. Allen and M.A. Robinson (eds.) The prehistoric landscape and Iron Age enclosed settlement at Mingies Ditch, Hardwick-with-Yelford, Oxon. Oxford Archaeological Unit. Thames Valley Landscapes: The Windrush Valley Volume 2.

Roland, T.P., Daley, T.J., Caseldine, C.J., Charman, D.J., Turney, C.S.M., Amesbury, M.J., Thompson, G.J., Woodley, E.J., 2015. In The 5.2 ka climate event: Evidence from stable isotope and multi-proxy palaeoecological peatland records in Ireland. Quaternary Science Reviews 124, 209-223.

Sadler, J., Bell, D. 2002. Invertebrates of Exposed River Sediments. Phase 3 – Baseline faunas. Environment Agency, Technical Report W1-034/TR, Bristol.

Schumm, S.A., 1977. The Fluvial System. Wiley, New York.

Schumm, S.A., Lichty, R.W., 1965. Time space and causality in geomorphology. American Journal of Science 263, 110-119.

Schumann, R. R., 1989. Morphology of Red Creek, Wyoming, an arid-region anastomosing channel system, Earth Surface Processes and Landforms 14, 277-288.

Schweingruber, F.H. 1990. Anatomie europaischer Holzer. - Anatomy of European Woods. Eidgenossische Forschungsanstalt fur Wald, Schnee und Landschaft, Birmensdorf, (Hrsg.) Haupt, Bern und Stuttgart.

Schweingruber, F.H., 1982. Microscopic Wood Anatomy: Structural variability of stems and twigs in recent and subfossil woods from Central Europe 2nd Ed. Fluck-Wirth, F. Internationale Buchhandlung fur Botanik und Naturwissenschaften, CH-9053 Teufen AR.

Shaw, S.B., Riha, S.J., 2011. Assessing temperature-based PET equations under a changing climate in temperate, deciduous forest. Hydrological Processes 25, 1466-1478.

Sherrell, F.W., 1970. Some aspects of the Triassic aquifer in east Devon and west Somerset. Quarterly Journal of Engineering Geology and Hydrogeology 2, 255-286.

Sear, D.A., Millington, C., Kitts, D.R., Jeffries, R., 2010. Logjam controls on channel:-floodplain interactions in wooded catchments and their role in the formation of multi-channel patterns. Geomorphology 116, 305–319.

Sidell, J. (Ed.), 2000. The Holocene Evolution of the London Thames. Archaeological Excavations (1991–1998) for the London Underground Limited Jubilee Line Extension Project. Museum of London Archaeology Service Monograph no. 5.

Silvester. R.A., Berridge, P., Uglow, P.J., 1987. A fieldwalking exercise on Mesolithic and Neolithic sites at Nether Exe. Devon Archaeological Society Proceedings 45, 1-21.

Simm, D.J., 1995. The rates and patterns of overbank deposition on a lowland floodplain. I I.D.L. Foster, A. M. Gurnell and B.W. Webb (Eds.) Sediment and Water Quality in Catchments. Wiley, Chichester, 247-264.

Simon, J., Machar, I., Buček, A., 2014. Linking the historical research with the growth simulation model of hardwood floodplain forests. Pol. J. Ecol. 62 (375–359).

Smith, D. N., 2001. Disappearance of Elmid “riffle beetles” from Lowland river systems in Britain – the impact of alluviation. In R.A. Nicholson and T.P. O’Connor (Eds.) People as an Agent of Environmental Change, Oxbow Books, Oxford, 75-80.

Smith, D. G., Smith, N. D., 1980. Sedimentation in anastomosed river systems: examples from alluvial valleys near Banff, Alberta, Journal of Sedimentary Petrology 50, 157-164.

Smith, D. N., Roseff, R., Bevan, L., Brown, A. G., Butler, S., Hughes, G., Monkton, A., 2005. Archaeological and environmental investigations of Late Glacial and Holocene river valley sequences on the River Soar, at Croft, Leicestershire. The Holocene 15, 353-377.

Smith, D. N., Roseff, R., Bevan, L., Brown, A. G., Butler, S., Hughes, G., Monkton, A., 2005. Archaeological and environmental investigations of Late Glacial and Holocene river valley sequences on the River Soar, at Croft, Leicestershire. The Holocene 15, 353-377.

Smith, D., Hill, G., Kenward, H., Allison, E., 2020. Development of synanthropic beetle faunas over the last 9000 years in the British Isles. Journal of Archaeological Science 115, 105075.

Smith, N.D., Cross, T.A., Dufficy, J.P., Clough, S.R., 1989. Anatomy of an avulsion. Sedimentology 36, 1-23.

Stace, C., 2010. New Flora of the British Isles, Third Edition, Cambridge University Press, Cambridge.

Steinhilber, F., Beer, J., Fröhlich, C., 2009. Total solar irradiance during the Holocene. Geophysical Research Letters 36, L19704.

Steinhilber, F., Abreu, J.A., Beer, J., Brunner, I., Christl, M., Fischer, H., Heikkilä, U., Kubik, P.W., Mann, M., McCracken, K.G., Miller, H., Miyahara, H., Oerter, H., Wilhelms, F., 2012. 9,400 years of cosmic radiation and solar activity from ice cores and tree rings. Proceedings of the National Academy of Sciences, 109, 5967-5971.

Stratford, C., Miller, J., Houes, A., Old, G., Acreman, M., Dueñas-Lopez, M.A., Nisbet, T., Newman, J., Burgess-gamble, L., Chappell, N., Clarke, S., Leeson, L., Monbiot, G., Paterson, J., Robinson, M., Rogers, M., Tickner, D., 2017. Do trees in UK relevant catchments influence fluvial flood peaks? A Systematic Review. CEH Project no. NEC06063, Centre for Ecology and Hydrology, Wallingford, Oxford 466p.

Stuiver, M., Reimer, P.J., and Reimer, R.W., 2020, CALIB 7.1 [WWW program] at http://calib.org, accessed 2020-4-15

Sweet, R.J., Nicholas, A.P., Walling, D.E., Fang, X., 2003. Morphological controls on medium-term sedimentation rates on British lowland river floodplains. Hydrobiologia 494, 177-183.

Swindles, G.T., Lawson, I.T., Matthews, I.P., Blaauw, M., Daley, T., et al., 2013. Centennial-scale climate change in Ireland during the Holocene. Earth Science Reviews 126, 300-320.

Thompson, D.M., Wohl, E.E., 2009. The linkage between velocity patterns and sediment entrainment in a forced-pool and riffle unit. Earth Surface Processes and Landforms 34, 177-192.

Tickner, D., Opperman, J., Abell, R., Acreman, M., Arthington, A. H., et al., 2020. Bending the curve of Global freshwater biodiversity loss: an emergency recovery plan. BioScience 70, 330-342.

Tipping, R., 1998. The chronology or late Quaternary fluvial activity in part of the Millfield basin, northeastern England. Earth Surface Processes and Landforms 23, 845-856.

Tockner, K., Tonolla, D., Uehlinger, U., Siber, R., Robinson, C.T., Peter, F. D.M. 2009. Rivers of Europe. Academic Press, New York.

Tooth, S., Nanson, G.C. 2000. Equilibrium and non-equilibrium conditions in dryland rivers. Physical Geography 21, 183-211.

Van Dijk, W. M., Teske, R., van de Lageweg, W. I., Kleinhans, M. G.m 2013. Effect of vegetation distribution on experimental river channel dynamics. Water Resources Research 49, 7558-7574.

Verstraeten, G., Broothaerts, N., Van Loo, M., Notebaert, B., D'Haen, K., Dusar, B., De Brue, H., 2017. Variability in fluvial geomorphic response to anthropogenic disturbance. Geomorphology 294, 20-39.

Walling, D. E., Bradley, S. B., 1989. Rates and patterns of contemporary floodplain sedimentation: a case study of the River Culm, Devon, UK. Geo Journal 19, 53-62.

Walling, D.E., Moorehead, P.W., 1987. Spatial and temporal variation in particle size characteristics of fluvial suspended sediment. Geografiska Annaler A 69, 47-60.

Walling, D.E., Fang, D., Nicholas, A.P., Sweet, R. J., 2004. The grain size characteristics of overbank deposits of British rivers. In V. Golosov, V. Balyaev and D.E. Walling Sediment Transfer Through the Fluvial System: Proceedings of the Symposium held in Moscow. IAHD Publ. 226-234.

Ward, J.V., 1998. Riverine landscapes: Biodiversity patterns, disturbance regimes and aquatic conservation. Biological Conservation, 83, 269–278.

Ward, J.V., Tockner, K., 2001. Biodiversity: towards a unifying theme for river ecology. Freshwater Biology, 46, 807–819.

Ward, J. V, Malard, F., Tockner, K., 2002. Landscape ecology: a framework for integrating pattern and process in river corridors. Landscape Ecology 17, 35–45.

Wheaton, J.M., Brassington, J., Darby, S., Kasprak, A., Sear, D., Vericat, D., 2013. Morphodynamic signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-bed river. Journal of Geophysical Research 118, 759-779.

White, J.Q., Pasternak, G.B., Moir, H, J. 2010. Valley width variation influences riffle–pool location and persistence on a rapidly incising gravel-bed river. Geomorphology 121, 206–221.

Wilkinson, D.M., 1999. The disturbing history of intermediate disturbance. Oikos, 84, 145–147.

Woodcock, B.A., Mcdonald, A., 2020. What goes wrong? Why the restoration of beetle assemblages lags behind plants during the restoration of species rich flood-plain meadow. Fritillary 5, 21-30.

Woodland Trust, 2014. Hunkin Wood Management Plan 2014-2019. Woodland Trust, 20p.

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