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VEGETATION-HYDROGEOMORPHOLOGY INTERACTIONS IN A LOW-ENERGY, HUMAN-IMPACTED RIVER

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ABSTRACT

The geomorphological dynamics of rivers have been traditionally explained largely by the physical processes of water flow and sediment erosion and deposition, but the significant role of a third element, vegetation, in driving geomorphological changes has been increasingly highlighted recently. However, few studies have documented how both aquatic and woody riparian plants interact with fluvial processes to induce landform development and initiate channel adjustment. This paper presents analyses of historical maps, recent aerial images and field observations from the River Frome (Dorset, UK), which, as a result of human pressures, has been subject to an increased supply of sand and finer sediment, particularly over the last 50-60 years. Analysis of these information sources indicates that this low-energy river has adjusted to this delivery of finer sediment by narrowing and increasing its sinuosity. The analysis also indicates that this has been achieved through interactions among vegetation, water flow and sediment. Emergent aquatic macrophytes were observed to retain sediment, which leads to the development of submerged shelves that aggrade and become colonised by other plant species to form bars, berms and benches, eventually leading to the extension of river banks into the channel and also the formation of islands. Where woody riparian vegetation is well developed, complex geomorphic changes were observed, with fine sediment being absorbed into a diverse mosaic of geomorphic features initiated by living trees and large wood. These observations underline the importance of vegetation for the geomorphic dynamics and adjustment of lowland, low energy rivers and its potential for inclusion in the development of sustainable, process-based river management and restoration strategies.

KEY WORDS

Low energy river, Aquatic plants, Riparian vegetation, Hydrogeomorphology, Fine sediment

INTRODUCTION

Rivers and their floodplains are suffering increasing human pressures, and yet, when their natural function is maintained, they form some of the most biodiverse and dynamic environments on the Earth's surface (Tockner and Stanford, 2002). Human pressures have resulted, amongst many other impacts, in the disappearance and degradation of riparian woodland and floodplain wetlands; their replacement by more intensive land use including agriculture, housing, commercial and industrial buildings and transport infrastructure; reduced connectivity between rivers and their floodplains; and the modification of the size, planform, sediment dynamics and geomorphological complexity of river channels (e.g. Nilsson and Svedmark, 2002; Chin, 2006; Comiti, 2012; Downs et al., 2013; Petts and Gurnell, 2013).

Natural river dynamics have been traditionally attributed to the fluvial processes of flow and erosion-transport-deposition of sediment, but recently research has highlighted a third element, vegetation, which interacts with water and sediment-related fluvial processes to contribute to, and in some cases to drive, channel and floodplain morphodynamics (Corenblit et al., 2007, 2009; Collins et al., 2012; Gurnell et al., 2012, 2015a; Wohl, 2013).

In this paper, we describe how a low-energy, groundwater-dominated river has responded to catchment to reach scale changes in sediment delivery that result from human pressures (Grabowski and Gurnell, 2015). These pressures include widespread and increasingly intensive agriculture, the removal of most functioning riparian vegetation along much of the main stem, and the installation of flow control structures such as weirs and sluices. These changes have driven a major change in fine sediment dynamics within the catchment, which has resulted in accumulation of sand and finer sediment within the river channel (Cotton et al., 2006; Heppell et al 2009). Given the low energy of the river and the low stability of the delivered (sand and finer) sediment, riparian and aquatic vegetation has become a key component in the river's morphological response to this increase in sediment delivery (Gurnell et al. 2006), and in the longer term vegetation could be an even more important component in the sustainable management of the river system.

This paper builds on previous research that has investigated the causes and quantified the changes in flow and sediment processes within the catchment (Grabowski and Gurnell, 2015). It investigates three information sources (historical maps, aerial imagery, field survey) to build a picture of how this extremely low energy river has adjusted to increased fine sediment delivery, highlighting the role of vegetation-hydrogeomorphology interactions and the resulting vegetation-dependent landforms that drive this adjustment. Whilst the research focuses on a single river system, its outcomes are relevant to other very low energy temperate river systems affected by increased sand and finer sediment delivery from agricultural land. Thus, the research has broader relevance to understanding, managing and rehabilitating low energy rivers that are subject to similar human pressures.

STUDY AREA

The Frome Catchment and Drainage Network

The River Frome is located in Southern England. It drains a catchment area of 459 km², which is underlain mainly by Cretaceous chalk, with Cainozoic marine deposits in the lower catchment and Cretaceous sandstone, Jurassic limestone and mudstone within the upper part of the catchment. The predominantly calcareous bedrock provides a highly productive, unconfined aquifer across 65% of the catchment area. The topography is characterised by low, rolling hills with a relative relief of only 267 m.

Using the hierarchical hydrogeomorphological assessment framework developed within the REFORM project (Gurnell et al., 2015b; Figure 1), the catchment has been subdivided into 3 Landscape Units (LU), reflecting contrasts in elevation, geology and land cover. Land use is predominantly agriculture. Arable land covers 26%, 55%, and 44% and pasture covers 72%, 39% and 29% of the area in the upper (LU1), middle (LU2) and lower (LU3) parts of the catchment, respectively. The 66 km main stem has been divided into 6 river segments (S1 to S6, Figure 1), mainly reflecting changes in catchment area at major tributary confluences, and 17 river reaches (1 to 17, Figure 1) according to changes in planform and disruption of longitudinal continuity by major weirs (rectangles, Figure 1). The main stem is unconfined by its valley and its planform changes from predominantly sinuous and meandering in LU1 to increasingly low-energy anabranching (anastomosing) through LU2 and LU3.

Changing Flow and Sediment Regimes

This paper focuses on channel adjustments along the River Frome in response to changes in flow and sediment dynamics, which have been reported elsewhere (Grabowski and Gurnell, 2015). As a context for the investigation of channel adjustments in this paper, key elements of these changes in processes are summarised in this section (see Grabowski and Gurnell, 2015, for more details).

The River Frome has an extremely reliable flow regime that is dominated by groundwater inputs from the chalk aquifer. Analysis of daily flow records from three gauging stations (one in each of LU1, LU2, LU3) reveals a perennial stable or perennial superstable flow regime (Rinaldi et al., 2015). Furthermore, comparison of flow records for the two twenty year periods 1966-1985 and 1992-2011 at the most downstream gauging station (in LU3) suggests a shift from a perennial stable regime in the earlier period to a perennial superstable regime in the later period, accompanied by an increase in the baseflow index.

The Frome is a very low gradient river, with a main channel slope decreasing from 0.010 to 0.003 m.m⁻¹ in reaches 1 to 4 (LU1) and then to 0.002 or less in the reaches within LU2 and LU3 (apart from reach 6 – 0.004 m.m⁻¹ and reach 9 – 0.003 m.m⁻¹). Based on the median of the annual maximum flow recorded in a 15 minute flow series, total stream power is very low, with lowest values in the upstream reaches (1 - 3) increasing to a maximum of 439 W.m⁻¹ in reach 14. Specific stream power is also extremely low, with the highest values observed in Reach 1 (mean = 43 W m⁻²) where the channel is

narrowest and steepest. Specific stream power decreases downstream from reach 1 to reach 9 and then fluctuates around a mean of approximately 14 W.m^{-2} in the remainder of the main stem, reflecting variations in channel gradient and width.

An analysis of land cover and agricultural changes within the catchment has identified a lack of any significant riparian buffer zone along the river. Agriculture extends to the river banks across much of the catchment, although a sparse line of riparian trees usually provides a very narrow riparian strip, typically around 5m wide, on the bank tops (e.g. Figure 2). Most of the catchment is under agriculture and has been so for centuries, and the floodplain along the main stem has been subject to widespread and long term drainage. Although the proportion of arable to pasture land has changed little, agricultural production has intensified, particularly since the 1940s. Livestock numbers have increased, particularly the number of cattle and pigs; there has been an enormous increase in wheat and barley production; and changing cultivation practices have resulted in an increase in crop yields.

Sediment input and transfer through the Frome main stem were modelled using the Sediment Impact Assessment Method (SIAM) developed by the US Army Corps of Engineers (Grabowski and Gurnell, 2015). Estimates of sediment inputs drawn from Pan-European Soil Erosion Risk Assessment maps (PESERA, Kirkby et al., 2004) and bed sediment calibre estimates based on River Habitat (RHS, UK Environment Agency) and Mean Trophic Rank (MTR, Centre for Ecology and Hydrology) survey data were used in the modelling. The RHS and MTR data record the dominant bed material (bedrock, boulder, cobble, gravel, sand, silt, clay) and bank material (bedrock, boulder, cobble, gravel-sand, earth, clay) at ten cross sections within a surveyed reach. These surveys indicate a gravel bed combined with significant quantities of sand and finer sediment and predominantly earth banks (>90% bank composition in all 17 reaches) throughout the main stem of the Frome. The presence of a gravel bed and a lack of gravel in the banks suggests that there has been no significant incision of the gravel bed. SIAM was applied at the segment scale to estimate the gain or loss of sediment and thus a sediment budget for each of the six segments of the main stem. The model predicted a positive budget (net gain in bed sediment) for segments 2-6 (i.e. reaches 2 to 17) and a negative budget (net loss in bed sediment) from segment 1 (i.e. reach 1) and from the main tributaries to the Frome. Furthermore, the potential for transporting both sand and gravel-sized bed sediment was low throughout segments 2 to 6 regardless of the sediment transport equation that was used. This low transport capacity is coherent with the extremely low unit stream power, and related bed shear stresses approximating 30 N m^{-2} for reaches 5 to 17, and indicates the extremely low probability of mobilisation of the gravel bed, except possibly during very extreme flood events.

METHODS

River channel changes and their links with vegetation-hydrogeomorphology interactions were investigated using three sources of information.

Historical Maps

Broad changes in the position, size and planform of the main stem river channel (interpreted as the largest channel branch in the anabranching reaches) spanning a period of more than 100 years, were investigated using historical and contemporary 1:2500 scale Ordnance Survey maps. The Ordnance Survey adopts a standard protocol for recording the position of river edges as the limits of normal winter flow (Harley, 1975), allowing river edge mapping from different dates to be validly compared. Overlays of the channel margins from three mapping dates (1889, 1960/1975 – date varies among reaches, 2013) were analysed within ArcGIS to estimate the following five properties of main channel adjustment between survey dates in each of the seventeen reaches: change in channel area (in m²); area changed from channel to floodplain (in m², called deposited area); area changed from floodplain to channel (in m², called eroded area); change in channel sinuosity index (calculated as channel mid-line length divided by length of overall planimetric course); change in average channel width (in m, calculated by dividing channel area by channel mid-line length). Despite the consistency in method used to define channel edges, there are numerous potential errors in the map sources and data processing that can affect the outcome of such analyses (Gurnell et al., 2003). However, this map-based analysis provides some insights into potential long-term channel adjustments that can be compared with the following two types of evidence to indicate consistent trends over different timescales.

Recent Aerial Images

A more detailed investigation of planform features and their temporal changes was conducted using colour aerial images extracted from Google Earth. The style and magnitude of recent channel planform changes was captured for 6 sub-reaches drawn from reaches 5, 7, 9 (two subreaches), 12 and 13, which showed notable adjustments over a six year period. Images for 2002, 2005 and 2008 were available for all investigated sub-reaches, representing summer low-flow conditions. Raw images were extracted from Google Earth, applying a fixed window on each sub-reach and with no further rectification. Sub-reaches were selected where the channel was clearly visible (i.e. no significant riparian tree cover), and where planform changes were sufficiently large to be clearly observable. Channel 'edges' were defined using the edge of the continuously vegetated area above the ambient water level. In this low energy, groundwater-fed system, areas of exposed sediment are extremely rare. Except where bank erosion is active, dense riparian vegetation extends down the river banks to the low flow water edges and emergent aquatic plants also grow in abundance in many unshaded or partly-shaded areas of the river bed. The edges of distinct, dense vegetation stands, whether riparian or emerging from the river bed were digitised to represent the active channel edge. All identified edges were overlain to produce a map showing planform changes across the three image dates for each investigated sub-reach. Again, there are a number of potential errors inherent in this type of analysis of river edges. Spurious planform changes may emerge because of differences in the rectification of images within Google Earth, differences in river stage and differences in the

development (and possibly management) of the riparian and aquatic vegetation between images. However, there was little evidence of these sources of error in the analysed images. At all six sub-reaches, the three images showed well-developed vegetation and appeared to have been captured under baseflow conditions. Furthermore, differences in rectification, which would be recognised as consistent shifts in the interpreted river edges between images, were not identified in any of the sub-reach overlays. Finally, it is important to note that because a different protocol is used to determine the channel margins in this analysis in comparison with that used for the historical mapping, channel planform dimensions from the two sources cannot be directly compared.

Field Survey

Finally, interpretation of geomorphic features and their association with vegetation was undertaken in the field within sub-reaches of reaches 4 (LU1), 5 and 6 (LU2), where access was granted by land owners. In the sub-reaches of reaches 5 and 6, it was possible to investigate morphological features within relatively unshaded channels, where aquatic plants were abundant, and to undertake a biogeomorphic interpretation of features that had been observed in the colour aerial images as well as the analysis of historical maps. The sub-reach of reach 4 is one of the few sections of the River Frome bordered by relatively unmanaged riparian woodland. Trees completely obscure the river channel in aerial images but historical map information allowed assessment of long-term channel changes. Field observations along the sub-reach of reach 4 provide biogeomorphic information on how the River Frome channel adjusts when a riparian woodland buffer zone is present. Here, aquatic plants are largely absent because the channel is shaded, but riparian trees interact freely with the river leading to the development of biogeomorphic features that are not currently present in reaches where a functioning riparian zone is absent.

RESULTS

Historical Map Analysis.

Changes in five river planform properties were estimated for all seventeen reaches of the Frome between 1889 and 1960/75, 1960/75 and 2013, and 1889 and 2013. Estimates of the area converted from river channel to floodplain (deposited area) were divided by the area converted from floodplain to river channel (eroded area) to provide a ratio. This ratio and the remaining three planform properties extracted from channel edge overlays (change in channel area; change in sinuosity index; change in channel width) are all displayed in Figure 3 as columns of three graphs, one for the early period (1889 to 1960/75), one for the recent period (1960/75 to 2013), and one for the entire period of over a century from 1889 to 2013.

The ratio of area deposited to area eroded is mainly positive in all time periods and the channel area ratio is generally negative. These both indicate a reduction in channel area as a result of net deposition

within the channel in all time periods, and this trend is particularly consistent along virtually the entire river length in the recent time period (1960/75 to 2013). The remaining two indicators (change in sinuosity and change in channel width) illustrate how this net loss of channel area has been achieved. Sinuosity has generally increased, particularly in the recent period, so that in 2013 it ranges from 1.08 in reach 2 to 2.08 in reach 16. An increase in sinuosity lengthens the channel so that any change in channel area is distributed along a longer channel length. Despite this, average channel width has generally decreased, so that in 2013 it increases steadily downstream from 2.8 m in reach 1 to 14.1 m in reach 17. The increase in sinuosity and reduction in channel width are both particularly consistent along the river in the recent period (1960/75 to 2013). The estimated reduction in average channel width is small, rarely exceeding 2m in a period that spans approximately four decades, but this constitutes a significant proportion of the channel width (average 11% width reduction in reaches 3 to 13 between 1960/75 and 2013). Although such small estimated changes may be strongly affected by the cumulative errors involved in the map sources and the manipulation of the channel edge data extracted from those sources, the consistency in the trends revealed in Figure 3 suggest genuine reductions in channel area and width and increases in sinuosity, even if the absolute values of those changes may incorporate significant error. These trends were explored further using recent aerial images and field observations.

Aerial Image Analysis

Recent channel adjustments in six sub-reaches of the River Frome between 2002 and 2008 are illustrated in Figures 4 and 5. It is important to stress once again that these reaches were selected not only because they were relatively free of riparian trees and thus clearly visible on the images but also because they showed changes that were sufficiently large to be clearly captured using image overlays for this six year period.

Four sub-reaches (Figure 4) showed quite simple styles of adjustment over the six year period, providing evidence for channel narrowing in all of the sub-reaches, and an increase in sinuosity in three sub-reaches (Figures 4 A, B and C). These short-term trends are similar to those identified over a longer period from the analysis of historical maps, although the rates of change are considerably larger. However, the historical and recent changes were identified using different criteria (edge of normal winter flow, edge of vegetation) and in the latter case for reaches that were deliberately selected because they show clear change in this six year period. Furthermore, one might expect short term changes to fluctuate quite widely through time, with changes often reversing direction so that the long term average trend would be expected to be much more gradual than any trends observed in the short term. A further important feature of the channel changes shown in Figure 4 is the presence of small islands in some images, many of which become incorporated into areas of encroaching river edge in later images (Figures 4 B, C, D) or in some cases they remain as islands that enlarge in later images (Figures 4 A, B).

More complex channel adjustments are shown in Figure 5. Channel narrowing, increased sinuosity, the formation of islands and their incorporation into the channel edges are all still clearly apparent, and are more marked than in the examples shown in Figure 4, but in addition, channel changes in these two particularly dynamic sub-reaches are sufficiently large that lateral channel movements are also evident at tight river bends.

All of the subreaches illustrated in Figures 4 and 5 are unshaded heavily vegetated reaches, where the in-channel features are associated initially with the presence of emergent aquatic vegetation.

Field Evidence

Unshaded Channels

The historical map evidence indicates a trend of channel narrowing and increasing sinuosity throughout most of the Frome main stem over at least the last 50 to 60 years. Recent, aerial images of six unshaded, particularly dynamic reaches, indicate that a trend of narrowing and increasing sinuosity is also evident in recent years and is associated with the development of small vegetated islands and side bars or benches within the active channel, where the initial vegetation, because of its in-channel location, is composed of emergent aquatic species. Furthermore, there is evidence that small islands at one image date are often located within the area encompassed by new or extending side bars, berms or benches at a later date. In the two most active reaches, the vegetated margins of the channel indicate channel migration, particularly at tight bends, suggesting that erosion of the outer bank is tracked by the development of vegetated side bars, berms and benches on the opposite bank.

Field evidence for channel changes associated with emergent aquatic vegetation in unshaded reaches was collected from sub-reaches of reaches 5 and 6 (LU2) during visits at different times in the growing season. In these reaches, the banks are approximately 1.5 m high (from floodplain to channel bed, RHS data) and the average channel width is 8.4 and 9.6 m in reaches 5 and 6, respectively (normal winter flow level, 2013 map). Specific stream power, estimated using the median annual flood, is approximately 21 and 24 W.m⁻² in reaches 5 and 6, respectively. These are well below the upper limit of 100 W.m⁻² for channels with significant emergent and submerged macrophytes identified from a national data set by Gurnell et al. (2010). They are also well below the 60 to 110 W.m⁻² identified by Gurnell et al. (2013) for channels that support a maximum 25 to 50% cover of the common emergent macrophyte *Sparganium erectum*.

The visited sub-reaches of 5 and 6 are closely bordered by agricultural land, with only a narrow (typically <5 m wide) strip of riparian vegetation supporting occasional riparian trees and shrubs. The lack of channel shading and low stream power has allowed a diverse and abundant cover of perennial aquatic plants to develop within the river channel of both sub-reaches, shooting from below-ground organs in early spring to produce a maximum above-ground biomass in July and August, which then senesces and detaches from September to November. *Ranunculus penicillatus* and *Sparganium erectum* are by

far the most abundant species. However, *Callitriche stagnalis*, *Myriophyllum spicatum* and *Rorippa nasturtium aquaticum* are also found widely in the channel with *Phalaris arundinacea* extending into the channel margins. While reach 5 maintains a very sinuous, laterally migrating channel pattern, reach 6 is relatively straight, probably as a result of artificial straightening in the past (Figure 6 A and B). Reaches 5 and 6 have shown sizeable changes in planform and reductions in width and sinuosity since 1889 (Figures 6A and 6B). Much of these changes have occurred since the 1960s, during which reaches 5 and 6 have experienced 12% and 16% reductions in average channel width and an increase in sinuosity of 0.022 and 0.006, respectively. The sub-reach of reach 5 has also shown sizeable recent planform changes, including those shown in Figure 5A, whereas recent changes in the sub-reach of reach 6 have been relatively smaller.

Field evidence of channel narrowing and island development within the subreaches of reach 5 and 6 are shown in Figure 7. In both subreaches, a gravel bed is exposed in the middle of the channel, but fine sediment has infiltrated the gravel and buries it in slackwater areas. The emergent species *Sparganium erectum* is abundant in both reaches and is associated with the island and marginal vegetated features observed in the aerial images and the leading edges of areas of channel narrowing observed in the map overlays for the recent period (1960/75 to 2013). Channel narrowing and increased sinuosity at the downstream end of the sub-reach of reach 6 (Figure 6B) is illustrated in Figure 7A. The approximate position of the 1889 channel edge is indicated by a black solid line, and a sequence of three depositional features can be seen within the 1889 channel: (i) a relatively high, bench feature, the upper (outer) edge of which is approximately 0.5 m below floodplain level (just below the black line on the left of Figure 7A) and appears to mark the current 'bankfull' level (approximately 1 m above the river bed); (ii) a lower, vegetated berm which extends from the lower (inner) edge of the bench (black dashed line, Figure 7A), and shows recent sediment deposition and aggradation, and (iii) a submerged shelf of predominantly silt (between the solid and dashed white lines, Figure 7A) below the low flow water level that is colonised by *S. erectum*, and abuts onto the gravel bed of the river. The role of *S. erectum* in stabilising the silt at the margins of the gravel bed is clearly crucial to the lateral and vertical development of this silt shelf at the outer edge of the vegetated bar. The other photographs in Figure 7 illustrate how silt is retained and stabilised within the inundated part of the channel by *S. erectum*, and how the aggrading silt initiates and extends island (Figures 7B and 7C) and marginal shelf-berm-bar features (Figures 7D and 7E) within the two visited reaches. Without the above ground biomass of *S. erectum* to trap and aggrade fine sediment (e.g. Figure 7E) and its below ground web of rhizomes to stabilise and retain the aggrading submerged shelf of fine sediment through the winter (e.g. Figure 7B), the fine sediment would either move on downstream, or would further infiltrate and bury the exposed gravel bed.

Channels bordered by Riparian Woodland

The surveyed sub-reach of reach 4 is unusual for the River Frome, in that it is bordered by relatively unmanaged riparian and wetland vegetation, and thus provides an indication of how the floodplain

vegetation might have functioned prior to the introduction of agriculture across the floodplain. Reach 4 has higher specific stream power (30 W.m^{-2}) than reaches 5 and 6, but this is still a very low value that would not prevent the presence of abundant aquatic plants. However, aquatic plants are rare in this sub-reach, and the river is lined by mature trees and shrubs of mainly riparian species including *Alnus glutinosa*, *Corylus avellana*, *Fraxinus excelsior*, *Prunus spinosa*, *Salix caprea*, *S. fragilis*, *S. triandra* and *S. viminalis*. Both trees and large wood are influencing channel development, although the form of the river channel is not free of direct human interventions. The river was straightened and probably deepened when an embanked railway line was built next to the river in the mid-19th century. The presence of the railway embankment restricts lateral channel movement on the left bank, but there is evidence from historical maps of channel narrowing and an increase in sinuosity within this sub-reach (Figure 7C), which based on field measurements at 7 cross sections has banks that are on average 1.0 m high (from floodplain to channel bed) and an average bankfull channel width of 5.8 m. Reach 4 as a whole has shown negligible narrowing since the 1960s, but sinuosity has increased by 0.035, which is more than in reaches 5 and 6. Unfortunately, because tree canopies completely obscure the channel in aerial images, it was not possible to identify any in-channel features or their temporal development from such imagery. Therefore, interpretation of the impact of vegetation on the channel change identified from historical maps has had to depend entirely on geomorphological interpretation of features observed in the field.

Figure 8 shows geomorphological sketch maps of seven contiguous sections (A to G) of the sub-reach, with the direction of flow running from A to G and from the top to the bottom of each mapped section. This field survey revealed that, although the gravel river bed is occasionally exposed, much of the bed in this part of reach 4 is buried by fine sand and silt deposits, and this finer sediment is an important component of many of the landforms that are being created as a result of interactions among fluvial processes, riparian trees and large wood.

Dead wood features include small log steps (Figure 8 - features 5 and 14), a jam completely spanning the channel but with water flowing freely through it at low flow (Figure 8 - feature 2), an hydraulically active jam that creates a step in the water surface profile even at low flow (Figure 8 - feature 21, Figure 9A), and several flow deflection jams (Figure 8 - features 11, 17, 22).

There are also many features linked to standing riparian trees and 'living' (sprouting) wood. Dense areas of exposed roots (Figure 8 - feature 9; Figure 9C) and branches (Figure 8 - feature 19) trail into the channel, forming jam-like and bar features, respectively, and in one case rooting into the bed and retaining wood and sediment to build an island (Figure 8 – feature 4, Figure 9B). This latter feature appears to be the final stage of bar development induced by rooted trailing branches. The island is comprised of large quantities of wood and silt that have been trapped by the young trees that have sprouted from branches that touched the channel bed (and are still connected to their parent tree on the bank). The accumulation of wood and sediment around the sprouting branches has raised the surface of the island to the level of the surrounding floodplain. In section G, trailing branches, leaning and J-shaped trees and adventitious roots contribute to the development of lateral and mid-channel submerged shelves, bars and benches comprised of fine sediment (Figure 8 - 23, 24, 25; Figures 9D

and 9F), which, when combined with intervening areas of eroding banks, are leading to the development of a more sinuous channel planform. Indeed, the leaning and J-shaped trees are indicative of bank instability that is being arrested locally by bar and bench-development at the bank toe. Several other sections of the river support large riparian trees that are buttressing the river bank and leading to the development and, through root reinforcement, the retention of fine sediment benches (Figure 8 – features 1, 3, 6, 10, 12, 13, 15, 18; Figure 9I). In many cases, these trees appear to grow out of the bank face, with the upper part of their J-shaped trunk growing vertically, and with adventitious roots growing vertically downwards from the base of the trunk's 'J' shape into the channel bed. At the same time, other adventitious roots grow horizontally into the bank face, reinforcing bench features (Figure 9I) between the tree trunk and the original river bank. In several locations, shrubs are also growing into the channel, retaining sediment and wood, and narrowing the channel (Figure 8 - 8, 16).

One of the most striking features of the sketch maps in Figure 8 is the widespread occurrence of lateral bars and benches, comprised of fine sediment and usually associated with riparian trees. In addition, immediately upstream of a large active jam (Figure 8 - feature 21, Figure 9A) in section F is a complex of vegetated and unvegetated bench and bar / ridge features in the downstream part of section E (Figure 8 – feature 20; Figure 9E). Individual, steep-sided, fine sediment bars / ridges (both unvegetated and vegetated) also occur elsewhere in sub-reach 4, for example, just upstream of the confluence of small side channels in sections B and D, and also in the middle of the channel in section B (Figure 8 - feature 7; Figure 9G). Although the origin of these features is unclear, they appear to result from a combination of smaller pieces of sprouting wood and aquatic plants retaining fine sediment. The complex of these features in section E (Figure 8 - feature 20, Figure 9E) is comprised of scroll-like vegetated ridges, with intervening, lower areas that are exposed during low flows. The lower areas are reinforced by tree roots and probably act as flood channels when the water surface is elevated upstream of the active jam during high flows. The jam also supports complex in-channel flow pathways, which have resulted in the scour of pools under the jam, and these flow pathways probably propagate upstream during flood-ponding to create the feature complex at location 20 (Figure 8 – feature 20). A similar explanation could be proposed for scroll-like unvegetated ridges observed upstream of the two minor stream confluences (Figure 8 – sections B and D (located upstream of the confluence and adjacent to a pool)).

In conclusion, although planform recovery is very slow in this low energy, sub-reach, individual trees and wood accumulations appear to be influencing planform change and a large increase in the morphological complexity of this historically-channelised section of the River Frome. Riparian trees and large wood form flow obstructions. They also create new obstructions by rooting and sprouting when in contact with the channel bed, and by retaining and root-reinforcing accumulations of fine sediment. In many cases trees and wood are acting together to retain sediment and build landforms that impact on channel morphological change. Although fine sediment is burying the entire gravel bed in many parts of this sub-reach, accumulation of fine sediment into these wood and tree associated landforms is narrowing the channel to induce local increases of flow velocity and mobilisation of finer sediment to expose the underlying gravel bed in many locations.

SUMMARY AND CONCLUSIONS

The River Frome suffers from significant inputs of sand and finer sediment as a result of the development of agriculture across virtually its entire floodplain and surrounding hillslopes (Grabowski and Gurnell, 2015). Agricultural activities have intensified markedly over the last 60 years and the widespread presence of drainage ditches and lack of a significant, naturally-functioning riparian zone along most of the river have ensured high connectivity of agricultural areas with the river. Because of its low energy, groundwater-dominated flow regime, the river is rarely competent to move gravel. Movement of finer sediment occurs but the majority of the main stem currently shows a positive sediment budget, whereby there is a net accumulation of sand and finer sediment within the channel (Grabowski and Gurnell, 2015). This process has resulted over the last century and particularly the last few decades in widespread channel narrowing and increases in channel sinuosity. Because of the extremely low energy of the river, channel changes are slow and, therefore, challenging to observe directly in the field. However, they have been identified through the analysis of historical map evidence. In some particularly active reaches, it has been possible through the analysis of aerial images to gain insights into how such changes have occurred in the shorter term. Field observations have provided further information on the three-dimensional features that appear to be a component of these past planform channel adjustments. Field observations have also revealed that fine sediment delivery has had a significant effect on the calibre and structure of the river bed as well as on channel form. Although a gravel bed remains in all visited reaches, fine sediment has infiltrated the gravel bed (e.g. Heppell et al., 2009) and, in slackwater areas, particularly in the sub-reach of reach 4, has buried the river bed in many places. Thus channel narrowing has not been accompanied by bed incision, but, if anything, by some bed aggradation.

Vegetation appears to be a crucial component in the river's response to fine sediment delivery and it has the potential to make a major contribution to the management of this river towards a more balanced sediment budget.

Under current environmental conditions and human impacts, aquatic and riparian vegetation and large wood all contribute to channel narrowing and increasing sinuosity by trapping and stabilising sediment into landforms, most of which attach to the river channel margins.

Within unshaded reaches, analysis of aerial images has indicated a process of island and marginal bar-berm-bench development within the channel that could only be initiated by plants that can grow in continuously inundated conditions. Time sequences of images indicate not only encroachment of the channel edges but incorporation of islands of vegetation into this encroachment process. In the field, *S. erectum* was observed to occupy the leading edge of vegetation – hydrogeomorphology interactions. This species grows in water up to approximately 1m deep at low flow (Haslam, 2006), enabling it to grow across shallow channels but to be confined to the margins in deeper channels. *S. erectum* has been shown to act as an important physical ecosystem engineer in low energy British rivers because of its resistance to uprooting, and its ability to retain fine sediment and produce dense networks of rhizomes that reinforce and protect retained sediment (Liffen et al., 2011, 2013 a and b). These traits

allow this and other emergent aquatic species to create landforms in the channel margins and in the centre of river channels where the water is shallow, so facilitating colonisation by other plant species as the landforms emerge above the low flow water level (Gurnell, 2014; Gurnell et al., 2015a). On the river Frome, *S. erectum* is performing an important role in trapping and stabilising fine sediment to produce landforms that are narrowing and increasing the sinuosity of the river. Channel narrowing increases flow velocities and thus the potential of the river to mobilise fine sediment deposited in unvegetated sites on the channel bed. Without stabilisation into landforms by vegetation, the fine sediment would remain highly mobile, enabling it to increasingly penetrate and bury the gravel bed of the river.

Although much of the river Frome lacks a wooded riparian margin and is subject to abundant aquatic plant growth, one wooded reach with few aquatic plants also showed channel narrowing and increased sinuosity over the last century. Because of the complete shading of the channel by tree canopies, it was not possible to identify evidence from aerial images of the role of trees and wood in this narrowing process. Nevertheless, geomorphological interpretation of features observed in the field suggested strong interactions between fluvial processes and dead wood, sprouting wood and living trees and shrubs. A series of features created by living and dead riparian woody species were retaining fine sediment and in many cases the fine sediment was being reinforced by the vegetation. Dead wood (e.g. Abbe and Montgomery, 2003; Collins et al., 2012), sprouting wood and established riparian trees (e.g. Corenblit et al., 2007, 2009; Gurnell et al., 2005, 2012) have all been recognised as important influences on river form and dynamics. However, a riparian zone supporting naturally-functioning riparian woodland can also act as a buffer zone, trapping fine sediment before it reaches the river and so reducing the amount of fine sediment available to accumulate within the channel (e.g. Parkyn et al., 2003; Carline and Walsh, 2007; Collins et al., 2013).

The processes of channel narrowing and increasing sinuosity that have occurred along much of the river Frome have progressed slowly but are not sustainable in the longer term. Furthermore, the continued retention of fine sediment has the potential to cause significant impacts on fisheries in the low energy chalk rivers of southern England by clogging and burying spawning gravels (e.g. Acornley and Sear, 1999). Our observations suggest that without some change in the way the catchment and river are managed, the channel will ultimately become too small and avulsions and accelerated floodplain accretion are likely to become widespread. Such processes would eventually lead to the reinstatement of the natural dynamics associated with low energy anabranching river systems, which reflect strong interaction between vegetation and channel evolution. However, to avoid the human and economic consequences of avulsions and increased flooding and sedimentation of agricultural land, management actions should incorporate reinstatement of functioning riparian woodland buffer zones around the river. Such buffer zones would (i) intercept a proportion of the fine sediment currently being delivered from agricultural land to the river and (ii) absorb it into the natural landform dynamics of the riparian zone; (iii) increase channel shading and so reduce excessive aquatic plant growth, allowing aquatic plants to interact with hydrogeomorphological processes in a more patchy way than at present, and (iv) moderate stream temperatures; (v) to provide a connected river-riparian system that is not damaged by flooding

or sedimentation. Such a river-riparian system can display high and dynamic morphological and habitat complexity, including the development of additional channels, as a result of a natural and balanced interaction among plants, wood and hydrogeomorphological processes. Such a management strategy would initially require the sacrifice of some agricultural land, but in the medium to longer term, it would lead to more sustainable agriculture coupled with a rich river-riparian ecosystem that could enhance the economic status of the river's already important trout fishery.

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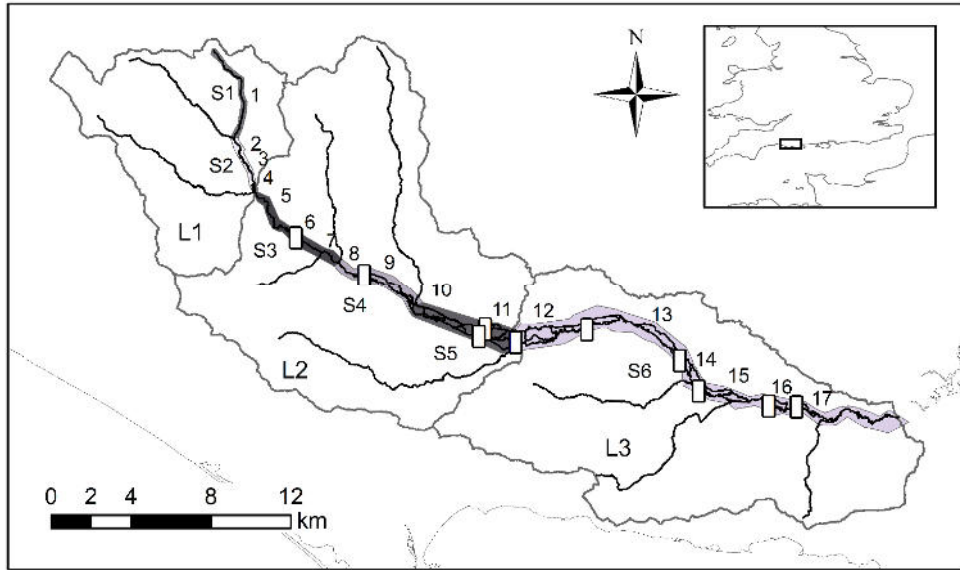


Figure 1. The River Frome catchment is delineated into 3 landscape units based on elevation, geology and land cover/use (L1 to L3), 6 segments based on valley setting and major tributary confluences (S1 to S6) and 17 reaches based on planform and longitudinal discontinuity (e.g. major weirs – indicated as open rectangles).



Figure 2. A section of the River Frome in reach 5, showing the low hilly landscape, unconfined valley, extensive agricultural land use and very narrow strip of riparian trees and shrubs bordering the main channel. . The photograph was taken in April shortly after a flood – the standing water in the foreground and middle distance picks out depressions marking old channel positions on the floodplain. (photograph: A.M. Gurnell)

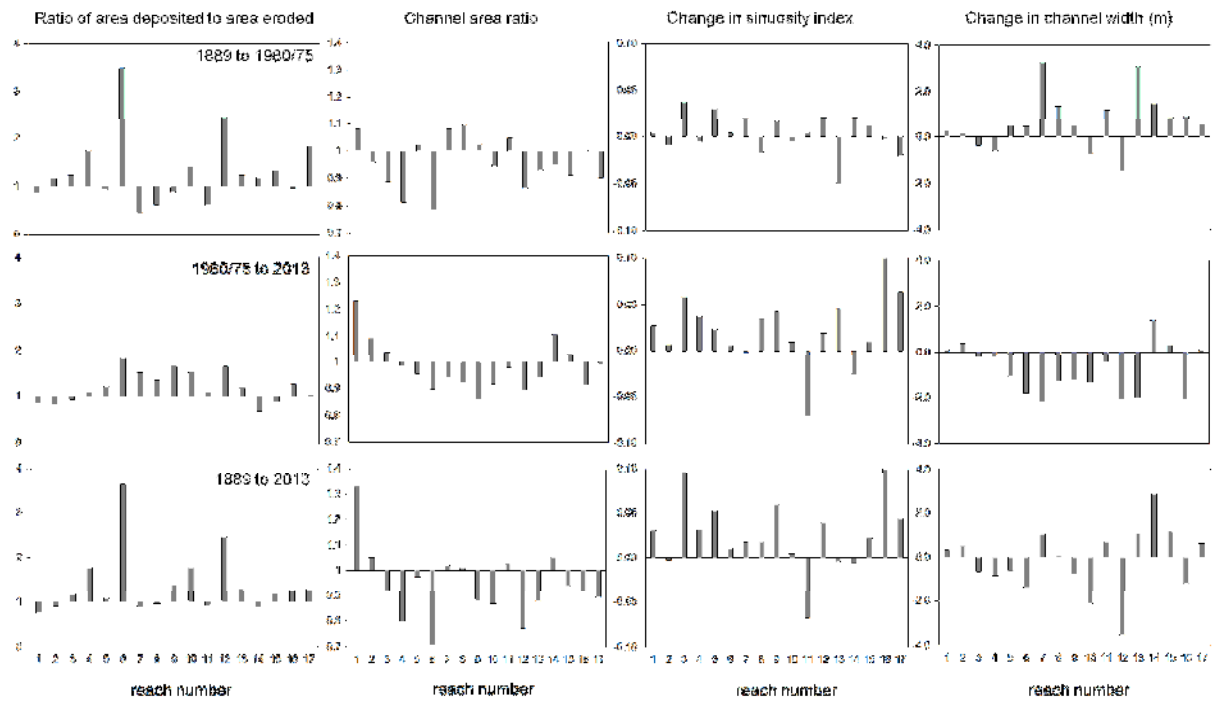


Figure 3. Changes in the planform of seventeen reaches of the River Frome identified from historical maps. The graphs show changes between 1889 and 1960/1975 (top row); 1960/75 and 2013 (middle row); and 1889 and 2013 (bottom row) in four indicators of channel planform change: left column - the land area that started the time period as river channel and ended as floodplain (area deposited) divided by the land area that started as floodplain and ended as river channel (area eroded) (dimensionless ratio); second column - the area of the river channel at the end of the time period divided by the channel area at the start of the period (dimensionless ratio); third column - the change in channel sinuosity between the start of the time period and the end of the period (dimensionless index change); right column - the change in average channel width between the start of the time period and the end of the period (in m).

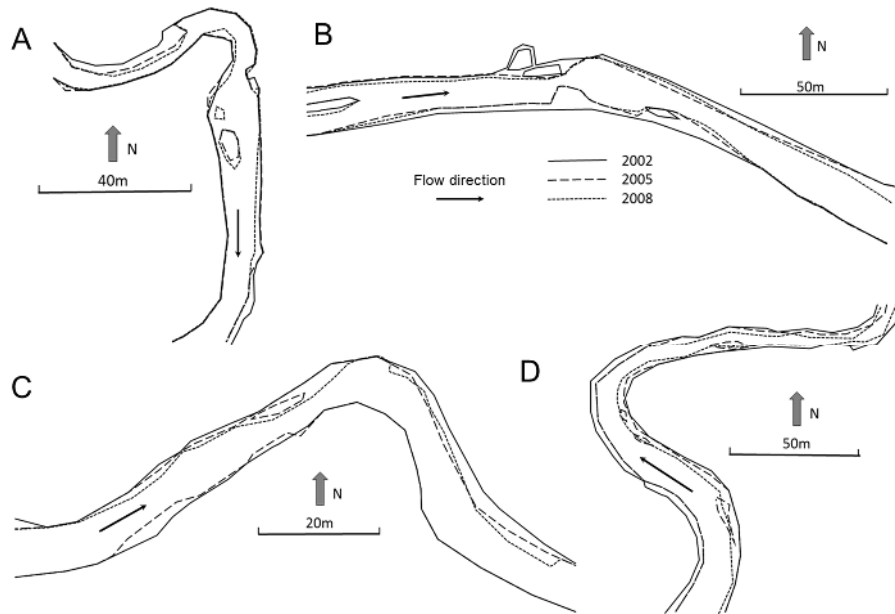


Figure 4. The position of vegetated channel edges and islands extracted from colour aerial images captured in 2002, 2005 and 2008 for sub-reaches of A. reach 9; B. reach 7; C. reach 9; D. reach 12 of the River Frome.

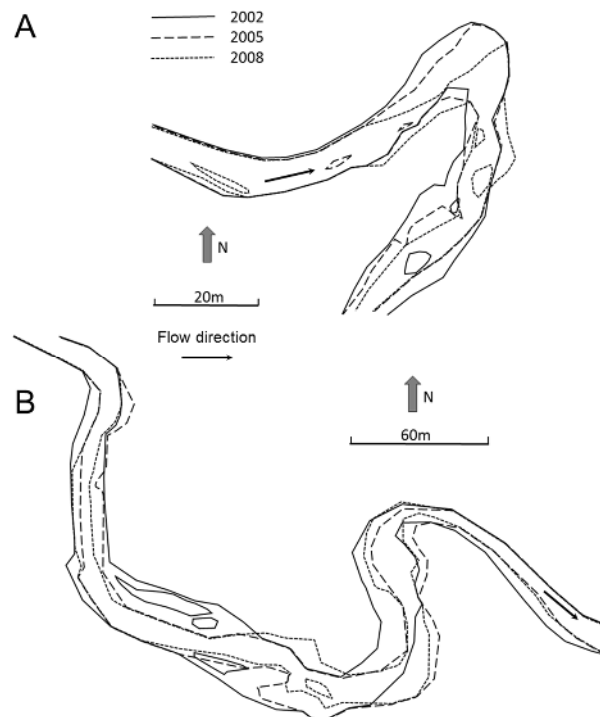


Figure 5. The position of vegetated channel edges and islands extracted from colour aerial images captured in 2002, 2005 and 2008 for sub-reaches of A. Reach 5; B. reach 13 of the River Frome.

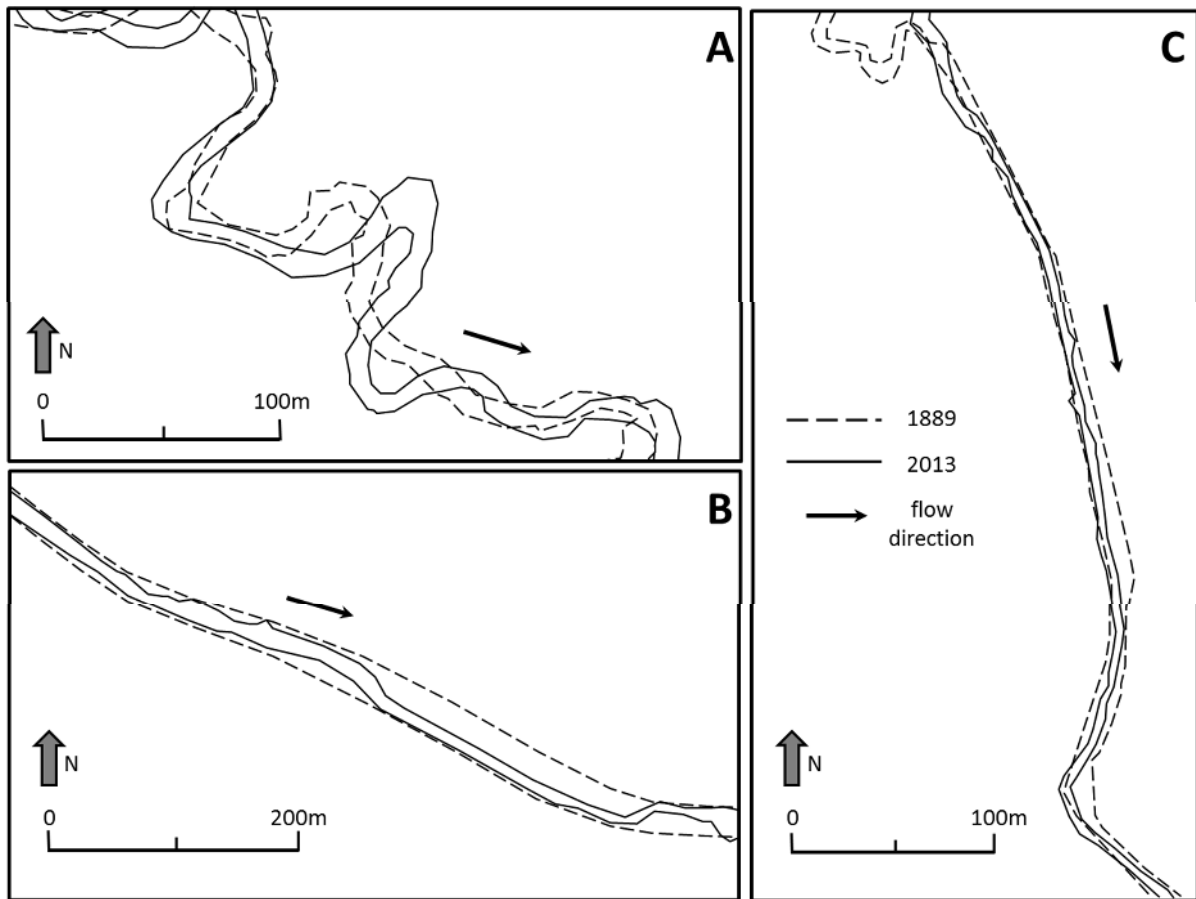


Figure 6. Changes in river width and planform 1889 to 2013 in sub-reaches 4 (A); 5 (B); and 6 (C).

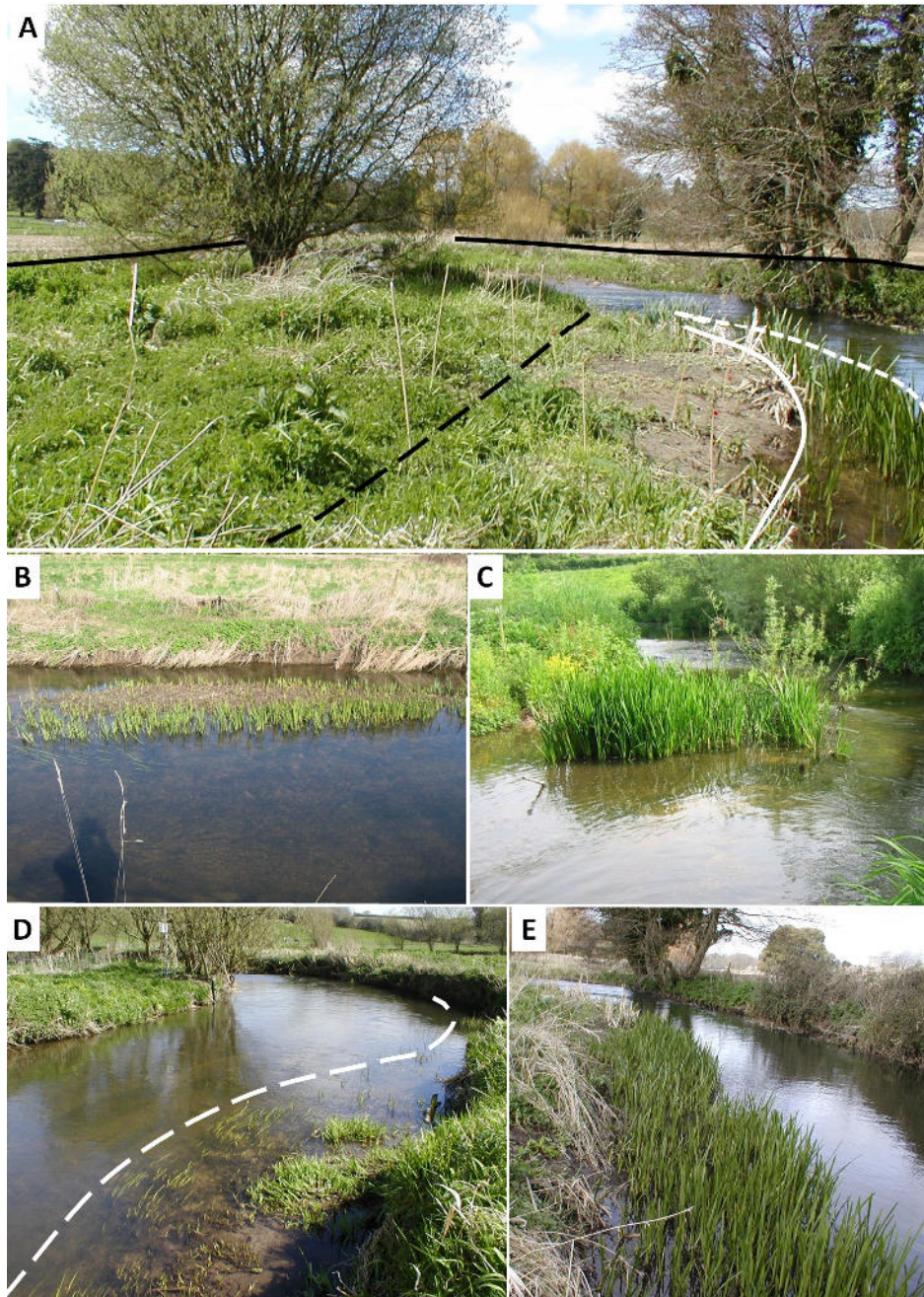


Figure 7. River channel narrowing and the role of fine sediment trapping and stabilisation by emergent aquatic plants, particularly *Sparganium erectum*. A. Landform development associated with channel narrowing in sub-reach 6, showing the initial channel width (black solid lines approximate the 1889 channel edge), the inner edge of a bench (black dashed line), the inner edge of a vegetated bar/berm (solid white line) and the inner edge of a submerged shelf retained by *S. erectum* (dashed white line). B. A vegetated bar in early spring in reach 6 – *S. erectum* sprouts around the edges of the bar but its centre has aggraded to the baseflow water surface level and so no longer supports *S. erectum*. C. A similar bar feature to that shown in B. but photographed in early summer in reach 5 and showing colonisation by other plants including a young willow. D. Channel narrowing driven by *S. erectum* in early spring in reach 5. E. Channel narrowing driven by *S. erectum* in late spring in reach 6. (photographs: A.M. Gurnell)

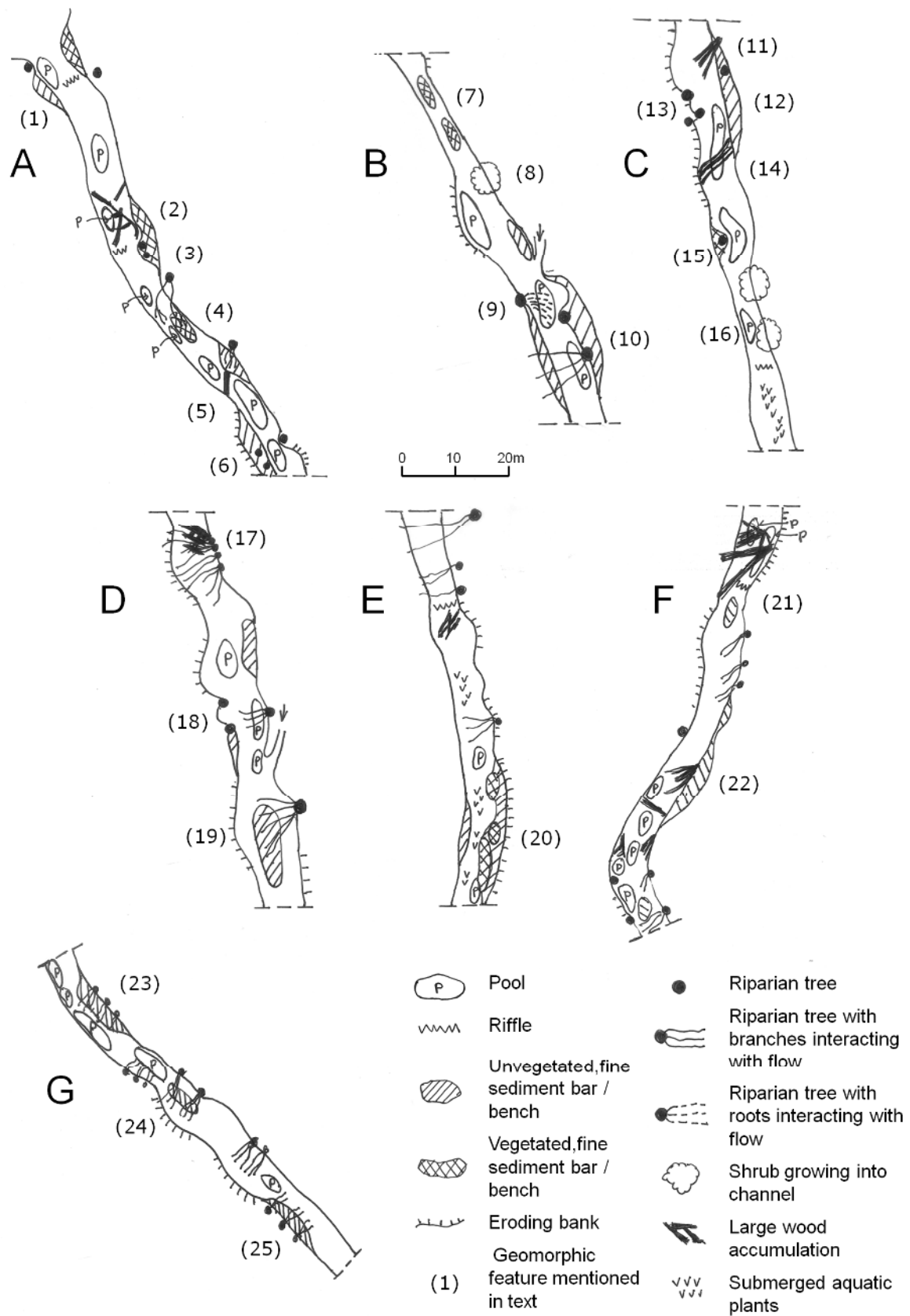


Figure 8. Sketch maps of tree and wood related features in reach 4 from upstream (A) to downstream (G).

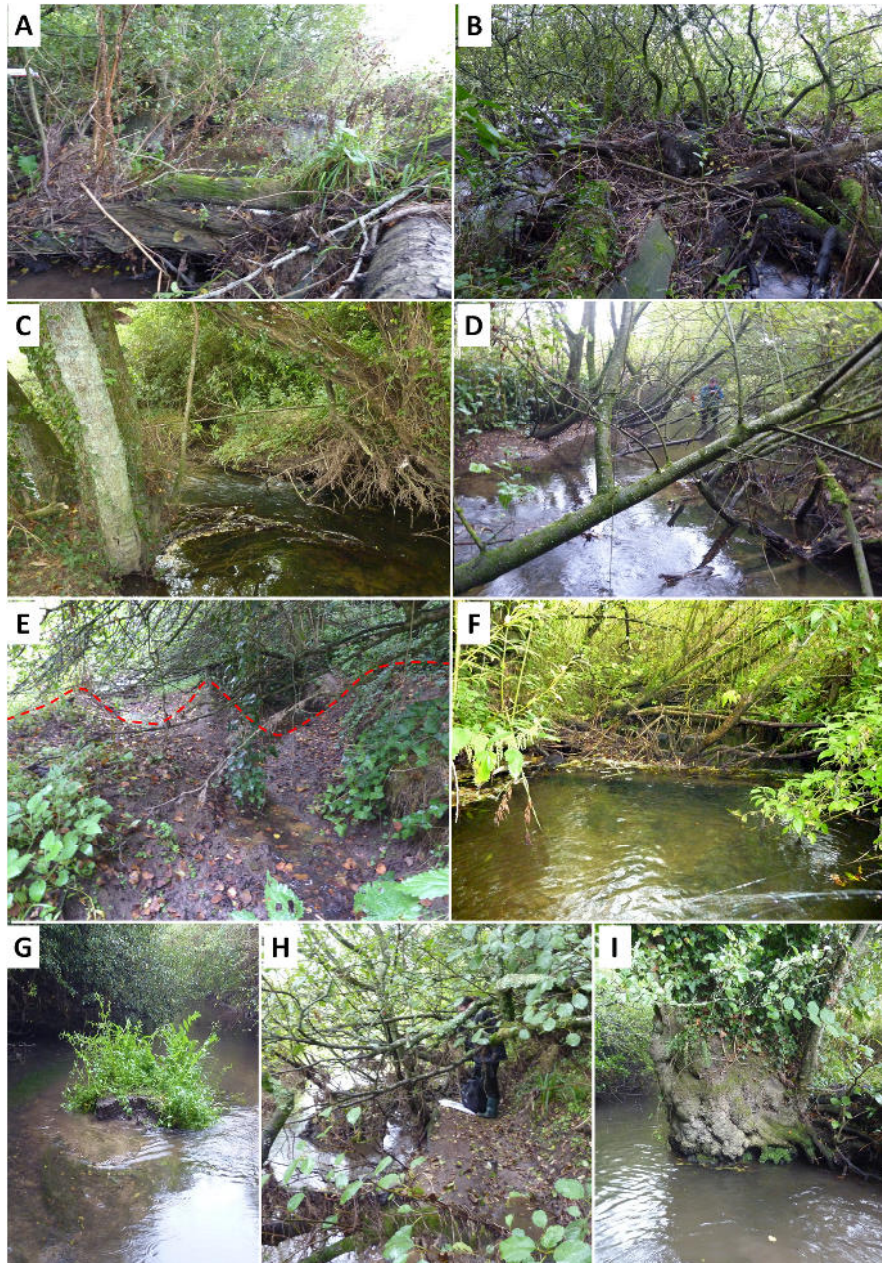


Figure 9. Living vegetation and large wood trapping fine sediment to build landforms in sub-reach 4 (bracketed numbers refer to features identified in Figure 5). A. Active wood jam (21). B. Island formed by large wood and fine sediment trapped by branches rooted into the channel bed (3). C. Wood jam created by living tree roots (9). D. Leaning and J-shaped trees inducing lateral bar development (23). E. Side channels separated by vegetated ridges (to left and in the middle distance) that are above the low flow water level (20). The river bank is on the right. F. Leaning trees trapping wood and rooting into the channel bed (24). G. A vegetated mid-channel bar of fine sediment (7). H. Fine sediment bench protected by a flow deflection jam and riparian trees (11, 12). I. Alder tree buttressing river bank (15). Note the old roots growing downward from the base of the 'J' shaped trunk, and also into the river bank to support a bench (right of picture) that is significantly lower than the flood plain at the rear of the photograph (photographs: R.C.Grabowski) .