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Published in:

Earth Surface Processes and Landforms

DOI:

[10.1002/esp.5453](https://doi.org/10.1002/esp.5453)

Publication date:

2022

Citation for published version (APA):

Gurnell, A. M., Hill, C. T., Davis, R. J., & Tooth, S. (2022). Trees, large wood and streams: Using archive survey data to inform changing interactions in a human-impacted landscape. *Earth Surface Processes and Landforms*. <https://doi.org/10.1002/esp.5453>

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RESEARCH ARTICLE

Trees, large wood and streams: Using archive survey data to inform changing interactions in a human-impacted landscape

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Abstract

Monitoring is the key to understanding fluvial systems and a crucial foundation for assessing the outcomes of river restoration. The New Forest, southern England, was designated a National Park in 2005 in recognition of its highly valued landscape, which has been both positively and negatively impacted by over 1000 years of human management. Here we analyse archive field maps and tabulations extracted from walkover surveys that record the distribution and character of wood jams along ~59 km of New Forest streams in 1991. By integrating the 1991 archive survey data with other historical information, we analyse associations among stream channel characteristics, wood jams, riparian land cover, and stream and land management at that time. We reveal associations among these factors that reflect the imprint of centuries of grazing, forestry and stream management practices. Along ~10 km of one stream (the Highland Water), we analyse data collected during additional walkover surveys in 1997 and 2021, to track changes since 1991. We illustrate how a reduction in stream and wood management over recent decades and the restoration of some stream reaches in 2005 has resulted in overall increases in stream sinuosity and the number of wood jams. The walkover surveys on which our results are based provide an approach to characterizing the impacts of river corridor management in the New Forest landscape that are both cost and time effective and could be applied by non-specialist volunteers ('citizen scientists') following appropriate training. Survey data of the spatial coverage achieved in 1991 are rare but need to be encouraged in the New Forest and farther afield to provide a robust framework into which more local, specialist surveys can be integrated, and from which the broad impacts of river corridor management approaches can be monitored.

KEYWORDS

citizen science, landscape management, large wood jams, lowland streams, New Forest National Park, stream management

1 | INTRODUCTION

Scientific research investigating the role of wood in river and stream ecosystems commenced in the 1970s. Much early work was conducted in the Pacific Northwest of the United States, focusing on forested catchments under native, mainly coniferous, tree species. Since then, research has investigated the hydrological, geomorphological and ecological roles of large wood within a wide variety of

forest types across the world in both semi-natural and managed contexts (Gurnell & Bertoldi, 2022; Swanson et al., 2021). Following the proposal of the river continuum concept (Sedell et al., 1989; Vannote et al., 1980), numerous field investigations have refined concepts of how trees and wood influence river channel and floodplain ecosystems. These include the floodplain large wood cycle hypothesis (Collins et al., 2012), the natural wood regime in rivers (Wohl et al., 2019), and proposals regarding how these natural

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dynamics are disrupted by human actions (Collins et al., 2012; Scott & Wohl, 2018).

The impacts of humans on river systems have become more intense, varied and widespread during the Anthropocene (Brown et al., 2017; Downs & Piégay, 2019). Wohl (2014, 2019) discusses the legacy effects of human alterations of river corridors, including manipulation of large wood. She stresses the importance of recognizing the existence, nature, timing and spatial distribution of human alterations, as well as natural processes, on river-floodplain morphodynamics, to inform river restoration design.

Recently, Gurnell and Hill (2021) presented a multi-scale investigation of the legacy effects of human activities on stream environments in the New Forest, southern England. Their study revealed both positive and negative impacts of humans on this sensitive, predominantly wooded landscape, which has been subject to a variety of land and river management practices for over 1000 years. In particular, an historical analysis of a ~10 km reach of the Highland Water revealed the negative effects of historical woodland and channel management practices, and the recovery of a stream section restored in 2005.

In this article, we further investigate tree-wood-management interactions in the New Forest, focusing on the stream network (i.e., channels typically < 10 m wide, though predominantly < 5 m) of the wider Lymington River catchment in which the Highland Water reach is located (Figure 1). We revisit a walkover survey of ~66 km of streams conducted in 1991, which was previously analysed by Gregory et al. (1993) to identify spatial patterns in the load of large wood ($\text{kg}\cdot\text{m}^{-2}$ channel area) retained in the streams. The 1991 survey has not been repeated in full in subsequent years, but as an example of the potential information that could be revealed from analysis of repeat surveys, we have extracted the same set of variables collected in 1991 from surveys of ~10 km of the Highland Water undertaken in 1997 and 2021 (Gurnell & Hill, 2021). The straightforward nature of the surveys allows us to consider the potential of additional surveys

being repeated by river scientists as well as by volunteers ('citizen scientists') following appropriate training. In the New Forest and other locations, such a 'crowd-sourcing' approach (e.g., Gurnell et al., 2019; Shuker et al., 2017) would allow much larger areas to be surveyed than would otherwise be possible in a cost- and time-effective manner, with the repeat surveys potentially identifying responses to changing river corridor management practices.

Analysis of remotely-sensed data is increasingly reducing the need for traditional ground surveys (Tomsett & Leyland, 2019), but this is not always a solution for all environments and survey types. Airborne remote sensing approaches have been devised to monitor changes in wood retention in rivers, particularly the analysis of LiDAR (light detection and ranging) data (e.g., Abalharth et al., 2015; Atha & Dietrich, 2016). However, such approaches are not currently viable on the small, lowland streams investigated here, which are < 10 m wide and are usually overhung by a dense tree canopy. Furthermore, even if wood accumulations could be identified by such means, additional ground survey would be needed to distinguish between different large wood jam types and/or fallen trees (Figure 2), many of which are associated with distinctive physical habitat assemblages and dynamics (Gregory et al., 1985).

In this article we analyse the aforementioned field-survey data sets to address the following specific aims:

- i. To use the areally extensive 1991 surveys and related archive data to examine inter-relationships and interactions among the characteristics of the predominantly single-thread surveyed stream channels, the number and types of wood accumulations and fallen trees, and the nature and management of riparian land cover in the New Forest at that time.
- ii. To compare data extracted from repeat surveys of the Highland Water in 1997 and 2021 to illustrate spatial and temporal trends in stream channel characteristics, wood jams and fallen trees, and

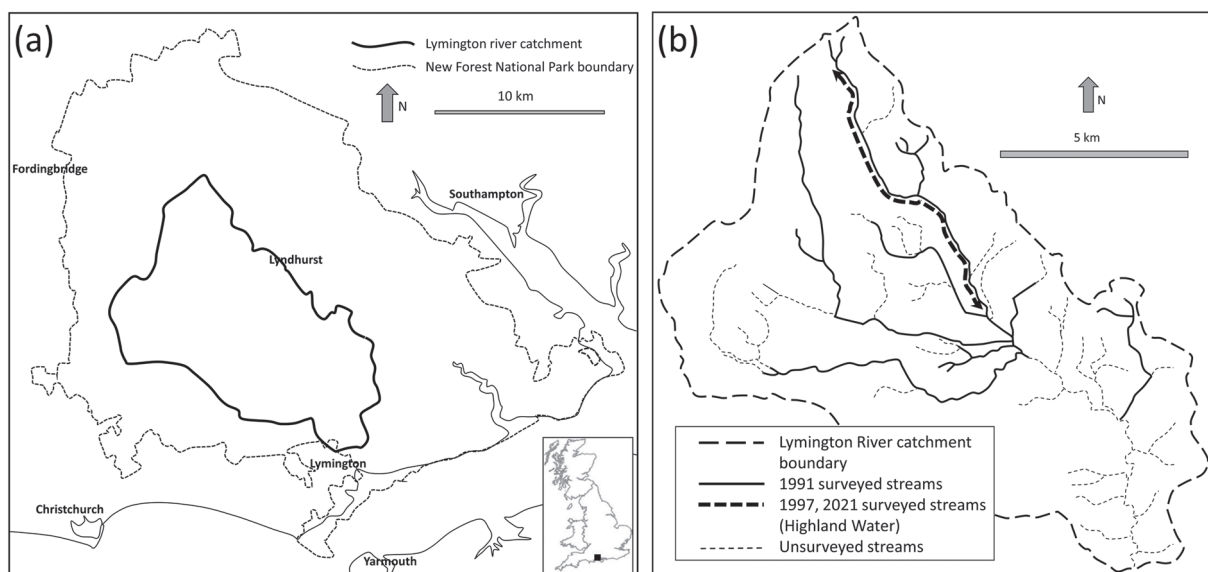


FIGURE 1 (a) Location of the Lymington River catchment within the New Forest in southern England. (b) Locations of the surveyed streams within the Lymington River catchment (127 reaches) that were surveyed in 1991 and within the Highland Water (22 reaches) that were resurveyed in 1997 and 2021. Unsurveyed streams are those that either were not included in the original 1991 survey (i.e., ephemeral headwater streams, streams draining catchments lacking woodland, streams where access was not possible), or were parts of the 6.7 km stream length for which original maps and tables from 1991 are no longer available.



FIGURE 2 Examples of the four wood jam types that were mapped. (a) Active (note the higher upstream (left) than downstream (right) water level), (b) Complete, (c) Partial, (d) High. All photographs by A.M. Gurnell

so identify the impacts of changing riparian land cover and stream management practices.

- iii. To discuss how our findings support and extend previous research regarding trees, large wood and streams, and how walk-over surveys could provide a broad scale framework for monitoring streams and their responses to changing river corridor management practices.

2 | THE STUDY AREA

The study area within the New Forest, southern England, is the second most densely populated National Park in England after the South Downs (63 people per km²). Gurnell and Hill (2021) reviewed the landscape character and management of the New Forest that is relevant to its stream systems. We summarise their findings in this section.

The New Forest is underlain by Eocene deposits of the Bagshot gravels and sands, the Barton sands and clays, and in the south by the Headon marls. Locally, these are overlain by Pleistocene river gravels. The New Forest landscape is gently undulating with abundant peat accumulations forming valley and hillslope mires. Streams generally have gravel and finer bed materials with some local exposures of clay.

The New Forest was subject to land clearance for agriculture and settlement long before it was established as a hunting forest by King William in 1079 CE. Since then, in addition to hunting, the land has been used continuously to the present by 'commoners' (i.e., persons with rights of commons; Short, 2008) for grazing their animals but also in past centuries for the collection of wood and peat for fuel.

Woodland is a characteristic feature of the landscape, and includes both natural and planted stands. Planting trees to produce timber commenced in the 17th century and the plantations were usually fenced to exclude grazing animals. In 1877, the New Forest Act formally permitted 'the Crown' to enclose (fence off from grazing) a maximum fixed area of land for timber production (Statutory Inclosures), formalizing a complex mosaic of land cover and management that persists to the present with open (unenclosed) grazed areas referred to as 'Open Forest'.

The Inclosures were planted initially with native deciduous hardwood species, particularly beech and oak, but from the 1930s, commercial, predominantly non-native, conifer species were also planted. Over the same timeframe, a mix of heathland, grassland ('lawns') and 'ancient and ornamental woodland' containing predominantly native, deciduous, hardwood species have persisted within the Open Forest, including water-related habitats such as wet woodland and carr woodland adjacent to valley mires (Grant & Edwards, 2008). The land cover mosaic in the Open Forest is maintained by grazing by wildlife (e.g., deer) and the animals of 'commoners', particularly by cattle and horses.

Over the last two centuries, deliberate human interventions in the streams of the New Forest have expanded dramatically. Initially, these interventions were aimed at 'improving' land drainage. In Inclosures, drainage schemes were especially widespread. Streams were frequently realigned (straightened), re-sectioned (deepened) and networks of feeder drains were often cut prior to planting single species stands of trees up to the stream channel margins. In the Open Forest, many valley mires and lawns were also subject to drainage schemes to improve grazing.

Over the last ~30 years, however, drainage schemes have given way to stream and wetland restoration programmes. The latter have intensified since the designation of the New Forest as a National Park in 2005. Our spatially extensive 1991 survey, and the more focused 1997 and 2021 Highland Water surveys, thus collectively span a period during which there was a move away from fallen tree and wood jam management and a move towards restoring streams back to a more natural form. In 1991 there had been no stream restorations and the main direct human impacts on streams were related to drainage 'improvements' and indirect impacts from forestry operations. Following a severe wind storm in 1987 and a lesser storm in 1989 that caused widespread tree fall, there had been clearance of many of the largest trees that had fallen across or into New Forest streams. This added to a history of removing or reducing the size of some of the largest wood jams to improve flow conveyance by the stream network. The 1991 survey, and to some extent the 1997 survey, record the character of New Forest streams at the end of this accumulated management history. In 2005, two of the surveyed reaches of the Highland Water were subject to a major restoration involving: (i) clearance of a non-native conifer plantation on the floodplain-stream margins that had been planted c. 1960; (ii) leaving any native deciduous trees that were present on the floodplain-stream margins; (iii) returning the straight, incised stream channel that had been cut c. 1960 to accompany planting of conifers to its previous sinuous course; and (iv) adding gravel to the channel to raise its bed to the level that existed prior to straightening and incision. A further four reaches that had been straightened in the early 19th century to accompany planting of native deciduous trees continued to recover from this intervention, aided by some addition of wood in 2005. Along with the 1997 survey, the 2021 survey provides insight into how 22 reaches of the Highland Water have responded over the last 30 years to channel straightening in six reaches, two of which were restored in 2005, as well as providing evidence of changes in 16 other relatively naturally-functioning reaches.

3 | METHODS

3.1 | Wood jam types

Our analysis of the changing interactions between trees, large wood and streams is based on the separation of wood accumulations into active, complete, partial and high types. These wood jam types are widely observed in small, lowland streams and rivers (Gregory et al., 1985) and have different hydraulic impacts (Figure 2). Active jams (Figure 2a) extend across the entire stream bed width, are in contact with the bed and are sufficiently water-tight to induce an upstream to downstream step in the stream water surface at all flow stages. Complete jams (Figure 2b) extend across the entire bed width, are in contact with the bed, but are sufficiently open, leaky structures that water flows freely through them at low flow. Partial jams (Figure 2c) are large wood accumulations that are in contact with the stream bed but do not extend across the entire bed width. High jams (Figure 2d) extend across the channel width but are suspended above the bed. They are usually composed of fallen trees and associated trapped wood pieces that extend from one bank face to the opposite

bank top or from one bank top to the other. They only make contact with stream flows when the water is sufficiently deep to fill the area under the jam. To qualify as a high jam, the contact water depth must be less than or equal to the bankfull channel depth (see Figure 2d). Fallen trees are those that span streams but remain suspended above the bank full level, supported by other trees or by their branches.

3.2 | Extracting a data set for analysis from the 1991 archive materials

The 1991 survey maps locate the end points of reaches (~500 m length) used in the original analysis (Gregory et al., 1993) and indicate the locations of active, complete, partial and high wood jams and fallen trees. In places, the maps are annotated to indicate stream channel width, land cover types, and contemporary management actions. Despite the 30 year gap since they carried out the field surveys, two of the co-authors of this article (RJD and ST) were able to provide clarifications that helped to assemble and interpret the data analysed in this article.

In the present analysis, the end points of the original ~500 m stream reaches were retained. The numbers and types of wood jams and the numbers of fallen trees in each of the reaches were extracted from the maps, as was information on potential controlling factors on wood input/retention within each reach including channel characteristics, proportions of channel margins that were within an Inclosure, and proportions of channel margins that were under five land cover-management types (Table 1). Although our core data came from the original survey maps, wherever possible cross-checks were made using other data sources. The reach centre-line length and straight-line length (i.e., straight line length between the upstream and downstream ends of the reach), which were used to estimate sinuosity, were measured from 1:2500 scale Ordnance Survey maps dating to around 1960, with adjustments to the 1991 channel positions (mainly straightening) based on information from the 1991 survey. Land cover information was derived from a combination of annotations on the survey maps, Ordnance Survey 1:2500 maps, and Google Earth images (particularly imagery from 1999 and 2000). The Google Earth images were particularly useful sources for corroborating likely tree age classes around the time of the 1991 survey based on the size of tree crowns.

3.3 | Extracting a data set from the 1997 and 2021 surveys of the Highland Water

The start and end points of the ~100 m long 1997 and 2021 survey reaches of the Highland Water were cross-matched to the ~500 m long reaches mapped in 1991 so that information from the 1997 and 2021 surveys could be aggregated and compared to the longer 1991 survey reaches. Although a perfect match was not always possible, each ~100 m reach was assigned to the 1991 - 500 m reach with which there was the greatest overlap, with mismatches estimated to be < ~25 m over a ~500 m long reach. Relevant data were then extracted from the 1997 and 2021 surveys to reproduce the set of variables captured in 1991.

TABLE 1 Variables quantified for each of 127 stream reaches included in the 1991 survey

Variable name	Units and explanation
<i>Channel dimensions</i>	
Reach (centre-line) length (m)	The length (in metres) of the channel centre-line measured from 1:2500 scale Ordnance Survey maps (approximate field survey date – 1960) with corrections for any major changes (mainly channel realignments) to match the 1991 survey date.
Reach (start to end point straight line) length (m)	The straight-line length (in metres) between the upstream-downstream 500 m reach end points.
Distance from source	Cumulative channel centre-line length (in metres) from the stream source.
Sinuosity	Channel length/reach length
<i>Wood jams and fallen trees</i>	
Active jams	Number of active jams recorded in each reach expressed as active jams per 500 m reach (centre-line) length.
Complete jams	Number of complete jams recorded in each reach expressed as complete jams per 500 m reach (centre-line) length.
Partial jams	Number of partial jams recorded in each reach expressed as partial jams per 500 m reach (centre-line) length.
High jams	Number of high jams recorded in each reach expressed as high jams per 500 m reach (centre-line) length.
Fallen trees	Number of fallen non-interacting trees recorded in each reach expressed as fallen trees per 500 m reach (centre-line) length.
<i>Land cover-management of stream bank tops</i> (estimated for the time of field survey from archive notes, 1:2500 scale Ordnance Survey maps and aerial images, particularly Google Earth images dated 1999 and 2000)	
Inclosure	Proportion of bank tops within an Inclosure.
Deciduous woodland	Proportion of bank tops under deciduous woodland at the time of survey.
Deciduous age class	Age class in 1991 estimated from archive notes and dominant/typical tree crown size on 1999/2000 aerial images (0 – no deciduous woodland, 1 – < c. 20 years, 2 – c. 20–80 years, 3 – > c. 80 years).
Coniferous woodland	Proportion of bank tops under coniferous woodland
Coniferous age class	Age class in 1991 estimated from archive notes and dominant/typical tree crown size on 1999/2000 aerial images (0 – no coniferous woodland, 1 – < c. 20 years, 2 – c. 20–80 years, 3 – > c. 80 years).
Felled	Proportion of bank tops where woodland was recently felled.
Heath-scrub-lawn-mire	Proportion of bank tops under heath-scrub-lawn-mire with limited tree cover.
Fields-gardens	Proportion of bank tops occupied by fields or gardens.

3.4 | Data analysis

The channel centre line lengths extracted from 1:2500 Ordnance Survey maps and, where necessary, corrected for known differences due to channelization/restoration of channel planform at each survey date, were used to adjust the observed wood jam and fallen tree numbers to a standard 500 m reach (centre-line) length (Table 1) prior to further analysis.

All data analyses were conducted using XLSTAT version 2020.5.1.1079 (Addinsoft, 2021). Inter-relationships among the assembled variables from the 1991 survey were explored through scatter plots, cumulative line plots, correlation analyses, and principal components analysis (PCA) of sets of variables selected from those listed in Table 1.

PCA estimates new uncorrelated variables (principal components, PCs), which are linear combinations of the original variables and which sequentially maximize the variance in the original data set that each PC explains. PC biplots, where variable vectors and reach scores are plotted in relation to axes representing two of the PCs, allow the relative importance (vector lengths) and associations (proximity of vectors) among the variables to be observed. PC biplots also reveal the degree to which different reaches show similar characteristics in relation to the proximity of their scores (plotting positions) to specific variable vectors and with respect to the PCs. Jolliffe and Cadima (2016)

provide a recent overview of this analysis technique. In short, PCA reveals broad associations among the variables (channel characteristics, wood jams, fallen trees, adjacent land cover-management) at the time of the 1991 survey and also broad groupings of the 127 reaches according to their PC scores and proximity to variable vectors.

Temporal changes were explored by adding the 1997 and 2021 survey data for 22 reaches of the Highland Water to the 1991 data set and repeating the PCA on this enlarged data set. This analysis allowed any temporal changes in scores of the Highland Water reaches on the PCs to be tracked from 1991 to 1997 and to 2021 across PC biplots as well as highlighting spatial differences in plotting positions of sections (groups of reaches) affected by different land cover-management. Bar graphs were then constructed to represent the changing temporal PC scores of each Highland Water reach from upstream to downstream on each of PC1, PC2 and PC3. These graphs were examined for evidence of both temporal (1991, 1997, 2021) and spatial (upstream to downstream) trends in reach PC scores. They were also examined for further evidence of contrasting temporal and spatial patterns in the PC scores within sections of the Highland Water that had been the subject of different land cover-management. The statistical significance of changes in the PC scores across the Highland Water reaches between monitoring years was tested using paired *t* tests. Finally, the wood jam data alone were considered. The total number of wood jams and the number recorded as active,

complete, partial or high per 500 m reach (centre-line) length in each of the 22 reaches in 1991, 1997 and 2021 were investigated using line plots and cumulative relative frequency distributions.

4 | RESULTS

4.1 | Data description

From the 1991 survey, data were extracted for 127 reaches of the original 138 surveyed (Figure 1b), covering a total of ~59 km stream length. Original survey data were not available for 11 of the reaches.

In some places on the survey maps, measurements of channel width had been noted, indicating a median channel width of 2.8 m and a range from < 1 m to ~10 m. Descriptive statistics for the continuous variables where information was available for all reaches (Table 2) show that although the median reach (centre-line) length was 500 m, there was considerable variability around this length. This results from the inclusion of a number of shorter or longer reaches (all < 1 km long) – for instance, as related to the entirety of short headwater tributary streams, the final stream reaches above tributary confluences, and some small deviations from 500 m that were identified when the channel (centre-line) lengths were measured from Ordnance Survey 1:2500 scale maps to support the present analysis. Channel sinuosity [i.e., reach (centre-line) length divided by reach (start to end point straight line) length] varied from straight (1) to sinuous (close to 2). High spatial variability in wood jam frequency, land cover and management is revealed by the descriptive statistics (Table 2) but the surveyed reaches contained a total of 746 wood jams (114 active, 305 complete, 262 partial and 67 high) and 212 fallen trees. Of the total surveyed bank length, 49% was within an Inclosure, 59% was under deciduous woodland, 18% was under coniferous woodland, 4% was along recently felled woodland, 18% was bordered by heath-scrub-lawn-mire and 1% was bordered by field-garden land cover.

Data were also extracted from the 1997 and 2021 surveys of the Highland Water that contained 22 of the original 1991 surveyed reaches (Figure 1b). These data were combined with the 1991 data set to enable temporal and spatial trends to be identified. These 22 reaches represent streams whose distance from source at their downstream end ranges from ~1.6 to 12.3 km, and sinuosity ranges from 1.1 to 1.9. The reaches can be grouped from upstream to downstream into seven sections (section A through to section G). All these sections are under mature deciduous woodland apart from section C, which was restored in 2005. In the 1991 and 1997 surveys, section C crossed a coniferous plantation, but conifers on the stream banks and floodplain were felled in 2005 to allow the recovery of native deciduous woodland. Section A (incorporating two reaches) drains an Inclosure but the stream and surrounding deciduous woodland appear relatively natural with no obvious evidence of woodland or stream management. Section B (four reaches) is in the Open Forest. Sections C, D and E (two, one and four reaches, respectively) are all located in Inclosures. Section D is highly sinuous (sinuosity in 2021 was 1.9) and is bordered mainly by deciduous trees but with some patches of conifers. Section E was straightened in the early 19th century and drains a deciduous plantation. Sections F and G (five and four reaches, respectively) are in the Open Forest, and are separated by a major road crossing that likely disrupts downstream passage of water, sediment and wood. In 1991, 1997 and 2021, the 22 reaches contained a total of 173, 481 and 563 wood jams, with the breakdown for the three survey dates as follows: active jams (37, 31, 71), complete jams (37, 47, 112), partial jams (80, 276, 175), high jams (19, 127, 205). Of the remaining variables, distance from source was deliberately retained unchanged across survey dates as a surrogate for catchment/channel size. There was a small increase in average sinuosity (1991 – 1.30, 2021 – 1.48) across all 22 reaches, with increases observed in all sections A–G. Small average increases (≤ 0.1) were observed between 1991 and 2021 in sections A, B and F. Restored section C showed the largest increase (from 1.06 to 1.62), followed by

TABLE 2 Descriptive statistics for the measured variables (Table 1, excluding deciduous and coniferous age class variables) across 127 reaches of the Lymington stream network included in the 1991 survey

Variable name (units)	Median	Mean	Standard deviation	Minimum	Maximum
Reach (centre-line) length (m)	500	466	113	100	731
Reach (start to end point straight line) length (m)	421	403	108	100	724
Distance from source (m)	4576	5922	4627	220	15778
Sinuosity	1.12	1.17	0.17	1.00	1.97
Active jams (number/500 m) ^a	0.00	1.18	2.80	0.00	25.89
Complete jams (number/500 m) ^a	1.84	2.98	4.11	0.00	28.48
Partial jams (number/500 m) ^a	1.17	2.26	2.47	0.00	12.79
High jams (number/500 m) ^a	0.00	0.66	1.49	0.00	12.79
Fallen trees (number/500 m) ^a	1.00	1.84	2.77	0.00	21.19
Inclosure (proportion of bank length)	0.50	0.50	0.49	0.00	1.00
Deciduous woodland (proportion of bank length)	0.60	0.59	0.39	0.00	1.00
Coniferous woodland (proportion of bank length)	0.00	0.19	0.31	0.00	1.00
Felled (proportion of bank length)	0.00	0.04	0.12	0.00	0.60
Heath-scrub-lawn-mire (proportion of bank length)	0.00	0.18	0.32	0.00	1.00
Fields-gardens (proportion of bank length)	0.00	0.01	0.06	0.00	0.60

^a500 m refers to 'reach (centre-line) length'.

section D (from 1.32 to 1.91), section G (from 1.20 to 1.41) and straightened section E (from 1.07 to 1.17). There was no (recent) felling recorded and no change in the proportions of reach margins within Inclosures or under woodland, heath-scrub-lawn-mire, or fields-gardens. There was also no change in reach woodland type (all predominantly deciduous) and age class (mainly age class 3, occasionally age class 2, Table 1), apart from section C (reaches 7 and 8) where the woodland cover changed from coniferous woodland (age class 2) in 1991 and 1997 to deciduous woodland (age class 1) in 2021. Lastly, during the period from 1991 to 2021 there were no major wind storms equivalent to those in 1987 and 1989 that could have caused notable inputs of wood and fallen trees to the river system.

4.2 | Analysis of the 1991 data set

In addition to the two categorical variables (deciduous age class, coniferous age class), descriptive statistics for the continuous variables extracted from the 1991 archive materials (Table 2) illustrate that none were normally distributed. Therefore, all statistical analyses used non-parametric methods.

Two channel characteristics were considered for inclusion in an analysis of the potential controls on wood retention in lowland streams: distance from source and sinuosity. Distance from source provides a surrogate for catchment area and thus likely river flows, and also channel size, the latter being a key influence on a channel's

TABLE 3 Spearman's rank correlation coefficients estimated between pairs of variables indicative of (a) channel dimensions; (b) wood jams and fallen trees; (c) land cover and management (all variables selected from and expressed in the units listed in Table 2 and derived from 1991 survey data for 127 reaches of the Lymington stream network)

(a) Channel dimension variables					Sinuosity	
Distance from source					0.179*	
(b) Wood jam and fallen tree variables		Complete jams	Partial jams	High jams	Fallen trees	
Active jams		0.359***	0.197*	0.285***	0.180*	
Complete jams			0.209*	0.257**	0.268**	
Partial jams				0.376***	0.157 ^{ns}	
High jams					0.262 ^{ns}	
(c) Land cover and management variables		Deciduous woodland	Coniferous woodland	Felled	Heath-scrub-lawn-mire	Fields-gardens
Inclosure		-0.125 ^{ns}	0.536***	0.129 ^{ns}	-0.369***	0.003 ^{ns}
Deciduous woodland			-0.559***	-0.229**	-0.530***	-0.018 ^{ns}
Coniferous woodland				0.122 ^{ns}	-0.246**	-0.126 ^{ns}
Felled					-0.090 ^{ns}	0.107 ^{ns}
Heath-scrub-lawn-mire						-0.118 ^{ns}

The results of testing the null hypothesis that there is no correlation in the underlying population are indicated as follows: ^{ns}not significant, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

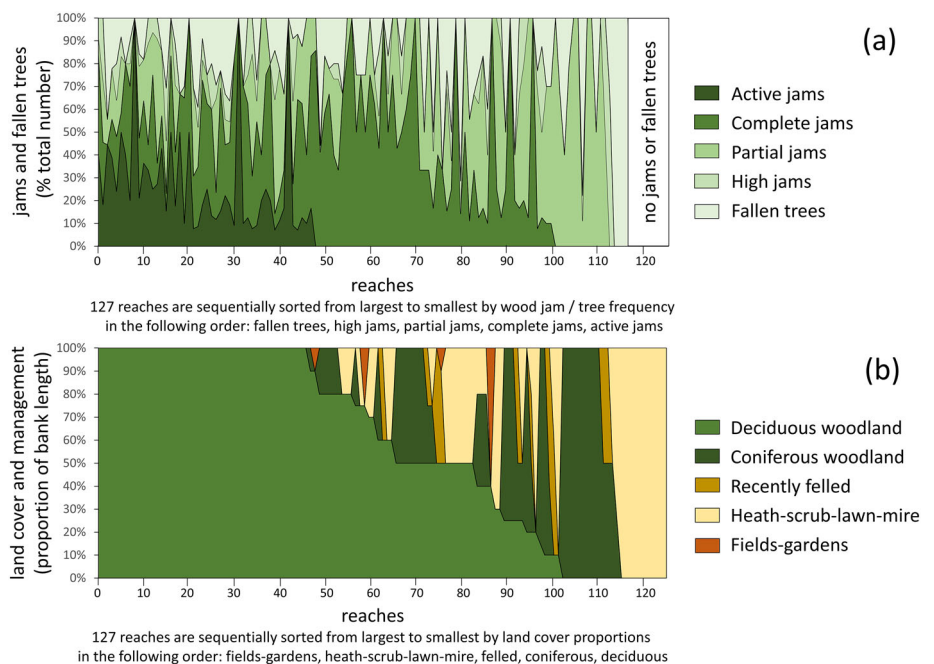


FIGURE 3 Cumulative line graphs showing (a) the percentage of the wood jam types and fallen trees within each individual reach following sorting of the reaches in the order: fallen trees, high jams, partial jams, complete jams, active jams, (b) the proportion of the channel margins under different land cover types within each individual reach following sorting of the reaches in the order: fields-gardens, heath-scrub-lawn-mire, recently felled, coniferous woodland, deciduous woodland.

ability to retain wood. Direct measurements of channel size were not included in the analysis as measurements were not available for all of the reaches. Planform sinuosity also influences a channel's ability to snag and retain large wood but sinuosity shows only a weak association with distance from source (Table 3) and so provides additional information as a second channel dimension variable for integrative analysis.

The 1991 archive materials provide data sets regarding the types and frequencies of wood jams and fallen trees retained by the surveyed streams, and also the extent of different types of marginal land cover management. These two data sets were separately sorted before being summarized in cumulative line plots (Figure 3) to give an impression of both variability and trends across the surveyed reaches. In the case of wood jams and fallen trees (Figure 3a), the data were sequentially sorted in order of likely hydraulic influence from least to most: the number of fallen trees, high jams, partial jams, complete jams, and active jams as a percentage of the total number within each reach. Figure 3(a) reveals that several reaches contained no jams or fallen trees or a restricted range of jam types. Those reaches that supported the highest numbers of the most hydraulically-impactful active jams also typically supported all of the other jam types. In the case of land cover (Figure 3b), the data were sequentially sorted in order of likely inputs of large wood from least to most likely: proportion of the reach bank tops under fields-gardens, heath-scrub-lawn-mire, recently felled, coniferous woodland, and deciduous woodland along the margins of each reach. The cumulative line plot (Figure 3b) shows the dominance of deciduous woodland in the data set, which if mature and unmanaged is likely to input the largest, most irregularly-shaped and thus most readily retained large wood pieces. Significant lengths of stream margin were under coniferous woodland in reaches where deciduous woodland was also observed, but there were also reaches which were entirely bordered by coniferous woodland or by heath-scrub-lawn-mire.

Rank correlations among the groups of variables describing wood jams and fallen trees (Table 3) reveal that all of the jam types are significantly positively correlated with one another, with active, complete and high jams being most strongly correlated. Fallen trees are significantly positively correlated with active and complete jams. Rank correlations among the group of variables describing land cover and management (Table 3) reveal that coniferous woodland is highly-significantly positively correlated with Inclosures, whereas deciduous woodland is significantly negatively correlated with recently felled areas. As would be expected for the three main land cover types and the proportional measures used, deciduous woodland, coniferous woodland and heath-scrub-lawn-mire are all significantly negatively correlated (Table 3).

Given the strong inter-correlations among the measured variables, PCA was used to reduce the dimensionality of the data set and to identify the broad gradients and inter-relationships within it. PCA was applied to all the variables listed in Table 3, and to the estimated age classes for the deciduous and coniferous woodland (Table 1). Variables reach (centre-line) length and reach (start to end point straight line) length (listed in Tables 1 and 2) were excluded because their ratio is used to calculate sinuosity, which is included. The eigenvalues, variance explained and variable loadings for the first four PCs (all those whose eigenvalues exceed 1) are presented in Table 4. The variable loadings and reach scores on PC1 to PC3 are presented in Figure 4.

TABLE 4 Eigenvalues, variance explained, and variable loadings on the first four components of a principal components analysis (PCA) of a set of 15 channel dimension, wood jam/fallen tree, and landcover and management variables observed in 1991 within 127 reaches of the Lymington stream network [note that variable loadings on each principal component (PC) that are larger than 0.7 are set as bold and loadings between 0.6 and 0.7 are set as bold and italicized]

	PC1	PC2	PC3	PC4
Eigenvalue	3.270	2.883	1.723	1.236
Variability (%)	21.8	19.2	11.5	8.2
Cumulative (%)	21.8	41.0	52.5	60.7
<i>PC loadings</i>				
Distance from source	-0.508	0.025	-0.661	0.230
Sinuosity	-0.382	-0.272	-0.210	-0.269
Active jams	-0.071	-0.417	0.663	-0.064
Complete jams	0.138	-0.569	0.382	0.000
Partial jams	-0.319	-0.572	-0.116	0.063
High jams	-0.123	-0.526	0.340	0.311
Fallen trees	0.188	-0.613	0.058	-0.111
Inclosure	0.547	-0.506	-0.107	0.084
Deciduous woodland	-0.797	-0.375	-0.151	-0.137
Coniferous woodland	0.849	-0.294	-0.311	-0.121
Felled	0.245	-0.170	0.110	0.546
Heath-scrub-lawn-mire	0.111	0.706	0.504	-0.058
Fields-gardens	-0.124	0.000	-0.072	0.781
Deciduous age class	-0.571	-0.468	0.093	-0.169
Coniferous age class	0.788	-0.318	-0.335	-0.115

The variables with the strongest loadings on PC1 (Table 4, bold numbers) indicate that this component describes a gradient of increasing coniferous woodland cover and age and decreasing deciduous woodland cover. PC2 describes a gradient of decreasing fallen trees and increasing heath-scrub-lawn-mire cover. PC3 describes a gradient of decreasing distance from source and increasing numbers of active wood jams. These three PCs explain over half (52.5%) of the variance in the data set. PC4 has a high loading on fields-gardens but the eigenvalue for this PC is only slightly larger than 1 and this land cover type is only present along a very small length (1%) of the surveyed channels (Figure 3b, Table 2), so this component was not considered further.

The variable vectors on the PC1-PC2 biplot (Figure 4a) separate heath-scrub-lawn (upper half of the plot) from the two woodland types, wood jams and fallen trees (lower half of the plot). The coniferous woodland vector is closely associated with (plots close to) the Inclosure vector. The deciduous woodland vector is located close to the sinuosity vector; partial jams, active and high jams plot closer to deciduous than coniferous woodland; and complete jams and fallen tree vectors are positioned roughly equidistant between the two woodland types. The proximity of the distance from source vector to the deciduous woodland vector suggests that the latter, particularly older age classes, may be observed more with increasing distance from the stream source.

The PC1-PC3 biplot (Figure 4b) illustrates a strong inverse association between distance from source and active, complete and high wood jams, with the latter increasing in number towards a stream's

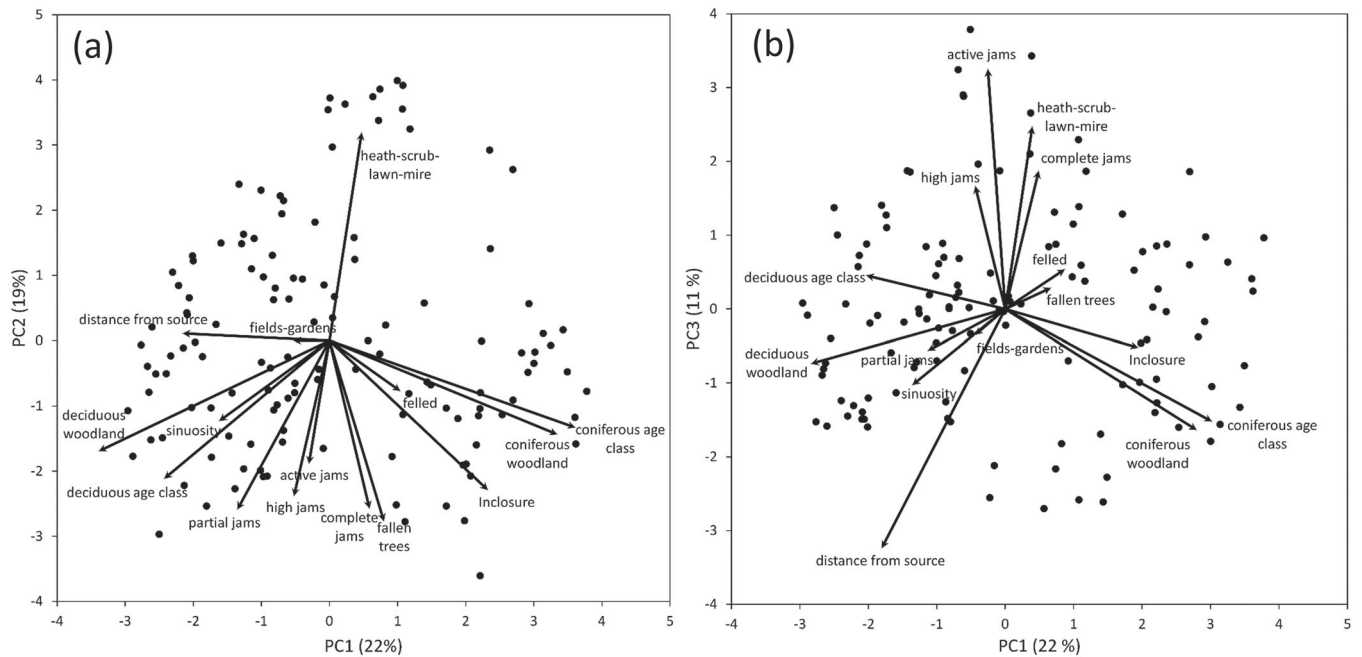


FIGURE 4 Variable loadings and reach scores on (a) PC1 and PC2 and (b) PC1 and PC3 of a PCA performed on a Spearman's rank correlation matrix of associations among jams and fallen trees, channel dimension and river margin land cover. Data were derived from 127 stream reaches of the Lymington catchment stream network included in the 1991 survey.

source (i.e., along smaller headwater channels). The biplot also shows an inverse association between distance from source and heath-scrub-lawn-mire land cover, suggesting an increase of this cover type along headwater channels.

4.3 | Analysis of the combined 1991, 1997 and 2021 data sets

PCA was also applied to an enlarged data set that incorporated 1997 and 2021 data for 22 reaches of the Highland Water in addition to the full 1991 data set for the Lymington River stream network. Despite the addition of 44 observations for Highland Water reaches in 1997 and 2021, this analysis gave very similar results (Figure 5a,b) to the PCA on the 1991 data alone (Figure 4a,b). When compared with the PCA on the 1991 data set alone, the orientation of the variable vectors has rotated on the biplots with respect to PC1 to PC3 (Figure 5a,b). However, the relative position of the variable vectors remains largely unchanged, particularly in relation to PC1 and PC2, such that the associations among the analysed variables in the 1991 data set remain largely unchanged.

The scores on PC1, PC2 and PC3 for the 22 Highland Water reaches in 1991, 1997 and 2021 are presented in Figure 5(c,d) (note the correspondence of the graphed areas with the grey shaded areas of Figure 5a,b), capturing both spatial and temporal changes. In relation to spatial patterns, the circles representing all three observations (1991, 1997, 2021) on the 22 reaches (66 observations in total) are colour coded according to the stream section in which each reach is located (sections A, B, C, D, E, F and G). There is a general downstream increase in scores on PC1 and a downstream decrease in scores on PC2 and PC3 through the more naturally-functioning sections A, B, F and G (white through grey to black circles). The reach in section D (green circles) is located between the heavily managed

sections C (yellow circles) and E (orange circles) and the more naturally functioning sections A, B, F and G. Straightened section E tends to have distinctly lower scores on PC1 than all other sections apart from section C.

In relation to temporal changes, the arrows in Figure 5(c,d) indicate how PC1 scores for the two reaches in section C shift from being closely associated with the coniferous woodland vectors in 1991 and 1997 to being associated with the deciduous woodland vectors in 2021. Temporal changes in all reach scores on PC1, PC2 and PC3 are illustrated in Figure 6. Scores on PC1 to PC3 tend to show a progressive increase through time within most of the 22 reaches. Figure 6 also reveals spatial changes in reach scores across the seven sections. More naturally-functioning reaches in sections A, B, F and G score higher than sections C, D and E on PC1 but otherwise there is no obvious downstream trend. Sections A, B, E, F and G tend to show an overall downstream decrease in scores on PC2, with reaches C and possibly D showing anomalously high scores relative to their position in the downstream sequence. Sections A, B, F and G show a downstream decrease in scores on PC3 with section C, in particular, showing anomalously low scores relative to its position in the downstream sequence.

To assess the statistical significance of the apparent overall temporal changes across all of the 22 Highland Water reaches, paired *t* tests were used to compare scores on PC1, PC2 and PC3 for 1991 and 1997, and also for 1997 and 2021. The average PC scores across all reaches in 1991, 1997 and 2021 were as follows: for PC1, 1.055, 1.657 and 2.304, respectively; for PC2, -0.272, 0.348, 0.742, respectively; and for PC3, -0.367, -0.389, 0.239, respectively. Paired *t* tests revealed statistically significant changes in PC scores for PC1 between 1991 and 1997 ($p < 0.001$) and between 1997 and 2021 ($p = 0.007$) and for PC2 between 1991 and 1997 ($p < 0.001$) and between 1997 and 2021 ($p = 0.220$). For PC3, however, a statistically significant change only occurred between 1997 and 2021 ($p < 0.001$).

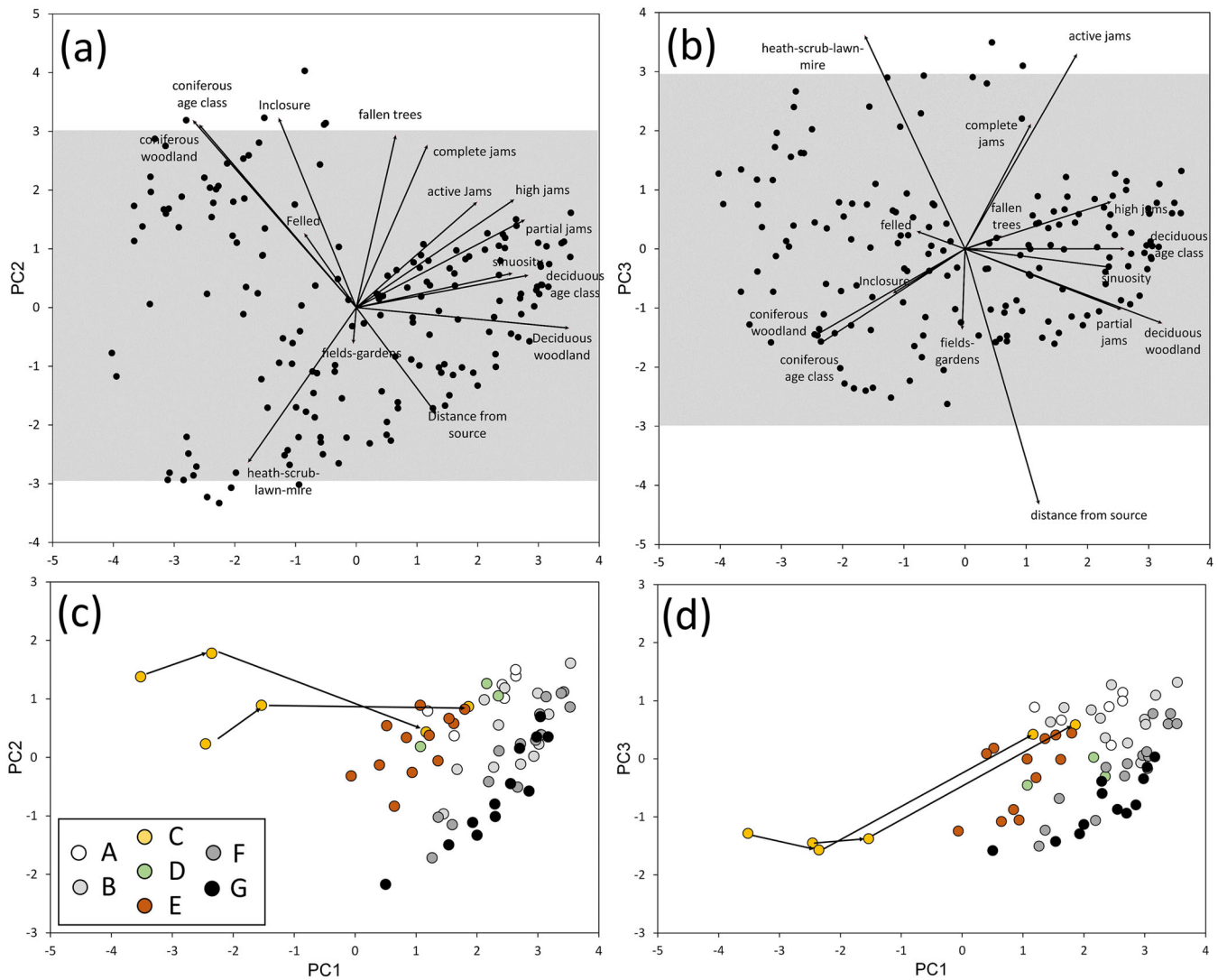
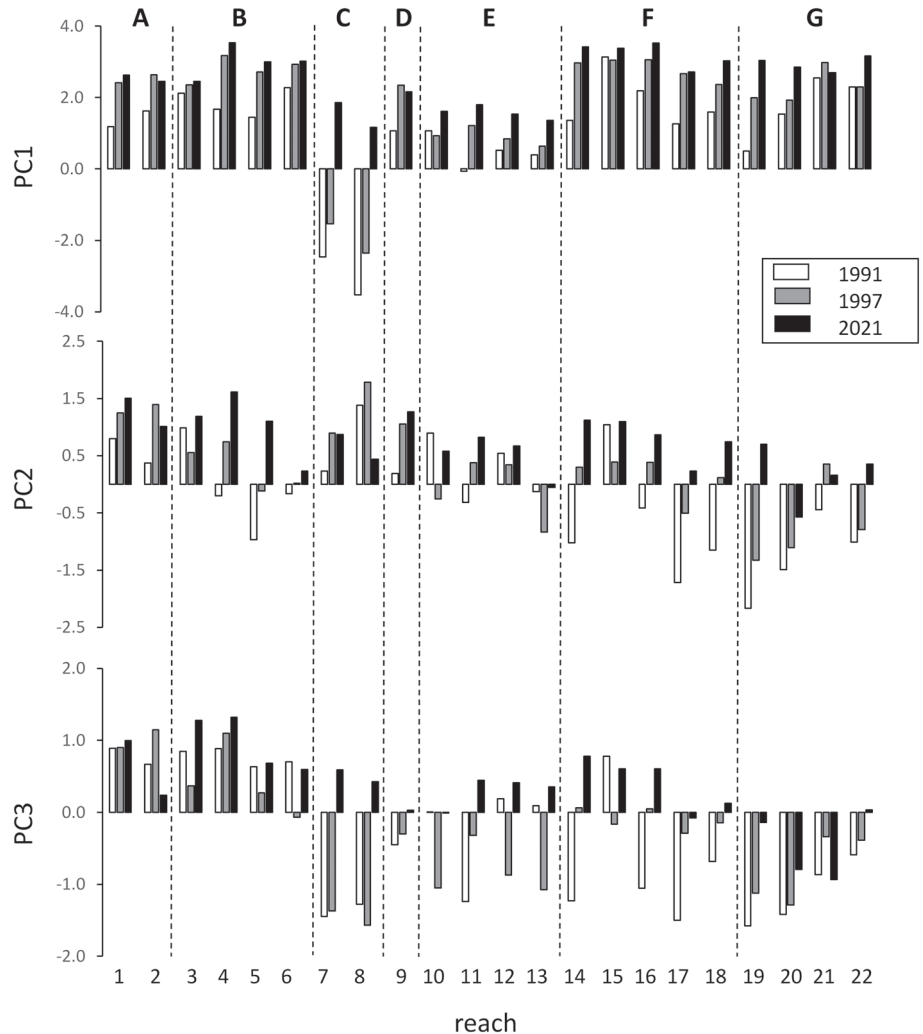


FIGURE 5 Variable loadings and reach scores on (a) PC1 and PC2 and (b) PC1 and PC3 of a PCA performed on a Spearman's rank correlation matrix of associations among jams and fallen trees, channel dimension and river margin land cover. Data were derived from 127 stream reaches of the Lymington catchment stream network included in the 1991 survey and, additionally, 22 reaches of the Highland Water included in the 1997 and 2021 surveys. The grey shaded areas of (a) and (b) refer to the parts of these plots reproduced in (c) and (d) for a smaller number of reaches. Reach scores on (c) PC1 and PC2, (d) PC1 and PC3 for the 22 reaches of the Highland Water in 1991, 1997 and 2021 surveys (i.e., a total of 66 observations). Coloured dots refer to sections of the Highland Water subject to different management practices, ordered from upstream (section A) to downstream (section G). The arrows joining the yellow dots for section C track the changing PC scores from 1991 through 1997 to 2021.

Temporal trends were further considered by focusing in detail on the number and types of wood jam observed along the Highland Water per 500 m reach (centre-line) length. Figure 7 shows the total number of wood jams in each of the 22 reaches in 1991, 1997 and 2021 (Figure 7a) and also the number of active (Figure 7c), complete (Figure 7e), partial (Figure 7g) and high jams (Figure 7i) in these reaches. Each of these line plots is accompanied by three cumulative relative frequency plots for the three survey years (Figure 7b,d,f,h,j), showing the relative frequency of occurrence of different numbers of jams per 500 m reach (centre-line) length in the 22 reaches. The cumulative relative frequency plots all show that there were generally higher frequencies of all jam types across the 22 reaches in 1997 and 2021 in comparison with 1991. They also show that the total jam frequency tended to be slightly higher in 1997 than 2021 (Figure 7b) but there was also a change in the

numbers of different types of jam with higher numbers of high and partial jams per 500 m reach in 1997 and higher numbers of the more hydraulically-impactful complete and active jams in 2021. The two reaches in restored section C retained virtually no jams in 1991 but ~10 jams per 500 m before (1997) and after (2021) restoration. However, in 1997 virtually all of the jams were partial or high whereas by 2021 - four active and approximately two complete jams were present per 500 m. Straightened section E shows notable increases in high (from ~5 to ~10 per 500 m) and complete (from ~2 to ~5 per 500 m) jams between 1997 and 2021 with a smaller increase (from ~2 to ~3 per 500 m) in active jams. Although section E has not been restored, its reaches retain more jams than reaches in section C, and only slightly less than would be expected from the downstream trend in total jams through sections B, F and G, which are not in Inclosures.

FIGURE 6 Scores on PC1, PC2 and PC3 of the 22 reaches of the Highland Water included in the 1991, 1997, and 2021 surveys. The reaches are separated from upstream to downstream into sections A to G, which have been subject to different management practices.



5 | DISCUSSION

We have shown how a carefully assembled data set, extracted from ~30 year old survey maps and tabulations, has supported an informative analysis of associations among wood jams and fallen trees and two groups of controlling factors (distance from source/sinuosity and land cover type and management) along ~59 km of streams in the Lymington River catchment. By combining this data set from 1991 with more recent survey data (1997, 2021), our analysis has also revealed changes through time along ~10 km of the Highland Water in both relatively naturally functioning and more managed sections, but also notable differences in the sections subject to different types and levels of management. These findings can be used to support and extend previous investigations into the natural and anthropogenic factors controlling the spatial and temporal patterns of large wood in streams, and our approach has wider implications for the monitoring of river restoration schemes involving large wood, both in the New Forest streams and farther afield.

5.1 | Supporting previously-recognized distributions of large wood in streams

Our analysis has identified patterns within the 1991 data set that support previous understanding of wood in stream channels. First, with

increasing distance from source (i.e., as channels increase in size) the number of wood accumulations per unit channel length tends to decrease, and second, in these small channels the wood is not transported very far once it enters the channel, since relatively few wood jams were observed in channels not bordered by woodland. These tendencies are captured by PC2 (Figure 4a), which identifies a gradient of decreasing numbers of fallen trees and wood jams with increasing heath-scrub-lawn-mire (i.e., non-woodland) cover and by PC3 (Figure 4b) which describes a gradient of increasing numbers of jams, particularly active jams, with decreasing distance from source. These characteristics of in-channel wood distributions have long been recognized. Indeed, some of the earliest research on wood in channels revealed inter-relationships among wood supply, wood piece sizes and jams, channel dimensions and the flow regime (e.g., Bilby & Ward, 1989, 1991; Meehan et al., 1977). These inter-relationships highlighted their importance for stream ecosystems within the River Continuum Concept (Vannote et al., 1980), and these topics have been subsequently revisited and refined (e.g., Wohl & Jaeger, 2009).

5.2 | Revealing associations among trees, wood, land cover and stream management

Other associations have emerged from our analysis of the 1991 data set that relate wood jams to local land and stream management

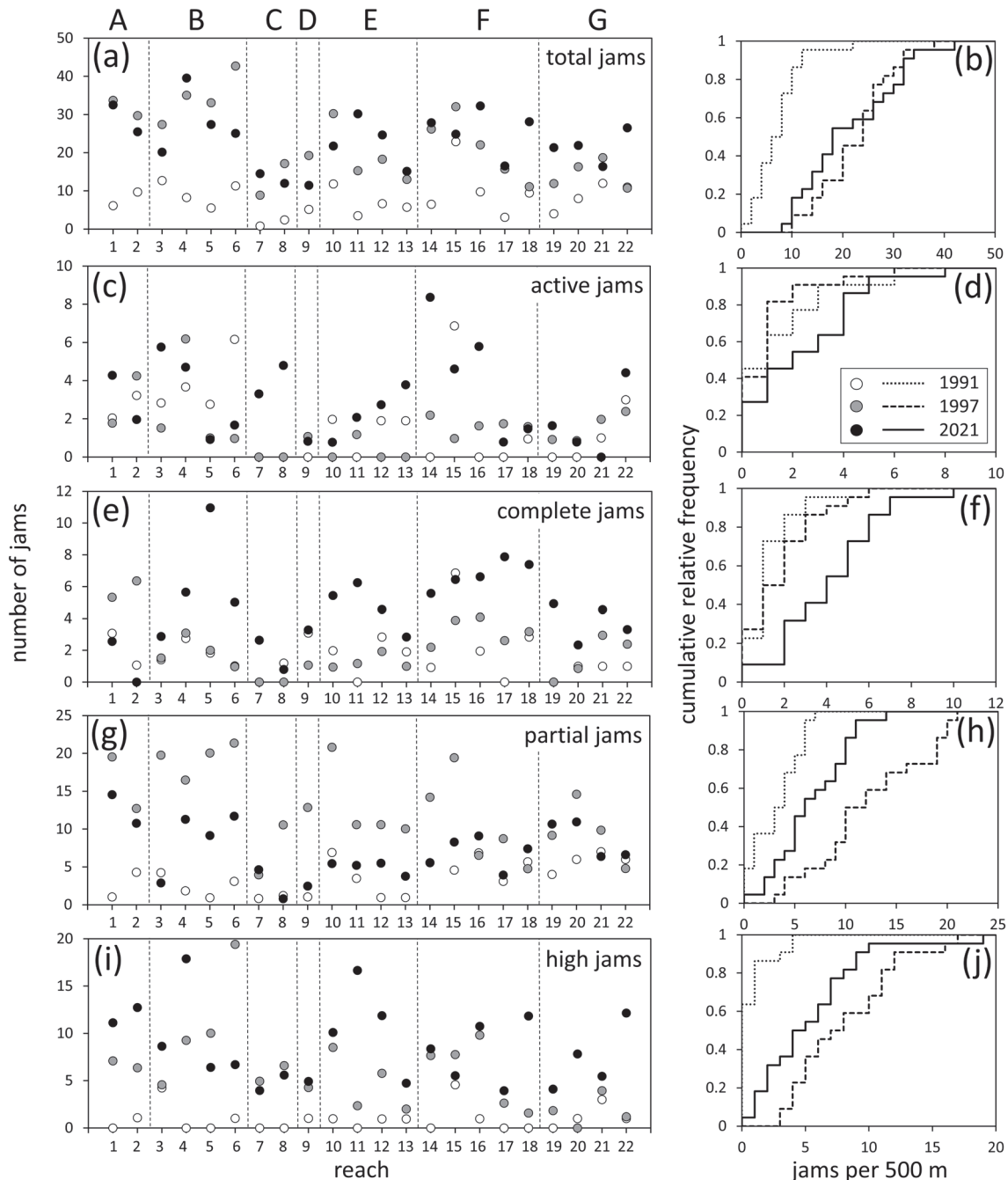


FIGURE 7 The total number of wood jams (a, b) and the number of jams classified as active (c, d), complete (e, f), partial (g, h) or high (i, j) in the 22 reaches of the Highland Water in 1991, 1997 and 2021, expressed as jams per 500 m of reach (centre-line) length. The data are presented as the number of jams per 500 m in reaches 1 to 22 (a, c, e, g, i). The vertical dashed lines in (a), (c), (e), (g), and (i) separate the reaches from upstream to downstream into sections A to G, which have been subject to different management practices. The data are also presented as cumulative relative frequency distributions for each of the jam types in each survey year across the 22 reaches (b, d, f, h, j).

practices. These associations enhance our understanding of the controls on stream-wood interactions in this long-managed landscape and are most clearly illustrated by the direction and length of the variable vectors in Figure 4.

Land and stream management in the New Forest has differed historically between Inclosures and Open Forest (Chatters, 1995; Tubbs, 1986). The Inclosure vector in Figure 4(a) is closely associated with coniferous woodland, plots close to the short (and thus weak) felled vector, shows no association with (i.e., is almost perpendicular to) the heath-scrub-lawn-mire vector, and points in the opposite direction to the deciduous woodland and stream sinuosity vectors.

This associates Inclosures with straighter (likely realigned/re-sectioned) stream channels, coniferous plantations (and some tree felling), or a mix of coniferous and deciduous trees. Since streams that are not in Inclosures are almost entirely in the Open Forest, management by grazing predominates. Associations can be made between the Open Forest (an imaginary vector opposing the Inclosure vector) and heath-scrub-lawn-mire, whereas the deciduous woodland vector is perpendicular to the Inclosure vector, so does not occur preferentially in either Inclosures or the Open Forest. The heath-scrub-lawn-mire vector opposes the sinuosity vector (i.e., it is associated with low sinuosity streams), whereas the deciduous woodland vector plots close to

the sinuosity vector (i.e., is associated with more sinuous streams) (Figure 4a). This follows observations by Gurnell and Hill (2021) that streams are less likely to be modified in the Open Forest, but, small, unmanaged, heath-scrub-lawn-mire streams tend to be less sinuous than those flowing through Open Forest woodland. Within the analysed data set, streams bordered by heath-scrub-lawn-mire were frequently headwater streams, explaining the inverse relationship between this cover type and distance from source (Figure 4b).

Vectors representing different types of wood jams and fallen trees are spread across the PC1–PC2 biplot (Figure 4a) along the gradient described by PC1 from coniferous to deciduous woodland. This indicates that their relative frequency changes along this gradient, with fallen trees and complete jams showing a similar association with both types of woodland (i.e., they are found in most woodland settings) whereas the proportions of active jams, high jams and partial jams tend to increase as the proportion of deciduous woodland increases. However, the PC1–PC3 biplot (Figure 4b) indicates that the frequency of active jams, complete jams, high jams and fallen trees decreases with increasing distance from source (i.e., increasing stream size) and that the largest streams appear to be associated with deciduous woodland in the Open Forest.

The fact that these associations emerge clearly within the space defined by the first three PCs demonstrates the pervasive influence of land cover and stream management on stream ecosystems in 1991. This reflects a time when stream management in the New Forest was concerned mainly with ‘improving’ land drainage and when many Inclosures were primarily being managed for timber production.

5.3 | Decadal-scale temporal changes

By including a sequence of three surveys (1991, 1997, 2021) for 22 reaches of the Highland Water within a second PCA, it has been possible to illustrate the power of this straightforward survey approach for identifying temporal change. The most detailed interpretations can be based on the upstream to downstream sequences of bar graphs depicting reach scores on the first three PCs (Figure 6). Since many of the variables included in the PCA have varied little over the last 30 years (e.g., distance from source, Inclosure, bank top land cover-management), any temporal changes in reach scores can be interpreted in relation to those variables that could have adjusted over the period 1991–2021, particularly sinuosity, fallen trees, wood jams and, for the two reaches in section C, woodland type and age class.

There have been steady increases in the scores of nearly all reaches on PC1 over the period 1991 to 2021 (Figure 6). In view of those variables that may have adjusted over this period, the increase most likely is related to general increases in the sinuosity of the Highland Water reaches and the number of all wood jam types per 500 m. The latter is supported by the raw observations of jam types and numbers per 500 m reach (centre-line) length (Figure 7). Increases in stream sinuosity and wood jam numbers probably reflect an overall reduction in management interventions on all New Forest streams over the 30 year period. The observed reduction in partial and high jams and increase in the more hydraulically-impactful complete and active jams (Figure 7) is a further indication of recovery from in-channel wood management. Wood jams are now recognized as crucial components of woodland stream ecosystems within the New Forest, as advocated by

Gregory and Davis (1992). Since 1991, wood management has markedly declined and land cover and stream restoration have become an increasing focus for stream corridor management across the New Forest, particularly within riverine ‘Sites of Special Scientific Interest’ (Mainstone & Wheeldon, 2016). Similarly, local Forest Design plans have sought to restore native deciduous woodland extent, function and processes to support habitats and species (Forestry Commission, 2017). The particularly large increases in the PC1 scores of reaches within section C (Figure 6) reflect two additional factors dating to the 2005 river restoration of this section: the felling of conifers on the floodplain to promote recovery of native deciduous tree species and the deliberate reinstatement of the straightened stream into its historical sinuous course. Section C is representative of the many other floodplain conifer plantations that have been felled across the New Forest over the last 30 years to enable the return of native deciduous species. Similarly, many other previously straightened sections of New Forest streams have been returned to their historical courses and to a less deep morphology that promotes stream-floodplain-connectivity and thus large wood supply and retention.

The general downstream decreases in reach scores on PC2 and PC3 reflect the widely-recognized downstream reduction in jams as channels become larger, which is also evident in the decrease in the total number of jams per 500 m (Figure 7a) through the sections of the Highland Water in the Open Forest (sections B, F and G). Scores on PC2 and PC3 also show within-reach increases through time in most reaches, which are confirmed by the numbers of jams per 500 m of all types apart from partial jams (Figure 7a,c,e,g,i), reflecting the impact of reduced wood management that has allowed more jams and, preferentially, more of the most hydraulically-impactful jams to develop. The particularly large increases in the scores of reaches in sections C and E on PC3 since 1997 indicate the additional impact of restoration (section C) and also probably the impact of simply adding wood (section E) on the development of active and complete jams, especially as the number of jams per 500 m in section E reaches show a marked increase in complete jams and a smaller but consistent increase in active jams since 1997 (Figure 7c,e). Section F also shows large temporal increases in PC3 scores. The reasons for this are unclear but could reflect some downstream effects of management in upstream Inclosures (sections C, D and E) on top of local recovery from past wood management.

These findings from the Highland Water suggest that if the 1991 survey of streams across the Lymington River catchment were to be repeated in the near future and analysed as a free-standing data set, a different picture might emerge. Given the changing management practices over the intervening decades, the re-analysis might be expected to show a weakening of some of the direct management linkages revealed in the 1991 data set. If so, the findings would provide evidence of the anticipated benefits for the nature conservation objectives and informed approaches to restoration and natural ecosystem function under Natural England’s post-2020 Nature Strategy (Mainstone et al., 2018).

5.4 | The potential of walkover surveys for monitoring

In the broader context of stream and river management, our analysis points to the potential utility of coupling historical research on

management practices with relatively rapid but appropriately designed, repeated walkover surveys. Particularly in the context of the United Nations “Decade on Ecosystem Restoration” (2021–2030), citizen science approaches have been recommended as one way of increasing local community engagement with, and longer term investment in, restoration efforts (e.g., Gann et al., 2019). In river and wetland contexts, many rapid assessment approaches for assessing channel and ecosystem health and/or monitoring restoration efforts have been developed (e.g., Gurnell et al., 2019; Kotze et al., 2019). Application of some of these approaches have included volunteer citizen scientists and have been shown to generate robust data sets (e.g., Gurnell & Downs, 2021), often in a cost- and time-effective manner. In the New Forest for instance, additional field surveys of similar detail to our 1991, 1997 and 2021 surveys could easily be collected by citizen scientists following a brief (1-day maximum) training course, capturing decadal changes or responses to particular events (e.g., wind storms, floods). Following the training, > 5 km of stream could comfortably be surveyed in 1 day by pairs of volunteers, so that a large proportion of the Lymington River stream network (e.g., equivalent to the spatial coverage of the 1991 survey) could be covered at relatively little cost with 10 to 12 days of effort.

Our approach and analysis could be extended from a primary focus on wood jams to incorporate other in-channel features of importance to stream ecosystems such as pools, riffles, bars and bank forms. This would require more training of volunteers, and would inevitably add to the time taken in surveying each stream reach, so might adversely affect the spatial coverage achieved. Nevertheless, a nested survey approach could be designed, whereby broad spatial coverage using straightforward surveys by non-specialists is then supplemented by detailed surveys of a smaller number of reaches by specialist river scientists.

As Wohl (2019, p. 5181) emphasizes, ‘the existence of forgotten legacies challenges river scientists to recognize the continuing effects of human activities that have long since ceased and also poses challenges for the application of scientific understanding to resource management’. Against this backdrop, walkover surveys clearly not only have the potential to provide a broad understanding of stream environments as a framework for more specialist local monitoring of human activities, including management interventions such as restoration, but application within citizen science frameworks is likely to be a key part of ensuring their wider application. Even for locations that have no existing archival materials, the surveys of today will become the archives of tomorrow, and undoubtedly will have analytical value in the decades to come.

6 | CONCLUSIONS

It is tempting to conclude that landscapes that appear natural are functioning naturally, but such assumptions are nearly always flawed in areas that have long-supported human populations and/or been subject to a long history of management. The New Forest presents one such case study. It is a unique landscape that has multiple conservation designations, is now under National Park management, and is enjoyed by its many visitors as an apparently ‘wild’ and ‘naturally-functioning’ environment. Nevertheless, its character and existence are a product of over 1000 years of human activities, including active management of woodlands and streams.

We have revealed some of the consequences of those activities for the New Forest stream channels through analysis of field survey data sets collected over the last 30 years. While many traditional management activities continue (e.g., extensive grazing) and contribute to maintaining highly valued habitats, other activities – particularly those applied to streams, their riparian margins and floodplains – continue to be reversed through an increasing programme of restoration and a move towards management for naturally-functioning systems. Our extensive 1991 survey data and associated analysis provides a benchmark against which the broader effects of these restoration strategies and activities can be judged. Indeed, our later survey data sets (1997, 2021) for the Highland Water show a trajectory of channel recovery following reduced wood and stream management, coupled with restoration of two reaches.

In a global context, our decades long data set regarding the changing interactions between trees, large wood and streams is very unusual, but the need remains for ongoing monitoring of stream recovery in response to past and ongoing management activities and the contribution of additional wood jams from future storm events. In the New Forest, and in many other human-impacted landscapes, the collection of well-designed but straightforward, rapid surveys of the type analysed here can provide a template for timely and repeated monitoring over decades, perhaps increasingly as part of citizen science projects. Particularly in view of the United Nations “Decade on Ecological Restoration”, monitoring is crucial for permitting analyses that develop understanding of how streams function and change, not least those that experience legacy effects of human activities across different time and space scales.

ACKNOWLEDGEMENTS

This research would not have been possible without the foresight of Professor Ken Gregory, who designed and led the 1991 survey on which our analysis is based and who passed on the archive to us. The authors dedicate this article to his memory. We also thank Forestry England for permission to conduct research in the New Forest.

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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How to cite this article: Gurnell, A.M., Hill, C.T., Davis, R.J. & Tooth, S. (2022) Trees, large wood and streams: Using archive survey data to inform changing interactions in a human-impacted landscape. *Earth Surface Processes and Landforms*, 1–15. Available from: <https://doi.org/10.1002/esp.5453>