Biogeomorphological response to river restoration of a suburban river with large wood: creating a restoration vision and cost-effectively monitoring the response trajectory using the citizen science MoRPh survey.

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ABSTRACT

Biogeomorphological responses to river restoration are rarely reported. Despite a transition in the emphasis and priorities of river management over the last 40 years from controlling river channel forms and processes to restoring and supporting natural processes, forms and functions, remarkably little information is available on project outcomes. Here, using the example of the Beverley Brook within Wimbledon Common, Greater London, UK, we illustrate how standardised detailed monitoring information can be assembled at very low cost using the citizen science MoRPh survey and we demonstrate the importance of having a pre-project vision of likely outcomes that can be tracked by the monitoring programme. We show how a pre-project and five post-project surveys undertaken over four years according to a BACI (before-after-control-impact) design provides scientifically robust data. Analysis of the survey data quantifies the nature, abundance and spatial distribution of restoration interventions, the immediate responses to those interventions, and the ensuing trajectory of biogeomorphological adjustments. Changes in the persistence, size, position, abundance and evolution of habitats reveal the degree to which the restoration achieved the pre-project biogeomorphological vision and why the recovery trajectory progressed at the observed rate and to the observed end point over four years. Our approach has enormous potential for monitoring the outcomes of river interventions. While our project was limited in its spatial scale and focus on physical habitats, we suggest how these limitations could be overcome while still containing costs.

KEYWORDS: river restoration, restoration vision, recovery trajectory, monitoring design, low cost monitoring, citizen science, fluvial geomorphology, biogeomorphology, biogeomorphological responses

1. INTRODUCTION

Over the last forty years there has been a transition in the emphasis and priorities of river management from controlling river channel forms and processes to restoring and supporting natural processes, forms and functions. This transition is a response to observed degradation and simplification of river ecosystems resulting from historical management practices, and has been driven by increasing legislation aimed at improving river condition (Palmer et al., 2005; Beechie et al., 2010; Roni and Beechie, 2013; Johnson et al., 2020; Oliveira et al., 2020). In 2007, Bernhardt et al. reported on a major survey of river restoration in the US. This revealed that although large numbers of river restoration projects had been implemented at enormous expense from the 1980s onwards, there was remarkably little information on project outcomes that could demonstrate whether works had been successful and on the factors that had supported that success or led to failure.

Numerous scientists and practitioners have published recommendations that seek to apply advances in scientific understanding to the practice of river restoration (in addition to those cited above see Wohl et al., 2015; Weber et al., 2018; Polvi et al., 2020). At an early stage Palmer et al. (2005) proposed five criteria for measuring restoration success (a design based on a 'guiding image'; achievement of measurable improvement in ecological condition; an increase in the river's resilience to external perturbations and a reduced requirement for maintenance; no lasting harm to the river ecosystem; collection and open availability of pre- and post-project assessment data).

Since then many similar sets of criteria and standards have been proposed with an increasing emphasis on the need to frame river analysis and restoration design within a multi-disciplinary context (hydrology, geomorphology, water quality, ecology); to adopt a multi-scale (time and space) approach to understanding a site; and to monitor river environment properties through pre-project, immediate post-project, and response-recovery stages in order to quantitatively demonstrate changes (e.g. Roni and Beechie, 2013; Polvi et al., 2020; Weber et al., 2018). However, when contemporary river restoration practice is evaluated, little improvement appears to have been achieved in these respects (e.g. England et al., 2021).

The literature and practitioner roles suggest two key areas where progress could be relatively easily achieved. The first is in setting a 'guiding image that describes the dynamic, ecologically healthy river that could exist at a given site' (Palmer et al., 2005, p210). The second is in designing and implementing a local monitoring programme capable of both assessing the degree to which the guiding image or vision for the recovered post-restoration state has been achieved and identifying the reasons for any underachievement.

At its simplest, a guiding image or vision could be based on nearby sites which display similar natural environmental conditions and processes but less degradation than the site that is being considered for restoration. A more broadly-based approach would be to assemble information on a set of suitable lightly-impacted sites that could indicate achievable outcomes under different natural environmental conditions or to develop functional visions for rivers of different biogeomorphological types that could be used and adapted by practitioners working in a specific biogeographical setting. The field of fluvial biogeomorphology has evolved over the same time period as river restoration (Gurnell et al., 2001, 2012, 2016; Corenblit et al., 2007, 2009, Haussmann, 2011; Coombes, 2016; Stallins and Corenblit, 2018; Castro and Thorne, 2019; Johnson et al., 2020; Larsen et al., 2021; Gurnell and Bertoldi, 2024). Fluvial biogeomorphology has much to offer in terms of building visions of the likely trajectory of biogeomorphological morphodynamics that could follow specific restoration interventions and ensuring that those interventions emulate nature as far as possible within the context of local constraints.

A lack of monitoring the responses to restoration actions and their biogeomorphological outcomes has been widely acknowledged (Angelopoulus et al., 2017). Buchanan et al. (2014) attributed this data gap to insufficient funding, incentive or regulatory requirements and noted that most assessments are based on a single survey. While pre-project surveys are usually conducted to inform restoration design and implementation, post-project surveys are relatively rare, and longer-term monitoring that can reveal the biogeomorphological effectiveness of any restoration measures is almost always lacking (Tedford and Ellison, 2018; Weber et al., 2018; Oliveira et al., 2020). Furthermore, when monitoring is performed it is often insufficiently well-designed to evaluate the biogeomorphological performance of a restoration project or its component measures. Selecting an appropriate monitoring method and then applying it within a relevant spatio-temporal monitoring design is essential if project performance is to be characterised effectively and efficiently (e.g. England et al., 2021). While person-power and funding are certainly barriers to robust monitoring, simple and cost-effective monitoring techniques are emerging and the rise of 'citizen science' (Cavalier and Kennedy, 2016; Stepenuck and Genskow, 2018) is providing an increasingly large, highly-motivated and capable body of volunteer surveyors who can apply these monitoring techniques and contribute to designing, gathering and interpreting monitoring data (e.g. Gurnell et al., 2019).

This paper focuses on the restoration of a 1.9 km reach of the Beverley Brook where this small river crosses Wimbledon Common, an area of public open space located in Greater London, UK. The suburban setting of the reach and the modest funding available placed constraints on the restoration location and the actions that could be implemented. Nevertheless, the project was centred on a biogeomorphological vision of the likely trajectory of adjustments and what could eventually be achieved. The vision was developed from observations of less-impacted streams of similar natural character located within the same biogeographical setting. The monitoring programme applied a simple and rapid survey method designed for use by both citizen scientists and river practitioners (MoRPh, Shuker et al, 2017, Gurnell et al., 2019) and was implemented according to a BACI design (Before-After-Control-Impact, e.g. Cooner et al., 2016) to allow effects and their causes to be identified. The entire implementation of the restoration and monitoring scheme was low cost while addressing many of the shortcomings raised above. In particular, we present the following:

(i) The constraints imposed on the restoration by its suburban setting; the restoration vision that was devised including an expected temporal trajectory of restoration biogeomorphological responses; and the implementation of the restoration measures.
(ii) The survey data that track the river's pre-restoration status and restoration response trajectory.
(iii) Analysis of the survey data to demonstrate the nature of the river's biogeomorphological response to restoration; the degree to which the response matched the restoration vision; and the lessons learnt.

By considering this river restoration example, we illustrate how a science-based vision or guiding image coupled with a simple but robust monitoring programme can allow restoration biogeomorphological success to be assessed even where there are significant time and cost constraints.

2. METHODS

The study site

The study site (Figure 1), a 1.9 km reach of the Beverley Brook, is located within Wimbledon Common, an area of open space surrounded by suburban housing and roads. The upstream and downstream limits of the reach (marked by arrows in Figure 1) are located at the following latitude and longitude, respectively: 51.421755, -0.250886; 51.436910, -0.253669. The reach has a gradient of approximately 0.0012 $m.m^{-1}$ and a catchment area of 43.5 km^2 to the flow gauging station that is located within the reach. The gauged records (1935 to 2022, source: National River Flow Archive, station 39005) show a mean daily flow of 0.539 $m^3.s^{-1}$, median daily flow (Q50) of 0.421 $m^3.s^{-1}$, and a 5% exceedance flow (Q5) of 1.266 $m^3.s^{-1}$. The flow regime is affected by runoff from extensive (sub)urban land cover with treated sewage effluent contributing significantly to base flows (Perkins et al, 2021).

A preliminary baseline reconnaissance walkover revealed that the Brook within the study reach has average bed and bank full widths of approximately 6 m and 11 m, respectively, and a gravel-sand bed showing significant superficial silt deposits and negligible physical bed features. The pre-restoration river channel displayed a generally smooth, straightened course; overdeep channel cross profile (see Gurnell and Downs, 2020, for methodology used to identify legacy channel overdeepening); and the presence of wooden toe board reinforcement along much if its length (e.g. Figure 2a), indicating significant human interventions. Vegetation colonisation and development coupled with some natural morphological adjustments within the high, steep bank profiles emphasise the historic nature of these interventions and some recovery since their imposition. A lack of large wood on the channel bed, despite the many mature trees lining the river banks, is indicative of sustained wood clearance from the river channel. Figure 2a shows a typical view of the river prior to restoration.

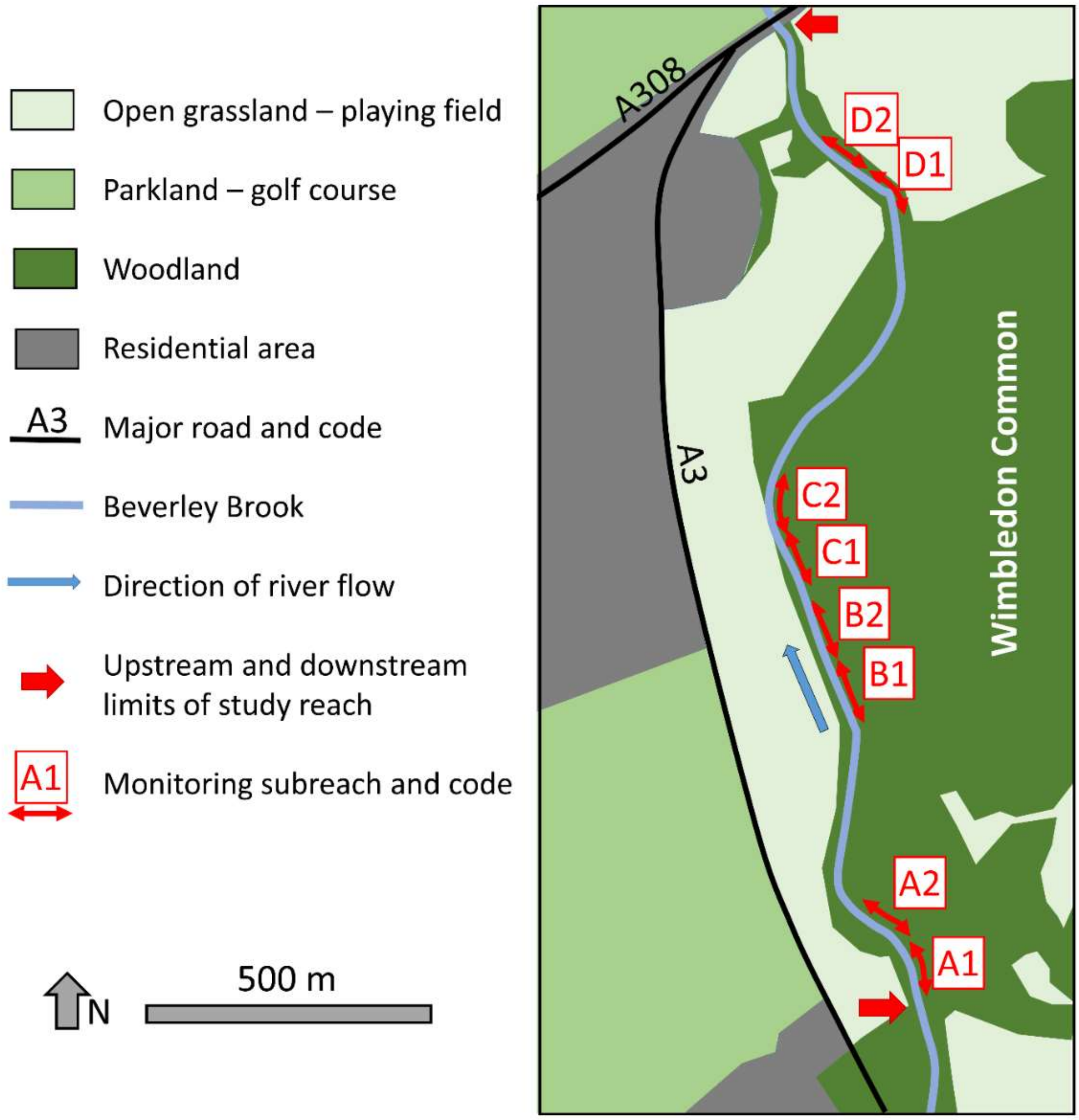

Figure 1: The study reach (between the two large red arrows), showing the surrounding land cover and the layout of the 8 monitoring subreaches (control subreaches – A1, A2; treatment subreaches – B1, B2, C1, C2, D1, D2)

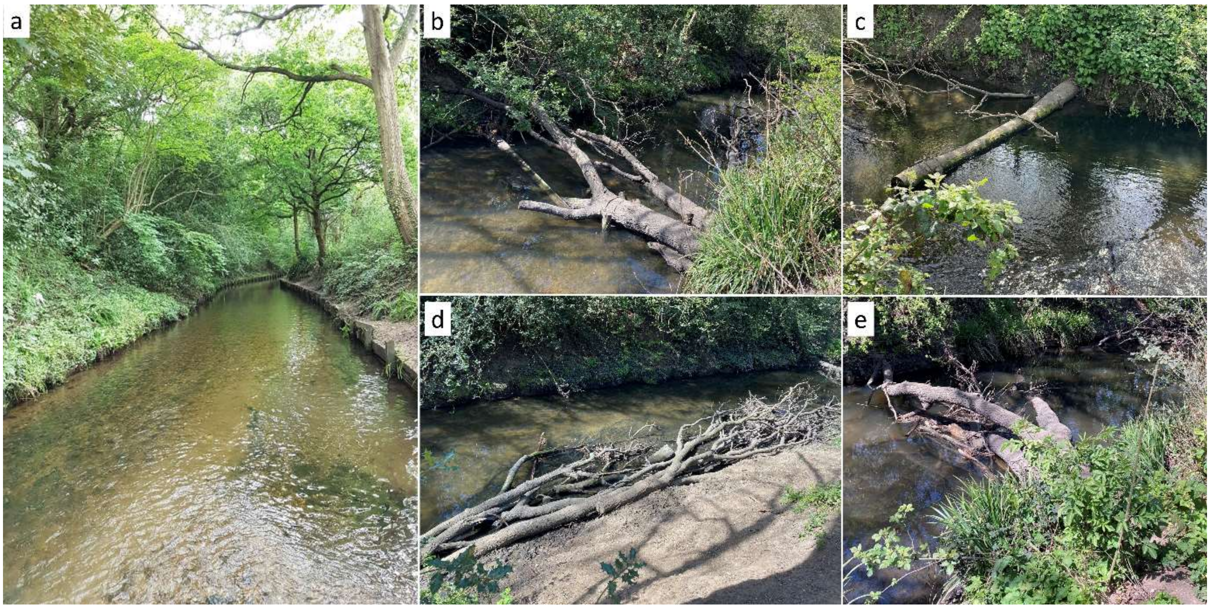

Figure 2: (a) a typical view of the Beverley Brook prior to restoration. The three types of wood introduced during restoration: trees (b), large logs/trunks/stumps (c, e), brash/branches/small logs (d).

Restoration constraints and vision

Restoration in a suburban setting has to balance the requirements of many stakeholders, including consideration of the potential to increase the risk of flooding. Also, as noted by Bernhardt and Palmer (2007, p 738), 'restoration in urban streams is both more expensive and more difficult than restoration in less densely populated catchments. High property values and finely subdivided land and dense human infrastructure (e.g. roads, sewer lines) limit the spatial extent of urban river restoration options'. The restoration at the studied reach was similarly constrained in its areal extent, ambition and scale of interventions, with wider prevailing catchment issues such as hydrological regime and water quality representing pressures beyond the scope of the project, but ones that could potentially be improved through the enhancement of reach scale hydromorphological processes. The restoration approach was based on the introduction of large wood to the river bed in order to stimulate biogeomorphological interactions that had previously been curtailed by large wood removal from the channel.

Large wood is a natural component of most river systems and is increasingly being used in river restoration (Roni et al., 2015, Grabowski et al., 2019; Cashman et al., 2021). It is very appropriate to the studied reach (and its location adjacent to wooded parts of Wimbledon Common, Figure 1) because all lowland rivers across southern England would have drained wooded catchments prior to landscape development by humans. Indeed, the name of the Beverley Brook originates from 'Beaver Ley' (Perkins et al., 2021), reflecting the Brook's likely wood-influenced historic character. To date, understanding of the likely effects of large wood emplacement in a river has been heavily based on studies of relatively steep, high-energy rivers (Matheson et al., 2017). In the present case, long-term research observations from near-naturally-functioning streams of similar size, (low) gradient and bed material located elsewhere in southern England (Gregory et al., 1985, 1994; Gurnell and Sweet, 1998; Gurnell et al., 2022, Gurnell and Hill, 2022) supported the development of a vision for the restoration and its likely trajectory of outcomes (Figure 3).

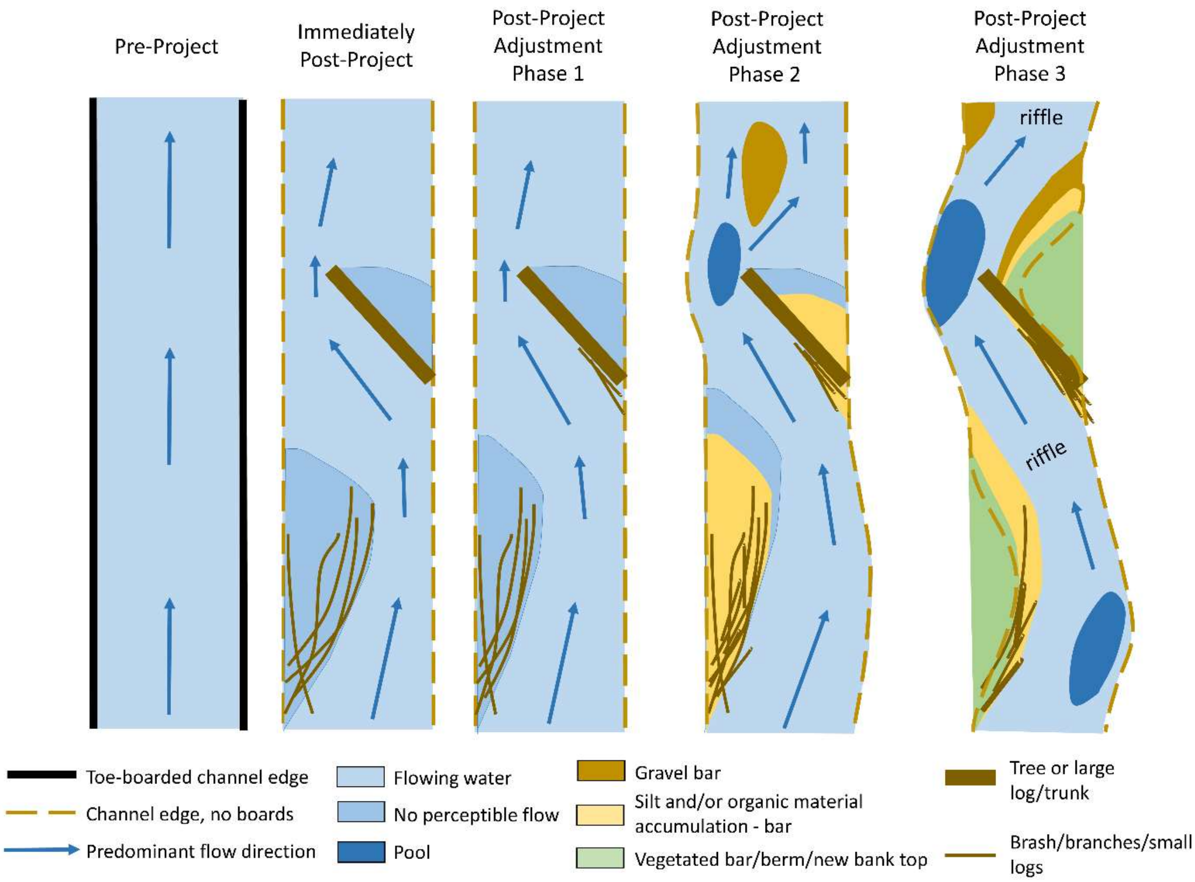

Figure 3: Restoration vision: visualisation of the initial straight course of the river confined by toe boarding, the appearance of the river immediately following restoration (emplacement of wood, removal of toe-boarding), and the three phases of post-project adjustment that were envisaged.

The restoration vision mainly focused on reinstating a range of natural biophysical processes and forms by:

(i) removing wooden toe board reinforcement to allow the river channel's biogeomorphological responses to extend across the bed and into the margins;
(ii) introducing large wood to the river bed to induce biogeomorphological responses that would create a more complex suite of self-sustaining and dynamic physical habitats;
(iii) selectively felling riparian trees along the reach to provide local wood for emplacement in the channel to kick-start a more natural 'wood cycle' (Collins et al., 2012) that could sustain future biogeomorphological processes, and also to provide light to promote vegetation colonisation and sediment retention/stabilisation of evolving marginal biogeomorphic features.

However, there were three main constraints imposed on the restoration design that needed to be incorporated into the vision:

(i) Some trimming, shaping and securing of the introduced large wood was required to confine it to the river bed and to a relatively low profile that would not strongly affect flood conveyance. To meet environment permit requirements, adequate anchorage of the wood was also required to prevent it from washing downstream during floods and potentially creating blockages.
(ii) Some wooden toe board reinforcement had to be retained where it protected infrastructure and was also retained where it protected several veteran trees.

(iii) No actions could be included to help overcome the overdeep channel cross profile, which provides a larger as well as deeper channel than would otherwise be expected for a reach in a less historically modified setting.

These constraints prevented restoration of in-channel wood from fully emulating natural tree fall and wood dynamics. They also prevented full reinstatement of erodible river banks of appropriate dimensions for the river that would allow lateral dynamics and hydrological connectivity with the evolving river margins. The vision attempted to incorporate these constraints by assuming that the emplaced wood would drive a more positive biogeomorphological trajectory than would occur in their absence, with a more rapid development of physical features around the fixed locations of the anchored, emplaced wood. However, the trajectory would be more constrained and less complex than would occur in the absence of the above-mentioned constraints. The vision incorporated three anticipated phases of biogeomorphological adjustment (Figure 3) during which distinct processes and forms evolve:

Phase 1 - the emplaced wood settles, is realigned by the flow within the constraints imposed by tethering, and retains any loose, mobile wood (particularly any entering from the local wooded riparian habitats and that left by restoration operations) to form larger wood structures that slow water flows locally and funnel faster-flowing water into the gaps between the emplaced wood structures.

Phase 2 - the continued funnelling of flow and enhanced flow velocities between the wood structures mobilises finer bed sediments and transfers them into the areas of 'no perceptible flow' sheltered by the emplaced wood. This leads to silt/sand bar development within and around the wood which further confines the faster flowing water into a narrow, sinuous path, increasingly characterised by exposed gravels; induces bed erosion to form shallow pools; and some localised bank erosion where flows scour exposed unprotected areas of the bank toe, especially during periods of high flow.

Phase 3 - depositional bars continue to develop laterally and vertically, trapping any mobile wood and fine sediment and becoming vegetated. The vegetation drives further aggradation of the bar surfaces to form elevated benches and new areas of bank top; the development of a narrowing, more sinuous river bed; the mobilisation and sorting of increasingly coarse bed material; and the development of riffles, pools and bars and erosion along exposed bank sections.

In summary, the vision suggests a more constrained and spatially-fixed development of flow patterns and landforms than would be expected in a more naturally-functioning system but a distinct increase in physical habitat diversity and turnover in comparison with pre-restoration conditions. Despite cost constraints, the restoration represents a far more ambitious approach in terms of the variety and scale of interventions than simply installing fixed log deflectors, which are reportedly the core of most wood-based restorations implemented in the UK to date (Cashman et al., 2019, 2021).

Restoration implementation

To meet the design constraints, three broad types of wood ('trees', 'large logs/trunks/stumps', 'brash/branches/small logs') were prepared from locally felled trees prior to emplacement on the river bed (Figure 2).

'Trees' were felled tree trunks with several branch stumps still attached (e.g. Figure 2b).

'Large logs/trunks/stumps' were entire tree trunks without any branches; other large, fairly uniform large logs; and tree stumps (e.g. Figure 2c and e).

‘Brash/branches/small logs’ were a variety of branching and smaller wood pieces (although often incorporating parts that were at least 10 cm in diameter and 1 m long), that were mainly cut from the felled tree canopies (e.g. Figure 2d).

In some cases, very large, individual, trimmed but irregular branches may have been recorded as trees, but in all cases a recorded tree had a distinct stem (trunk) supporting several smaller branches or branch stumps. Large logs were identified as pieces of unbranched wood that were at least 10 cm in diameter and 1 m long, although in practise most were much larger since they were usually parts of tree trunks or the main stems of large branches. They were typically placed as single pieces on the river bed (e.g. Figure 2c) but in some cases up to three pieces were bound and fixed together (e.g. Figure 2e).

Wood classified as either trees or large logs/trunks/stumps was recorded as a count. Wood classified as brash/branches/small logs was recorded according to its areal extent across the river bed (i.e. it was scored from 0 to 10 to represent units of 10% of the bed area within the affected survey area). Because the introduced wood had to be tethered to restrict its downstream movement, it was attached to wooden stakes driven into the river bed or, in the case of the largest trees or logs/trunks/stumps, the wood was secured with a single Platypus© ground anchor. This meant that whereas any wood entering the river by natural processes during the monitoring period was untethered and could move freely, the introduced wood could only move locally around the stakes or ground anchor to which it was tethered.

The wood was placed in the channel so that it projected from the bank toe and extended at varying angles from perpendicular to parallel to the bank face with intermediate angles oriented in a downstream direction. Although the wood placement was random and the quantities and sizes of wood varied along the treated channel, the broad approach was to alternate the introduced wood features between the left and right banks, to avoid creating complete barriers across the river bed and so to encourage development of a narrower, more sinuous low-flow channel (Figure 3).

The MoRPh survey – a simple method for tracking river physical habitat change

In addition to recording the large wood shortly after its emplacement, we used a ‘physical habitat’ survey method, the Modular River (Physical) or MoRPh field survey, to track changes in river sediments, physical features and vegetation structure as the river responded to the restoration actions. The MoRPh survey was developed in 2016 for application by volunteers (Shuker et al., 2017, Gurnell et al., 2019). Recently it has been incorporated into a professional River Condition Assessment method (Gurnell et al., 2020), which is a component of the UK government’s Statutory Biodiversity Metric tool for assessing biodiversity net gain (Department for Environment, Food and Rural Affairs, 2023). The MoRPh survey offers enormous potential for monitoring river channel changes because it is quick to apply, allows precise relocation of survey sites, and records detailed information on the abundance of different sediments, landforms, vegetation structural components, and human pressures and interventions within short lengths of streams or rivers and their margins to 10m from the bank top. These survey characteristics allow rapid, accurate, repeat surveys to reveal changes in surveyed river lengths. The MoRPh survey has been described in the above-mentioned papers and the survey manual, field guide, survey forms, and indicator formulations are freely available in the public domain and downloadable from https://modularriversurvey.org/. Therefore, we give a very brief description here.

The MoRPh field survey records properties of a stream or river’s bed, bank faces, and bank tops up to 10 m from the channel / bank top edge. It is mainly applicable to small single thread to transitional rivers, but can also be applied to individual channels of multi-thread systems. It is applied to short lengths of river channel called ‘modules’, whose length varies with channel bed width (length = 10 m if the bed width is < 5 m; length = 20 m if width is in the range 5 m to < 10 m;

length = 30 m if width is in the range 10 to < 20 m; and length = 40 m if width is in the range 20 to < 30 m). For larger channels (>30 m wide) a module length of 50 m could be applied, but limitations on visibility of the river bed, far bank and riparian zone should be noted and taken into account during data analysis. Surveys of several contiguous MoRPh modules can characterise longer lengths of river. Table 1 summarises the types of features recorded across the bank tops, bank faces, and river bed. In most cases the abundance of each survey element is also recorded either by using a simple abundance scale (A = absent, T = trace [<5%], P = present [5–33%], E = extensive [>33%]) or by counting the number of features of a given type.

Table 1. Broad categories of materials, physical features and vegetation properties, including human pressures and direct modifications, that are characterized by a MoRPh survey.

	Bank top-Floodplain	**Bank face-Channel margins**	**Channel bed**
Materials		Natural materials. Reinforcement materials.	Channel bed natural materials, including degree of siltation. Channel bed reinforcement materials.
Physical features	Water-related features. Artificial-managed ground cover.	Natural and modified bank profiles. Natural physical features of the bank face, toe and channel margin. Artificial physical features.	Natural physical features. Water surface flow patterns. Artificial physical features.
Terrestrial (Riparian) and Aquatic Vegetation	Terrestrial vegetation structure. Tree and large wood features. Non-native invasive plant species.	Terrestrial vegetation structure. Tree and large wood features. Aquatic vegetation at the channel margin. Non-native invasive plant species.	Aquatic vegetation. Terrestrial vegetation, large wood and other organic matter interacting with the wetted channel. Non-native invasive plant species.

Monitoring design

MoRPh surveys were conducted on six occasions over four years by the same two surveyors to monitor the impact of the restoration using a Before-After-Control-Impact (BACI) monitoring design. Figure 1 illustrates the layout of the field surveys within the studied reach. Monitoring was conducted within 8 subreaches (A1, A2, B1, B2, C1, C2, D1, D2), each comprised of 5 contiguous MoRPh modules, so that a total of 40 MoRPh surveys were conducted on each survey occasion. Because the Beverley Brook within the study reach had an average bed width of approximately 6 m (i.e. between 5 and 10 m wide), each MoRPh module was 20 m long, each subreach was 100 m long, and a total of 800 m of river were surveyed.

Subreaches A1 and A2 were located towards the upstream end of the studied reach and were not restored, providing control subreaches for comparison with six downstream treatment subreaches. Treatment (Impact) subreaches (B1, B2, C1, C2, D1, D2) were located to capture variability in the expected application of the restoration measures, which, prior to restoration, were envisaged to proceed from downstream to upstream. The upstream extent of the measures was dependent on time and resources and so was unknown when the monitoring sites were selected and pre-project surveys were conducted.

The pre-project baseline surveys were conducted in December 2018 and the restoration was implemented early in 2019. Three further surveys were conducted at six-monthly intervals to include a post-project survey (June 2019), a survey one year after the pre-project survey (December 2019), and one year after project completion (June 2020). A further two, more widely spaced surveys in April 2021 and September 2022 allowed changes over a period of approximately four years from the pre-project survey to be captured.

The BACI design allowed observations from unrestored subreaches A1 and A2 to provide controls against which observations from treatment subreaches B1, B2, C1, C2, D1, D2 could be compared, allowing responses to the restoration actions to be separated from responses to other factors, such as the occurrence of large flow events. Subreach A2 experienced natural tree fall and inputs of large wood during the survey period. As a result, subreach A1 provided a true control (no significant change in in-channel wood during the monitoring period), while A2 evidenced responses to natural additions of untethered wood.

Monitoring protocols aimed to minimise operator variance in the survey data by defining standardised terms and recording techniques for novel wood interventions and also using cross channel photographs to precisely relocate the mid-point for surveying each MoRPh module.

Data analysis

The MoRPh survey data were used to summarise: (i) the restoration actions; (ii) the immediate physical effects of the restoration actions; and (iii) the vegetation/wood, sedimentary and morphological responses to the restoration actions over the five post-project MoRPh surveys.

All of these aspects were investigated by plotting graphs representing the aggregated observations of surveyed properties across groups of 5 MoRPh modules (i.e. a 100 m subreach). MoRPh surveys either record the number or count (e.g. pools) or the aerial or linear abundance (e.g. silt bed material, side bars) of properties/features of the river bed, bank faces and bank tops. For the number/count fields, the aggregate over the five MoRPh modules was the sum of these numbers/counts. Where the APTE (absent, trace, present, extensive) abundance scale was used, the observed abundances in each MoRPh survey were translated into mid-point percentages (0, 2, 19, 67%, respectively, for A, P, T, E) and then summed over the 5 MoRPh modules. Therefore, the maximum possible aggregated value for the APTE fields is 335 (i.e. 5x67) for bed features and 670 (i.e. 2x5x67) for features recorded on both bank faces or both bank tops. However, in practice many bank features tend to alternate from one bank to the other along the length of a river (e.g. side bars), giving a likely achievable maximum of 335.

To summarise the restoration actions, an inventory of the quantity and type of introduced wood was recorded during the first post-project survey (June 2019).

To quantify the immediate effects of the restoration actions, the areal extent of wood on the river bed, the linear extent of bank toe reinforcement, and the areal extent of trees on each river bank top and face were plotted for the pre- and post-project surveys (December 2018, June 2019). These illustrated the main locations and the extent of wood additions, the extent of bank toe reinforcement removal, and the extent and location of tree felling that supplied the introduced wood and increased light penetration to the channel.

To quantify the river's responses to the restoration actions, changes in the abundance (areal extent) of the following over the six surveys were computed and graphed:

- the main surface flow pattern types (indicative of adjustments in flow hydraulics);
- the aerial exposure of different sizes of bed material (indicative of scour, deposition and sorting of bed materials);

- different physical features comprised of wood and organic material (indicative of adjustments in tree-related physical habitats on the river bed);
- sedimentary landforms (indicative of adjustments in other physical habitats on the river bed); and
- tree-related habitats across the bank faces and the linear extent of sedimentary landforms along the channel edges (indicative of adjustments in physical habitats along the channel margins).

Observation based semi-quantitative field surveys inevitably generate a degree of operator variance in the data, which may lead to apparent changes between surveys even when no change has occurred. Therefore, we identified ‘notable’ changes between surveys as those where differences in the aggregated values exceeded 20% of the potential range. For example, for data fields based on the APTE scale, a 20% change is equivalent to a numerical change of 67 when the potential range is 0 to 335. This is equivalent to an observation in at least one of the five MoRPh surveys along a subreach moving from A (absent) to E (extensive, >33%), which is an enormous change that is highly unlikely to be the result of observer error. Alternatively, it is equivalent to at least 4 MoRPh surveys showing an increase from A (absent) to P (present, 5-33%), which is a sizeable change across almost all of the five MoRPh surveys and is again unlikely to be the result of observer error. We also identified ’consistent’ changes as those where several subreaches show the same (positive or negative) direction of change between surveys, even where the changes are less than 20% of the possible range. It is unlikely that such consistent changes across several subreaches would occur simply through observer error.

3. RESULTS

Restoration actions and their immediate effects

The main restoration action was the placement of large wood on the river channel bed. The wood varied in type (trees, large logs/trunks/stumps, brash/branches/small logs) and also quantity (number or areal extent) across the 6 treatment subreaches (Figure 4). No wood was deliberately introduced into the control subreaches (A1, A2). The greatest variety and quantity of introduced wood was observed in subreaches B1 and B2. Subreaches C1 and D2 received less wood than B1 and B2, and whereas C1 received all three types of wood, no trees were added to subreach D2. Only small amounts and a restricted range of types of wood were introduced into subreaches C2 and D1 (Figure 4). The immediate effect of this wood addition was a notable increase in the areal abundance of wood on the river bed in subreaches B1, B2, C1 and D2 (Figure 5a).

A second restoration action was the removal of toe boarding along the channel lower banks. This was recorded within a potential numerical range of 0 to 335 on each bank and thus 670 for both banks (Figure 5b). The linear extent of toe board reinforcement in the control subreaches (A1, A2) was very high and remained unchanged, whereas there were major reductions in the linear extent of toe board reinforcement in all the treatment subreaches (all observed reductions exceed 134, representing >20% of the potential 0 to 670 range), with almost complete removal of toe reinforcement along subreaches B1, C1 and D2.

The third restoration action was tree works, including felling and scrub clearance, which provided the wood material for placement in the river channel. Figures 5 c, d, e, f show the areal extent of trees on each river bank top and face before and after the restoration. The only notable reduction in tree cover on the left bank (i.e. a change exceeding 67) is observed on the bank face of subreach D2 (Figure 5d) but notable reductions in tree cover occur along the right bank of the river across bank tops (Figure 5d, subreaches B2, C1 and D2) and bank faces (Figure 5f, subreaches B1, B2, D2).

These restoration actions and their immediate effects within each subreach are summarised in Table 2.

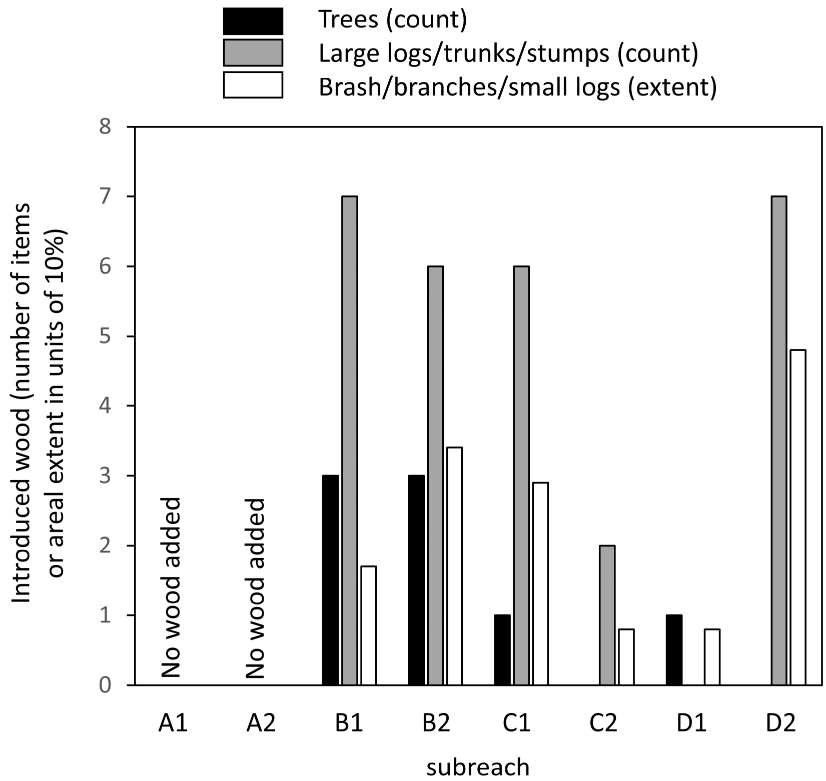

Figure 4: the amount and types (whole trees, large logs/trunks/stumps, brash/branches/small logs) of wood added to the subreaches. Note that where the vertical axis refers to brash/branches/small logs, it is expressed in units of approximately 10% cover of the river bed.

Table 2 Summary of presence / absence of restoration actions at each subreach

Restoration action	**Subreach**							
	A1*	**A2***	**B1**	**B2**	**C1**	**C2**	**D1**	**D2**
Introduced trees			✓	✓	✓		✓	
Introduced large logs			✓	✓	✓	✓		✓
Introduced small logs, branches, brash			✓	✓	✓	✓	✓	✓
Notable (>134) toe board removal			✓	✓	✓	✓	✓	✓
Notable (>67) tree felling and scrub clearance on at least one bank top or face			✓	✓	✓			✓

* No restoration actions were applied in the control subreaches (A1, A2).

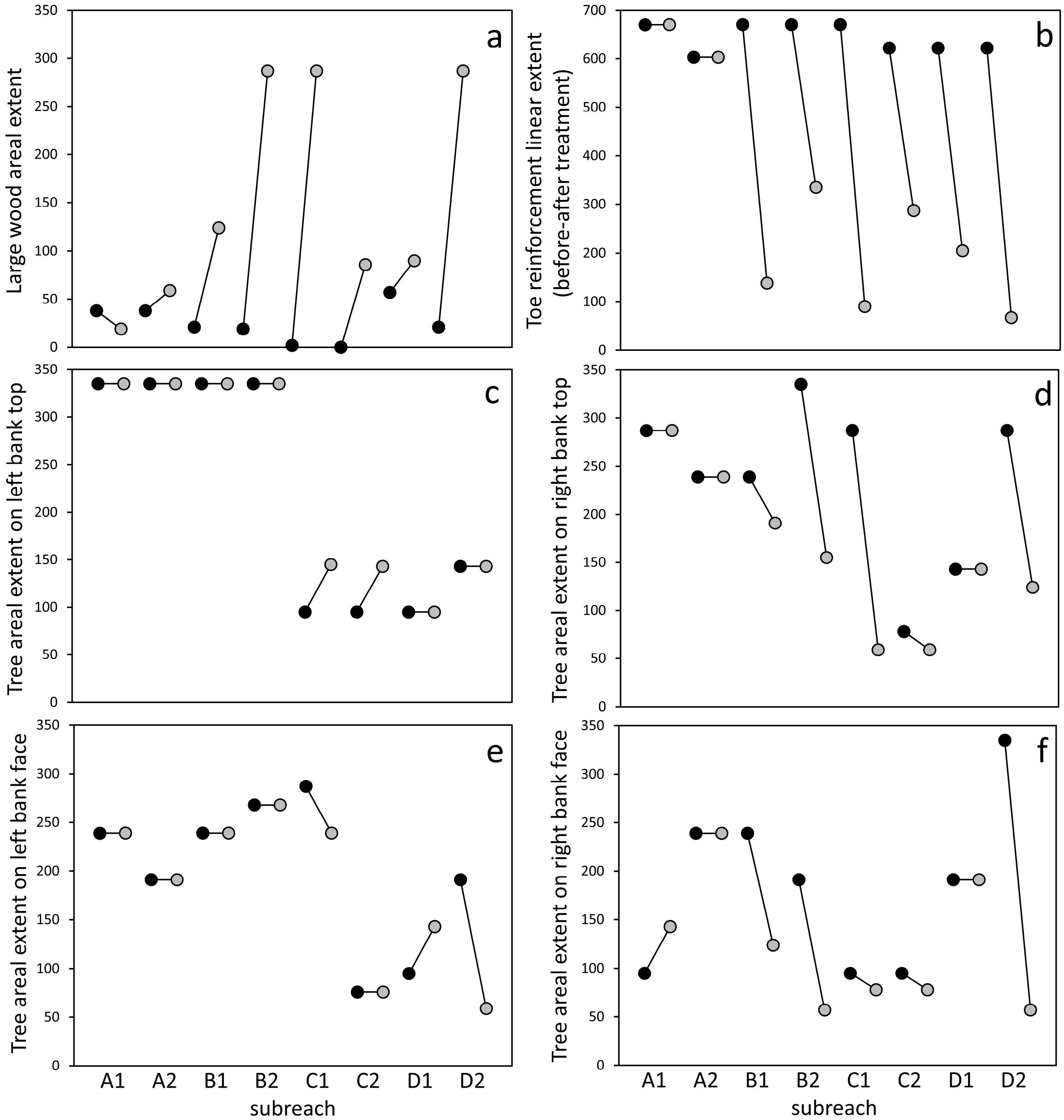

Figure 5: A summary of river restoration actions (observed changes between the pre-project survey in December 2018 (black dots) and the first post-project survey in June 2019 (grey dots) linked by a line for each subreach): (a) areal extent of large wood on the river bed (maximum possible value 335); (b) change in the linear extent of bank toe reinforcement (maximum possible value 670 across both bank faces); (c, d, e, f) change in the areal extent of tree cover (maximum possible value 335) on the left and right bank tops (c, d) and left and right bank faces (e, f).

Bio-physical responses to the restoration actions

Responses to the restoration actions over the four year monitoring period are illustrated in Figures 6 to 10. In each of the Figures the time sequence of changes is represented by six dots joined by lines for each subreach, with the pre-project survey represented by a black dot and the five post-project surveys represented by grey dots.

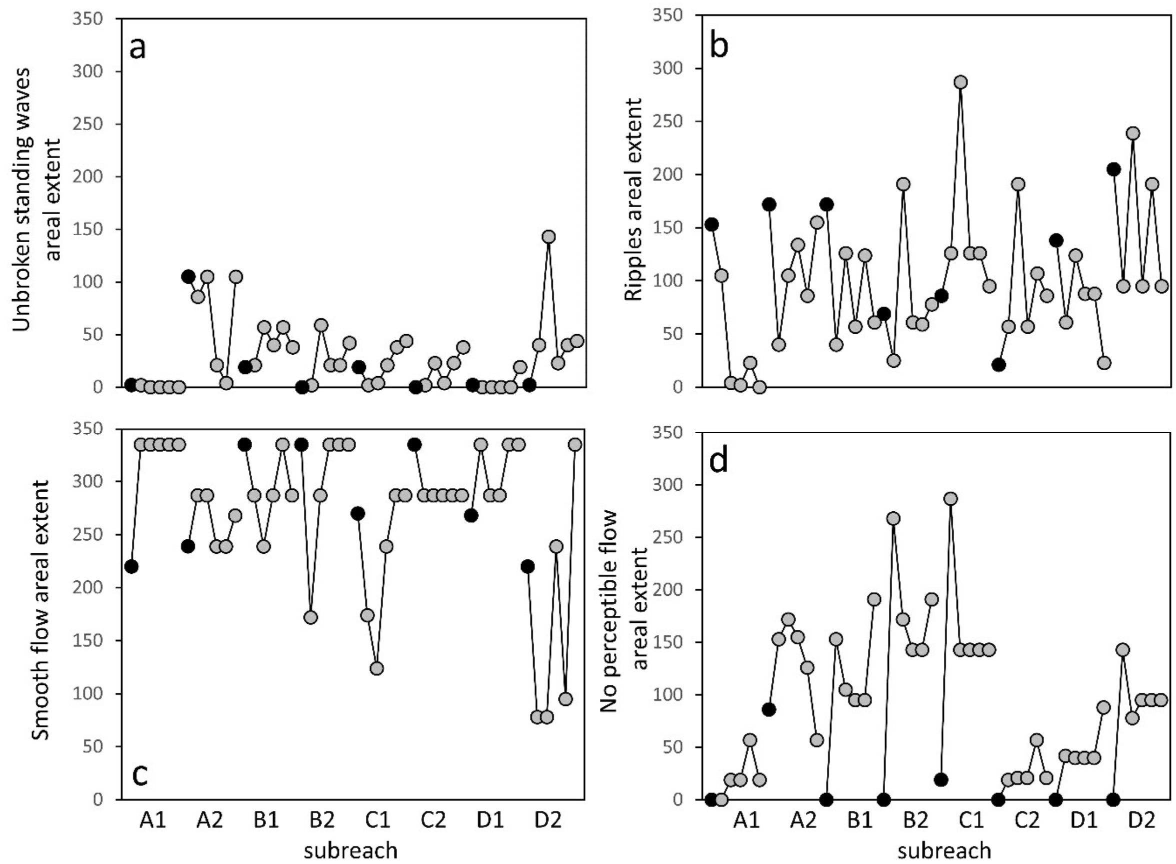

Figure 6: Temporal changes in the areal extent of different water surface flow patterns (all during low flows) through the six surveys (black dot - pre-project survey, grey dots - post-project surveys joined by a line for each of the eight subreaches). (a) unbroken standing waves; (b) ripples; (c) smooth; (d) no perceptible flow.

Four main water surface flow patterns, indicative of hydraulic habitats within the flow, are observed across the subreaches in the pre- and five post-project surveys, all of which were undertaken during low flow conditions: unbroken standing waves; ripples; smooth; and no perceptible flow (Figure 6). Smooth and rippled flow patterns have the highest abundances. The four flow patterns show little variation through time in control reach A1 apart from an early reduction in the areal extent of ripples. This control subreach is dominated by smooth flow. All other subreaches show temporal variability in all four flow pattern types with notable fluctuations in the areal extent of ripples, smooth and no perceptible flow within and between subreaches. The only flow pattern that shows a consistent temporal trajectory in areal abundance across the treatment subreaches is no perceptible flow. This flow pattern consistently increases immediately following treatment and then tends to fall or stabilise around an increased areal extent. The initial increase is notable in subreaches B1, B2, C1 and D2, which also show a small consistent fall between the second and the third survey (June 2019, December 2019) after which the areal extent of no perceptible flow shows little temporal variability. The second control reach, A2, shows greater temporal variability in all four flow types than A1, probably induced by natural tree fall within this subreach. Also A2, shows a notable early increase in no perceptible flow but, in contrast to the six treatment subreaches, this is a more gradual increase over the first three surveys followed by a gradual decline.

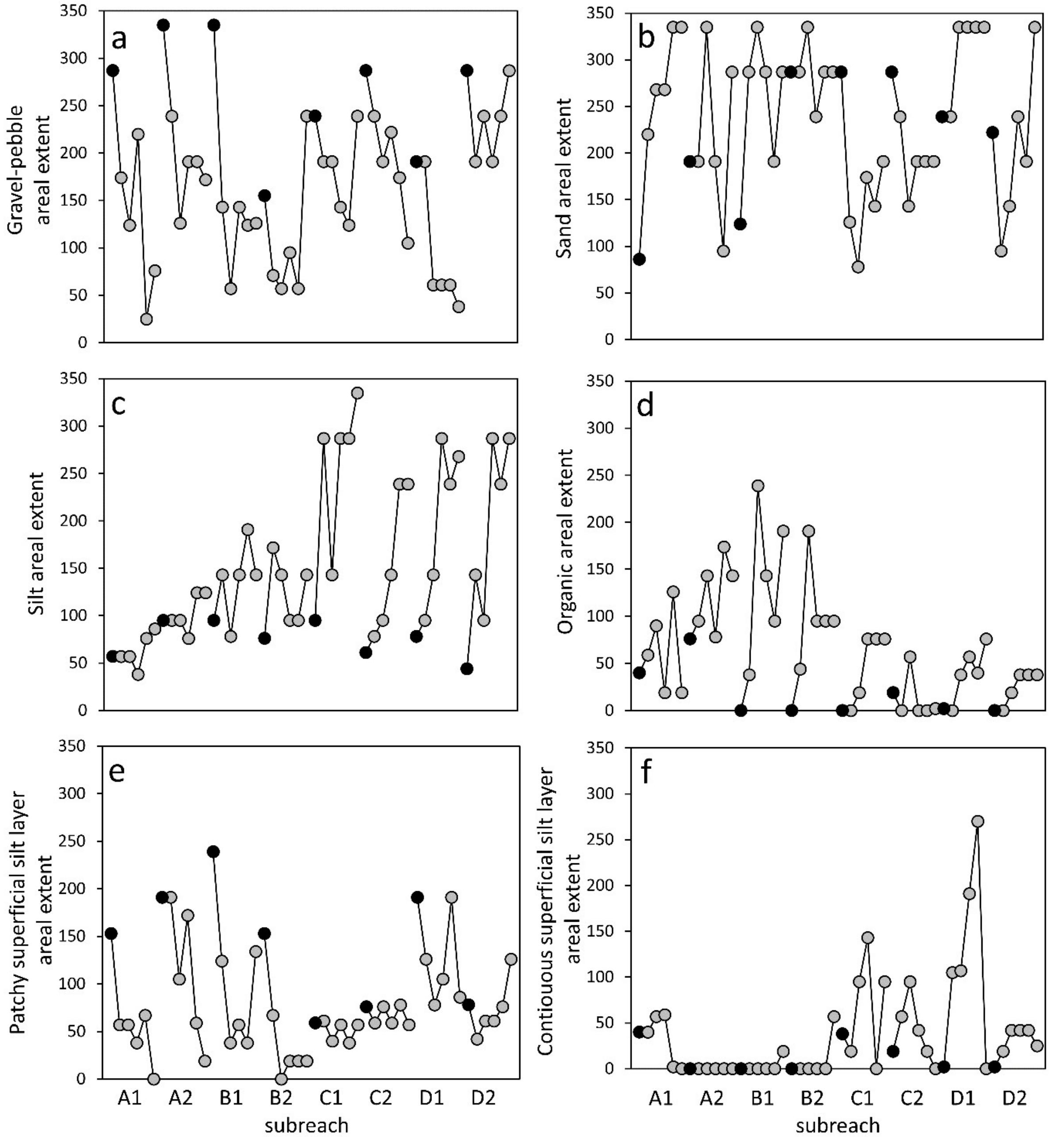

Figure 7: Temporal changes in the areal extent of different classes of river bed material through the six surveys (black dot - pre-project survey, grey dots - post-project surveys joined by a line for each of the eight subreaches). (a) gravel-pebble; (b) sand; (c) silt; (d) organic; (e) patchy superficial silt; (f) continuous superficial silt.

Four main bed material size classes are present on the river bed: gravel-pebble, sand, silt and organic material (Figure 7 a, b, c, d). Thin layers of superficial silt are also present. These layers are sufficiently thin that the underlying coarser bed material (gravel) can be seen either protruding through the silt (patchy superficial silt) or is expressed as a continuous undulating thin silt layer with no protruding coarse particles (continuous superficial layer) (Figure 7 e, f). Control subreach A1 shows a notable decline in gravel-pebble area (Figure 7a) and a notable increase in sand area (Figure 7b) over the six surveys with little change in silt or organic bed material (Figure 7c and d). Subreach A1 also shows a gradual decline in the areal extent of patchy superficial silt (Figure 7e), as the gravel-pebble area is gradually covered by sand. Reach A2 shows similar but less strong changes in the areal extent of gravel-pebble and patchy superficial silt to subreach A1. There is no consistent change in the areal extent of gravel-pebble or sand across the six treatment subreaches. Subreaches B1, C2 and D1 show a notable decrease in the areal extent of gravel and subreaches D1 and D2 show a notable increase in sand cover. Subreaches C1, C2, D1 and D2 show a notable increase in silt cover, whereas subreaches B1 and B2 show a notable increase in the area covered by organic material and a decrease in patchy superficial silt. Finally, subreaches C1, C2, D1 and D2 show a consistent increase and then decrease in the areal extent of continuous, superficial silt.

Four river bed landforms show consistent if small changes over the observation period in their number or areal extent (Figure 8). All subreaches apart from A1 show a consistent increase in the number of pools (Figure 8b), with notable increases observed in A2, B1, B2 and C1. Very few riffles are observed, but a small number develop in subreaches A2 and D2 over the study period. Mid-channel bars are small and rare, but a consistent emergence of both vegetated and unvegetated mid channel bars is observed in the final survey of subreaches B2, C1 and D2. Subreach A2, which received natural tree fall, is distinguished by increases in the number of riffles and pools and a notably higher area occupied by unvegetated mid-channel bars than all other subreaches.

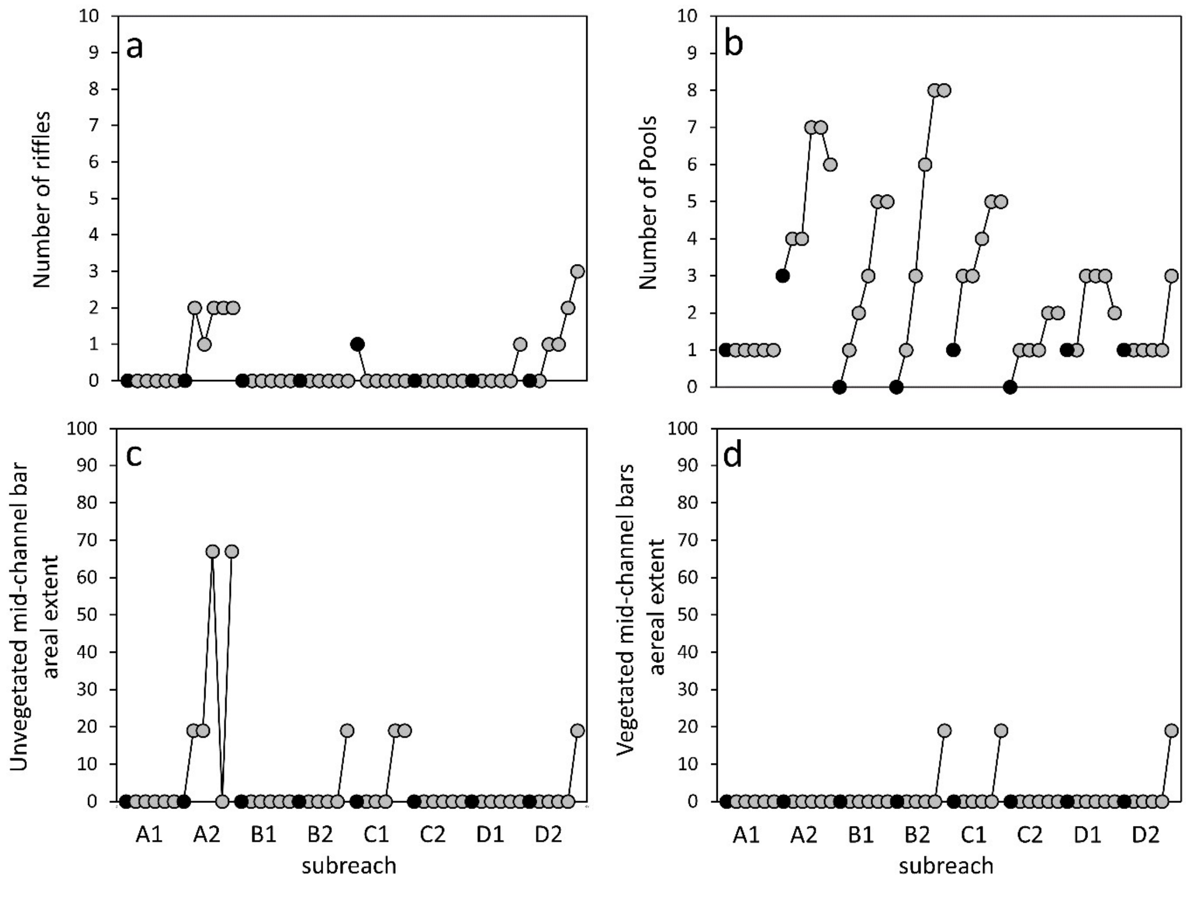

Figure 8: Temporal changes in the number/areal extent of different river bed landforms through the six surveys (black dot - pre-project survey, grey dots - post-project surveys joined by a line for each of the eight subreaches). (a) riffles; (b) pools; (c) unvegetated mid-channel bars; (d) vegetated mid-channel bars.

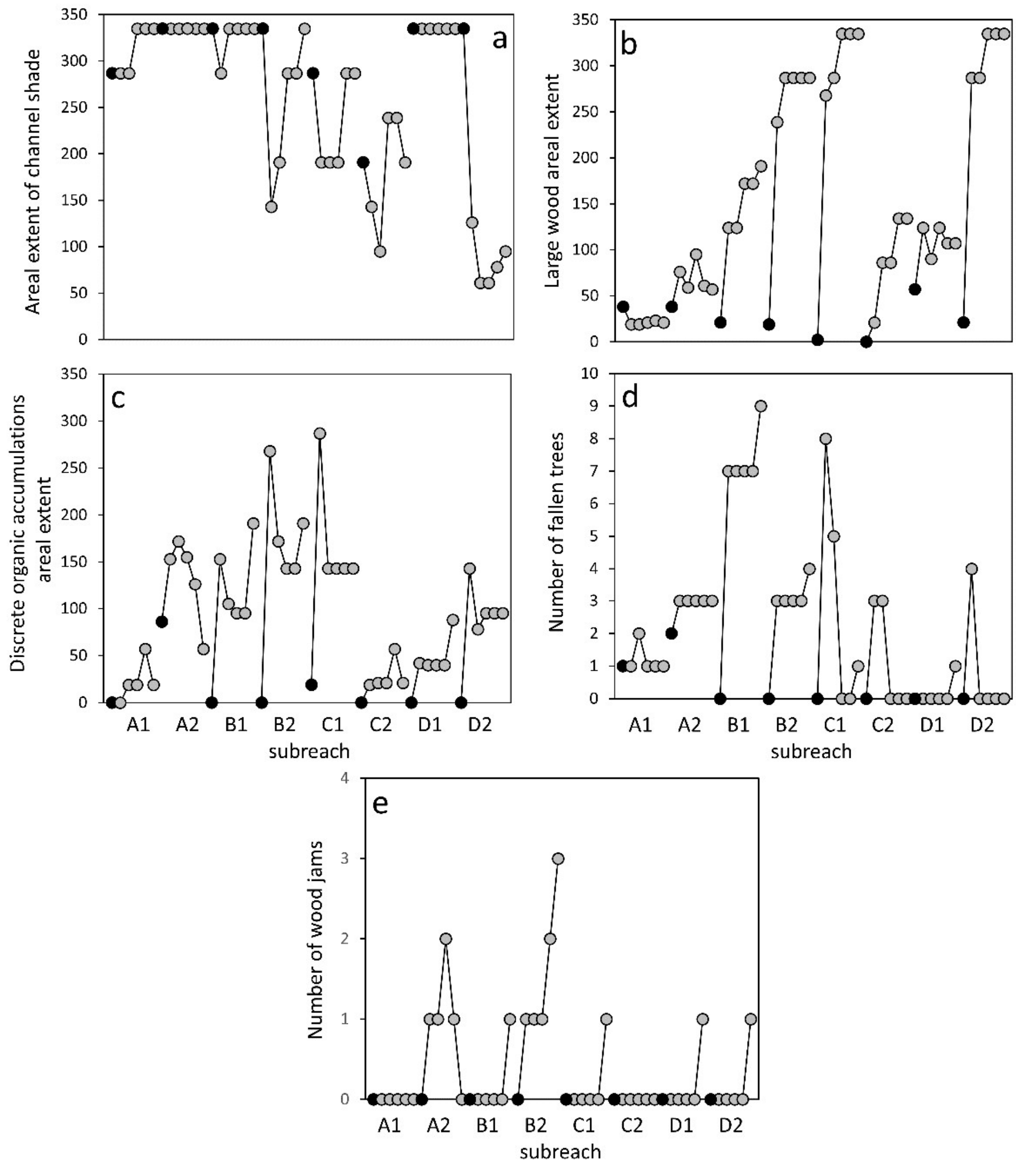

Figure 9: Temporal changes in the number / areal extent of different river bed tree-related features through the six surveys (black dot - pre-project survey, grey dots - post-project surveys joined by a line for each of the eight subreaches). (a) channel shade; (b) large wood; (c) discrete organic accumulations; (d) fallen trees; (e) channel-crossing wood jams.

Changes in river bed tree-related features are illustrated in Figure 9. Early changes in shading of the channel occurred between the first and second survey observations (Figure 9a). While high and persistent shade is observed in subreaches A1, A2, B1 and D1 throughout the four year observation period, there are notable early reductions in shade immediately following restoration within subreaches B2, C1, C2 and D2 in response to tree felling (Figure 5d, f). These are followed by a gradual increase in shade in the same subreaches as the riparian vegetation starts to re-establish over the remaining survey dates (Figure 9a). The areal extent of large wood (Figure 9b) shows notable increases in all reaches apart from the controls (A1, A2) with much larger increases in subreaches B1, B2, C1 and D2 than C2 and D1, reflecting differences in the quantity of wood emplaced during restoration (Figures 4, 5a). All of these early increases in the areal extent of large wood in the treatment reaches are followed by a consistent pattern of smaller increases and then stabilisation towards the end of the monitoring period, indicating trapping of mobile wood by the emplaced wood. One component of this large wood is 'fallen' trees (Figure 9d). In the treatment reaches, most fallen trees were emplaced, explaining the large counts in B1 and B2 (Figure 4), but Figure 9d also indicates the appearance of additional trees in these and other subreaches, including A2, through the study period. Furthermore, bed-spanning wood jams (Figure 9e) start to appear in all subreaches apart from A1 and C2. These develop towards the end of the study period in the treatment subreaches, but earlier in A2, where they are associated entirely with natural tree fall. These observations illustrate that as the areal extent of large wood and the number of fallen trees increases, the wood accumulates to build jams that cross the entire channel bed. Discrete accumulations of smaller organic material also show notable early increases in subreaches A2, B1, B2, C1 and D2 between the first two surveys. All of these subreaches apart from A2 also show subsequent small reductions to achieve consistently higher organic retention after restoration than before, mainly around the emplaced wood. Subreach A2 shows a different temporal pattern but also higher organic retention than reaches A1, C2 and D1.

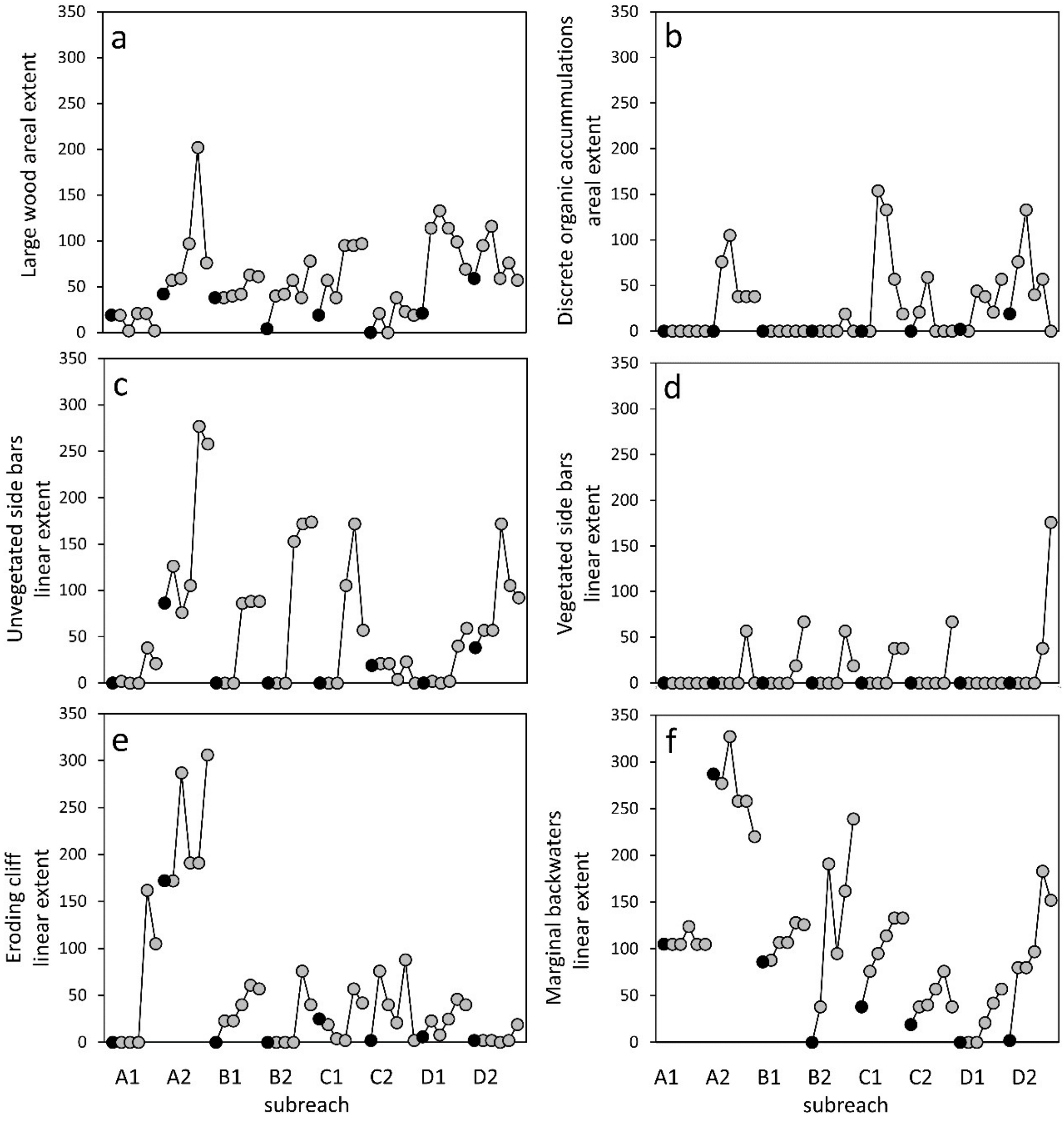

Figure 10: Temporal changes in the areal / linear extent of different bank face / water edge features through the six surveys (black dot - pre-project survey, grey dots - post-project surveys joined by a line for each of the eight subreaches). (a) large wood; (b) discrete organic accumulations; (c) unvegetated side bars; (d) vegetated side bars; (e) eroding cliffs; (f) marginal backwaters.

In addition to the changes across the river bed illustrated in Figures 7 to 9, changes in channel margin / bank face landforms are illustrated in Figure 10. As wood moves along the river and trees fall into the channel, there are consistent but small increases in large wood on the bank faces of most treatment subreaches (Figure 10a). No such increase is observed in subreach A1, but the largest increase is observed in A2 in association with natural tree fall. Subreaches A2, C1 and D2 also show early notable increases in the abundance of discrete accumulations of organic material on the bank faces followed by slight reductions to lower levels (Figure 10b). These represent the retention of organic material within and around large wood. Unvegetated side bars show notable early establishment and then gradual increases in linear extent along all treatment reaches that received significant quantities of emplaced wood (B1, B2, C1, D2, compare Figures 10c, 4 and 5a). However, the most rapid increase and the highest final linear extent of unvegetated side bars occurs in subreach A2 in association with natural tree fall. Furthermore, small but consistent vegetated side bars develop in all of these subreaches towards the end of the study period (Figure 10d) as the unvegetated bars start to stabilise. The development of all of these physical features is accompanied by the consistent, progressive creation of marginal backwaters (Figure 10f) in all treatment subreaches, although the most extensive marginal backwaters are observed in subreach A2. To date, bank erosion has been limited throughout the surveyed subreaches (Figure 10e) but is most apparent in subreach A2 in association with natural tree fall, and is recently observed at the downstream end of subreach A1.

The main observed changes in the eight subreaches over the study period are summarised in Table 3.

Table 3: Summary of the main secondary physical consequences of the restoration actions.

Notable and/or consistent changes	Subreach							
	A1	A2	B1	B2	C1	C2	D1	D2
HYDRAULIC FEATURES								
Notable initial increase in areal extent of no perceptible flow.		✓	✓	✓	✓			✓
Consistent stabilisation of increased areal extent of no perceptible flow through the study period.			✓	✓	✓	✓	✓	✓
BED MATERIALS								
Notable decrease in areal extent of gravel substrate over study period.	✓	✓	✓			✓	✓	
Notable increase in areal extent of sand substrate over study period.	✓						✓	✓
Notable increase in areal extent of silt substrate over study period.					✓	✓	✓	✓
Notable increase in areal extent of organic material.			✓	✓				
Notable decrease in areal extent of discontinuous (patchy) superficial silt layer over study period.	✓	✓	✓	✓				
Consistent increase then decrease in areal extent of continuous superficial silt layer over study period.					✓	✓	✓	✓
PHYSICAL BED FEATURES								
Consistent increase in the number of pools.		✓	✓	✓	✓	✓	✓	✓
Notable increase in the number of pools.		✓	✓	✓	✓			
Consistent, recent development of small mid-channel vegetated and unvegetated bars.				✓	✓			✓
Development of notable unvegetated mid-channel bars through study period.		✓						
TREE-RELATED BED FEATURES								
Early notable reduction in the areal extent of channel shade followed by some recovery.				✓	✓	✓		✓
Notable early increase in the areal extent of large wood followed by further smaller increases.			✓	✓	✓	✓		✓
Notable early increase in the areal extent of discrete organic accumulations followed by small reductions to a stable increased areal extent.			✓	✓	✓			✓
Development of one or more channel-spanning wood jams during the monitoring period.		✓	✓	✓	✓		✓	✓
PHYSICAL AND TREE-RELATED BANK FACE / WATER MARGIN FEATURES								
Consistent but mainly small increase in areal extent of bank face wood.		✓	✓	✓	✓	✓		
Notable early increase in the extent of discrete organic accumulations followed by reduction and stabilisation.		✓			✓			✓
Notable increased linear extent of unvegetated side bars.		✓	✓	✓	✓			✓
Consistent, late appearance of small vegetated side bars.		✓	✓	✓	✓	✓		✓
Consistent, mainly notable increased linear extent of marginal backwaters.			✓	✓	✓	✓	✓	✓

4. DISCUSSION

In this section, we discuss the outcomes of the restoration of the studied reach within the framework of developing a vision for the restoration and then tracking the delivery of that vision through a monitoring programme. We then consider the lessons learnt in terms of tracking the achievements of low cost restorations more generally.

4.1 Delivering and tracking the restoration vision for the studied reach

In the introduction to this paper, we note that although numerous recommendations have been published regarding the science and practice of river restoration, few of these recommendations are being routinely implemented. While deep and complex multi-scale, multi-disciplinary investigations may be costly and challenging, there are other recommendations that could be met at relatively low cost. In this paper we have incorporated a science-based vision that considers the likely trajectory of outcomes from a river restoration centred on introducing large wood to a river reach. Also, we have implemented a low cost monitoring programme and have shown how analysis of the monitoring data set can characterise the response trajectory, demonstrate successes and identify lessons learnt from the outcomes.

The science-based vision of the likely trajectory of responses, the potential project outcomes and the likely timescale over which the outcomes might be achieved (Figure 3) provided a baseline against which to judge the monitored outcomes from the project. The vision was based on scientific investigations of more naturally-functioning rivers of similar size, gradient and bed material located within a similar biogeographical setting to represent the likely outcomes of introducing large wood to the river channel. However, it was also tempered by several constraints reflecting the suburban setting and the requirements of stakeholders and regulators.

As acknowledged previously, some trimming, shaping and securing of the introduced large wood was required to confine it to the river bed and to a relatively low profile that would not strongly affect flood conveyance. As noted earlier, installation of fixed log deflectors are the core of most wood-based restorations implemented in the UK to date (Cashman et al., 2019, 2021) and the present authors have observed that tethered wood is being used quite widely to improve habitat in suburban rivers around London. However, the present case study stands out in terms of the relatively large quantities, large piece sizes and reduced trimming of the introduced wood.

The key lessons learned from comparing the monitored outcomes with the trajectory proposed in the vision are that (i) natural untethered wood inputs induce a stronger and more rapid response than trimmed, emplaced and tethered wood, even where the latter are arranged to emulate natural wood accumulations; (ii) the greater the quantity and piece sizes of introduced (accompanied by minimal tethering), the greater the biogeomorphological responses; (iii) if at all possible, natural wood inputs have the greatest physical habitat impacts and should not be removed.

These lessons were learned from a rapid, low cost monitoring programme that tracked responses to the restoration from pre-project through post project stages on six monitoring occasions over a period of almost four years. The programme incorporated monitoring of two upstream unrestored (control) subreaches as well as six restored (treatment) reaches. The significant value of the monitoring method and design can be summarized in the following specific analytical outcomes:

1. The restoration responses follow the trajectory and vision presented in Figure 3 and demonstrate that the forecast trajectory has reached the early stages of phase 3.
2. High, steep, confining river banks and some remaining toe boarding appear to have restricted the nature and rate of recovery and may prevent or delay the full attainment of phase

3. Specifically, the relatively modest extents of bank erosion (i.e. eroding cliffs), side bars and marginal backwaters (Figure 10) suggest limited lateral movement over the observation period in the treatment subreaches and thus slow development of the sinuous planform envisaged in phase 3.
4. The impact of natural tree fall within control reach A2 has induced a far greater biogeomorphological response than the emplaced wood in the treatment reaches. This response has occurred even though the number of fallen trees was smaller than the total of emplaced and naturally-fallen trees in several of the treatment reaches (Figure 9d) and the aerial extent of large wood was also much smaller than in many of the treatment reaches (Figure 9b). Responses to the natural inputs of wood across the bed of subreach A2 included the development two channel-crossing wood jams, two riffles, several pools, and the only large, gravel, mid-channel bar in the studied subreaches (Figures 8 and 9). In addition, the channel margins showed the most extensive bank erosion (i.e. eroding cliffs), marginal backwaters and unvegetated side bars of any of the studied subreaches (Figure 10). These responses indicate a major increase in the diversity and size of bed and bank habitats and the highest lateral dynamics in response to a relatively modest natural input of large wood. These morphological changes induced by natural, untethered wood structures contrast well with the relatively limited morphological evolution of a few of the more open, emplaced and tethered, brash/branch structures where velocities during high flows appear to remain sufficient to restrict the retention and accumulation of sediments.
5. Natural tree fall and wood inputs in control reach A2 and consistent increases in the amount of wood and the number of fallen trees observed in many the treatment reaches (Figures 9 and 10), indicate the presence of an active natural wood cycle within the studied reach. Also, the responses observed in subreach A2 suggest that, if left unmanaged, this cycle has the potential to maintain the biogeomorphological interactions identified during the monitoring period and to amplify them as tethered wood decays and is replaced by fresh, moveable wood introduced naturally from the riparian woodland.

4.2 Careful design and monitoring of restoration need not be costly and can be extremely effective

Through the implementation of a simple yet comprehensive physical habitat monitoring method and observation programme, a robust scientific investigation of changes in response to restoration interventions has provided a valuable evidence base for lessons learned and future adaptive management. The data gathered using the MoRPh field survey have enabled an audit of activities and tracking of geomorphological responses from immediate post project ‘as built’ stages through early recovery. Thus, the approach presented here addresses a recognized widespread lack of data and monitoring, and the urgent ongoing need for evidence to inform future cost-effective restoration activities (England et al, 2021, Catchment Partnerships in London, 2020).

The opportunity to interrogate and compare rapidly-assimilated, standardized data across a diverse range of interventions plus an unrestored control site, provides an enormous depth of detail at both habitat patch and subreach scales, enabling both to be considered in relation to larger reach to sub-catchment contexts (Huggett and Shuttleworth, 2022)

In the present study, only very restricted aspects of hydrology and ecology are incorporated alongside the core biogeomorphological analysis. Furthermore, nothing is included on water chemistry, although indicators of geomorphic processes (erosion and deposition, and flow habitats) offer some potential for (a) inferring where internal channel functions may contribute towards local remediation or retention of pollutants; and (b) where integrated analysis of spatially and temporally coordinated data records may be possible over longer time scales. In the present case, limited resources prevented investigation of these aspects, although the urban nature of the catchment and the fact that gauged flows are significantly affected by treated effluent returns suggests a high likelihood of poor water quality.

A complementary collection of data and evidence of effluent inputs and sewage infrastructure misconnections could be most effectively captured by continuous monitoring devices (especially where diurnal patterns can be detected). Alternatively, where budgets are limited, coordinated citizen science campaigns to record dry weather outfall discharges (for example, the Outfall Safari methodology, Zoological Society of London, 2019) could provide powerful evidence to support dialogue with local water companies in relation to their own pollution investigations and remediation programmes. Alternative low budget methodologies using other simple citizen science methods could capture wet weather sources of urban or rural run-off containing fine sediments and associated particulate or chemical pollutants (for example, Mud Spotter, Modular River Survey, 2022). Such investigations could also be aligned with biological monitoring (e.g. macroinvertebrate information captured using the the UK-based citizen science, Anglers' Riverfly Monitoring Initiative (ARMI), Di Fore and Fitch, 2016) and extended monitoring of physical habitats to support stronger cases for remedial actions. Where reductions in pollution are achieved, such combined data would provide valuable exemplar case study material to support integrated action elsewhere in similar catchment contexts.

The limited spatial and temporal scales of the present restoration also reflect the lack of resources to extend investigations to the wider suburban catchment. However, a number of options exist that could extend similar studies within a restricted budget, including drawing upon more secondary sources of data, such as historical maps and time sequences of aerial images, or adopting rapid reconnaissance approaches, such as reach scale walkover surveys along accessible channel lengths.

Awareness of the value of citizen science-sourced data in delivering the objectives of river restoration and ecological recovery is increasing (e.g. Gurnell et al, 2019; Collins et al, 2020). This is especially relevant in situations where local volunteers can respond quickly and at short notice to gather standard scientific data, for example following sudden, significant environmental events (e.g. flash floods or pollution incidents). Engaging highly motivated and knowledgeable local volunteers in scientific data collection also helps to build stakeholder networks and lay-knowledge bases, including observed but unrecorded or photographic evidence built up over long term visits to local sites of interest.

Engaging local citizen scientists in structured monitoring activities using simple scientific methodologies can also open up opportunities for significant, wider legacy benefits such as involvement in monitoring and stewardship activities (as ‘river care’ maintenance or adaptive management). Where involvement incorporates co-design and co-creation of restoration interventions, as was achieved in the restoration of the Beverley Brook at Wimbledon Common, it provides ways to sustain engagement and build understanding of river recovery. Both expected and unexpected response trajectories can also build and reinforce a strong sense of ownership and motivation for continuing to observe, record and care for local river physical habitats and ecosystems.

5. CONCLUSION

Our study demonstrates the value of conducting sufficient preparatory work to develop a realistic vision and accompanying development trajectory to guide river restoration interventions and assess the success of the outcomes.

It also demonstrates that cost-effective data collection and analysis using the citizen science MoRPh field survey method and tools has revealed detailed information on the response of a river reach to restoration interventions. Analysis of this detailed information has allowed the responses of the river to restoration activities and natural events to be demonstrated in depth. Specifically, analysis has revealed the degree to which the restoration vision has been achieved, the rate at which it has been achieved, and the likely reasons why certain aspects of the vision have yet to be achieved.

The benefits of using a simple standardised accessible approach can also be extended through coordination with larger scale reconnaissance surveys or other low cost, citizen science monitoring campaigns, where complementary data on other aspects of the river environment are recorded at the same times and locations.

The longer term outlook for advancing evidence and knowledge of river restoration success or otherwise, will depend upon robust, rapid, low cost and easily accessible standard methods that can be used by non-specialists alongside professional practitioners. Most of all, where adaptive management needs are identified, the involvement of community-based volunteers in the process of recording and interpreting data on their local watercourses will be an essential part of collective decision making, understanding of geomorphological trajectories, and participation in appropriately defined stewardship activities.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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