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The use of indices of flow variability in assessing the hydrological and instream habitat impacts of upland afforestation and drainage

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Abstract

Although the impact of plantation forestry and ground-preparation drainage on headwater runoff response has been widely studied, there are remaining uncertainties concerning the time scale of changes, scale effects of catchment size and impacts on flow variability. Flow variability, along with changes in sediment loads and water quality, is likely to be a defining element of the overall instream habitat quality of headwater catchments. In this paper a method is described for the characterisation of flow variability using 15-min data on the 1.5 km^2 Coalburn catchment, from 1967 to 1998, over a period of change from natural moorland to closed canopy coniferous forest. The method is based on annual number, and average and total duration of pulses above selected threshold flows but decouples the effects of variable annual rainfall. The number of pulses increased from pre- to post-drainage but pulse number has declined steadily and pulse duration increased with forest growth—the catchment has become more, then less ‘flashy’. The method provides a comprehensive, continuous and quantitative picture of changes in hydrological regime that is relevant to current assessments of instream physical habitat and ‘environmentally acceptable flows’.

It is possible that low invertebrate numbers and low levels of fish recruitment in the Coalburn channel may be in part attributable to changes in flow regime. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Hydrology; Flow regime; Land-use impacts; Freshwater ecology; Forests

1. Introduction

Hydrological research has established convincing links between land-use change, land management practices and the runoff regime, especially in headwater areas. These headwater areas are seen as vital by catchment managers concerned with biodiversity (Furze et al., 1991). Commercial plantation forestry has attracted much of the hydrological research activity (especially in the UK), occurring as it does largely in upland areas of high rainfall, moderate relief and sensitive soils; however, to date research related to habitat impacts has been largely restricted to acidification (Mounsey and Newson, 1995). When it is stated that the links made have been ‘convincing’, this is in part due to the robust simplicity of the flow analyses and modelling techniques that have been employed, e.g. water balances, source-area hydrographs and flow-duration curves (comparisons with the current method are given by Archer (2000)). These techniques have been used because they are standards for the water industry, the main traditional

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beneficiaries of the research findings (e.g. Kirby et al., 1992; Robinson et al., 1998). However, with increasing focus on freshwater ecosystems from policies aimed at 'sustainable river basin management', the impacts of land-use and land management upon instream flow conditions may need new survey, data capture and analytical techniques in geomorphology (Padmore, 1998), water quality (Newson et al., 2001) and hydrology. This paper makes a contribution to the latter category by using the *complete flow record* and making a *fuller description of the flow regime* (both 'natural' and as modified by catchment/flow management), a development called for by Petts (1996).

2. Upland afforestation in the UK: background

Approximately 10% of the UK is wooded and just over one half of that is coniferous woodland, predominantly upland plantations. The area has doubled since the beginning of the twentieth century and further forestry development is planned throughout the UK (HMSO, 1995), although currently lowland broadleaved plantations have gained in policy preference.

Since much plantation forestry occurred in the past in poorly drained wet upland soils, including peat, forest planting has been preceded by ground preparation involving intensive cultivation and open ditch drainage. In addition to forestry drainage, large areas of upland and lowland have been drained for agricultural purposes in the UK which is one of the most extensively drained countries in Europe. Government grants for drainage were available from the 1940s until 1985 and during that period extensive upland drainage occurred with the object of lowering the water table and improving grass and heather growth for sheep and grouse (Johns, 1997).

The impact of forestry and drainage on headwater runoff response has not been widely studied but there have been summaries of results in the UK for forestry by Hudson and Blackie (1993) and for other forms of drainage by Robinson and Rycroft (1999). Although there is now broad consensus on the (often separate) effects of drainage and afforestation on runoff volumes, on low flows and on the magnitude and time distribution of flood flows (Robinson et al., 1998), there are remaining uncertainties which limit the capacity of resulting models to give quantitative predictions of impacts on ungauged catchments or on new sites of drainage and afforestation. Three specific areas are noted:

(1) Drainage and afforestation may have opposite effects on runoff response, notably with respect to volume. Water losses from mature forest exceed those from moorland vegetation due to greater evaporation from intercepted precipitation on aerodynamically rougher conifer canopies (Calder, 1990). Bosch and Hewlett (1982) in a review of 94 catchments on four continents concluded that conifer forests reduce yield on average by 40 mm per 10% forest cover. However, pre-plantation forest cultivation and drainage generally results in increased runoff, with effects persisting at least until canopy closure (Robinson, 1998). There is uncertainty concerning the time scale of change from the early dominance of drainage effects to later dominance of the closed canopy.

(2) Most studies of the hydrological impacts of drainage and afforestation have been conducted on small experimental catchments, generally less than 25 km^2 and frequently less than 1 km^2. There is uncertainty concerning scale effects and the applicability of results to larger, partially drained or afforested catchments (Newson, 1997). There is a widespread popular impression in upland rural Britain that drainage and/or afforestation have resulted in floods of greater intensity and shorter duration than in the past (on large as well as small catchments). Such impressions (particularly by anglers) have not been widely substantiated by hydrological analysis but data from the hydrometric network have not been seen as presenting opportunities for such research. On one river, the Wear in northern England, analysis using methods described below suggested that no such changes in hydrological response had occurred on a 172 km^2 catchment from 1960 to 1998, despite quite a range of land-use change on the catchment (Archer, 2000).

(3) One important aspect of hydrological behaviour, namely flow variability, has rarely been studied with respect to land use changes. Flow variability or *hydrological disturbance* is, on the one hand, a potential indicator of land use change but is also an important control on river ecology. Some biologists believe that hydrological disturbance is the dominating factor in stream ecology (Resh et al., 1988).

Clausen and Biggs (1997) showed that measures of flow variability, amongst all tested flow parameters had the most significant correlations with biological variates including species richness and diversity; impacts of coniferous afforestation on benthic invertebrates and fish have been widely recorded in the UK uplands. Newson and Newson (2000) indicate that flow exceedance values determine, via the interaction with bed morphology and substrates, hydraulic conditions for channel biota. However, flow exceedance values, along with most other routine hydrological analyses, do not indicate the degree of disturbance deriving from flow events; disturbance is a key element of instream habitat.

This paper describes a method specifically to address the third issue of the impact of drainage and afforestation on flow variability, using the already well-documented Coalburn catchment (Robinson, 1980, 1998). It also tracks the changes in flow variability over the period of profound land-use change on the catchment from natural moorland to closed canopy coniferous forest.

3. The catchment

The Coalburn catchment is a rolling upland catchment with an area of 1.5 km^2 and varying in altitude from 270 to 330 m OD (Fig. 1). Much of the catchment has a cover of blanket peat, 0.5–3 m thick overlying glacial till up to 5 m in thickness. The catchment originally had moorland vegetation of *Molinia* grassland and peat bog species and was used for rough grazing by sheep. It was ploughed in 1972 with ditches 0.8 m deep at 4.5 m spacing giving a drainage density of about 200 km/km^2 and 60 times greater than the original stream network. Turf ridges were created adjacent to the furrows from the excavated material to provide drier elevated sites for planting. In addition, a network of collector drains was excavated to link the furrow system.

The catchment was planted, predominantly with Sitka spruce (*Picea sitchensis*) in spring 1973; 90% of the catchment was planted. Growth rates have been variable and relatively slow in places, reaching 1 m height in 1978 and 7–12 m in 1996, by which time

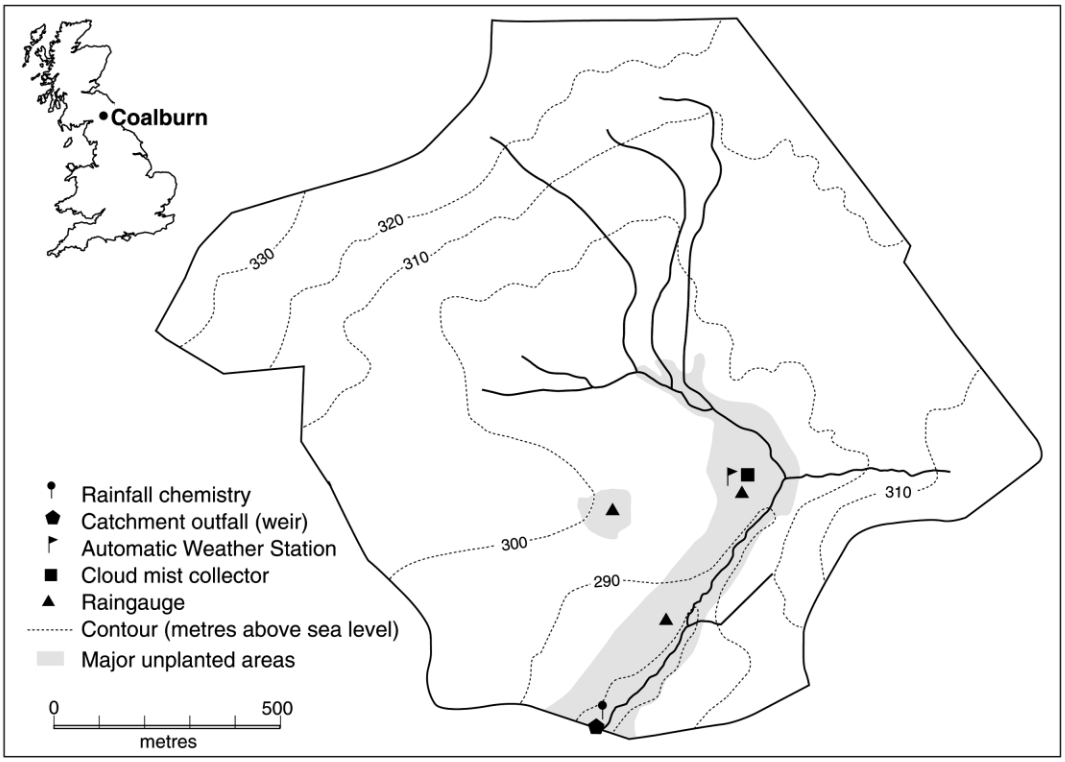

Fig. 1. Map of Coalburn catchment and its location in northern England.

some 60% of the catchment had reached canopy closure (Robinson et al., 1998).

Surveys of instream biota (fish, invertebrates) in 1993 (Robinson et al., 1998) revealed that whilst stocks of brown trout (*Salmo trutta*) were not pathologically low as in forested streams which have become highly acidified, the lack of mayflies (Ephemeroptera), Mollusca and Crustaceans, gave rise to concerns about biodiversity. Acidification is episodic, not chronic, at Coalburn (Mounsey and Newson, 1995) and whilst the flow gauging weir attracts attention as a possible complication to fish recruitment, this is the first consideration of instream physical habitat in the catchment in relation to biodiversity issues.

4. Data

Streamflow data are the primary requirement for this analysis and measurement is made by Crump weir at a site on a bedrock outcrop, thus minimising the possibility of leakage. A flow data archive at 15-min intervals, based on measurements using a punched tape recorder or logger is available from 1967 to 1998. The record for 1991 is not available in an appropriate format and there are missing data periods of several months in 1972 and 1973, unfortunately during the period between ditching and planting and also in the driest sequence of years in the record.

An automatic weather station has operated since 1971 and weekly rainfall is measured at four ground level gauges (records from 1967).

4.1. Characterisation of hydrological disturbance

Ideally an effective method to define hydrological disturbance with respect to influences of land use change should have the following properties:

- It should focus on those attributes of flow which are said to have been influenced by land use change, i.e. the *number and frequency of rises and falls* above selected levels (pulses) and their duration
- The *measurement interval* considered should be sufficiently short to detect effects of land use on a small catchments such as Coalburn. Daily mean flows are unlikely to be an adequate basis for analysis when catchment lag is much less than one day (one to three hours at Coalburn). A continuous record or measurement at a sub-daily interval is required.
- There is a natural variability in the level of flow disturbance regime from year to year due to the sequence of weather and climate. There should be a means of *decoupling the effect of climate and weather* of a particular period from the effects of land use.
- It should permit the *detection of step changes and trends* in disturbance characteristics at a site and their validation by statistical tests.
- It should provide a means of *comparison between rivers* and between different locations on the same river.
- The indices should also have a demonstrable *link to measurable ecological properties* such as living and total biomass and species richness and diversity.

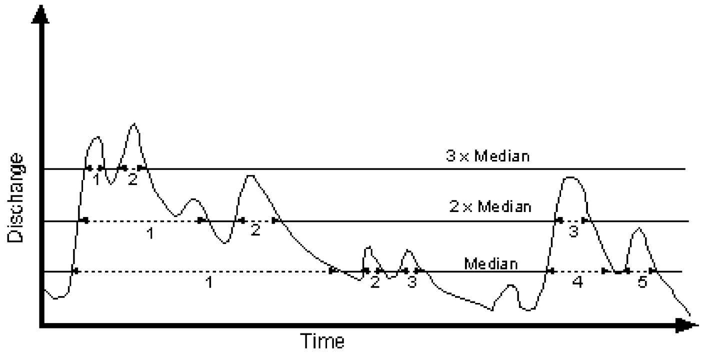

Fig. 2. Definition diagram showing numbered pulses above selected thresholds and pulse duration (between arrows).

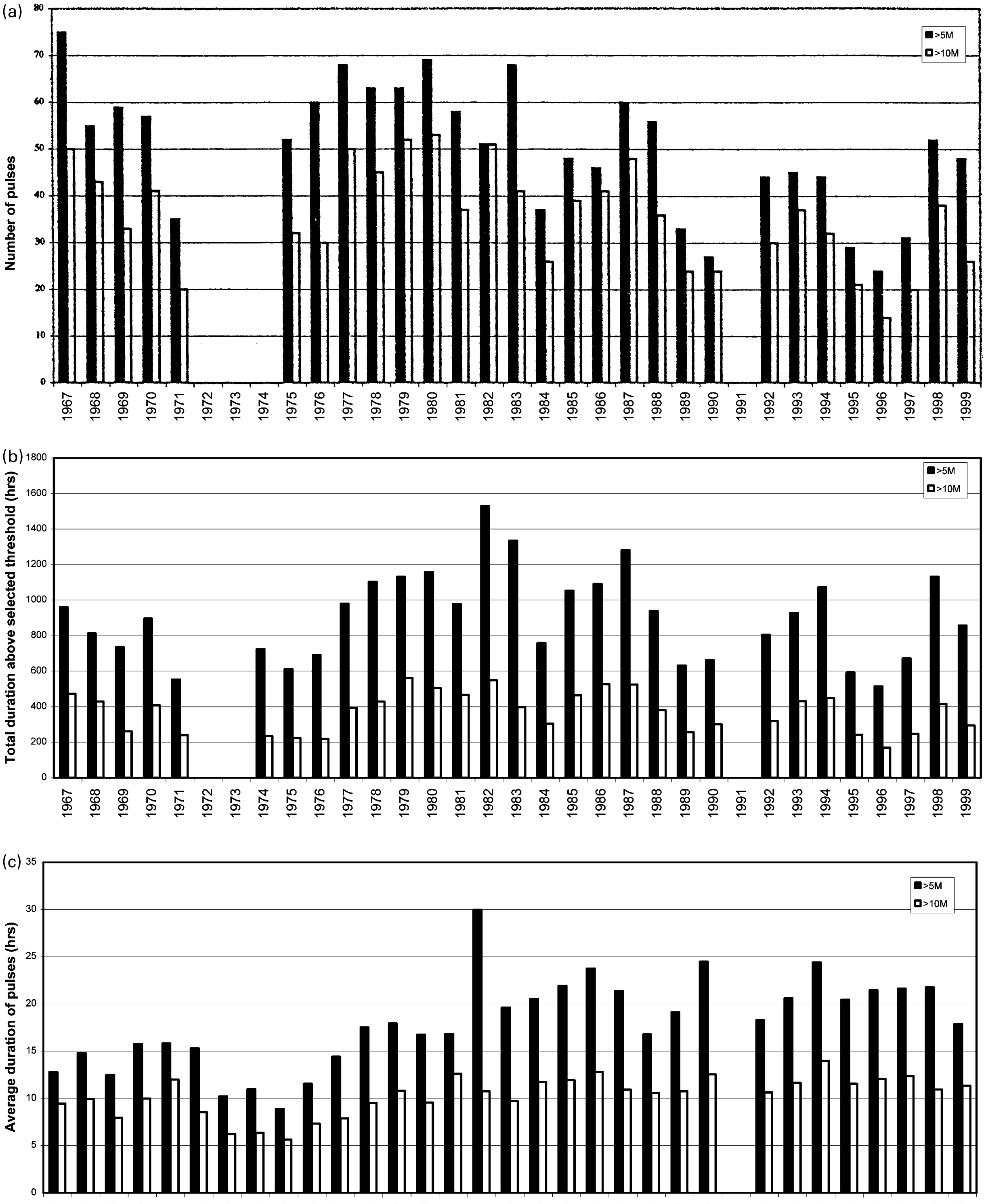

Fig. 3. Time series of (a) pulse numbers (b) total pulse duration and (c) average pulse duration above 5 and 10 times the median flow (5*M* and 10*M*) thresholds.

5. Method

This analysis of hydrological disturbance is based on the frequency and duration of pulses above threshold flows, selected as multiples of the median flow (Fig. 2). A pulse is an occurrence of a rise above a given flow and pulse duration (between arrows on the figure) is the time from rising above the threshold to falling below the same threshold. Data were analysed in yearly blocks, using a purpose-built computer program to scan the 15-min digital flow data. For each year from 1967 the total number of pulses was counted and the total duration above the threshold for the year and the mean duration per pulse was computed. Incomplete pulses at the beginning and end of the year were excluded. The full spectrum of disturbance was assessed by repeating for 18 selected multiples of median flow (M) as $0.5M$, M, $2M$, $3M$, $4M$, $5M$, $6M$, $7M$, $8M$, $10M$, $15M$, $20M$, $30M$, $40M$, $50M$, $60M$, $80M$ and $100M$. The median flow has been taken over the whole period, though it has been shown to change, but only slightly from the adopted value of 0.020 cumecs, equivalent to 43% of the mean flow.

For the incomplete years in 1972 and 1973, only mean duration was computed for the available period. As examples, pulse number time series for $5M$ and $10M$ are shown in Fig. 3a and for total duration above the same threshold and average duration in Fig. 3b and c.

The method is a development of procedures defined in Archer and Williams (1995) to define and evaluate the degree of hydrological disturbance resulting from different regulating policies on the River Tyne downstream from Kielder Reservoir and hydropower scheme. It was also used to evaluate impacts of moorland gripping without afforestation (Archer, 2000). Similar analysis was carried out in New Zealand by Clausen and Biggs (1997) but using daily rather than sub-daily data.

This initial analysis suggested that the data showed both trend and step changes related to land use change. Pulse number and duration above each threshold were therefore calculated for the entire period and for four time blocks:

1967–1971: Pre-drainage and planting
1974–1982: Immediate post-planting
1983–1990: Intermediate period
1992–1999: Approaching/reaching canopy closure.

The relationship between *pulse number* and flow threshold is shown in Fig. 4a for the full period and for each of the sub-periods. Pulse numbers are at a maximum at $3M$. At higher flows they obviously decline because of the less frequent occurrence of high flows. Below $3M$ they have a small number due to increased duration and coalescence of pulses. In wet years the flow may fall less frequently below $0.5M$ and M, thus also resulting in fewer pulses.

Total annual pulse duration (Fig. 4b) is essentially a transformation of the flow duration curve. However, since only completed pulses were included, a protracted time period above the threshold at the beginning and end of each year could be excluded from the duration.

The *mean duration of pulses* (Fig. 4c) decreases with increasing flow. Since mean duration becomes much higher at $0.5M$ and M, they have been excluded from Fig. 4c to allow suitable scaling for higher flows.

Part of the variation in each of the measures is due to the weather and climate conditions of the particular year. To assess the impact of climate (and to isolate its effects from those of catchment and land use conditions), correlation and regression analyses were carried out between each set of annual pulse numbers, total and mean duration and the annual catchment rainfall for 1967–1999, as provided by the National Water Archive based on the gauges within the catchment.

Table 1 shows the results of this regression analysis. Although the correlation coefficients are not high, with the highest for total pulse duration at $15M$ and $20M$ exceeding $+0.7$, the slopes and intercepts of the regressions show stable and consistent patterns. The relationships deteriorate sharply at low flows and more gradually at high flows. The basis for the use of the simple measure of annual rainfall to account for the influence of annual variation in climate depends on the previous experience with using the method for a catchment for which there was no evidence of effects of land use (Archer, 2000). That analysis

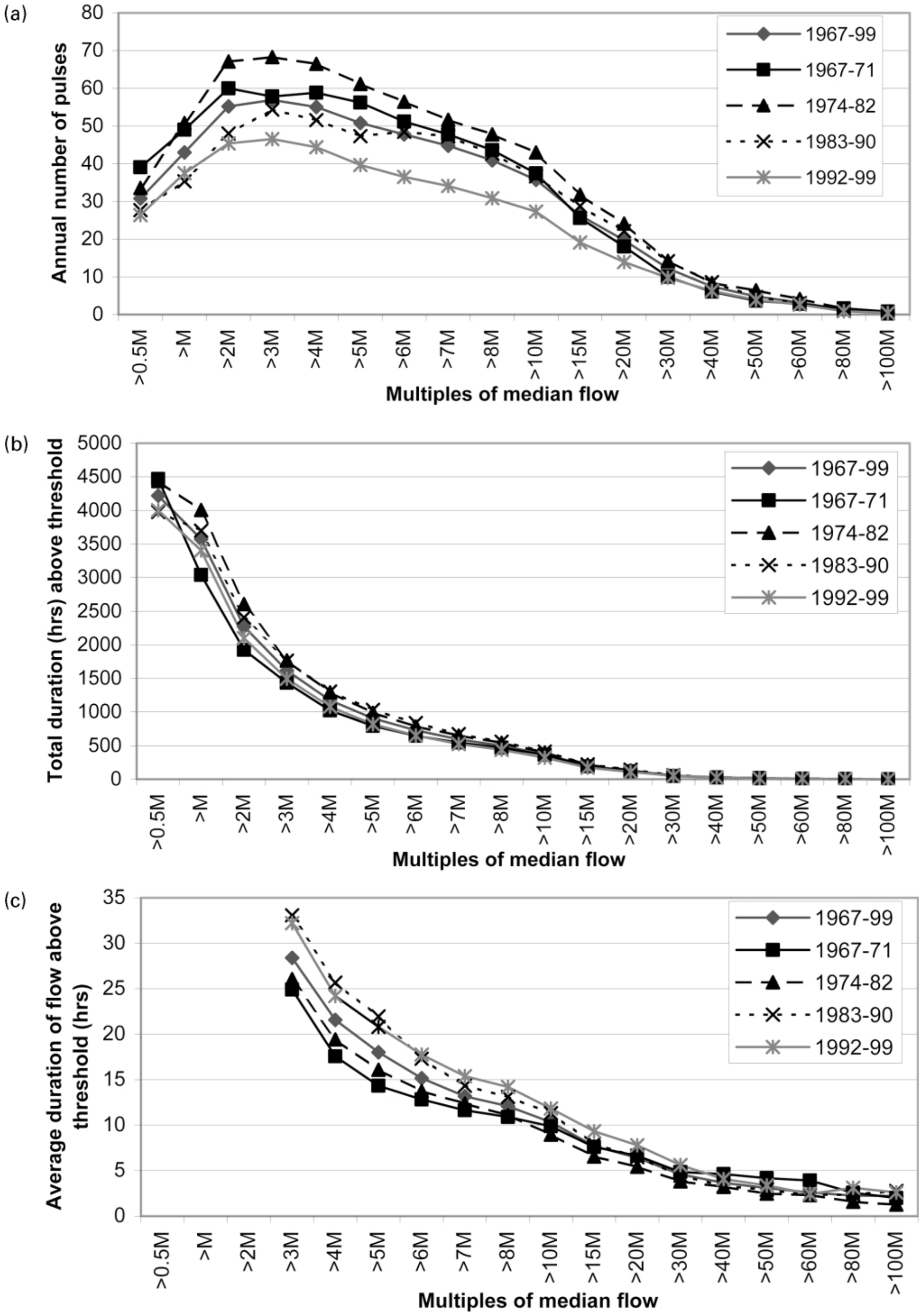

Fig. 4. (a) pulse number, (b) total pulse duration and (c) average pulse duration for Coalburn over the full range of flow and comparing pre- and post-drainage and planting periods.

Table 1
Correlation and regression statistics for relationships between annual rainfall and pulse numbers, total and annual duration for selected multiples of median flow (note: figures in bold are significant at 95% level)

	0.5*M*	*M*	2*M*	3*M*	4*M*	5*M*	6*M*	7*M*	8*M*	10*M*	15*M*	20*M*	30*M*	40*M*	50*M*	60*M*	80*M*
Regression between annual rainfall and number of pulses																	
Corr coeff (r)	−0.27	−0.19	−0.04	0.15	0.19	0.30	0.34	**0.42**	**0.52**	**0.49**	**0.62**	**0.64**	**0.63**	**0.58**	**0.46**	0.29	0.38
Slope	−0.010	−0.015	−0.003	0.012	0.016	0.024	0.025	0.030	0.034	0.031	0.034	0.029	0.018	0.010	0.006	0.003	0.002
Intercept	43.7	62.6	59.4	40.8	35.0	19.4	15.7	5.97	−3.44	−3.79	−17.7	−17.8	−11.5	−5.34	−3.16	−0.64	−1.84
Regression between annual rainfall and total annual duration of pulses																	
Corr coeff (r)	−0.11	0.33	**0.42**	**0.48**	**0.50**	**0.56**	**0.59**	**0.64**	**0.65**	**0.69**	**0.74**	**0.70**	**0.67**	**0.57**	**0.46**	**0.38**	0.30
Slope	−0.64	1.36	1.16	1.11	0.90	0.81	0.72	0.63	0.56	0.46	0.31	0.20	0.09	0.04	0.02	0.01	0.00
Intercept	5038.4	1781.2	762.4	165.6	6.1	−149.6	−214.4	−222.4	−225.5	−223.9	−198.6	−128.9	−61.1	−27.7	−14.7	−8.6	−3.6
Regression between annual rainfall and mean duration of pulses																	
Corr coeff (r)	0.17	**0.55**	**0.51**	**0.49**	**0.48**	**0.40**	**0.52**	**0.50**	**0.40**	**0.44**	0.26	0.15	0.06	0.14	0.08	0.13	−0.15
Slope	0.043	0.090	0.035	0.018	0.013	0.010	0.009	0.008	0.005	0.005	0.002	0.001	0.0004	0.001	0.0005	0.0011	−0.000
Intercept	79.22	−28.76	−2.570	5.505	4.540	4.896	3.0926	3.429	5.154	3.979	4.348	4.839	3.985	2.321	2.400	1.102	3.586

for the River Wear gave correlation coefficients between the disturbance indices and annual rainfall which were much higher than at Coalburn (r average of 0.82 for pulse numbers between 5*M* and 20*M*; and 0.88 for total pulse duration—compared with equivalent figures for Coalburn of 0.48 and 0.65). For the River Wear the standard deviation of the number of pulses and total pulse duration was more than halved by accounting for the effects of climate, using annual rainfall only.

The lower correlation coefficients for the Coalburn are postulated as due to the additional effect of land use change. An example plot of the relationship between annual rainfall and pulse numbers over the 20*M* threshold (Fig. 5) shows how the number of pulses for given rainfall, shifts over periods of land use change. The pre-drainage pulse numbers (years labelled in plain text) are close to the mean regression line. Post drainage pulse numbers (italic) are generally above the regression line whilst during the period of approaching forest maturity (bold), pulse numbers are always below the mean regression line. It was therefore considered appropriate to use the linear relationships for the full data sets as a basis for removing the effect of rainfall variability.

For each year and flow threshold, the expected number and duration of pulses was calculated from catchment rainfall using the appropriate equation in Table 1. This expected number was then subtracted from the observed value to give a residual with zero mean for the full period.

The time series of *residuals of pulse numbers* (which represents the departures from the regression line with rainfall) is shown as an example in Fig. 6a for 5*M* and 10*M*. Total and average duration are shown in Fig. 6b and c. These illustrate much more clearly the progressive changes that have occurred with drainage and afforestation.

For the full range of flow thresholds, the residual annual number of pulses is shown in Fig. 7a. Similar residual relationships are shown for total duration in Fig. 7b and for average pulse duration in Fig. 7c.

6. Results

The analysis shows, in a consistent and comprehensive manner, the changes in hydro-ecological

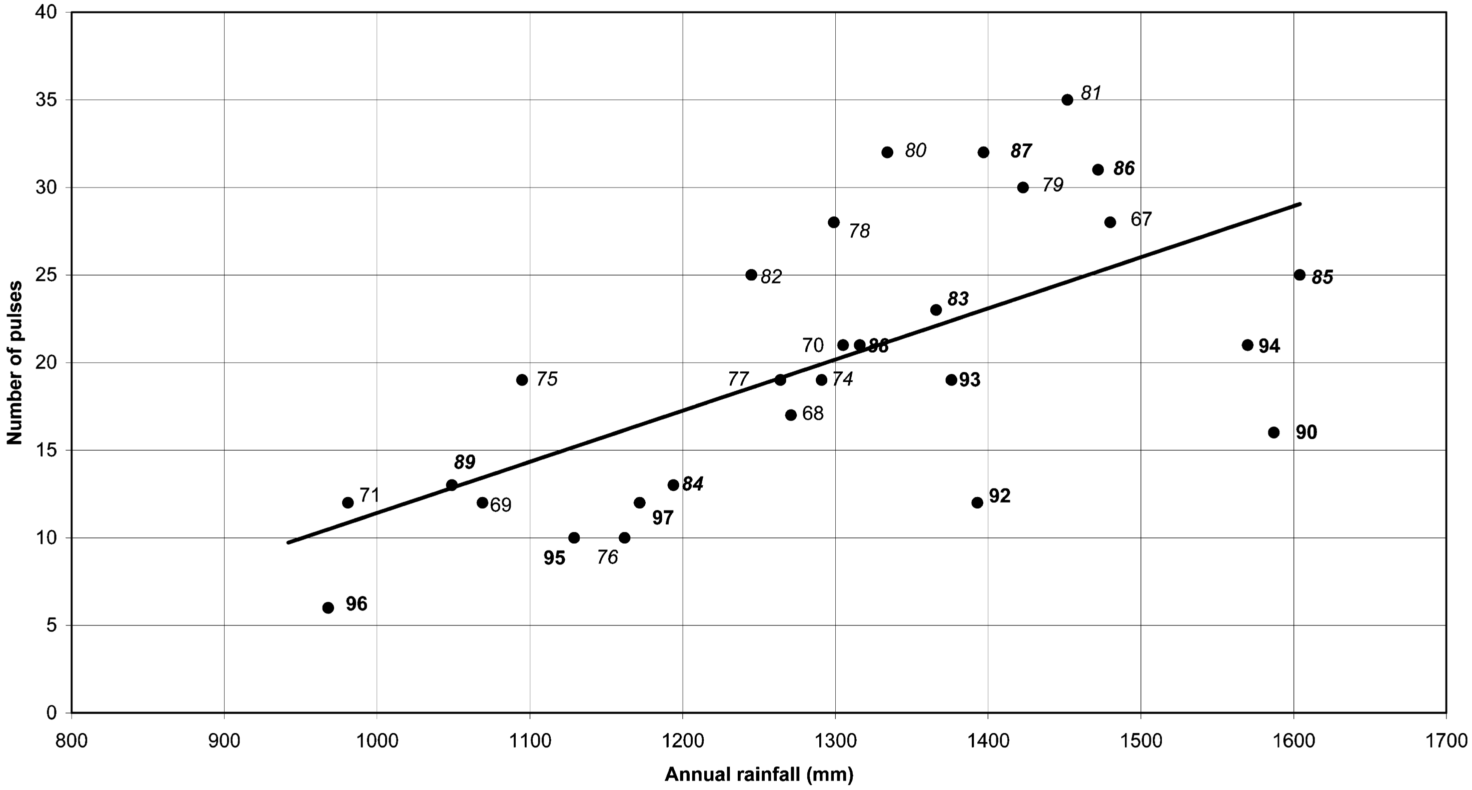

Fig. 5. An example relationship between annual rainfall and annual number of pulses above the 20*M* threshold, showing the relationship shifting with time and changing land use.

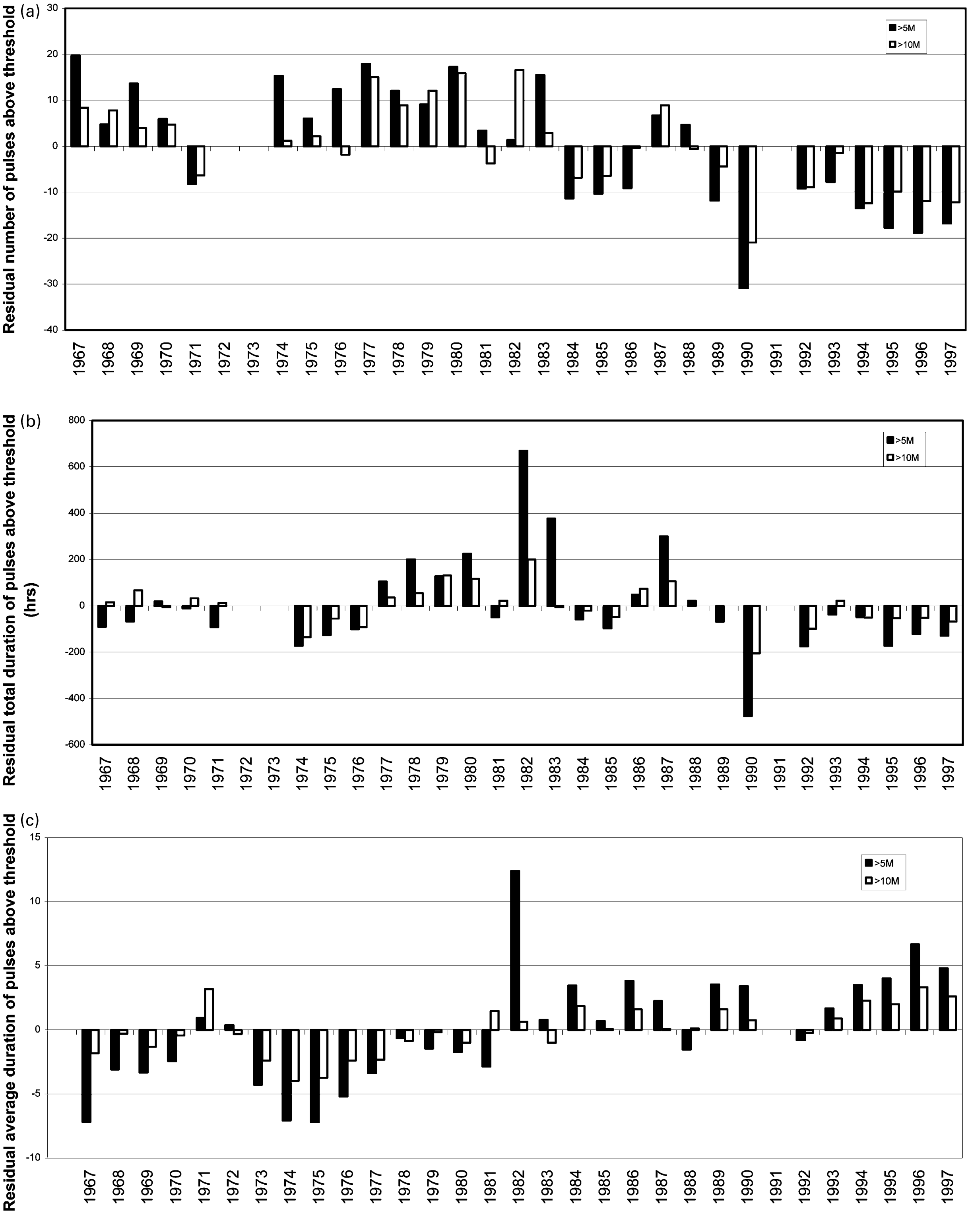

Fig. 6. Time series of (a) residual pulse numbers, (b) total pulse duration and (c) average pulse duration above 5*M* and 10*M* thresholds.

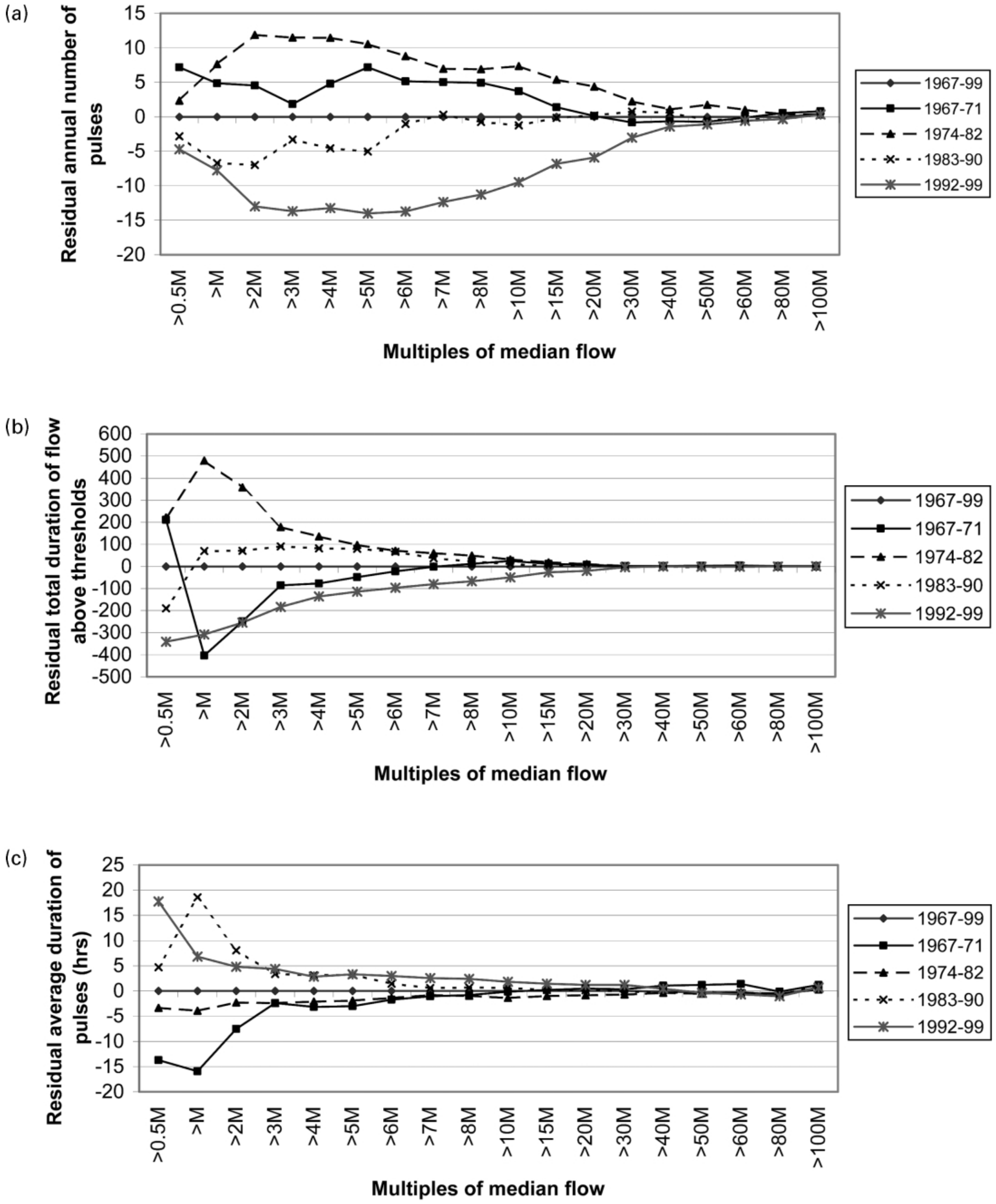

Fig. 7. Comparison of pre- and post-drainage and planting periods with respect to residual (a) pulse numbers, (b) total pulse duration and (c) average pulse duration.

regime which have occurred progressively with land use change and which have been illuminated by more conventional analytical techniques (Robinson, 1998; Robinson et al., 1998). These show more clearly in the residual diagrams (Figs. 6 and 7) than in the original series which do not take the effect of varying rainfall into account (Figs. 3 and 4).

Thus in Fig. 3a there are no obvious differences between the number of pulses immediately before and after drainage and planting. However there is an increase in pulse numbers in 1977 sustained until the early 1980s. Thereafter, there appears to be steady decline in pulse numbers above all thresholds. The total duration above the 5*M* and 10*M* thresholds (Fig. 3b) is at its lowest in the immediate post planting period but with a steady rise to a peak number in the early 1980s, thereafter also showing a steady decline. The average duration of pulses is more revealing (Fig. 3c), with a sharp step to the lowest average duration in the year following planting and then a rise in average duration which continues through the remaining period of record.

A similar sequence of changes occurs over each of the multiples of median flow as shown in Fig. 4a–c. With respect to pulse numbers (Fig. 4a) the immediate post planting period has by far the most flashy response but there is a marked and steady decline for the later periods as forest growth becomes established and the drainage lines become partially blocked or vegetated. The pre-plantation moorland response is closest to the immediate post drainage and planting period.

With respect to total duration (Fig. 4b) the moorland response (1967–1971) has surprisingly the lowest values over lower thresholds whilst the immediate post planting period has the highest duration. The pre-planting period also appears to have the lowest average duration per pulse (Fig. 4c) for thresholds up to 8*M* but, at thresholds above 40*M* this period has the highest average duration.

Results from the residual diagrams are similar but trends and step changes appear more clearly. With respect to pulses above the 5*M* and 10*M* threshold (Fig. 6a), little change is detected from the pre- to the post-plantation period but the steady decline from the early 1980s to the present is emphasised. For total duration (Fig. 6b) there appears to be a delay from the onset of planting in 1973–1976 before higher durations are established. This may represent the effects of exceptionally dry summers during that period. The relationship between pulse duration and rainfall may become non-linear when rainfall is exceptionally low and hence the rainfall correction during this period may be inadequate. A similar large deviation occurs in the summer drought year of 1990. However the decline in total duration from the early 1980s to the present is clearly seen. Residual average duration (Fig. 6c) emphasises the step change to lower duration after drainage and planting and the steady increase in average duration thereafter.

Residual diagrams of pulse number and duration over the full range of thresholds (Fig. 7a–c) provide the best basis for quantitative assessment of changes in catchment-scale runoff regime. Thus from Fig. 7a there are typically 10–15 fewer annual pulses in the most recent period (1992–1998) than the average over the whole period for thresholds in the range 2*M*–10*M*. There are nearly 20 fewer than under the natural moorland vegetation. In contrast, average pulse duration has increased by several hours over the same range. Total duration in the most recent period is lower than at any previous time except below the 2*M* threshold. The duration above the 2*M* threshold is now 700 h (nearly 1 month) less than during the immediate post planting period.

7. Discussion

This study complements the evidence for changes in hydrological regime already investigated on the Coalburn catchment (Robinson, 1998). However it presents these changes in a form relevant to the disturbance regime of instream habitat.

For example with respect to effects on high flows Robinson (1980) used unit hydrograph analysis to demonstrate that the UH peak was 40% higher after drainage than before, and that the time to peak was shortened. This study shows that for flows over a threshold of 8*M* the pre-afforestation average hydrograph duration was indeed greatest; however, changes in very high flows are not pronounced. What was not previously shown is that from pre- to post-drainage, the number of pulses and the total duration above each threshold increased substantially up to ca. 20*M*. Forest growth has brought about even more radical changes. Robinson (1993) notes that peak value and rise time are now close to the average pre-drainage levels. The marked and continuing reduction in pulse numbers (Figs. 4a and 7a) and increase in average pulse duration (Figs. 4c and 7c) had not previously been noted. The reduction in the number of pulses is more critical so that for all flow thresholds above $2M$ the total annual duration (Figs. 4b and 7b) is now lower than in any previous period.

The method does not address directly the effect of land use on water balance. Robinson (1993) noted reduced losses at Coalburn in the post drainage period and other studies have shown an increase in annual flow following artificial drainage (Seuna, 1980). This view is supported in principle by the increased duration above lower thresholds in the post-drainage period. However the subsequent reduction in total duration in 1992–1999 (Fig. 7b) suggests that losses through forest evapotranspiration have now overtaken the effects of drainage in their effect on water balance.

The method described is least satisfactory with respect to effects of land use on low flows and requires supplementation by other procedures such as Robinson's comparison of base flow index (BFI) over five year periods. This imperfection is important in relation to use of the technique to 'set' regulated low flows (e.g. downstream from reservoirs) but is less relevant in 'spatey' (or 'flashy') flow environments where biota become stressed, or reliant on refugia for longer periods, if higher flow thresholds are exceeded more frequently (see below).

Changes in the flow regime are but one impact of land-use changes on the river environment. Water quality, sediment transport, water temperature and light intensity together with changes in the flow regime may alter the river ecosystem. Plantation forestry in the UK uplands is known to have potential or actual impacts in all these categories. However, as Resh et al. (1988) have postulated and Clausen and Biggs (1997) have demonstrated, flow variability is a critical factor in determining the ecological status of a river. Where mitigation of e.g. water quality impacts is possible through precautionary land management it is the physical factors of runoff and sediment production which come into focus.

The use of the described indices of flow variability therefore not only provide a means of assessing the impact of land use change but also of examining the potential impact on river ecology. Where, for example, the physical habitat requirements of indicator species are known, the results of flow-variability analysis can illuminate both spatial and temporal changes in the availability of these conditions under certain land-use scenarios.

8. Conclusions

It is claimed that indices of flow variability provide a more comprehensive picture of hydrological regime changes due to changing land use than any other method currently in use. Furthermore, the analysis described uses a much-neglected archival data source in the UK (i.e. 15-minute flow data), on which considerable capital and operational funds are expended.

It is believed that it can be more widely used to track land use changes not only with respect to upland afforestation but also with respect to urbanisation and lowland drainage and to investigate the difficult problem of scale effects in land use change. A current focus for the technique is to extend the analysis downstream to the larger, River Irthing catchment to assess synchroneity of response at larger scales and the complications arising from other (known) rural land-use changes over time.

In terms of providing a hydro-ecological device for catchment management, the technique is at an early stage. It is easy to understand that an increased frequency, but shorter duration, of threshold crossings at higher flow exceedances (as proven here for the early stages of afforestation) may have a direct relationship with stress to instream biota—in ways that unit hydrographs and flow duration curves would not illuminate. For example, the availability of refugia (e.g. marginal deadwaters and pools), stability of individual bed material grains and velocity distribution in the general channel cross-section would all be profoundly affected. Such changes may partly explain the rather restricted (but improving) fauna of the Coalburn catchment and Upper Irthing, to which it contributes. It is appreciated that calcareous inputs from groundwater and high coloration from peaty (organic soil) sources of runoff both act to protect Coalburn fauna from episodic acidification but there are no such physical 'buffers'. The most recent surveys of benthic invertebrates and fish at Coalburn are indicating a recovery in diversity and biomass and, as data collection continues it is the aim of this research to update the flow variability analysis to set up a parallel data series.

However, full development of the technique relates to an integration with geomorphological survey techniques that map meso-scale habitats in physical terms (Newson and Newson, 2000). It is already appreciated that in many rivers the optimum diversity of physical (hydraulic) habitats occurs at median flows or above (Newson and Newson, 2000), and so the reduced resolution of the flow variability technique at low flows is less of a problem. By relating pulse analysis of gauging station records to repeated mapping of physical biotopes in nearby reaches (Newson et al., 2002) the space/time behaviour of biotopes which have known significance for biodiversity (e.g. riffles and pools), can be visualised as a function of flow regime in the spirit of Petts (1996). Thereby, assessment and management of 'environmentally acceptable flow' (regimes) and departures from such standards can be assisted by empirical, as well as hydraulically modelled information. This simple data-based approach may prove essential for such national-scale policies as catchment abstraction management.

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