Regional flow–ecology relationships in small, temperate rivers

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Abstract
Flow–ecology relationships within river systems are an important area of ongoing investigation, because of potential applications such as understanding the ecological impact of flow alteration at modified sites. This study analyses relationships between flow characteristics and benthic macroinvertebrates from 18 streams of similar size and typology within Northern England, to develop quantitative flow–ecology relationships applicable at regional scale. High and low flow event frequencies displayed statistically significant relationships with the ecological metrics of LIFE Score, Shannon’s Diversity and a velocity flow affinity trait score. Results suggest that flow event frequencies have a significant role in influencing ecology within the river network system. Hence, this indicates that future flow regime design in the region may be enhanced if this variable is considered.

KEYWORDS
catchment management, ecohydrology, modelling, remediation, river

1 | INTRODUCTION

A global increase in water demand and energy requirements has led to the widespread proliferation of flow impoundments. The resulting flow modification, even by small impoundments and hydropower schemes, can adversely impact riverine ecology (Anderson et al., 2017; Poff et al., 1997), and despite recent efforts, there remains a lack of consensus as to how ecological impacts arising from flow regime change should be mitigated (Gillespie, Desmet, et al., 2015). A better understanding of the relationship between ecology and flow regime is therefore a critical area of investigation. Such understanding is imperative for the design of mitigation measures such as environmental flows (e.g., Gillespie, Brown, et al., 2015; Hough et al., 2019), defined by the Brisbane Declaration, 2007 as ‘... the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems.’ (Overton et al., 2014, p. 861).

Several theoretical frameworks describe the relationship between riverine ecology and the flow regime (e.g., Junk et al., 1989; Poff et al., 1997; Vannote et al., 1980), and there is substantive and growing evidence to show how components of the flow regime, such as the timing, magnitude, frequency, duration and variability of flow peaks, can influence a range of ecological metrics (e.g., Praskievicz & Luo, 2020).

Magnitude is seen as a significant influence in the river system because of its effects upon river morphology, river habitat, sediment and nutrient transport, and physical forcing upon biota (Power et al., 1995). Timing is also because of morphological and behavioural adaptations of biota (Lytle & Poff, 2004). Frequency, duration and variability are likewise influential, because of their impact on nutrient cycling (Junk et al., 1989) or role as biological filters (Rolls et al., 2012).

Previous studies have discussed the challenges presented by rivers as open systems and the degree of uncertainty often associated with studies investigating specific variables (Konrad et al., 2011), when attempting to better understand flow–ecology relationships and possible mitigation of ecological impacts (e.g., arising from flow modification as a result of impoundments). The challenge is further enhanced because of the conflicting interests of multiple stakeholders...
present in most systems (Summers et al., 2015), such as water utility companies, industry and the general public. Developing mitigation measures that satisfy multiple stakeholders, while also making sufficient provision for environmental requirements such as ideal flow times and volumes for the system’s biota, is a difficult task.

The building block approach (King & Louw, 1998) has been widely used to determine environmental flows as a means of mitigating the impact of modified flows, for example, for the design of flows downstream of impoundments. However, this site-specific, intensive approach relies upon expert judgement, which is impractical for mitigating the impacts of the majority of smaller-scale systems (i.e., flows >5 m$^3$/s), which are widespread and frequently failing to meet legislated ecological targets (Voulvoulis et al., 2017). Thus, there is a need for general and transferable information about flow–ecology relationships to support flow design in such systems.

This study focuses upon the relationship between flow and ecology at a regional level, with the aim of informing future mitigation recommendations. Specifically, we consider flow–ecology implications within smaller-scale river systems as an area in need of further research (Voulvoulis et al., 2017). Studies continue to affirm the use of regional-scale efforts (O’Brien et al., 2018) rather than site-specific evaluation, as such work can offer significant scientific value and act as a first step towards designing mitigation measures within impacted systems without detailed and expensive site investigation (Hough, 2020; Poff et al., 2010). Flow–ecology trends identified at a regional level, based on considering combined datasets from different sites, may allow for the establishment of transferable environmental flow principles between sites of similar character (Arthington et al., 2006), which may increase the number of sites meeting legislated targets.

This study thus aims to make first steps towards addressing the needs of smaller-scale riverine systems by developing a flow–ecology model applicable at a regional scale. We utilize and agglomerate historic long-term flow and ecological datasets across sites in the north of England to identify ecologically-influential flow characteristics at a regional level. Such data are freely available and thus allow for analyses that are not too resource- or time-intensive, maximizing transferability. Analyses were performed on river systems of similar characteristics in order to reduce the likelihood of noise from controlled sources of variation obscuring observable relationships (Konrad et al., 2011) and allow clearer examination of a range of hydrological drivers: magnitude of flow in particular may overwhelm other hydrological drivers when assessed across too broad a scale, because of its dominant influence upon hydraulics and morphology (Monk et al., 2006). This investigation therefore focuses on rivers of a similar magnitude of mean daily flow and physical character, located across the region of Northern England.

The study also focuses on functional, as well as taxonomic, measures of ecological community structure. Focusing upon taxonomic composition alone may not detect some influences that flow exerts upon ecosystems, such as in cases where composition is altered but overall richness is not (Chinnayakanahalli et al., 2011). A broader suite of metrics is therefore required to fully assess ecological impact (Arthington et al., 2018). In this study, we combine diversity and trait characteristics with ecologically important flow metrics to identify the strongest flow–ecology relationships within the region studied.

## 2 | METHODS

This study utilized Indicators of Hydrologic Alteration (Richer et al., 1996) derived from historical flow data, in order to identify hydrological characteristics at each site. Sites were characterized ecologically based on macroinvertebrate diversity and flow preference. Relationships between flow and ecology metrics across all the selected sites were analysed using multiple linear regression.

### 2.1 | Site selection and data

Sites were selected from a range of sites across Northern England (Figure 1) and were chosen using the Environment Agency’s (EA) online Catchment Data Explorer (Environment Agency, 2018). Selected study sites ranged from 0.31 to 2.83 m$^3$/s annual mean daily flow, with a minimum of 5 years continuous flow and ecological sampling data, with samples in both seasons each year. When identifying appropriate sites, some were also excluded because of external factors that could influence invertebrate composition, such as poor water quality. The sites selected for study were of ‘good’ chemical quality according to the most recent EA assessment. Eighteen sites were selected for analysis. They were all low gradient, straight or low sinuous, alluvial reaches on a sandstone and/or mudstone bedrock. Most were unmodified reaches in agricultural areas, although some reaches were in urban or suburban settings with some channel modification (see Appendix 1). Site characteristics were obtained from EDINA Digimaps Ordnance Survey Service (2020) and Google Earth Pro.

Publicly available time series datasets were obtained from the EA and the Centre of Ecology and Hydrology National River Flow Archive (CEH, 2021). Flow data were in the form of mean daily flows. The time series of flow data varied from 12 to 56 years of continuous data between sites; with 10 sites having over 30 years of data. Appendix 3 addresses potential concerns relating to the use of time series of varying lengths. Ecological data, collected as part of EA routine monitoring, included taxon abundance at a species or family level and Lotic-invertebrate Index for Flow Evaluation (LIFE) scores (Extence et al., 1999), typically with samples taken in spring and autumn each year and spanning 5–10 years. The coordinates of the data were checked to ensure that the sites for the flow and ecology data had no significant intervening flow inputs such as tributaries between them.

### 2.2 | Data analysis

A number of ecologically relevant flow variables were obtained from the flow data, based on principles outlined by Richter et al. (1996) and using indicators advocated for within the hydrological community (Dunbar et al., 2010; Monk et al., 2006): Q10, Q25, Q50, Q95,
standard deviation, range, annual maxima and minima, mean daily flows, and frequency and duration of high and low flow events. Statistical analysis of IHA variables was conducted to check that the length of time series data at each site was sufficient to generate stable and reliable flow statistics. Ecological data from each site were processed to provide velocity affinity and Shannon’s diversity metrics for spring and autumn seasons; LIFE score was already available in EA data. LIFE is a widely used metric for the ecological monitoring of freshwater benthic macroinvertebrates based upon the flow affinities of macroinvertebrate species and families (Dunbar et al., 2010). Taxonomic diversity was used as a measure of ecological response between sites using the Shannon diversity index ($H'$) for macroinvertebrate family data in spring and autumn:

$$H' = \sum_{i=1}^{s} p_i \ln p_i$$

where $s$ is the number of families present in the sample and $p_i$ is the proportional abundance of each family.

Because of variation in the taxonomic resolution of the invertebrate data (data varied between species and family level depending upon site and time of measurement), all data were converted to family level, and the mean annual family abundances were calculated for each site separately in spring and autumn samples.

2.2.1 | Velocity affinity

Velocity affinity has been utilized in a number of ecological analyses (Schneider et al., 2016, Conallin et al., 2010). It was used in this study because of its strong relationship with the flow rate, and it represents the expected response of biota to various flow conditions. Species preferences were taken from Bis and Usseglio-Polatera (2004). Preferences were assigned to families by taking the mean trait affinity value of all species present within that family, an approach justified by the general similarity of traits within families, as seen in other studies such as White et al. (2017). Each family was also sorted into particular categories of flow preference.
described in Table 1. These categories were based upon defined flow ranges by Bis and Usseglio-Polaterra (2004), with additional categories created for more generalist families that displayed affinities for a broad range of flows. Populations within each category were summed up at each site based on the mean annual abundances of each family within a given category within spring and autumn. The distribution of abundances between categories provides an insight into functional composition of a site. Once population distributions across trait categories were calculated at each site, more extreme categories (e.g., very fast flow) were given higher weightings (see Table 1) because of the fact that taxa possessing extreme traits tend to be less common in typical conditions, yet the presence of even small numbers of such taxa is suggestive of a system’s character (Petchey & Gaston, 2006). Generally across sites, species preferring medium flows were prolific, and thus, weightings were used to better demonstrate fluctuations in functional distributions. Flow velocity categories were each given a score between 1 and 8. The abundances of families present in each category, relative to the total population, were multiplied by the weighted score. The sum of these values constituted the overall trait score, that is, a trait score of ‘1’ indicates a site dominated by lentic flow affinity species, whereas ‘8’ indicates that fast flow affinity species dominate.

Many families, while having some affinities for either high or low flows, also exhibited moderate affinities for a range of flows and therefore may be considered rather generalist with regard to flow preference. These were put into two categories; generalists with low-medium preferences, and generalists with medium-fast preferences, demonstrated in Table 1. At low-medium flows, most families in the sampled regions appear to be generalists, with those of specific low-medium affinity being very rare. As such, the weighting for the low-medium affinity was weighted the same as the low-flow affinity, which was also rare at most sites. Trait scores varied between spring and autumn seasons because of differing family populations between the two periods, and thus, ecological metrics were assigned to both seasons separately.

This form of trait-based analysis allows for ecological characteristics to be compared across sites directly alongside flow characteristics, for example, Alexandridis et al. (2017), Petchey and Gaston (2006).

### TABLE 1  Trait score categories and associated weightings

| Flow velocity preference | Trait score | Weighting |
|--------------------------|-------------|-----------|
| No flow (0 cm/s)         | 1           | 10        |
| Low flow (0–10 cm/s)     | 2           | 7         |
| Low-medium flow (10–20 cm/s) | 3   | 7         |
| Low-medium flow (generalists) | 4   | 4         |
| Medium flow (20–30 cm/s) | 5           | 1         |
| Medium-fast flow (generalists) | 6  | 4         |
| Medium-fast flow (30–40 cm/s) | 7   | 7         |
| Fast flow (>40 cm/s)     | 8           | 10        |

2.2.2 | Flow variables and relationships

Using the data across all selected sites, a principal components analysis (PCA) was undertaken to reduce redundancy among the hydrological variables. PCA is a method commonly used in redundancy analysis and the approach followed Monk et al., 2006, Gillespie, Brown, et al., 2015, and Chinnayakanahalli et al., 2011.

PCA was based on a Pearson product moment correlation using the metrics listed in Table 2 and performed using R version 3.2.4 (R Core Team, 2016). Variables were sorted into distinct groups based upon the strength and direction of vectors within the PCA biplot. The biplot distinguished two groups within the variables which were labelled ‘magnitude’ and ‘temporal’ (Figure 2 in Section 3). The groups were used to identify redundant variables, as variables within the same group were correlated and were considered to have a high degree of mutual explanatory power in relation to the dependent variable. Thus, multiple variables from the same group were not used in subsequent regression modelling.

### TABLE 2  Summary of flow and ecological metrics, along with their shorthand used in subsequent sections

| Metric                              | Characteristic described                           |
|-------------------------------------|---------------------------------------------------|
| Mean daily flow                     | Describes general magnitude of flow based on daily mean |
| Q10                                 | Discharge exceeded 10% of the time (i.e., very high flow) |
| Q25                                 | Discharge exceeded 25% of the time (i.e., moderately high flow) |
| Q95                                 | Discharge exceeded 95% of the time (i.e., very low flow) |
| Mean annual minima (MINYR)          | Describes extreme lows                             |
| Mean annual maxima (MAXYR)          | Describes extreme highs                            |
| Mean annual range (RNGYR)           | Describes general yearly range                     |
| Mean annual low flow frequency (LowFreq) | How frequently low flow events occur annually (median flow – 25%), as a mean |
| Mean annual low flow duration (LowDura) | How long low flow events tend to last annually (median flow – 25%), as a mean |
| Mean annual high flow frequency (HighFreq) | How frequently high flow events occur annually, (median flow + 25%) as a mean |
| Mean annual high flow duration (HighDura) | How long high flow events tend to last annually, (median flow + 25%) as a mean |
| Velocity affinity (velocity t)      | Family affinity for flow conditions, scored 1 to 8. 1 is very low flow affinity, 8 is fast flow affinity |
| Diversity                           | Shannon’s diversity, used as a measure of taxonomic diversity |
| Family LIFE                         | LIFE score (at family level) as another metric for flow affinity |

Abbreviation: LIFE, Lotic-invertebrate Index for Flow Evaluation.
Six data matrices were then constructed, containing one of the three ecological indices (diversity, LIFE or velocity preference) for either spring or autumn seasons. Each matrix contained all independent flow variables identified from the PCA analysis. Ecological indices vary seasonally because of shifts in the ecological community between seasons, whereas the flow variables do not vary as these flow characteristics are based upon yearly flow statistics.

Flow data were not normalized, as the main purpose of this study was to directly compare (and model) site flow against ecological response. This was appropriate for the study, as the river systems had a similar average mean daily flow range (within 1.2 m$^3$/s), with the exception of Eden and Pendle Water. Although distinctly higher in magnitude than other selected sites, these were retained by necessity as they presented good sources of data and met all of the criteria described for site selection in Section 2.1.

All metrics utilized are described in Table 2 below:

For each data matrix, multiple linear regression was used to fit a regionally applicable model for each ecological trait within each season. Regression models were created for all combinations of non-redundant variables (i.e., all combinations of variables that would contain one ‘magnitude’ and one ‘temporal’ variable), along with each variable individually (as univariate models).

Model fitting was performed for each ecological dependent variable with combinations of flow variables as the independent variables. The best fitting models for each dependent variable, in spring and autumn, respectively, were determined. These were judged from $p$ values, $R^2$ values, and as the primary deciding factor, the Akaike information criterion (AIC); a measure of the relative quality of a statistical model, taking into account both the variation explained and the model complexity (Aho et al., 2014). Variables above a $p$ value threshold of 0.2 were not analysed further to find their $R^2$ and AIC values, because of their obvious lack of statistical significance.

### RESULTS

Calculation of all ecological metrics was possible for all sites except one, where missing data meant that metrics could not be derived. Hydrological and ecological metrics for each site are listed in Table 3. Average annual mean daily flow across all 18 sites was 1.16 m$^3$/s. Of the sites, Skell (mean daily flow magnitude 1.51 m$^3$/s) was found to have the highest velocity trait score in both spring and autumn, whereas Calder (1.01 m$^3$/s) had the lowest score in spring and second lowest in autumn. Skell also had the highest LIFE score in both spring and autumn; an expected outcome as both LIFE and trait score are derived from similar data. Eastburn Beck (0.88 m$^3$/s) had the highest biodiversity in spring, and Heltondale (0.31 m$^3$/s) the highest in autumn. Blackfoss Beck (0.45 m$^3$/s) had the lowest biodiversity in spring, whereas Church Beck (0.85 m$^3$/s) had the lowest in autumn.

Results of the PCA analysis are shown in Figure 2. Variables were categorized into the two groups of ‘magnitude’ and ‘temporal’ after observing that variables likely driven by magnitude of flow correlated, whereas variables based on temporal occurrence (duration and frequency) displayed correlation between variables of the same category. PC1 separates sites Eden (14) and Pendle Water (17) from the other sites on account on differences in flow magnitude. Although these sites did have the highest mean daily flows, the sites differed most notably on account of the highest flows, namely, the MAXYR and RANGYR values. The two principal components accounted for 93% of the total variation. To avoid the redundancy among the variables in subsequent analyses, variables within the same category (i.e., ‘temporal’ or ‘magnitude-based’ as seen in Figure 2) were not used within the same model.

Once variable clustering was determined, fitting of linear models was performed for all possible combinations of non-redundant variables using data from all selected sites. The best-fitting model was chosen for each dependent ecological variable, both in spring and autumn, based upon the best (lowest) AIC value.

Mean annual high flow event frequency, in a univariate model, was found to have the strongest relationship with velocity trait score and family LIFE score, while mean annual low flow event frequency, again in a univariate model, was found to have the strongest relationship with biodiversity. Model values for the best results can be seen in Table 4. The full list of models and associated statistics can be found in Appendix 2.

A number of statistically significant relationships were identified at regional scale, with all the best fitting models containing only one flow variable. These relationships are plotted in Figure 3.
### Table 3: All study sites with their associated hydrological and ecological variables

| Site name          | Mean daily (m³/s) | Q10 (m³/s) | Q25 (m³/s) | Q95 (m³/s) | MINYR (m³/s) | MAXYR (m³/s) | RNGYR (m³/s) | LowFreq (events/year) | LowDura (days) | HighFreq (events/year) | HighDura (days) | Velocity trait (spring) | Velocity trait (autumn) | Diversity (spring) | Diversity (autumn) | Family LIFE (spring) | Family LIFE (autumn) |
|--------------------|------------------|------------|------------|------------|--------------|--------------|---------------|------------------------|----------------|------------------------|-----------------|------------------------|------------------------|----------------------|-----------------------|----------------------|----------------------|
| Heltondale         | 0.31             | 0.71       | 0.35       | 0.04       | 0.4          | 3.51         | 3.48          | 8.6                    | 6.58           | 13.25                  | 3.93            | 5.16                   | 3.14                   | 1.9                  | 2.71                  | 6.45                 | 6.61                 |
| Blackfoss Beck     | 0.45             | 0.86       | 0.4        | 0.04       | 0.04         | 8.43         | 8.39          | 6.63                   | 13.26          | 7.12                   | 2.4             | 4.8                    | 4.52                   | 1.22                 | 2.03                  | 6.89                 | 6.66                 |
| Went               | 0.57             | 1          | 0.57       | 0.16       | 0.17         | 7.22         | 7.06          | 10.43                  | 8.3            | 7.76                   | 2.87            | 4.65                   | 5                     | 2.23                 | 2.53                  | 7.4                  | 7.41                 |
| Ryburn             | 0.61             | 1.25       | 0.56       | 0.2        | 0.19         | 7.83         | 7.64          | 9.31                   | 9.21           | 9.22                   | 3.17            | 5.02                   | 2.83                   | 1.39                 | 2.03                  | 6.29                 | 6.56                 |
| Spen Beck          | 0.74             | 1.22       | 0.65       | 0.1        | 0.18         | 6.73         | 6.55          | 12.26                  | 7.65           | 7.34                   | 1.85            | 4.7                    | 5.27                   | 2.13                 | 2.08                  | 7.91                 | 7.48                 |
| Church Beck        | 0.85             | 3.68       | 1.3        | 0.09       | 0.08         | 8.71         | 8.62          | 11.07                  | 4.25           | 25.71                  | 2.21            | 4.57                   | 2.27                   | 2.03                 | 1.16                  | 6.3                  | 5.81                 |
| Eea                | 0.87             | 2.28       | 1.19       | 0.05       | 0.04         | 7.04         | 7             | 6.67                   | 8.79           | 12.5                   | 4.04            | 4.2                    | 4.62                   | 2.19                 | 2.47                  | 7.92                 | 7.49                 |
| Eastburn Beck      | 0.88             | 2.18       | 0.96       | 0.07       | 0.07         | 12.71        | 12.64         | 9.38                   | 11.38          | 16.1                   | 2.02            | 4.14                   | 3.97                   | 2.57                 | 2.53                  | 8.14                 | 7.55                 |
| Calder             | 1.01             | 2.57       | 0.98       | 0.05       | 0.06         | 12.1         | 12.05         | 10.6                   | 4.32           | 22.65                  | 2.08            | 4.09                   | 2.57                   | 1.46                 | 1.81                  | 6.26                 | 6.41                 |
| Crimple Blackstone | 1.06             | 1.95       | 0.91       | 0.15       | 0.13         | 36.59        | 36.46         | 13.47                  | 6.81           | 6.77                   | 1.46            | 5.59                   | 3.03                   | 2.01                 | 2.35                  | 6.18                 | 6.03                 |
| Swindale Beck      | 1.20             | 3.15       | 1.32       | 0.08       | 0.07         | 15.19        | 15.12         | 13.61                  | 4.08           | 30.72                  | 1.89            | No data                 | No data                | 5.68                 | No data                | 2.5                   | No data               |
| Douglas Wigan      | 1.22             | 2.37       | 1.33       | 0.37       | 0.41         | 9.26         | 8.85          | 13.56                  | 3.4            | 17.59                  | 2.58            | 6.74                   | 6.3                    | 1.7                  | 1.29                  | 7.75                 | 7.6                  |
| Foulness           | 1.28             | 3.12       | 0.77       | 0.05       | 0.05         | 18.18        | 18.14         | 5                      | 19.81          | 6.82                   | 3.68            | 6.27                   | 5.99                   | 1.87                 | 1.83                  | 6.69                 | 6.89                 |
| Darney             | 1.36             | 2.86       | 1.41       | 0.27       | 0.26         | 18.94        | 18.68         | 11.51                  | 8              | 10.54                  | 2.52            | 6.11                   | 6.75                   | 2.31                 | 2.64                  | 7.9                  | 7.73                 |
| Colne              | 1.44             | 3.18       | 1.54       | 0.33       | 0.29         | 17.31        | 17.02         | 17.03                  | 5.7            | 13.34                  | 2.39            | 6.43                   | 7.1                    | 2.4                  | 1.85                  | 7.43                 | 7.07                 |
| Skell              | 1.51             | 3.7        | 1.8        | 0.15       | 0.13         | 18.01        | 17.88         | 6.68                   | 13.06          | 12.77                  | 2.68            | 6.89                   | 7.01                   | 1.84                 | 2.18                  | 8.3                  | 8.29                 |
| Eden               | 2.66             | 6.74       | 2.7        | 0.17       | 0.15         | 43.84        | 43.69         | 9.42                   | 6.16           | 24.62                  | 2.19            | 5.55                   | 4.06                   | 1.57                 | 2.42                  | 7.22                 | 7.34                 |
| Pendle Water       | 2.83             | 6.83       | 2.91       | 0.46       | 0.44         | 38.12        | 37.68         | 12.64                  | 4.55           | 22.14                  | 2.46            | 6.26                   | 6.26                   | 2.09                 | 2.59                  | 7.79                 | 7.53                 |

Note: Mean daily represents mean daily flows, MINYR, MAXYR and RNGYR represent mean minima, maxima and flow ranges per year respectively, and Freq and Dura variables represent flow durations and frequencies.

Abbreviation: LIFE, Lotic-invertebrate Index for Flow Evaluation.
TABLE 4  Best performing models for each ecological metric, based on Akaike information criterion (AIC)

| Variables in model | p     | R²   | AI    |
|--------------------|-------|------|-------|
| LIFE scores—SPRING |       |      |       |
| HighFreq –         | 0.056 | 0.161| 40.256|
| HighFreq MINYR    | 0.1366| 0.131| 41.72  |
| HighFreq Q25      | 0.138 | 0.13  | 41.743|
| HighFreq MeanMag  | 0.1628| 0.11  | 42.141|
| LIFE scores—AUTUMN|       |      |       |
| HighFreq –         | 0.0157| 0.2561| 34.872|
| LowDura –          | 0.0543| 0.1539| 37.317|
| HighFreq MINYR    | 0.0545| 0.2181| 36.666|
| HighFreq Q25      | 0.0552| 0.2167| 36.699|
| Velocity trait score—SPRING |       |      |       |
| HighFreq –         | 0.0376| 0.1959| 49.79 |
| HighFreq Q25      | 0.055 | 0.2302| 49.847|
| LowDura –          | 0.0666| 0.2103| 50.307|
| LowDura –          | 0.0793| 0.1287| 51.237|
| Velocity trait score—AUTUMN |       |      |       |
| HighFreq –         | 0.01335| 0.269| 69.421|
| HighFreq Q25      | 0.03  | 0.2742| 70.135|
| LowDura –          | 0.0352| 0.1906| 71.357|
| HighFreq RNGYR    | 0.0467| 0.2329| 71.186|
| Biodiversity—SPRING|       |      |       |
| LowFreq –          | 0.0132| 0.301| 12.518|
| LowFreq RNGYR     | 0.0278| 0.3148| 13.005|
| LowFreq MAXYR     | 0.0281| 0.3139| 13.028|
| LowFreq MINYR     | 0.0394| 0.28  | 13.849|

Note: No statistically significant relationships were found for biodiversity in autumn.

high flow frequency provides the best fitting models for velocity trait scores and LIFE scores in both seasons. The best fitting models for biodiversity, on the other hand, relate to mean annual low flow frequency, and only during spring. R² values are generally low, indicating relatively high levels of unexplained variation.

4 | DISCUSSION

In this study, we have examined the degree to which there are general relationships between hydrological characteristics and ecological metrics, across a set of similar rivers in Northern England.

4.1 | Velocity preference trait and LIFE scores

The results suggest that in this region, high flow event frequency has a significant influence upon the functional composition of a system in terms of velocity preference of families, explaining 20%–27% of the variation in preference when considering trait score, and 16%–26% of variation when considering LIFE score (based on R² values). This suggests that it may be possible to identify particular aspects of the flow regime which could be important to focus on when developing potential mitigation solutions for flow alteration. IHA variables including the duration and frequency of high and low flow events were found to strongly influence stream macroinvertebrates in a similar study based on the ELOHA method in the United States using biological metrics primarily based on functional group composition such as measuring the percentage of individuals adapted for filter feeding (Buchanan et al., 2013). The mechanisms underpinning the positive relationships between high flow and flow preference and LIFE scores seem likely to be straightforward; the more frequently high flows occur, the more resilient the community at a site becomes in terms of functional composition.

The influences of high flow event frequency as an ecological driver may have significant implications when considering environmental flow regime design in the region and also suggest significant limitations in current ‘fixed’ hands-off flow-based regulations (Arthington et al., 2006). A lack of high flow events within a modified system may lead to a lack of an important biological filter, resulting in systems being dominated by species that are highly competitive within a steady, moderate-to-low flow environment, as discussed by a number of studies examining river deviation from natural flows (Lytle & Poff, 2004; Summers et al., 2015). Incorporating a moderate frequency of high flows events into environmental flow regimes to mitigate the impacts of modification through impoundments may serve to balance a system’s functional composition and be one facet in ensuring a stable and diverse ecosystem.

The only detected effect on family diversity was that low flow event frequency is negatively related to diversity, but in spring samples only. This may be because of differing conditions between the two seasons; functional composition is likely to differ significantly between the two seasons, either because of life history or external drivers. As such, response to the flow modification may vary because of these differences in composition between seasons. A negative correlation between low flow and diversity is consistent with other studies (e.g., Pardo & García, 2016), and Rolls et al. (2012) identify frequency of low flows as a ‘key biological filter’ and explain how low flows impact riverine ecology by controlling the extent, diversity and connectivity between physical habitats; mediating change in physical and chemical conditions and altering the sources and exchange of materials and energy within the systems.

If the influence of low flow event frequency is general, this could have significant implications for water managers wishing to increase biodiversity within managed systems. Low flows play a key role within natural river systems (Poff et al., 1997; Richter et al., 1996), and it would therefore be expected that such events would aid in regulating the ecosystem, preventing the dominance of certain species.
5 | CONCLUSIONS

Results from this study have provided evidence that there are key flow characteristics that are strongly associated with ecological response and that significant predictive relationships can be found on a regional scale. Despite limitations such as the narrow scope of variables utilized, results do affirm the conceptual frameworks and empirical evidence on flow–ecology relationships that the magnitude, timing, duration and variability of flows influence macroinvertebrate diversity and composition. This suggests that highly modified flows, such as those observed within impounded systems, are likely to result in ecological communities different from those which might be expected under the natural flow regime. This conclusion is similar to findings from other studies investigating the impacts of flow modification (Gillespie, Brown, et al., 2015; Nichols et al., 2006). This study also affirms the suggestion of Chinnayakanahalli et al. (2011) that taxon richness and functional composition respond differently to flow alternation, and using only one of these metrics may fail to recognize significant changes within the ecosystem and that a broader suite of ecological metrics are required in order to fully evaluate changes within the ecosystem (Arthington et al., 2018; Poff et al., 2017). Results from this study are likely to have implications for water management decisions, such as the integration of flow variation into the environmental regime design. From the results, one might derive principles for similar river systems, for example, that having few high flow events (compared with non-modified flow conditions) is likely to cause a shift in functional composition within the ecosystem. River systems of similar flow magnitudes, geological characteristics and climate to those studied could be assessed in terms of hydrological characteristics through the process described here. Environmental flow regimes could be designed around influential flow characteristics such as flow event frequency, as in Hough et al. (2019), although further
empirical testing is required in order to confirm that alteration of this metric via river modification follows the ecology–flow relationship observed in this study. We offer these observations as a promising area of further research in the context of mitigating anthropogenic impact on river systems, particularly through informing environmental flow design. Further research would help to develop specific design recommendations; further analysis of the seasonal timings of flow events, for example, may further understanding of the impact that events may have based upon when in the year they occur. The use of other metrics such as LIFE OE may also reveal further insights into how flow alteration is limiting the ecosystem.

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DATA AVAILABILITY STATEMENT
Publicly available time series datasets were obtained from the EA and the Centre of Ecology and Hydrology National River Flow Archive.

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**APPENDIX 1**

Site characteristics

| Site                  | Gradient | Sinuosity | Topsoil          | Confinement       | Modification     | Land use          |
|-----------------------|----------|-----------|------------------|-------------------|-----------------|-------------------|
| Blackfoss Beck        | 0.020    | 1.044     | Alluvial          | Not confined      | None visible    | Agriculture       |
| Colne                 | 0.020    | 1.040     | Alluvial/engineered | Not confined     | Heavily modified | Urban             |
| Crimple Blackstones   | 0.010    | 1.147     | Alluvial          | Not confined      | None visible    | Agriculture       |
| Dearne                | 0.050    | 1.090     | Alluvial          | Not confined      | Weirs           | Suburban          |
| Eastburn Beck         | 0.010    | 1.009     | Alluvial          | Not confined      | Weirs           | Agriculture       |
| Foulness              | 0.007    | 1.039     | Alluvial          | Not confined      | None visible    | Agriculture       |
| Ryburn                | 0.060    | 1.034     | Alluvial          | Not confined      | None visible    | Woodland/suburban |
| Skell                 | 0.011    | 1.030     | Alluvial/sand     | Not confined      | Weirs, Bridges   | Suburban          |
| Spen Beck             | 0.010    | 1.049     | Alluvial          | Not confined      | None visible    | Agriculture       |
| Went                  | 0.006    | 1.013     | Alluvial          | Not confined      | Railway bridge  | Agriculture       |
| Calder                | 0.008    | 1.007     | Alluvial          | Not confined      | None visible    | Agriculture       |
| Church Beck           | 0.017    | 1.007     | Alluvial          | Not confined      | Weir            | Agriculture       |
| Douglas Wigan         | 0.020    | 1.083     | Alluvial/engineered | Confined (Engineered) | Heavily modified | Urban             |
| Eden                  | 0.020    | 1.062     | Alluvial          | Not confined      | None visible    | Agriculture       |
| Eea                   | 0.015    | 1.103     | Alluvial          | Not confined      | None visible    | Agriculture       |
| Heltondale            | 0.021    | 1.033     | Alluvial          | Not confined      | None visible    | Agriculture       |
| Pendle Water          | 0.007    | 1.012     | Alluvial          | Not confined      | None visible    | Agriculture       |
| Swindale Beck         | 0.020    | 1.016     | Alluvial          | Confined          | Weirs           | Agriculture       |

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Gradient was calculated by taking elevations 50-m upstream and 50-m downstream of the flow gauging location; sinuosity was calculated along this same stretch by measuring the thalweg along the river, and the shortest direct path between upstream and downstream points, and dividing the thalweg length by the direct path between the two points. Topsoil, river confinement, river modification and land use were assessed visually through Google Earth Pro.

Site locations:

| Site name           | Flow gauging OS location | Ecology sample OS location | Distance between flow and ecology measurement sites |
|---------------------|--------------------------|----------------------------|---------------------------------------------------|
| Blackfoss Beck      | SE7249147392             | SE7251947416               | 36 m                                              |
| Colne               | SE1364416110             | SE0910914447               | 830 m                                             |
| Crimple Blackstones | SE4013252956             | SE3787951685               | 4000 m                                            |
| Deanne              | SE3497007279             | SE3477007932               | 690 m                                             |
| Eastburn Beck       | SE0203545263             | SE0148144826               | 702 m                                             |
| Foulness            | SE7797637277             | SE7800738044               | 763 m                                             |
| Ryburn              | SE0354718938             | SE0404819773               | 970 m                                             |
| Skell               | SE3157070949             | SE3185270904               | 286 m                                             |
| Spen Beck           | SE2247621023             | SE2261920934               | 242 m                                             |
| Went                | SE5506416309             | SE5650116142               | 1440 m                                            |
| Calder              | SD4978643349             | SD4988943319               | 108 m                                             |
| Church Beck         | SD3063997190             | SD3020097600               | 605 m                                             |
| Douglas Wigan       | SD5861706027             | SD5860906011               | 19 m                                              |
| Eden                | NY6045228312             | NY6039128147               | 175 m                                             |
| Eea                 | SD3643176385             | SD3610076600               | 390 m                                             |
| Heltondale          | NY4943720421             | NY4923520205               | 290 m                                             |
| Pendle Water        | SD8365535455             | SD8365535455               | 296 m                                             |
| Swindale Beck       | NY5146113169             | NY5360016300               | 3800 m                                            |

Site data and geology:

| Site               | Flow data | Superficial deposits                                                                 | Bedrock                              |
|--------------------|-----------|-------------------------------------------------------------------------------------|--------------------------------------|
| Blackfoss Beck     | 1974–2016 | Silty gravelly sand, alluvium (silty clay)                                         | Sandstone and mudstone              |
| Colne              | 1978–2016 | Alluvium, sand and gravel with sandstone                                           | Mudstone                             |
| Crimple Blackstones| 2000–2016 | Alluvium (clay, silt, sand and gravel)                                              | Sandstone and mudstone              |
| Deanne             | 1960–2016 | Alluvium (clay and silt)                                                            | Sandstone                            |
| Eastburn Beck      | 1988–2016 | Alluvium (clay, silt, sand and gravel), Alluvial fan deposits (clay, silt, sand and gravel) | Sandstone and mudstone              |
| Foulness           | 2000–2016 | Alluvium (silty clay), clayey sand, silty clay                                      | Mudstone                             |
| Ryburn             | 1981–2016 | Alluvium (clay, sand, and gravel)                                                   | Sandstone                            |
| Skell              | 1984–2016 | Alluvium (clay, silt, sand and gravel)                                              | Mudstone (calcerious)                |
| Spen Beck          | 1982–2016 | Alluvium (clay, sand and gravel)                                                    | Sandstone, mudstone, and siltstone   |
Details on modification:

| Site                  | Flow data | Superficial deposits                                                                 | Bedrock                                                                                                                                                                                                 |
|-----------------------|-----------|--------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Went                  | 1979–2016 | Alluvium (clay, sand and gravel) with nearby silty clay deposits                     | Mudstone, sandstone, and dolomitic limestone local (lack of data resolution to see specific bedrock at sample site)                                                                                    |
| Calder                | 1997–2016 | Alluvium (clay, sand and gravel)                                                     | Sandstone                                                                                                                                                                                             |
| Church Beck           | 2001–2017 | Alluvium (silt and gravel)                                                           | Siltstone and mudstone local (lack of data resolution to see specific bedrock at sample site)                                                                                                |
| Douglas (Wigan)       | 1977–2014 | Alluvium (clay, silt, sand and gravel)                                               | Mudstone, siltstone, and sandstone                                                                                                                                                                  |
| Eden                  | 1964–2017 | Till (diamicton)                                                                     | Sandstone                                                                                                                                                                                             |
| Eea                   | 2005–2017 | Clay, silt, sand, and gravel                                                         | Mudstone, siltstone, and sandstone                                                                                                                                                                  |
| Heltondale            | 1998–2016 | Till (diamicton)                                                                     | Sandstone                                                                                                                                                                                             |
| Pendle Water          | 1976–2016 | No superficial deposit data available around site, closest visible deposits are Alluvium (clay, silt, sand and gravel) and Till (diamicton) | Mudstone and sandstone                                                                                                                                                                                |

APPENDIX 2

Temporal and magnitude-based trait combinations used in modelling.
Note that combinations with a P value of 0.2 or greater were not given further statistical consideration in terms of $R^2$ or AIC
### TABLE B1  Spring LIFE score multivariate model fitting results

| Variable 1 | Variable 2 | p   | $R^2$ | AIC  |
|------------|------------|-----|-------|------|
| HighFreq   | None       | 0.056 | 0.161 | 40.256 |
| HighFreq   | MINYR      | 0.1366 | 0.131 | 41.72 |
| HighFreq   | Q25        | 0.138 | 0.13 | 41.743 |
| HighFreq   | MeanMag    | 0.1628 | 0.11 | 42.141 |
| HighFreq   | RNGYR      | 0.1697 | 0.105 | 42.241 |
| HighFreq   | MAXYR      | 0.1699 | 0.1052 | 42.243 |
| LowDura    | None       | 0.45 | n/a | n/a |
| LowDura    | Q25        | 0.5231 | n/a | n/a |
| LowDura    | MINYR      | 0.5235 | n/a | n/a |
| LowFreq    | None       | 0.55 | n/a | n/a |
| HighDura   | MINYR      | 0.5605 | n/a | n/a |
| HighDura   | None       | 0.6 | n/a | n/a |
| LowFreq    | Q25        | 0.6244 | n/a | n/a |
| LowDura    | MeanMag    | 0.636 | n/a | n/a |
| LowFreq    | RNGYR      | 0.6727 | n/a | n/a |
| LowFreq    | MAXYR      | 0.6766 | n/a | n/a |
| LowDura    | RNGYR      | 0.6808 | n/a | n/a |
| LowDura    | MAXYR      | 0.6848 | n/a | n/a |
| HighDura   | Q25        | 0.69 | n/a | n/a |
| HighDura   | RNGYR      | 0.7153 | n/a | n/a |
| HighDura   | MAXYR      | 0.7218 | n/a | n/a |
| LowFreq    | MeanMag    | 0.735 | n/a | n/a |
| LowFreq    | MINYR      | 0.7382 | n/a | n/a |
| HighDura   | MeanMag    | 0.822 | n/a | n/a |

### TABLE B2  Autumn LIFE score multivariate model fitting results

| Variable 1 | Variable 2 | p   | $R^2$ | AIC  |
|------------|------------|-----|-------|------|
| HighFreq   | None       | 0.0157 | 0.2561 | 34.872 |
| LowDura    | None       | 0.0543 | 0.1539 | 37.317 |
| HighFreq   | MINYR      | 0.0545 | 0.2181 | 36.666 |
| HighFreq   | Q25        | 0.0552 | 0.2167 | 36.699 |
| HighFreq   | RNGYR      | 0.0581 | 0.2117 | 36.82 |
| HighFreq   | MAXYR      | 0.0582 | 0.2116 | 36.823 |
| HighFreq   | MeanMag    | 0.0593 | 0.2097 | 36.869 |
| LowDura    | MINYR      | 0.1011 | 0.1552 | 38.135 |
| LowDura    | Q25        | 0.1298 | 0.1284 | 38.729 |
| LowDura    | RNGYR      | 0.1422 | 0.1184 | 38.946 |
| LowDura    | MAXYR      | 0.1434 | 0.1175 | 38.965 |
| LowDura    | MeanMag    | 0.1478 | 0.1141 | 39.038 |
| HighDura   | Q25        | 0.6611 | n/a | n/a |
| LowFreq    | RNGYR      | 0.8038 | n/a | n/a |
### TABLE B2  (Continued)

| Variable 1  | Variable 2 | \( p \)  | \( R^2 \) | AIC |
|-------------|-------------|-----------|-----------|-----|
| HighDura    | RNGYR       | 0.8039    | n/a       | n/a |
| HighDura    | MAXYR       | 0.8087    | n/a       | n/a |
| LowFreq     | MAXYR       | 0.8088    | n/a       | n/a |
| LowFreq     | Q25         | 0.8132    | n/a       | n/a |
| LowFreq     | MINYR       | 0.8468    | n/a       | n/a |
| HighDura    | MINYR       | 0.8698    | n/a       | n/a |
| HighDura    | MeanMag     | 0.8727    | n/a       | n/a |
| LowFreq     | None        | 0.8966    | n/a       | n/a |
| HighDura    | None        | 0.9093    | n/a       | n/a |
| LowFreq     | MeanMag     | 0.9224    | n/a       | n/a |

### TABLE B3  Spring velocity trait score multivariate model fitting results

| Variable 1  | Variable 2 | \( p \)  | \( R^2 \) | AIC |
|-------------|-------------|-----------|-----------|-----|
| HighFreq    | None        | 0.0376    | 0.1959    | 49.79 |
| HighFreq    | Q25         | 0.055     | 0.2302    | 49.847 |
| LowDura     | Q25         | 0.0666    | 0.2103    | 50.307 |
| LowDura     | None        | 0.0793    | 0.1287    | 51.237 |
| HighFreq    | RNGYR       | 0.0802    | 0.1905    | 50.752 |
| HighFreq    | MAXYR       | 0.081     | 0.1893    | 50.778 |
| HighFreq    | MeanMag     | 0.0937    | 0.1735    | 51.126 |
| HighDura    | None        | 0.094     | 0.11      | 51.573 |
| HighFreq    | MINYR       | 0.1041    | 0.1618    | 51.378 |
| LowDura     | MeanMag     | 0.1187    | 0.147     | 51.693 |
| LowDura     | RNGYR       | 0.197     | n/a       | n/a |
| LowDura     | MAXYR       | 0.197     | n/a       | n/a |
| LowDura     | MINYR       | 0.225     | n/a       | n/a |
| HighDura    | Q25         | 0.2314    | n/a       | n/a |
| HighDura    | MINYR       | 0.252     | n/a       | n/a |
| HighDura    | MeanMag     | 0.2573    | n/a       | n/a |
| HighDura    | RNGYR       | 0.259     | n/a       | n/a |
| HighDura    | MAXYR       | 0.259     | n/a       | n/a |
| LowFreq     | Q25         | 0.3697    | n/a       | n/a |
| LowFreq     | MeanMag     | 0.6084    | n/a       | n/a |
| LowFreq     | None        | 0.77      | n/a       | n/a |
| LowFreq     | MINYR       | 0.827     | n/a       | n/a |
| LowFreq     | RNGYR       | 0.934     | n/a       | n/a |
| LowFreq     | MAXYR       | 0.936     | n/a       | n/a |
| Variable 1 | Variable 2 | p     | $R^2$ | AIC  |
|------------|------------|-------|-------|------|
| HighFreq   | None       | 0.01335 | 0.269 | 69.421|
| HighFreq   | Q25        | 0.03   | 0.2742| 70.135|
| LowDura    | None       | 0.0352 | 0.1906| 71.357|
| HighFreq   | RNGYR      | 0.0467 | 0.2329| 71.186|
| HighFreq   | MAXYR      | 0.0468 | 0.2328| 71.188|
| LowDura    | Q25        | 0.046  | 0.2345| 71.146|
| HighFreq   | MeanMag    | 0.0458 | 0.2349| 71.136|
| LowDura    | MINYR      | 0.0515 | 0.2235| 71.417|
| LowDura    | MeanMag    | 0.0752 | 0.1859| 72.314|
| LowDura    | MINYR      | 0.0981 | 0.1584| 72.947|
| LowDura    | MAXYR      | 0.1165 | 0.1401| 73.354|
| LowDura    | RNGYR      | 0.1165 | 0.1401| 73.355|
| HighDura   | None       | 0.3449 | n/a   | n/a  |
| HighDura   | Q25        | 0.4644 | n/a   | n/a  |
| HighDura   | MINYR      | 0.496  | n/a   | n/a  |
| LowFreq    | Q25        | 0.509  | n/a   | n/a  |
| HighDura   | RNGYR      | 0.527  | n/a   | n/a  |
| HighDura   | MAXYR      | 0.5277 | n/a   | n/a  |
| HighDura   | MeanMag    | 0.5445 | n/a   | n/a  |
| LowFreq    | MeanMag    | 0.75   | n/a   | n/a  |
| LowFreq    | None       | 0.8729 | n/a   | n/a  |
| LowFreq    | MAXYR      | 0.9712 | n/a   | n/a  |
| LowFreq    | RNGYR      | 0.9713 | n/a   | n/a  |
| LowFreq    | MINYR      | 0.984  | n/a   | n/a  |

| Variable 1 | Variable 2 | p     | $R^2$ | AIC  |
|------------|------------|-------|-------|------|
| LowFreq    | None       | 0.0132 | 0.301 | 12.518|
| LowFreq    | RNGYR      | 0.0278 | 0.3148| 13.005|
| LowFreq    | MAXYR      | 0.0281 | 0.3139| 13.028|
| LowFreq    | MINYR      | 0.0394 | 0.28  | 13.849|
| LowFreq    | Q25        | 0.0426 | 0.2719| 14.039|
| LowFreq    | MeanMag    | 0.0472 | 0.2611| 14.289|
| LowDura    | MINYR      | 0.14   | n/a   | n/a  |
| HighFreq   | MINYR      | 0.14   | n/a   | n/a  |
| HighDura   | MINYR      | 0.14   | n/a   | n/a  |
| LowDura    | None       | 0.2016 | n/a   | n/a  |
| LowDura    | RNGYR      | 0.3757 | n/a   | n/a  |
| LowDura    | MAXYR      | 0.38   | n/a   | n/a  |
### Table B5  (Continued)

| Biodiversity—Spring | Variable 1 | Variable 2 | \( p \) | \( R^2 \) | AIC |
|---------------------|------------|------------|---------|---------|-----|
| LowDura Q25         | 0.42       | n/a        | n/a     |
| LowDura MeanMag     | 0.4515     | n/a        | n/a     |
| HighDura None       | 0.4613     | n/a        | n/a     |
| HighDura RNGYR      | 0.55       | n/a        | n/a     |
| HighDura MAXYR      | 0.5636     | n/a        | n/a     |
| HighDura Q25        | 0.76       | n/a        | n/a     |
| HighDura MeanMag    | 0.77       | n/a        | n/a     |
| HighFreq None       | 0.9322     | n/a        | n/a     |
| HighFreq MeanMag    | 0.97       | n/a        | n/a     |
| HighFreq Q25        | 0.99       | n/a        | n/a     |

### Table B6  Autumn biodiversity multivariate model fitting results

| Biodiversity—Autumn | Variable 1 | Variable 2 | \( p \) | \( R^2 \) | AIC |
|---------------------|------------|------------|---------|---------|-----|
| HighDura None       | 0.18       | n/a        | n/a     |
| HighDura RNGYR      | 0.29       | n/a        | n/a     |
| HighDura MAXYR      | 0.29       | n/a        | n/a     |
| LowDura RNGYR       | 0.31       | n/a        | n/a     |
| LowDura MAXYR       | 0.32       | n/a        | n/a     |
| LowDura None        | 0.36       | n/a        | n/a     |
| HighDura Q25        | 0.39       | n/a        | n/a     |
| HighDura MeanMag    | 0.4        | n/a        | n/a     |
| HighDura MINYR      | 0.42       | n/a        | n/a     |
| HighFreq RNGYR      | 0.42       | n/a        | n/a     |
| LowFreq RNGYR       | 0.43       | n/a        | n/a     |
| LowFreq MAXYR       | 0.43       | n/a        | n/a     |
| LowDura MeanMag     | 0.6        | n/a        | n/a     |
| LowDura Q25         | 0.62       | n/a        | n/a     |
| LowDura MINYR       | 0.64       | n/a        | n/a     |
| HighFreq None       | 0.65       | n/a        | n/a     |
| LowFreq None        | 0.7        | n/a        | n/a     |
| LowFreq Q25         | 0.78       | n/a        | n/a     |
| LowFreq MeanMag     | 0.79       | n/a        | n/a     |
| HighFreq MAXYR      | 0.8        | n/a        | n/a     |
| HighFreq MeanMag    | 0.8        | n/a        | n/a     |
| HighFreq Q25        | 0.8        | n/a        | n/a     |
| HighFreq MINYR      | 0.9        | n/a        | n/a     |
| LowFreq MINYR       | 0.92       | n/a        | n/a     |
APPENDIX 3

This appendix demonstrates that the use of datasets of differing length has a negligible impact on data, and their use is a justifiable approach. Four randomly selected sites from the dataset were chosen for this demonstration.

Before going into each individual site, a table is presented to show the range of values across all sites (maximum value minus minimum value) for each of the described metrics, so as to put any differences between full and shortened periods into perspective.

| Metric                        | Range across sites (max–min) |
|-------------------------------|-----------------------------|
| Mean annual flow (m$^2$/s)    | 2.52                        |
| Low flow frequency            | 12.03                       |
| Low flow duration (days)      | 16.41                       |
| High flow frequency           | 23.95                       |
| High flow duration (days)     | 2.58                        |

The above table will demonstrate, when the results below are observed, that the differences shown between the full and shortened datasets at any single site are very minor relative to the full range of the data across sites.

Blackfoss Beck (1974–2016) shows a higher occurrence of extreme events in recent years, but overall metrics for flow frequencies and durations see little change when comparing a full dataset with a 1998–2016 dataset. The mean daily flow between the two datasets does see some differences despite the majority of the dataset having regular flow patterns; as mentioned, this may be because of the decreased resilience to extreme events in the case of shorter datasets.

Church Beck (2003–2017) is mostly similar when comparing the full and the shortened datasets (2011–2017). The most significant difference between datasets is the mean duration of low flow events. Given that there is little change in mean annual flow or the frequency of low flows, it is possible that one or two extreme events are driving this discrepancy. Given that the shortened dataset in this case is only
6 years, this seems a good possibility—given that a shorter dataset will become increasingly less resilient to the influence of such events.

Colne (1978–2016) shows little characteristic change in terms of overall flow patterns across the dataset, and retains a very similar mean daily flow when comparing full and limited (1997–2016) datasets. High flow frequency and durations also remain similar between ranges of time. Low flows see some differences between full and shortened datasets; based on the similarities of all other metrics, this is likely because of the influence of extreme low flow events having a greater influence over the shorter dataset, and arguably the longer dataset better reflects mean and long-term conditions.

Heltondale Beck (1998–2016) has almost identical mean annual flows between full and shortened datasets (2006–2016). High and low flow duration and frequency are likewise almost identical between the two time periods. This flow time series appears to have few, if any, extreme events, which is likely why the shortened dataset remains so closely aligned to the metrics of the full dataset.

To conclude on the results of this testing, we believe that there is good evidence that the length of the time series carries only a minor impact on calculated IHA metrics, justifying the approach used. We would also mention that overly shortening time series data would theoretically decrease the resilience of our metrics to extreme events, meaning that longer time series would be expected to better characterize the general hydrological character of each site, and hence we have used as much data as was available for each site. Graphs providing a visual illustration of differences between datasets for each metric follow.
